Chapter 9

Conclusions and Outlook

In our travels through psychological and psychophysical color spaces it was shown that a uniform color space can only be defined for a narrow set of conditions and that there is a multiplicity of uniform spaces, each representative of a specific observation situation. It also has become clear that there are an infinite number of regular color spaces in which colors are ordered in systematic sequence (and in the same ordinal order as the perceptual space) but are not uniform. Color solids can fit into any desired euclidean space form if the concept of uniformity is absent. This text is limited to the case of achromatic surrounds, a situation that is not expressive of most natural viewing conditions but represents a useful elementaristic experimental simplification. It is also in agreement with usual industrial observation conditions for the purpose of color quality control. On this journey we have learned that we have only a fraction of the information required to build accurate models of human color vision that speak to the problem of uniform color space.

There are various uses of a color solid, and they have resulted in several different major kinds of spaces. There is the uniform color space, classically defined by Judd, in which equal geometrical distances in any direction (given standard viewing conditions) represent equal perceived differences. There is Hering's "natural color system" in which colors are ordered by their content of unique hues as well as blackness and whiteness. Here lightness is not an attribute and chromaticness is uniform for all maximal colors. There are nonuniform color spaces used in communication and color management, such as the RGB, HSB, or CMYK spaces. Finally there are a number of psy-

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chophysical color space models that order colors and generally have no claims of uniformity, such as the CIE tristimulus space, the x, y, Y space, the Luther-Nyberg space, and many others. For those without claim to uniformity, the general designation regular color space has been proposed. In addition there are spectral spaces derived from mathematical dimensionality reduction of spectral functions of color stimuli not involving cone or color-matching functions.

For a period of some 150 years there was belief that all object color perceptions, uniformly spaced, could fit into a simple geometrical solid. Munsell was the first to show that if uniformity of differences is a goal this belief is misplaced. Since then it has become evident that a Munsell level uniform color solid cannot fit into a euclidean space.

The following is a discussion of a number of significant issues related to color spaces and solids with stated or proposed answers (depending on the strength of current evidence).

9.1 WHAT ARE COLOR SPACES AND HOW CAN THEY BE JUSTIFIED?

Color spaces and color solids represent attempts to show a multitude of possible color perceptions in a systematic fashion. This is an effort that faces several philosophical and scientific problems. We do not know how we perceive colors as part of our consciousness. From an extreme point of view (see Saunders and van Brakel 2002) this dooms the entire enterprise. We can all agree that there is no generally valid direct relationship between spectral power entering our eyes, and thereby between reflectance functions of objects, and our experiences of color. Experimental work in color scaling under elementary conditions and work in color technology indicate, however, that for such conditions there is a reasonably solid relationship between members of a class of metamers and the resulting color experience as judged by an average color normal observer. Without it, colorant formulation and color technologies of various kinds (color photography, television, color printing, etc.) would not work as well as they do. Is viewing color fields under elementaristic conditions a true reflection of natural color experiences? The answer, obviously, is no. However, the evolutionary development of human color vision should not be confused with its current average operation. Arguments can be made that (in industrial countries) we experience color today more often in unnatural as well as quasi elementaristic conditions (looking at a video screen or color television) than in natural conditions (except when on vacation). Does it mean our color experiences are degraded? Does the color vision system of young children now develop differently from that of our grandparents? We do not know but it is unlikely to be so.

The hue sequence of the generally accepted hue circle derives its justification from the spectrum and the mixture in various ratios of narrow band energy from the two ends of the spectrum. For the reason that color experience is private we can only assume that one person experiences the colors of spectral lights approximately the same way the next one does (assuming they do not have impaired color vision). That photometry can produce an ordinal scale of gray objects viewed under elementaristic conditions is without doubt. Perceived brightness of chromatic objects, as was shown, is not in agreement with photometric results, for reasons that we do not know. Speculative models can, however, result in a high level of agreement with average visual data. Quantitative relationship at the ordinal level for elementary conditions also exists quite clearly between spectral power distributions of metameric sets and the resulting perceived saturation or chroma. All these relationships have high rank order correlations. Such information has provided the basis for simplistic color models attempting to relate under elementaristic conditions physical data of lights or materials with the resulting average perceived color. For the models to be quantitatively useful they must have a higher degree of complexity. There is no doubt, and the history of chapters 2 and 6 clearly indicates it, that often (in an absolute sense always) large houses of cards are erected in the building of these models. But as the history of science shows this is how progress toward reaching goals of understanding is made. Will humans understand their color vision system in 50 or 200 years, or never? Time will tell.

The curious thing (or perhaps not) is the considerable practical level of success that color science has gained in coloration technology, color device technology and color management with the kind of house of cards models just mentioned. None of these is perfect and perhaps never will be. One good reason is that there is just too much variation in individual experience from a given stimulus set. These relative successes have given color scientists and technologists a level of confidence that the conjectured relationships might not be totally coincidental. Coloration of textiles, paints and plastics can now be controlled at levels approaching just noticeable differences. Metamerism for a limited number of light sources can be avoided and it is even possible to obtain a good idea if a matched material sample will or will not have a similar appearance under different lights.

All existing color spaces and solids result in color experiences that are at least in ordinal order of perceived color. (It is not known if this applies universally to color normal observers.) To produce an atlas that is an accurate representation of a perceptually uniform color solid for a given set of conditions is impossible at the level of large differences. But this does not seem to be important as long as it is understood in what way the atlas configuration deviates from the space implied by its samples (as we know we cannot produce accurate large scale flat geographical maps). Such an atlas has not yet been produced. The best color difference formulas for small color differences have limited accuracy for reasons that have not yet been investigated in detail. The models are likely too simplistic but, as discussed before, there are also many issues of observer panels and observation conditions. The technical value of improved formulas makes their pursuit worthwhile.

9.2 WHAT CAUSES THE PERCEPTION OF COLORS AND THEIR DIFFERENCES?

Colors are psychological experiences. To explain them reductively with neurological processes (if that is possible) requires linking propositions that attempt to create a credible link between subjective experiences and objectively measured data related to neural responses or physical measures of reflectance (or spectral power). Today the chain of such arguments built to explain perception of colors is far from complete. But there is unanimous support for cones as the sensing devices for light entering the eye at daylight level. The path of the electrochemical signals generated by the cones as a result of light absorptionn leads through retinal cell layers into the brain and passes through the lateral geniculate nuclei as major way stations to visual areas V1 to V4 in the back of the brain. Area V4 is strongly implicated in color vision, and several kinds of cells have been identified as responding to color stimuli (up to date details can be found in Gegenfurtner and Sharpe, 1999, and De Valois, 2000). Here any degree of certainty ends. V4 signals may be said to disappear into a black box out of which color experiences appear in an unknown process. S. Zeki and A. Bartels (1999) believe that conscious color perceptions are generated in area V4 and may be directly related to (or are) the electrochemical signals in V4. Color categorization and difference perceptions, as discussed in Chapter 3, appear to involve additional regions in the front of the brain.

There is growing awareness that, to some extent, our perceptions of forms and colors are formed through empirical interpretation of the ambiguous light signals reaching our retinas, in a form of neural networks, based on our millennia-old experiences as a species and possibly also our experiences as individuals. A complete vision theory must be able to explain all perceptual results. *It is assumed that by limiting ourselves to simple targets and simple relativized observation conditions, it might be possible, for these conditions, to reduce much of the link to between, say, neural events in V4 and perceptions.*

In this path and chain of events several types of cells have been identified that combine in various ways the output of the three cone types over smaller or larger areas in the retina. Some ganglion cells and cells in the LGN have opponent character somewhat akin to that suggested by Hering. However, as seen earlier, there is no direct link between the output of these cells and unique hues. The implication is that there are additional steps required, for example, the subtraction of a fraction of the β opponent signal from the α opponent signal (Chapter 6). In addition the salience of the unique hues may be due to as yet unknown brain processes, and they may only be indirectly related to a and b opponent signals. Color cells in V4 do no longer appear to have simple opponent character, and opponency here may be between cell groups rather than within cells (De Valois, 2000).

The nature of the relationship between color matching and color appearance is not clear. Color-matching functions change with the size of the test fields. But there is little change in appearance of most colored materials as a function of field size. The output of a particular cell type correlates well with luminance as measured under specific test conditions and is likely to supply raw data for brightness and lightness perception. As mentioned in Chapter 5, chromatic perceptions carry with them a brightness component independent from flicker luminance, giving rise to the Helmholtz-Kohlrausch effect. Brightness discrimination, presumably, is the result of higher-level comparison of the brightnesses of two contrasting fields, influenced by how our visual system interprets the scene in which the two fields appear.

Color perceptions fill areas of the visual field surrounded by contrasting contours. A case can be made that color exists only as contrasts, since in the absence of contrasts, in a so-called *ganzfeld* view where the eye is covered by translucent, spherical, colored cups, color fades after brief exposure. This implies that signals from both sides of contours are compared along the visual path and color experiences are generated as the result of complex computations of the brain taking into account many aspects of the visual data provided by the eyes.

The fundamental nature of hue and lightness perception is not in doubt. The degree of contrast of any chromatic perception against a neutral surround, namely saturation or chroma, appears to be in terms of fundamentality a step below those primary perceptions, perhaps because achromatic surrounds as well as saturation or chroma scales are rare in natural scenes.

As discussed in Chapter 6, in simplified conditions hue perceptions are believed to be formed either as the result of a ratioing process where opponent signals are compared or as the result of perhaps weighted averaging of the output of a number of hue detection processes. Hue discrimination, presumably, is the result of a comparison of two fields with different opponent signal ratios or different averages of multiple hue processes (see Section 9.11).

While hue perceptions may be the result of a comparison of the ratio of opponent signals of a field to that of its surround, chroma perceptions may be the result of the absolute level of opponent signals generated by a field to that of the surround. Brightness perceptions, in turn, may be the result of a comparison of the luminance signal combined with a fraction of the opponent signals (if any) of the test field compared to the same combination of the surround. All three are affected by specialized processes that modify perceived hue and enhance or reduce contrast.

By limiting the visual field to a simple set of conditions, the effect of many of these specialized processes appear to remain relatively constant. In this case the variables may be limited, for object colors, to the reflectance functions of the surround and of the two test fields, as long as the display is viewed under a constant light source and in a standard configuration.

9.3 WHY IS OUR BASIC COLOR EXPERIENCE THREE-DIMENSIONAL AND WHY ARE THERE FOUR UNIQUE HUES?

These are very fundamental questions in regard to color space. Our immediate experience of the world as expressed through visual and tactile clues is three-dimensional. As discussed before, the geometry of our *visual* space is three-dimensional but with a Riemannian geometry. Further the fact of three cone types involved in color vision argues, on the surface, for a three-dimensional expression of color experiences. But, as discussed in Chapters 4 and 5, our psychological color space is not directly related to the cone sensitivity space. There are important transformations, some of which have only been guessed at so far. In relativized standard conditions the sum of *L* and *M* cone signals is related to the flicker brightness experience. Perceived heterochromatic brightness has a more complex basis. Hue experiences may be related to opponent color signals and are correlated with them in ordinal and even roughly interval order. Saturation scales result from additive mixture of stimuli, causing complementary chromatic, as well as mixtures, causing chromatic and achromatic experiences. The three cone types are not the immediate cause of our elementary three attribute color experience. The cause may be complex cone signal derived mechanisms one of which appears to result in hue, another in saturation and to some extent brightness experience, while a third contributes the major portion of the brightness experience.

In 1964 Judd and co-workers showed that a large variety of measurements of terrestrial daylight can be expressed with three basis functions. (However, such reconstruction is only reasonably accurate for correlated color temperatures down to 5000K, and the corresponding CIE procedure is only applicable to that limit. This limits the applicability to "white" light and excludes the more strongly colored lights of sunrises and sunsets or colored light reflected from vegetation, etc.) Shepard (1992, 1994) believes the three basis functions of natural daylight to be responsible for the existence of our three cone types and, thereby, for our three-dimensional psychological color experience. This conjecture appears to be anthropocentric and thus not to explain the reduced number of cone types in many other vertebrates as well as the spectrally shifted cone sensitivities of some vertebrate and invertebrate animals. In the animal kingdom numbers of color-related cone types with different spectral sensitivities in a species range up to ten (for mantis shrimp; Cronin and Marshall, 1989).

An alternative conjecture bases the number of cone types in a given genus, their spectral sensitivities, and the resulting refinement of the information in the brightness and opponent color systems on specific pressures in their ecological niches and the accidents of random gene mutations. The energy of sun radiation peaks in the visible region, a good reason for placing receptor sensitivities between approximately 320 to 760nm. While cone sensitivities found in nature are limited to this range, the number in a genus may be an empirical compromise between visual acuity (sharpness of vision) and need (at one time or another) for spectral discrimination.

The question why four basic hues (and not more or less) seems not yet satisfactorily answered. Hering has not posed it but merely stated the fact that there are four basic hues and black and white. This number appears also to be somewhat accidental. If basic hues are a result of opponent signals, then three cone types, in theory, make six basic hues possible. But because of the high degree of spectral overlap of the *M* and *L* cones, there would be a considerable amount of redundancy in the information. Four basic hues were sufficient to support the survival of our genus.

In the matter of the number of basic hues an intriguing conjecture was recently offered by Lotto and Purves (2002). They claim that we have four basic hues in response to the need "to solve the four-color [topological] map problem" as well as "to order spectra according to their physical similarities and differences."

It is evident that broad band sensors can only provide effective discrimination with overlap of the sensitive regions. Thus, having a short wavelength sensitive detector added with some overlap to a midwavelength sensitive detector improved discrimination capabilities in the visible region. Dichromats can discriminate more than monochromats. Adding a third, overlapping sensor improved discrimination further. Information manipulation was now required to avoid considerable redundancy of information and to normalize perceptions at different levels of lightness. Based on three cone types the minimal opponent system has four basic hues. It can be considered evolutionarily sufficient (since that is what we have), but it is certainly not optimal. There is a large spectral range (from about 580 to 730 nm, nearly 45% of the total visual spectral range) where there is comparatively little discrimination. On the short wavelength end the discrimination ability has been significantly improved (perhaps by up to 20%) by the reappearance of redness. Mathematical analysis shows that filtering of spectral data through the color-matching functions is not optimal in terms of extraction of the information from the spectral data and ordering of spectra according to their similarities. Three principal components and other techniques do a considerably better job. But cone absorption is a process with biological limitations, and our visual system represents a compromise between what is desirable and what is biologically possible. The question is which evolutionary pressure was larger, that of improving discrimination capability while maintaining a high level of visual acuity or the unambiguous solution of the four color map problem?

9.4 WHAT ARE THE FUNDAMENTAL PERCEPTUAL COLOR ATTRIBUTES?

The conventional, but not uncontroversial, view is that they relate to lightness and hue perception, as well as to intensity of coloration. In terms of evolutionary development brightness/lightness is the oldest perceptual variable. It antedates the development of color vision. Its current implementation in humans appears to be of complex nature, fine-tuned to allow useful interpretation of the visual field in terms of light, shadow, and forms. But today it is not the most salient attribute. This position belongs to hue. Color is defined primarily by hue because of the dramatic nature of our hue experiences. Natural hue experiences can be subdued in a late fall Northern landscape but are riotous in a tropical forest. Artificial coloration has expanded the possibilities of strong and varied hue experiences. The importance of hue is further supported by the fact that a seemingly elaborate (but in detail unknown) apparatus has been put in place to make possible our ability to make fine hue distinctions. Hue can be described psychologically in terms of the four Hering unique hues, as Hering, the developers of the Swedish NCS system, Indow, and others have shown.

Hering was clearly aware of brightness/lightness but did not accord it status of a fundamental color attribute. Instead, he used blackness and whiteness as modulators of hue, with a derived attribute of chromaticness. Such a system has steps, in terms of uniform perceived differences, of considerably varying size in all directions. Multidimensional analysis of the NCS system using magnitude of perceived difference between steps would undoubtedly arrange it in a Munsell type configuration with the samples placed at widely varying distances. Hering type systems that disregard lightness as an attribute can fit conceptually into a simple geometrical solid, as they are not concerned with uniform differences.

Judging the size of perceptual color differences between objects against a standard surround—a conventional psychological task—leads to a system based on hue, lightness, and chroma attributes. If hue and lightness are given fundamental status for colors of objects in relativized conditions, the third perceptual attribute is chroma, as Munsell discovered. A systematic arrangement based on uniformity of difference in such a system does not fit into a simple geometrical solid, nor can it be modeled in a euclidean space, as additionally discussed below. It apparently has never been tested competitively under controlled conditions which of the attributes, blackness/whiteness or chroma/lightness, can be experimentally measured with less variability.

While both types of system are uniform in some sense, it is proposed to reserve the term “uniform” for uniformity of perceptual distance only and to use the general term “regular” for others.

9.5 HOW ARE HUE, CHROMA AND LIGHTNESS PERCEPTIONS COMBINED?

In Nickerson’s Index of Fading the three components, properly weighted, are simply added. Indow has come to a comparable result based on his perceptual formula. The OSA-UCS data provide no information in this regard because the basis data for the set involved mixed hue and chroma differences. Suprathreshold small differences have only been evaluated as mixed hue, lightness, and chroma differences, and an untested assumption of their euclidean summation has been made (Chapter 5).

Boynton and Kambe (1980) have raised the possibility of hexagonal chromatic contours. The chromatic discrimination contours of Krauskopf and Gegenfurtner (1992) have been fitted with ellipses and circles, but many may be equally well described by polygons. Superelliptical contours were calculated by Teufel and Wehrhahn (2000) for threshold data. Rhombic chromatic threshold contours in cone contrast space have been fitted by Strohmeyer et al. (1998) and by Giulianini and Eskew (1998). Sankeralli and Mullen (1999) tested hue increment identification using combined hue and contrast increments and concluded that hue increment identification ignores differences in contrast (chroma) and that the two types of discrimination may be inherently separate.

There is strong evidence that in a polar coordinate, psychophysically "uniform" chromatic diagram (uniform hue and uniform chroma scales), the unit difference contours are elongated in the direction of chroma, indicating that hue difference discrimination is intrinsically more sensitive in terms of stimulus increments than contrast discrimination. Explicit evidence is found in the work of vision scientists as well as in threshold and suprathreshold object color difference data, including the Munsell system. Elongated unit contours are implicit in the basis data of OSA-UCS, a fact that has been suppressed in the final system. Such evidence is the basis of Judd's term "superimportance of hue."

The Nickerson and the Bellamy and Newhall evaluations indicate unit contours to become slightly more elongated when the differences become smaller (2:1 at the level of Munsell chips vs. 2.8:1 at JND). On average, for small suprathreshold chromatic differences the ratio is found to be approximately 2.2:1 (Chapter 8). The shape is generally taken to be elliptical. Conceptually it is unlikely to fit the simple geometrical form of an ellipse.

How chromatic and lightness differences are combined is also a not a question that is resolved. Recent neurological investigations show that "interactions between color and luminance variations can be complex and not easily predictable" (De Valois, 2000). In terms of color difference formulas the general assumption has been that the sum is euclidean. Based on his color-matching error work MacAdam maintained that the resulting ellipsoids have horizontal alignment (e.g., MacAdam, 1981; Section 8.4). Threshold and suprathreshold color differences are fitted better with formulas that result in an ellipsoid tilted at higher lightness in the direction of the neutral axis, as is the case with CIELAB and related formulas.

9.6 WHAT CAUSES THE PERCEPTION OF THE MAGNITUDE OF COLOR DIFFERENCES?

At this time the answer to this question, in neurophysiological terms, is not known. From findings in Chapter 8 we can conclude that at the color-matching error level differences are largely due to sensitivity limits of the cones. This is fully the case for the MacAdam data and largely for the Wyszecki-Fielder data. At the threshold level, based on the Richter data, an opponent color system seems fully engaged, as evidenced by the lower *S/L*, respectively *Z/X*, ratios. This is the case for larger color differences up to and, likely, exceeding the size of OSA-UCS differences. Here power relationships connect stimulus and perceived difference. The applicable powers and the weighting constants (different by semi axis) are found to vary widely in different experiments for reasons that are not clear but may involve the design of the experiments or the observer panels. Different optimal powers and weights appear to indicate independence of at least four chromatic processes. The immediate reasons for the power relationship are not known but assumed to be saturation effects of various cell types.

The relative enlargement of unit *L* increments against unit *S* increments for threshold and larger differences compared to CME data signals a sea change, the change from the Helmholtzian cone level to the higher zone, opponency level. The higher intrinsic sensitivity of the *L* and *M* cones compared to *S* is suppressed. Regardless of the input from cones, here one unit of *a* is equal to one unit of *b*, with the positive and negative functions in balance. The relative number of *L*, *M*, and *S* cones per unit area in the retina does not seem to play any role in this situation. The new ratio of implicit *L* versus *S* response of the first step from gray is valid throughout the range of differences from threshold to OSA-UCS sized (and very likely larger) differences.

9.7 CHRISPENING EFFECTS

Crispening effects impose significant modulation on the relationship between stimulus and perceived colors or color differences. They are the result of an environmentally useful adaptation that makes minor spectral differences of objects against surround especially well discernible. As discussed in Chapter 4, stimulus increments/decrements resulting in a criterion difference perception are smallest if the test field stimuli straddle that of the surround color. The more the surround differs in hue, chroma, or lightness from the test colors, the larger will be the required stimulus increment for a criterion difference response between the test colors. Highest chromatic discriminability is thus available in a chromatically relatively homogeneous environment, and comparably for lightness discrimination. Like lightness crispening, chromatic crispening may depend on test field size. Detailed quantitative data are not available in both cases.

Crispening effects result in V-shaped functions of unit increment versus stimulus (*L*, *M*, *S* or *X*, *Y*, *Z*) with the vertex pointing at the surround point (Chapter 8). In these functions different observers and, presumably, different observation conditions result in different angles between the legs of the V function. Functions for brightness and lightness data and for the *S* (or *Z*) cone have larger angles than functions for the *L* and *M* cones.

Lightness crispening in simple surround conditions is controlled by the luminous reflectance of the surround and, probably to a lesser extent, by the test field size. Increments for a criterion response become increasingly larger as the test field luminous reflectances differ from that of the surround. Color space and difference formulas so far have generally not considered this effect. If achromatic reference pairs are used the magnitude of difference perceived between them is also subject to the lightness crispening effect, that is, the psychological magnitude of the difference between two gray reference samples depends on the surround and the relative size of the fields. This issue affects comparability of different data sets based on different surrounds. The lightness crispening effect is active from threshold size differences to differences of the size found in the Munsell value scale and, likely, larger differences.

The chromatic crispening effect is, on a relative basis, about equally distinct for L and M compared to S. The L increment required for criterion response quadruples approximately over a change in L of 10 units from the neutral point in direction of increasing L, less so for decreasing L, as the increment is a sum of the fundamental increment and the chromatic crispening increment. As has been shown in Chapter 8, it is most strongly active at the level of CME and threshold differences and appears to gradually fade as chromatic differences become larger. It is absent at the level of Munsell double-chroma steps or OSA-UCS steps.

Chromatic crispening makes it possible to euclidize the Riemannian space implicit in small color difference data. The approximate factor 2 of the ratio of the longer (chroma-related) to the shorter (hue-related) diameter of the unit contour has been included in the S_C weight adjusting for chromatic crispening. Since this weight is a continuous function of chroma it can be integrated in the euclidization of formulas like CIE94.

9.8 PERCEPTUAL INCREMENT MAGNITUDE AS A FUNCTION OF STIMULUS INCREMENT MAGNITUDE

Despite the findings of Plateau the question of increment magnitude for a criterion response as a function of stimulus magnitude was dominated for the second half of the nineteenth century by Fechner and the Weber-Fechner law indicating the required increment to be a constant fraction of the stimulus. Study of lightness scales from black to white in the early twentieth century and additional investigations of other sensory magnitudes pointed to the applicability of power modulation. Different experimental conditions resulted in different optimal power modulations. The findings in regard to crispening discussed in Chapter 8 indicate that the Weber-Fechner law is generally not applicable to color differences. It is also apparent that simple power functions, as proposed by Stevens, are not representative of color differences from subthreshold to medium size.

In global psychophysical color space scaling efforts the Munsell value scale, with its suppression of the lightness crispening effect (and its fit with cube root modulation) and the proposal by Adams in 1942 to apply cube root modulation also to the X and Z tristimulus values, proved influential and continues to be the official paradigm of the CIE. This situation has been influenced in the past by computational difficulties and then by habit. The evidence derived from the Munsell Renotations and the Re-renotations is that different powers are optimal for the four chromatic semi axes. Conceptually it would be surprising if the complex processes of the visual and related cognitive systems could be accurately modeled with a single and simple power modulation. This matter has not yet been thoroughly investigated in regard to threshold and suprathreshold small color difference data.

Experimentally determined incremental and decremental stimulus amounts lack a solid foundation in neurophysiology. The prevailing explanation involves cone response saturation effects. It is unlikely to be the complete story. The situation is complicated by the fact that psychophysical models need to account for three effects in the chromatic plane:

1. Basic nonlinearity of the tristimulus space. Unit contours in the normalized X, Z diagram are elongated. They are largest and most elongated when Z values are large. The contours are smallest for yellowish-greenish colors. Power modulation of the scales linearizes them and makes the ovoid contours of small color difference data at a given chroma approximately equal in size. It makes the ovoid contours of Munsell data approximately equal in size throughout the diagram.
2. The chromatic crispening effect changes the size of contours of small color difference data as a function of chroma. The power-modulated (i.e., normalized in the four quadrants) contours differ in size by a factor of 4.4:1 as a function of chroma in a metric chroma range from 0 to 100 (Chapter 8).
3. The unit contour in a euclidean diagram is fundamentally elongated and the elongation may be a function of the size of the differences, as seen in the previous section.

In formulas such as CIE94 and CIEDE2000 the cube root formula addresses point 1. The weight on chroma differences and the chroma-related weight on hue differences addresses points 2 and 3.

9.9 HOW WELL DO FORMULAS PREDICT PERCEIVED COLOR DIFFERENCES?

As seen in Chapter 6, correlation between average visual data and formulas can be improved to some extent with empirical modification based on regularities observed in the data. Such modification is often specific to a given data set. When looking at agglomerations of data approximately two-thirds of the variation in average perceived difference is predicted by the best formulas. The performance factors PF/3 (a performance measure approximately equivalent to error percentage) of the combined data set used in the development of CIEDE2000 as well as of various subsets assembled from different original data sets (hue, chroma, and lightness differences, as well as others) are uniformly from 30 to 34. Similar values have been obtained with that formula for specific data sets such as BFD, Witt, and BIT. The only exception is the RIT-DuPont data with a value of 19. While the PF/3 results for the BFD data improve from 56 for CIELAB to 37 for CIEDE2000, the improvement for RIT-DuPont is only from 22 to 19.

Progress in the accuracy of prediction can only be made if the source(s) of the error component representing one-third of the total variation of the formula can be determined. In an analysis of five sets of data for several of them significant increases in correlation were obtained by adjusting the size of the perceived difference by size factors seemingly nonsystematic for each color subset (Kuehni, 2001b). No agreement in these factors for given color regions in the different sets could be found. The factors ranged from approximately 0.7 to 1.5. This indicates that the size of average judged difference in a given color region varies significantly in different experiments despite efforts at normalisation. At this point the changes appear to be random, but detailed investigation into the potential causes has not yet been made. When the remaining major discrepancies in the RIT-DuPont set are analyzed, they appear to involve primarily complex differences with hue, chroma, and lightness components, hinting at non-euclidean addition. Among other potential causes are observation conditions such as lighting and surround, composition of observer pool, subjective strategies of the observers, method of averaging individual results, choice of reference difference, and nature of dividing line between samples.

9.10 IS UNIFORM COLOR SPACE EUCLIDEAN?

Psychophysical models provide fits of greater or lesser degree to psychologically uniform color difference data. But euclidean depictions of psychological color space are not uniform, unless (for small color differences) achieved by a special euclidization step. The Munsell chromatic diagram is approximately uniform in terms of hue (at one chroma level) and in terms of chroma, but not both. If the scales are adjusted to equality the chromatic plane can only be illustrated as a crinkled fan. It is not known how far reaching Nickerson's investigation of the relationship of hue and chroma differences were as a function of chroma. If the S_H weight is a truer representation of facts than an assumption of a constant ratio between hue and chroma differences as in the Nickerson formula, the uniform color space is Riemannian. As discussed, a portion of S_C

(together with S_H) eliminates elongation of the unit contour. It is not clear that it actually does so because the complete hue circle has not been scaled relative to chroma in connection with color difference formulas that have such weights.

Euclidean structure has been denied by Judd (1968) in case of a space based on a constant achromatic surround with arguments involving the superimportance of hue and crispening effects. An additional argument was called "diminishing returns in color difference perception." MacAdam had pointed out in 1963 that if there are three color samples A, B, and C selected along a geodesic so that samples A and C appear equally distant from sample B, samples A and C are seen as having less than twice the difference between A and B or B and C. In other words, the applicable scale is an interval scale but not a ratio scale. This effect may be connected with the fading of chromatic crispening for larger differences and the changing of the unit contour elongation ratio as a function of size of the difference.

In 1995 Wuerger and co-workers reported on tests of euclidean color geometry. In one test they used proximity judgments to determine the angle between intersecting lines in color space, and three kinds of tests for the additivity of such angles were made. All three failed to support a euclidean structure. In a second experiment the increase in variability of judgments of similarity with the distance between test and reference stimulus was determined. Also this experiment failed to support euclidean structure.

The euclidean addition of hue, chroma, and lightness differences does so far not seem to have been tested explicitly at the level of suprathreshold small or large differences and under conditions representative of industrial practice (no control of local adaptation). Among the reasons are the difficulty in preparing accurate, well defined samples and the lack of replicated uniform chroma, hue, and lightness (including the Helmholtz-Kohlrausch effect) scales.

As mentioned, euclidean structure with luminous reflectance as one dimension also can be expected to fail because visual lightness perception of chromatic samples involves not only luminous reflectance but also the presumed contribution of the opponent color system in the Helmholtz-Kohlrausch effect. Resulting constant psychological lightness planes are not orthogonal to the achromatic lightness axis.

The question arises if it is useful and veridical to appropriately transform, for small color differences, a^* and b^* scales by integration so that the resulting diagram is of euclidean nature, as Thomsen and others have shown and as implemented in the DIN99 formula. Given the many remaining problems, some addressed in CIEDE2000, the result is likely less than satisfactory and not useful for large color differences. Another version of integration used in the past is projective transformation, extensively employed by MacAdam. However, his best effort in devising a nonlinear transformation for the OSA-UCS basis data did not result in correlation improved over that obtained with a cube root based euclidean formula.

9.11 UNIQUE HUES AND UNIFORM COLOR SPACE

A psychological euclidean color space with the unique hues on the axes is not uniform in terms of differences because hue differences representing identical hue angle differences are of different perceptual magnitude in the four quadrants (Chapter 4). In addition there is the matter of the elongated unit contours.

There is poor agreement between the cone contrast chromatic diagram axes and unique hues. There is only slightly better agreement in case of a chromatic diagram based on opponent functions derived from CIE color matching functions. But there are two major issues here also:

1. The implied unique hues of the two standard observers, taken as the crossover points of the opponent functions, are considerably different. This implies that the primaries represented by the system axes are of more or less mixed hues for both standard observers.
2. In terms of both standard observer opponent color functions objects seen on average as unique red and unique green have a considerable positive *b* ("yellowish") component.

No form of transformed color matching and related opponent functions seems to exist where the four average perceived unique hues fall on the axes and a constant perceived chroma circle is represented as a circle (Chapter 5).

The processes behind unique hues are unknown and may have a location different than opponent processing. But even when known, there remains a systematic discrepancy between a space based on unique hues and their standard increments and decrements and a uniform space.

9.12 EVIDENCE FOR THE OPERATION OF AN OPPONENT COLOR SYSTEM

Aside from the neurophysiological evidence and the purely psychological evidence in the Hering sense, there is considerable indirect psychophysical evidence. In a cone-sensitivity space an approximately perceptually uniform system such as the Munsell system is placed in alignment not in agreement with any of its axes (see Fig. 5-29). Rough alignment with the axes is only obtained in a tristimulus space and constant chroma circles at different lightness levels only become concentric if the chromatic diagram is based on opponent functions (Fig. 5-31). In other words, a reasonably accurate model that places the information contained in reflectance functions of the Munsell system into a corresponding psychophysical model requires opponent color functions.

Implicit evidence for an opponent system also comes from the fact that cone increments required for the perception of threshold and suprathreshold differences are, in case of L and M cones, not related to their intrinsic sensitivity as expressed in color-matching error but represent increments of approximately double relative magnitude. Such enlarged increments are consistent with the operation of an opponent system.

Perceived brightness/lightness of chromatic colors is not in agreement with power-modulated flicker luminance/luminous reflectance. But it can be modeled closely with addition of a portion of opponent color activation to flicker luminance (Chapter 5), indicating that perceived brightness/lightness of chromatic colors is not a dimension of tristimulus color-matching space.

9.13 OPPONENT SIGNALS: THE SOURCE OF HUE AND CHROMA PERCEPTIONS?

In Chapter 7 evidence was offered that it is not possible to represent the Munsell system as a uniform euclidean color solid because of the superimportance of hue. Because of chromatic crispening the effect of hue superimportance can be integrated in small color difference data to end up in a euclidean system. As mentioned, this may not be possible at the size of Munsell color differences where chromatic crispening no longer applies. This fact may be a consequence of our assumption that output of hue and chroma discrimination processes is caused by the same opponent color signals. Such mechanisms, while believed reducible to increments of opponent color responses, represent separate entities. Hue and chroma perception occupy the same two dimensions in a chromatic diagram. They would have to be balanced in terms of the relative perceptual magnitude of the unit stimulus increments to fit into a euclidean system. But as seen in Chapter 7, they are not.

Can opponent color signals be the immediate source of hue and chroma perceptions? In other words, is the hue system based on opponent signals only? As seen in Chapter 4, when implied opponent signals of an ideal hue circle are plotted as a function of hue angle they form offset sinusoidal curves. Hues that represent unit hue differences from selected reference colors along the constant chroma circle plot on a line parallel to the sinusoidal line of the circle (Fig. 9-1). For differences to be hue differences only, the following rule applies: the sum of a and b of the test must be identical to that of the reference; that is to say, differences in a and b between reference and test must be opposite in direction and identical in magnitude. Colors that do not follow this rule result in either chroma or mixed hue and chroma differences. For a pure chroma difference, differences in a and b between reference and test must not only be of the same magnitude but also the same direction. Mixed hue and chroma unit differences of a given magnitude are defined by a and b values that are bounded by the pure hue and pure chroma differences. In such a scheme it is difficult to see where the elongation factor 2 of unit perceived difference contours originates. It seems likely that different mechanisms are responsible for hue and chroma perception (certainly also lightness percep-

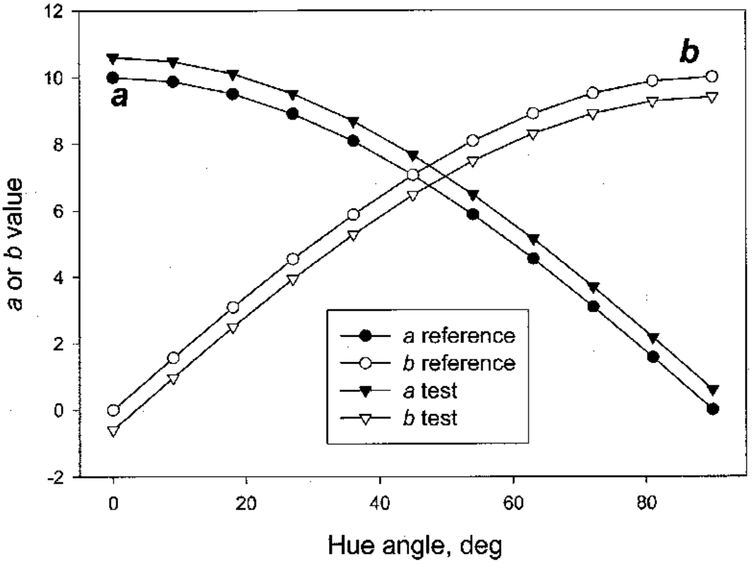


Fig. 9-1 *Values of an ideal, euclidean, constant chroma first quadrant with identical hue differences between adjacent colors. Circles represent the reference color, and triangles the test color.*

tion) and that additional processing takes place beyond simple opponency. The real hue and chroma perception and hue and chroma difference perception processes may be more complex as hinted at by the results of Chichilnisky and Wandell (Chapter 6).

9.14 THE APPROXIMATE SHAPE OF A UNIFORM COLOR SOLID

Given the difficulties alluded to in earlier sections and the lack of sufficiently detailed experimental data it is not possible to create an accurate geometrical model of a uniform object color solid. An approximation of the surface of such a space based on small color differences was calculated using simplifications and assumptions. At eight different levels of luminous reflectance twenty maximal object colors around the hue circle were determined. The luminous reflectances were adjusted to reflect the Helmholtz-Kohlrausch effect using the corresponding formula from OSA-UCS. These values were transformed into the L^*, a^*, b^* space and the a^* and b^* values euclidized using the Thomsen formula. As was mentioned in Section 9.9, it is not clear if this calculation adjusts also fully for the fundamental elongation of the unit contour. The results are points on the surface of a color solid uniform according to the conditions implied and are shown in three projections in Fig. 9-2*a*, *b*, and *c*. View 9-2*a* shows the solid facing the yellow to blue dimension and view 9-2*b* facing

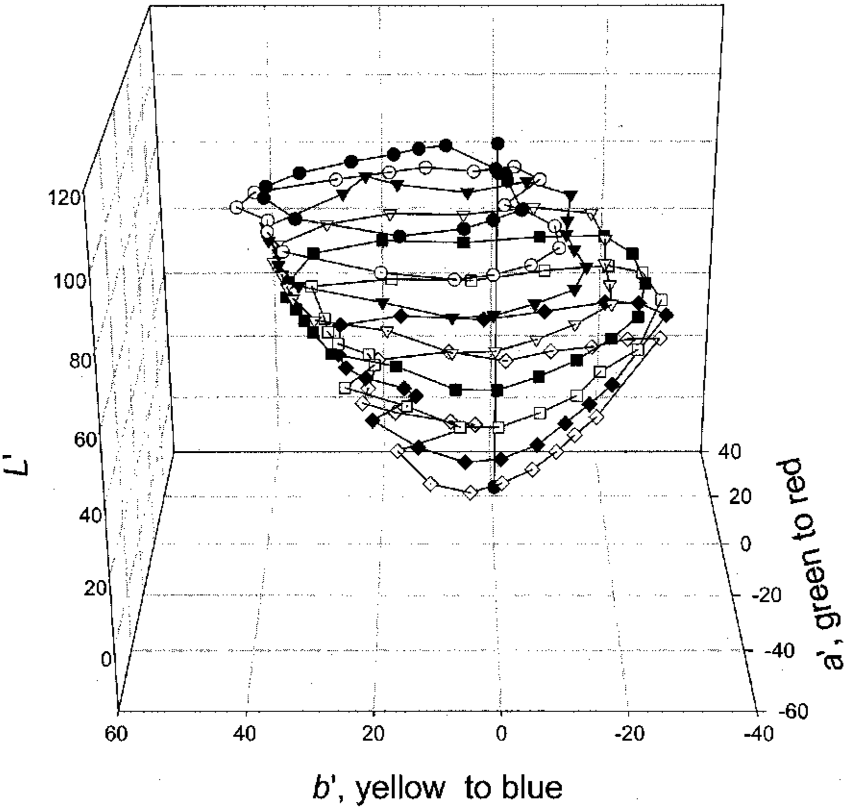


Fig. 9-2 View of a color solid approximately uniform at the level of small color differences. The vertical line connects achromatic colors from luminous reflectance 0 to 100. The different symbols represent colors of a given luminous reflectance at the object color limit. They have been adjusted for the Helmholtz-Kohlrausch effect. (a) View of the yellow-to-blue axis; (b) view of the green-to-red axis; (c) view from the top onto the chromatic plane.

the green to red dimension. Achromatic colors fall on the straight vertical line. The third view shows the solid from the top. Its irregular nature is clearly evident. It can be compared to Fig. 1-2.

9.15 A RESEARCH PROGRAM

Analysis of published data in regard to color attribute scaling and color difference scaling shows significant discrepancies in results between different efforts, despite large numbers of samples, observers, and observations. There are several potential reasons for such discrepancies: different observer panels, different visual context of samples and surround, different light sources, and

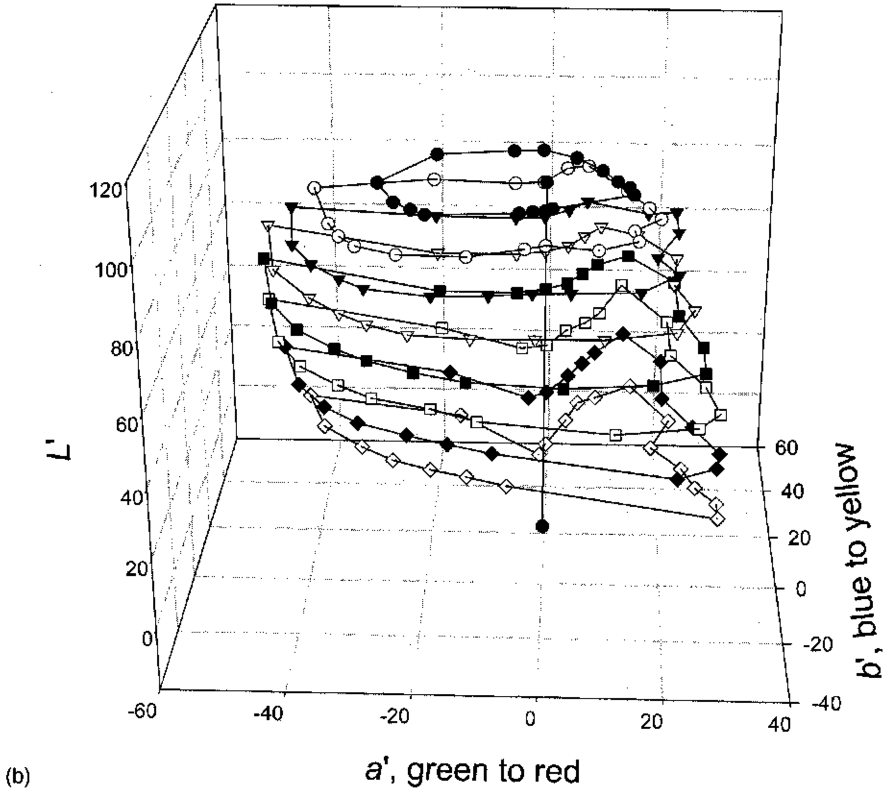


Fig. 9-2 (Continued)

unrecognized contextual clues that can affect the results due to empirical interpretation of the visual field.

Independent replication of experimental results is a standard requirement in science. The degree to which experimental color scaling results can be independently replicated needs to be established. Given the known and perhaps some unknown sensitivities of results to experimental conditions, it seems imperative that independent replication involve essentially identical viewing conditions: the same samples, the same visual context, and the same or very similar (implicit or explicit) light source. Today duplication of this kind is probably best achieved with simulated samples on a computer monitor. The same program creating the displays can be used in different locations, and the general surrounds can be duplicated with masks surrounding the monitor screen. Illumination of the room in which the monitor is viewed may be important for control of the complete adaptation situation. Monitor calibration is a critical issue that needs to be satisfactorily resolved. Variability of results from different observer panels in several locations can then be established. The results may indicate if the variability we see in past results is normal or if, given

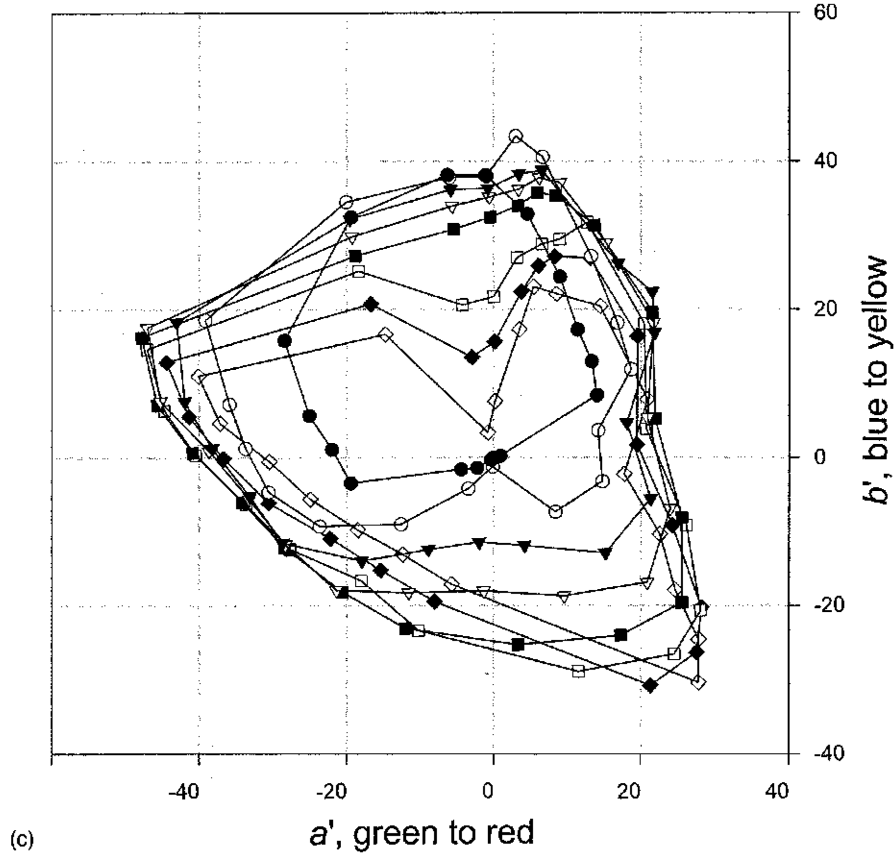


Fig. 9-2 (Continued)

tightly controlled test conditions, the variability can be substantially reduced and how many observers are needed to obtain a reliable average. Alternately, identical physical samples could be used in several locations with closely duplicated observation conditions but different observer panels. Global scaling with Munsell sized differences should be followed by scaling of smaller differences. Given the clear indications of hue superimportance, it appears that global scaling should be based on lightness, chroma, and hue scaling. Consideration has to be paid to the question of the reference difference used to ensure that lightness, chroma, and hue steps are of identical perceptual magnitude. In closed scales such as lightness and hue, selection of a particular size of reference difference may result in a number of steps that is not an integer.

Lightness Scaling

Once an intermediate lightness for the achromatic surround and a reference difference have been chosen, a 10- or 20-step gray scale can be established.

Planes of perceived iso-lightness in a linear *a*, *b*, *Y* space can then be determined at different levels of *Y* of the gray reference. This is not unproblematic because of the findings of Nayatani and co-workers (1994) that the magnitude of the Helmholtz-Kohlrausch effect depends on the experimental design. The reason for the significant differences reported by these researchers should be elucidated and the experimental design selected accordingly. Iso-lightness planes need to be determined at different levels of lightness. It is unlikely that the assumption of Wyszecki and Sanders and the OSA-UCS committee that planes of iso-lightness as a function of *Y* are parallel over a wider range of *Y* is valid.

Chroma Scaling

Once planes of constant lightness have been established chroma can be scaled at different levels of chroma and different levels of perceived lightness. Again, the work may be easiest to accomplish using monitor display colors that are adjustable essentially in one attribute direction only. As the observer adjusts fields for identical perceived chroma, the program should automatically make adjustments for the previously established constant lightness and follow approximate lines of constant hue as reported in the literature. Once 20 to 40 hues around the hue circle have been scaled for chroma, constant chroma contours can be established by interpolation of data points. Such contours need to be established minimally at 5 to 7 levels of chroma at several levels of perceived lightness.

Hue Scaling

With chroma scaling complete, constant chroma contours can be scaled for constant hue increments along the contours. Fine adjustments can be made to result in an integer number of differences. Again, the program should make automatic adjustments for perceived lightness and chroma as the observer makes changes of the perceived hue of the test field.

Many issues need to be decided. For example, should all three attributes be scaled separately for each observer, or should average perceived lightness and then average perceived chroma be used for the subsequent step?

Once results of the best achievable level of replication have been obtained, efforts to fit the visual data with psychophysical formulas can be undertaken. It remains to be seen if formula fitting achieves satisfactory agreement or if, in the end, lookup tables are required.

Complex Color Difference Scaling

With global scaling at the Munsell level complete efforts can be undertaken to determine the addition process required for complex color differences: Is the addition of hue, chroma, and lightness differences simple, euclidean, or some other geometry? This issue has to be studied for pairwise complex differences as well as for differences ranging through all three attributes. The replicated findings at the Munsell level of difference need to be confirmed or modified for small suprathreshold differences.

The apparent increase in chromatic crispening as the size of difference decreases requires quantification, both in regard to hue and chroma. Clarification is also required of the apparent nonlinear effect of lightness on the size of perceived chromatic differences, as discussed in Section 8.6. Additional quantification of the lightness crispening effect in small color difference evaluation is also desirable.

The form of the functions relating attributes and size of differences and the answer to the question of type of addition will shape the form of an equation for small suprathreshold color differences. Also here it remains to be seen if an analytical formula is useful or if the information should be used in form of lookup tables. The same question applies to a universal color difference formula. Can such a formula be meaningfully expressed with equations with changing parameters?

Robustness of Formula

The robustness of a formula developed in such a manner needs to be established. We have already seen that without several adaptable parameters such a formula is only strictly applicable to a narrow set of conditions in regard to samples, surround, and lighting. The question to be resolved is how much conditions can change before the accuracy of the formula is unacceptably reduced. This may involve sample size and structure, separating line, surround quality and structure, spectral power distribution, and intensity of the light source. Can the formula be meaningfully adapted to apply for incandescent or triband lamps?

9.16 KINDS OF SPACES

This text has made clear that the idea of a single fundamental color space is misplaced. As found in practice there are different kinds of color spaces and solids applicable with a degree of accuracy to different situations. Changes in the applicable conditions can quickly further reduce the accuracy of a formula to a significant degree.

Color spaces can be placed in a kind of hierarchy of complexity and meaning. The structural requirements for these kinds of spaces differ.

Uniform Color Appearance Spaces and Solids

These are spaces that for a specific relativized set of viewing conditions illustrate object color samples not only embodying qualitative systematicity in arrangement of colors according to three fundamental attributes but also quantitative systematicity according to the principle of visual uniformity of difference in all directions. Such a space, as we have seen, is non-euclidean in nature but (at least for small color differences) can be euclideanized. For spaces of this kind a high degree of correlation between psychological and psychophysical data is important. Their primary use is for quality control purposes. There is currently no sample set that can be said to satisfactorily express a uniform color solid for the average color normal observer and the applicable set of experimental conditions. Thus all currently existing physical sample sets must be classified as regular, rather than uniform. As a result there is no psychophysical space or color difference formula with satisfactory performance either, as seen earlier. It would be of considerable interest to know how high a degree of correlation can be obtained for an individual observer, given knowledge of that observer's personal cone sensitivities, luminance function, and other properties of the visual system. It might then become apparent to what degree individual experiences shaped our personal color vision apparatus in a way that cannot be systematically expressed with the kinds of simplistic color vision models currently at our disposal. Should the effect be of significant magnitude a color difference formula with much improved performance for the average observer may be impossible. Our current level of knowledge is insufficient to come to such a conclusion.

Regular Color Appearance Spaces

Much of what has been said in the previous subsection is applicable here also. In case of the NCS system differences in principal hue components, blackness and chromaticness are not linearly related to perceived magnitude of difference. Close agreement between the NCS psychological space and a psychophysical space is not important, and in fact no complete mathematical formulation has been attempted so far. Whenever translations seem necessary, they are made with the help of tables. Regular as well as uniform color solids are equally reflective of and variable with the experimental conditions. OSA-UCS, Munsell, and DIN are roughly uniform but euclidean. Ostwald and NCS have also quantitative systematicity but according to principles other than uniformity. Colorcurve, HSB, RGB, CYMK, and other systems have value as arrangements with ordinal systematicity with different kinds of stimulus increments: tristimulus increments in case of Colorcurve, electron gun output increments in case of HSB and RGB as related to video display, primary print color increments in case of CMYK. In the limited region of a color solid that can be covered with colorants or monitor phosphors, they are indicative of the variety of color experiences of the average color normal observer under the limitations of the system. OSA-UCS with its crystalline structure can display a wide variety of color scales varying simultaneously in all three perceptual attributes and changing in color in dramatic ways without, as shown, being uniform.

Psychophysical (Regular) Spaces

For spaces such as Luther-Nyberg, CIELUV, CIELAB, and others there are smaller or greater claims for uniformity, but they are just regular spaces with different principles of tiling. A particular example is the Derrington-Krauskopf-Lennie space with tiling according to macaque cell response in the lateral geniculate nucleus.

Color-Matching Spaces

Color-matching spaces include many examples, such as the Rösch-MacAdam space, the CIE tristimulus space, and the Cohen fundamental color space (with many possible configurations). The last derives its name from the decomposition of spectral power distributions into the so-called fundamental of each reflectance function, meaning the portion of each spectral function free of metameric black. Each related color perception is represented as a vector, just as in the other two spaces mentioned. Average visual metamers plot in the same location in all three cases. These spaces make no claims for quantitative systematicity in terms of appearance.

Spectral Spaces

Spectral spaces do not involve data related to human color vision and, therefore, should not be termed color spaces. They are based on finding components representing a given reduced dimensionality implicit in the spectral functions, such as by principal component analysis. Some three-dimensional spectral spaces place spectra of the Munsell colors in correct ordinal order, but the dimensions have no perceptual meaning and differences between colors in such spaces have no meaningful relationship to perceived differences. Visual metamers plot in different locations in such spaces.

Among the many kinds of color spaces the uniform space has the highest degree of systematicity if equal sense distance has the importance that psychophysics assigns to it. What degree of accuracy and repeatability is possible for a uniform color space for the average observer and a specific set of experimental conditions remains to be determined. Unless one wants to raise a charge of bias of some kind for the RIT-DuPont data, they show that significant improvement compared to many other data sets may be possible based on careful experimentation. Additional improvement resulting from a fuller understanding of the color vision process may also be feasible. Problems and uncertainties increase the more complete the color vision model is to be in its explanatory power, for example, as color appearance models indicate.

Given the view that vision is an animal type's best way to deal with the ambiguities of the information provided by the energy streams that we call light, it is evident that finding the one color space representative of human color vision is a problem without solution. Taxonomy, the classification of objects and phenomena, is an important human activity. Just as any other human activity it is open ended. We have found that a color classification free of context is of necessity very vague. To make it less vague, we must specify the context but the classification becomes applicable only to that context. To achieve the highest level of classification (a uniform color space), the context must be highly defined in all respects.

After some 300 years of effort the conclusion is that color appearance systems such as the Munsell system are general indicators of the multitude of color experiences that can be generated, for example, with pigments painted on paper and viewed in daylight. To reach the borders of our possible experiences work with monochromatic lights is necessary. But it is evident that claims for a given relationship between stimulus and resulting experience are only applicable to closely circumscribed conditions of viewing. A uniform color space (not euclidean) defined in terms of stimuli is only possible for a closely circumscribed set of viewing conditions and in theory only applicable to one observer.

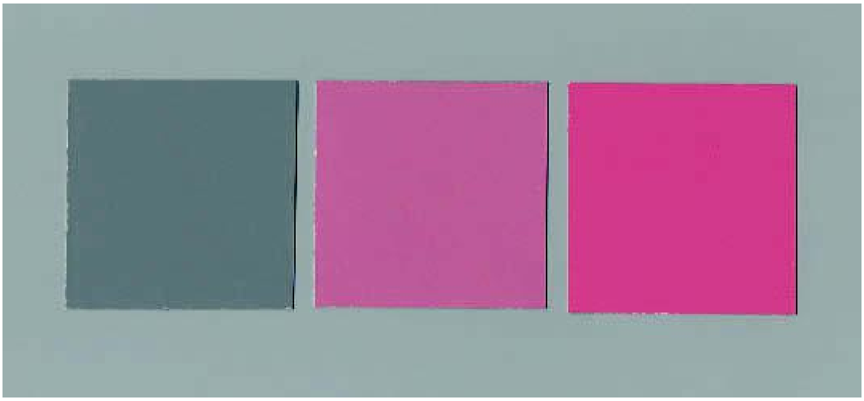


Fig. 1-1 *Images of chips of the OSA-UCS system.* Left*: Color 000;* center*: color 00-4;* right*: color 00-8.*

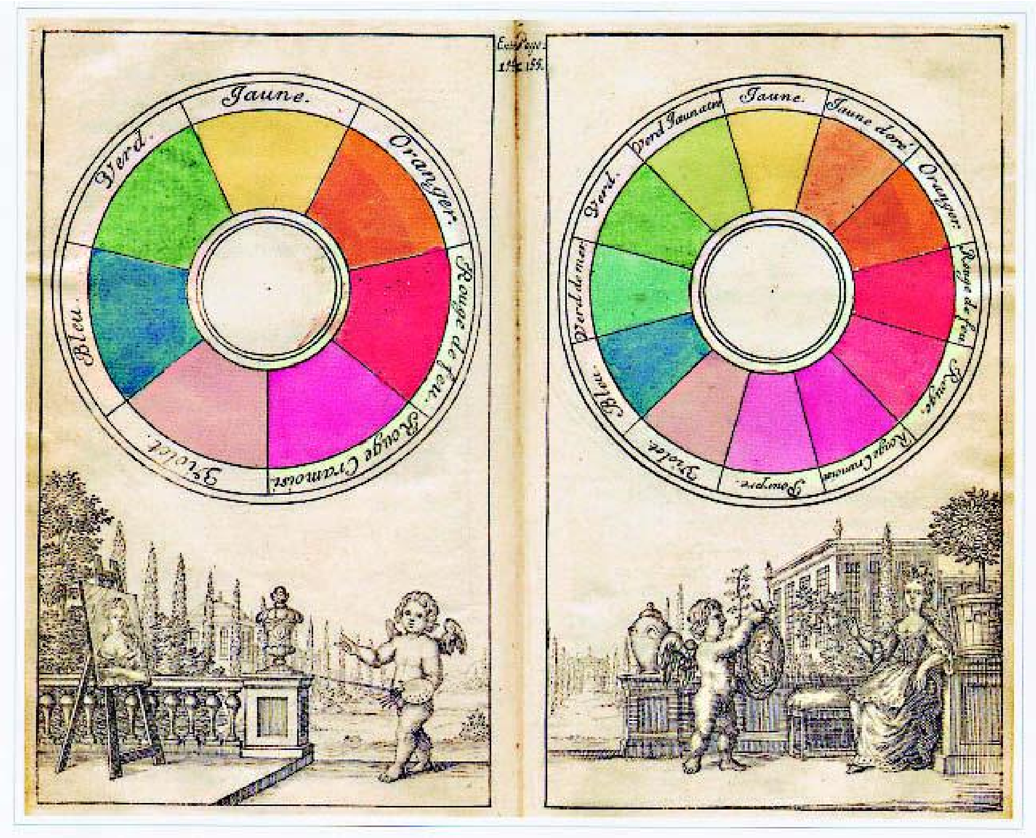


Fig. 2-12 *C.B.'s hand-painted color circles, 1708. Left: The seven-color circle; right: the twelve-color circle. Note that the pigments used for some of the colors have deteriorated.*

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

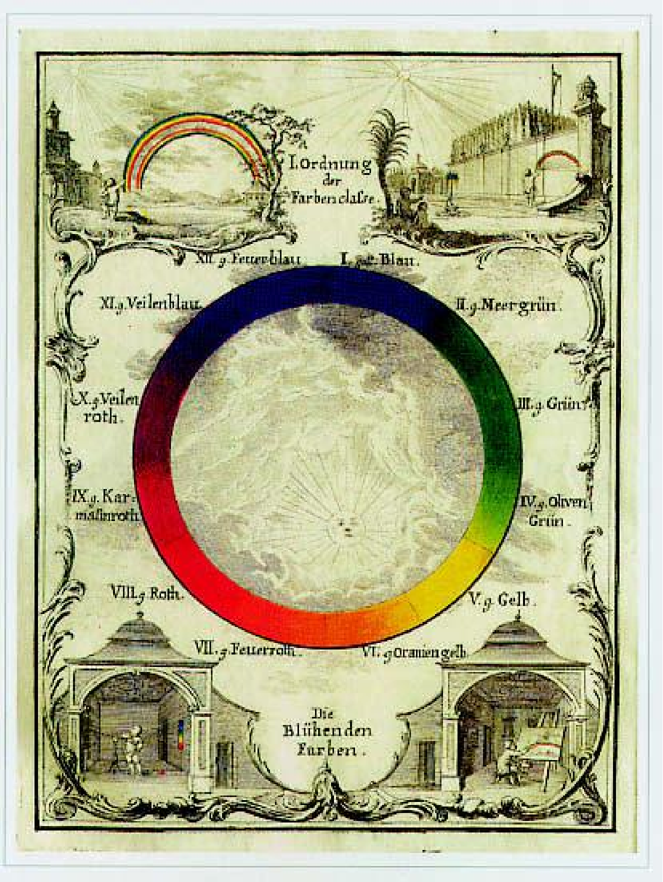


Fig. 2-13 *Continuous color circle of Ignaz Schiffermüller, with twelve classes of colors, 1771.*

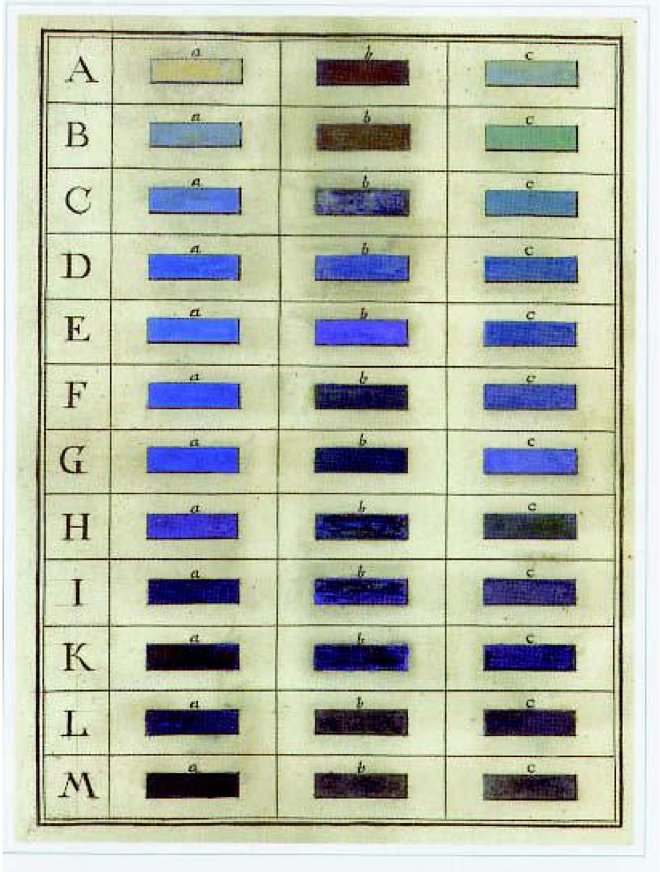


Fig. 2-14 *Schiffermüller's tonal scales of three blues, from his 1771 work. Some of the colorations have deteriorated.*

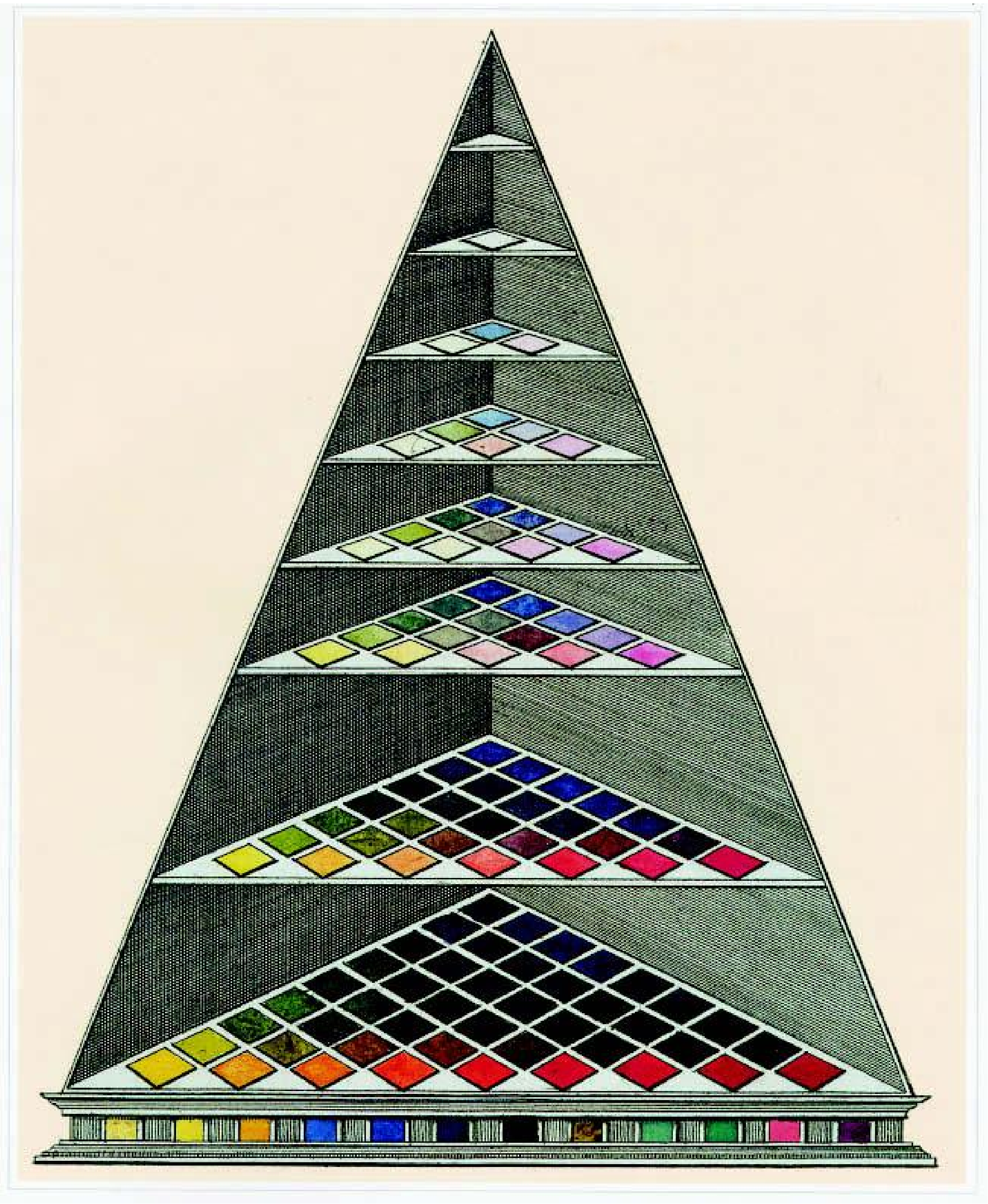


Fig. 2-18 *Depiction of Lambert's color pyramid, 1772. The lowest level contains the 45 colors identified in Fig. 2-17. The higher levels contain reduced sets at higher lightness, ending in white on top of the pyramid. Black is located on the lowest level. The colors displayed on the front of the model represent well-known artist's pigments of the time.*

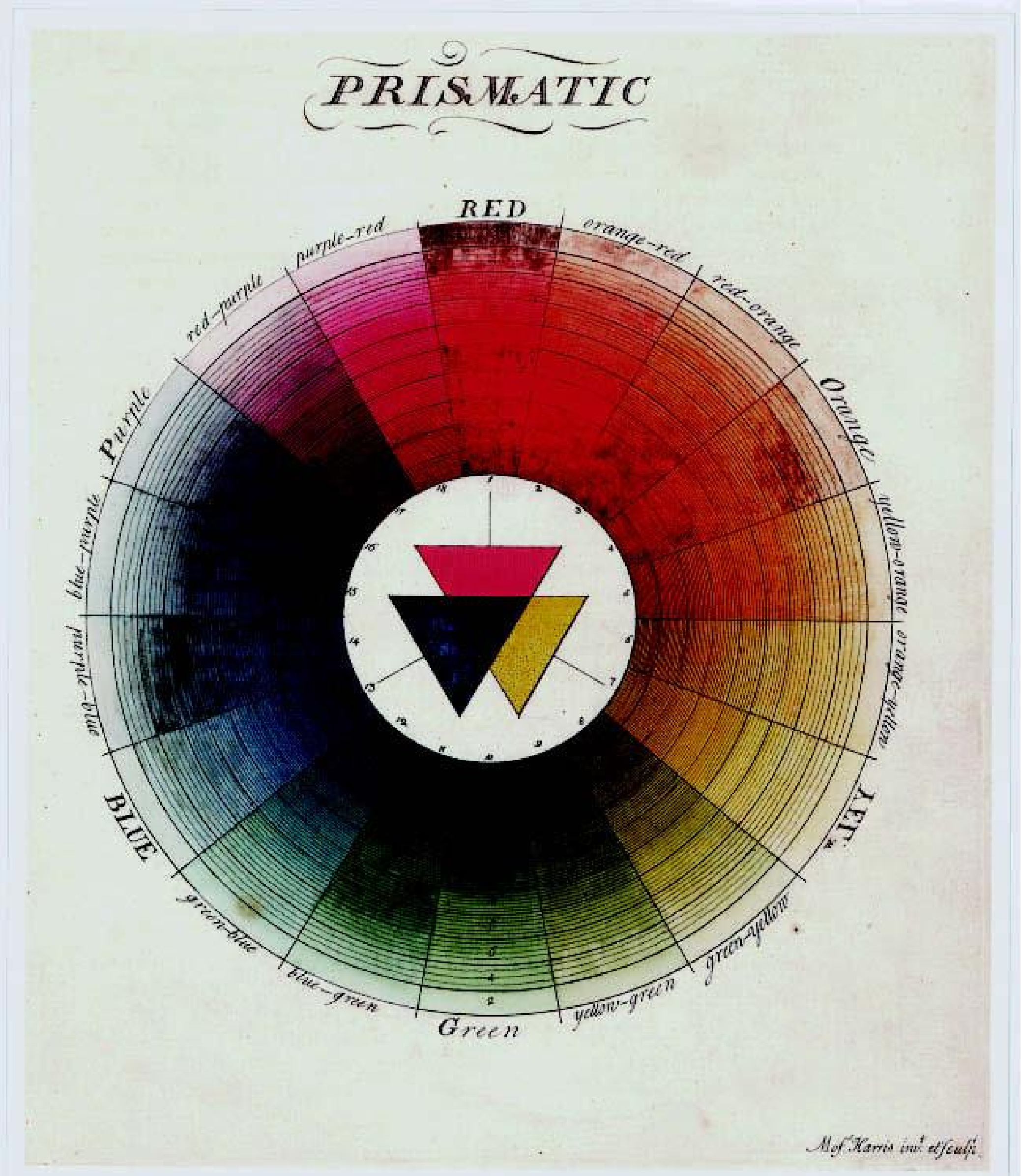


Fig. 2-19   *Prismatic version of Moses Harris's color circle of 1786. Some deterioration of colorants is evident.*

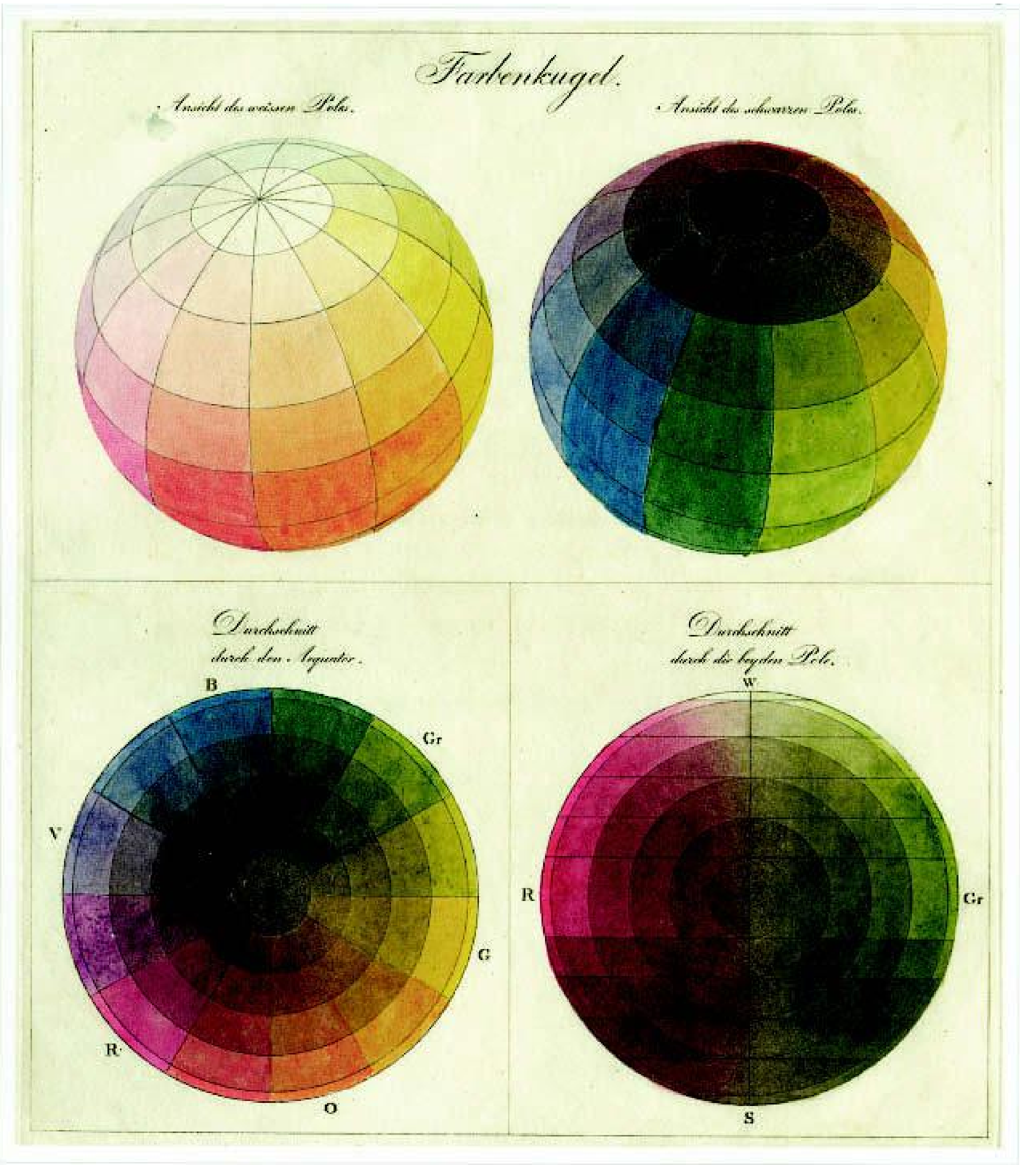


Fig. 2-22 *Hand-colored copperplate of Runge's Farben-Kugel (1810). Views toward the white and black poles are on top. The equatorial cross section is on bottom left and the polar cross section on the right. There are four saturation steps between the full color on the surface and the middle gray in the center of the sphere.*

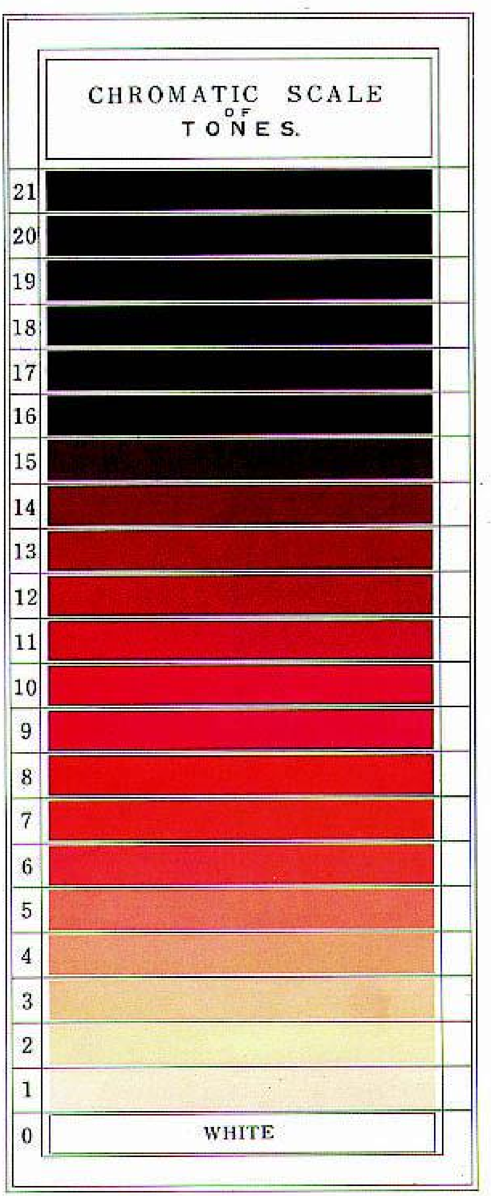


Fig. 2-25 *One of twelve chromatic scales by Chevreul, with local discoloration. The colors range from white through the full color (grade 11) to black. These scales are located on the base plane of the hemisphere.*

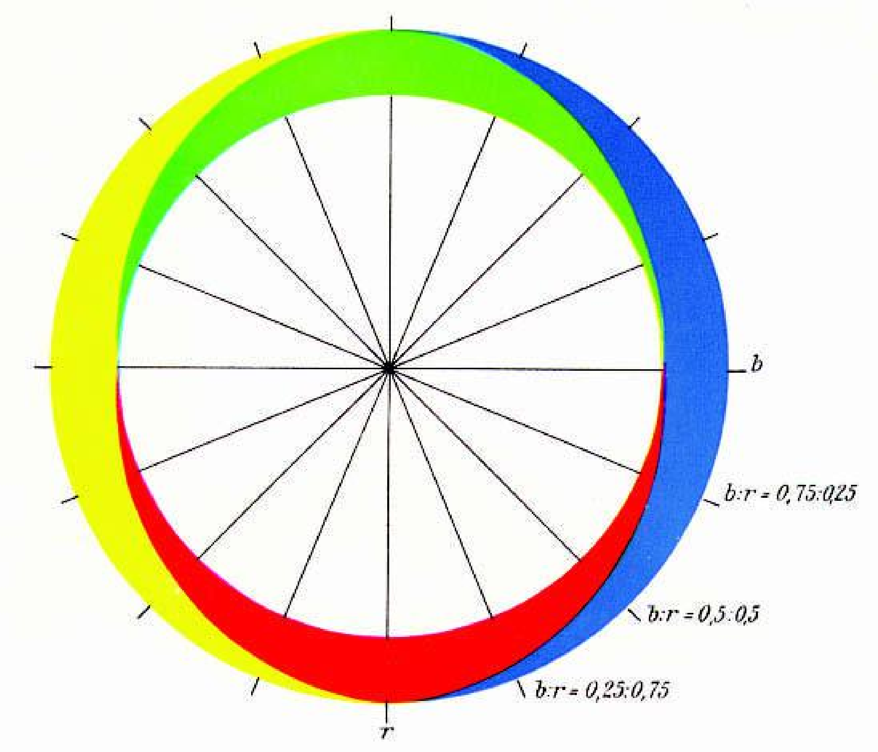


Fig. 2-32 *Hering's diagram illustrating the composition of mixed hue perceptions from the unique hues located on the main axes. The fractions of blue and red of three mixed hues are shown bottom right, 1905–1911.*

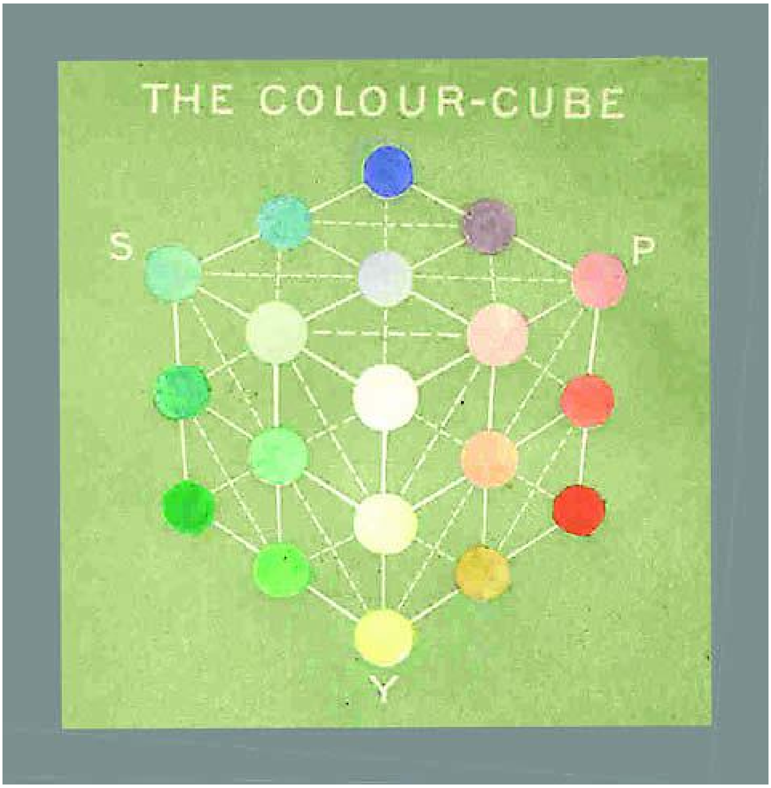
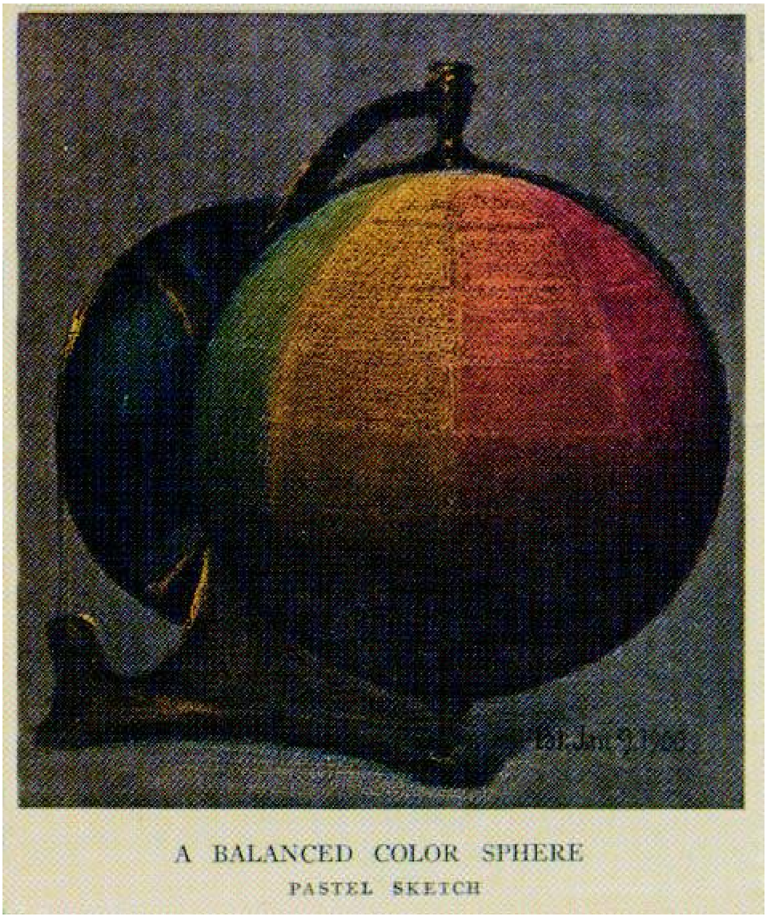


Fig. 2-34 *View toward the top, white corner of Benson's tilted color cube, 1868. The gray scale is hidden behind the white sphere.*



A BALANCED COLOR SPHERE
PASTEL SKETCH

Fig. 2-41 *Artist’s rendition of Munsell’s balanced color sphere, patented in 1900. The sphere was rotatable to achieve additive color mixture to gray and thereby show the “balance” of the colors on the sphere. The mirror in the back discloses the blue region of the sphere.*

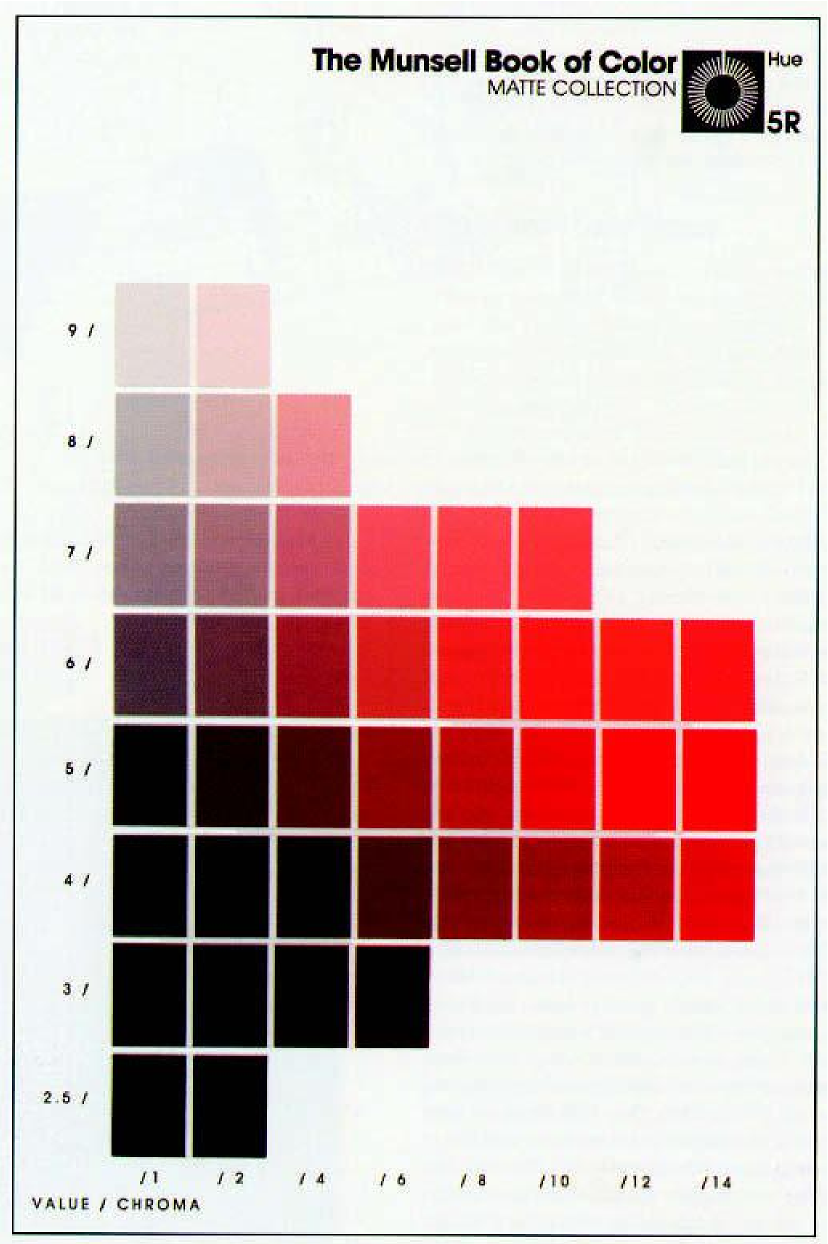


Fig. 2-42 ***Fig. 2-42*** *Constant hue page from a modern version of the Munsell Book of Color. The gray scale is not shown. The chroma scale begins at 1 and continues from 2 at two-grade intervals to chroma 14. Value grades are shown from 2.5 to 9. Courtesy Gretag-Macbeth Company.*

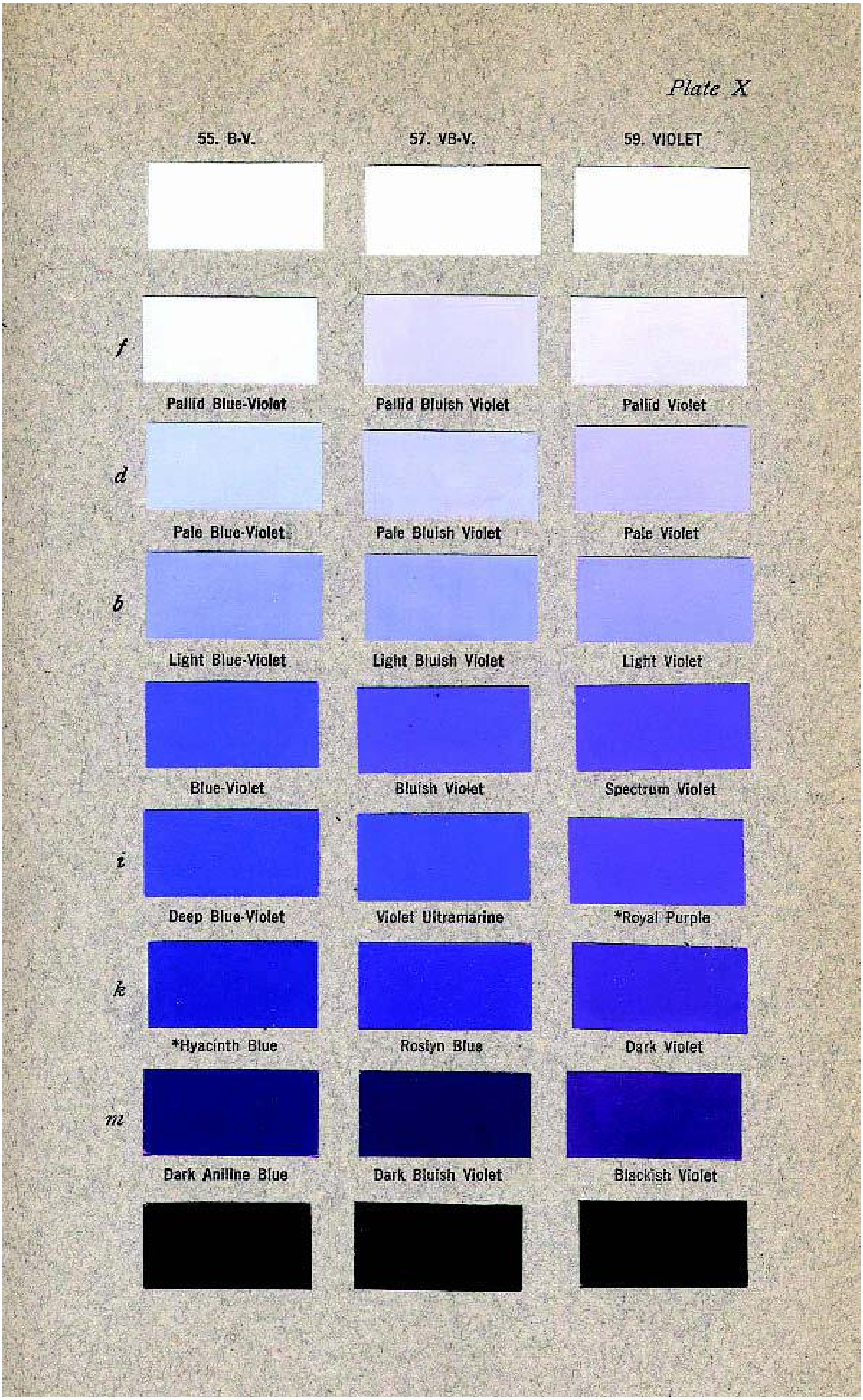


Plate X

	55. B-V.	57. VB-V.	59. VIOLET
f	Pallid Blue-Violet	Pallid Bluish Violet	Pallid Violet
d	Pale Blue-Violet	Pale Bluish Violet	Pale Violet
b	Light Blue-Violet	Light Bluish Violet	Light Violet
	Blue-Violet	Bluish Violet	Spectrum Violet
i	Deep Blue-Violet	Violet Ultramarine	*Royal Purple
k	*Hyacinth Blue	Roslyn Blue	Dark Violet
m	Dark Aniline Blue	Dark Bluish Violet	Blackish Violet

Fig. 2-43 *Page from Ridgway's color atlas showing three reddish blue hues lightened from the central color in three steps toward white and darkened in four steps toward black, 1912.*

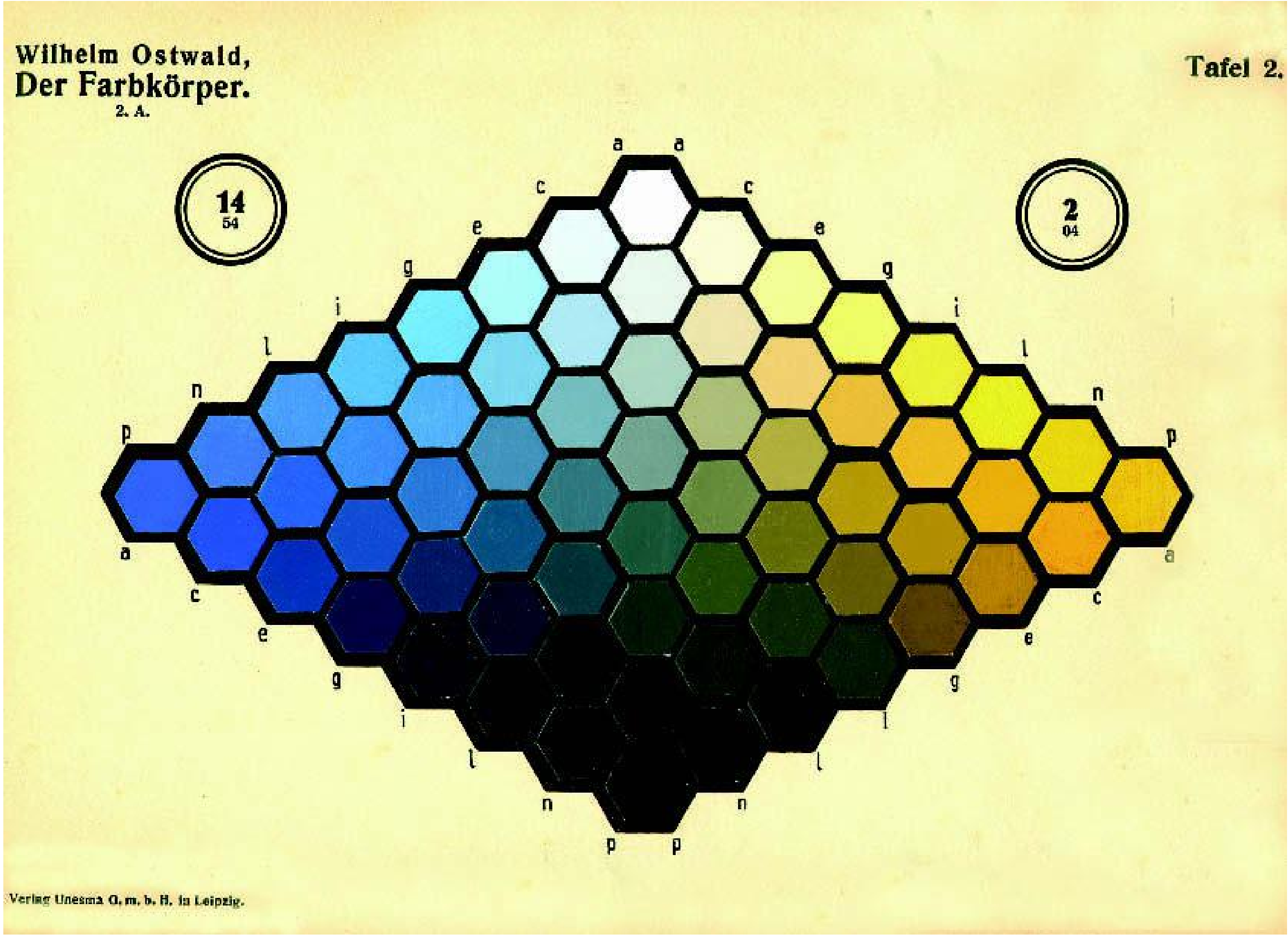


Fig. 2-45 *Vertical cross section through Ostwald's double-cone color solid illustrating constant hue colors 1 and 13, with veiling toward white and black. The achromatic scale is at the center. From Farbkörper, undated.*

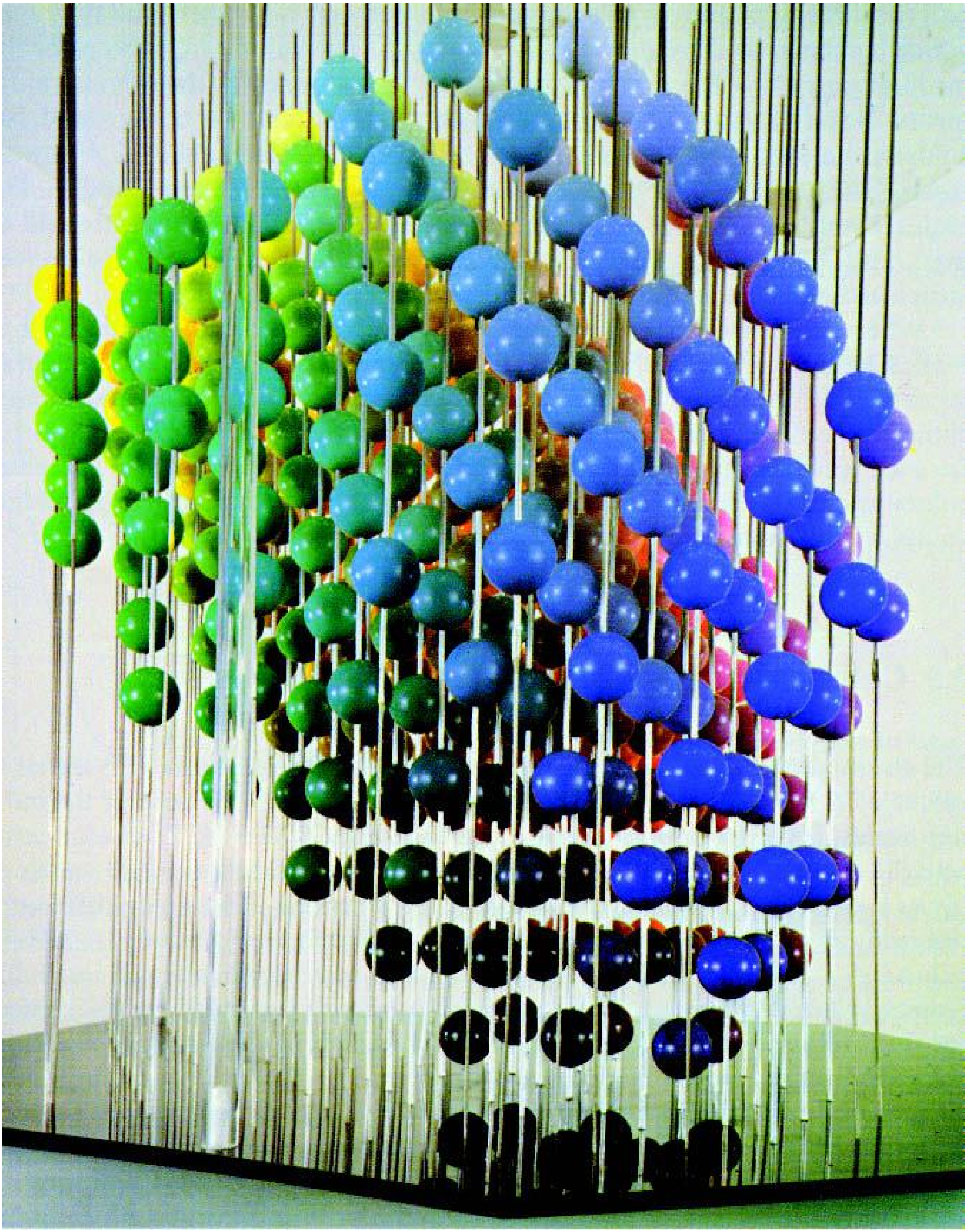


Fig. 2-51 View of MacAdam's model of the OSA-UCS color solid illustrating the existence of several cleavage planes. See text for more detail. Slide courtesy D. L. MacAdam.

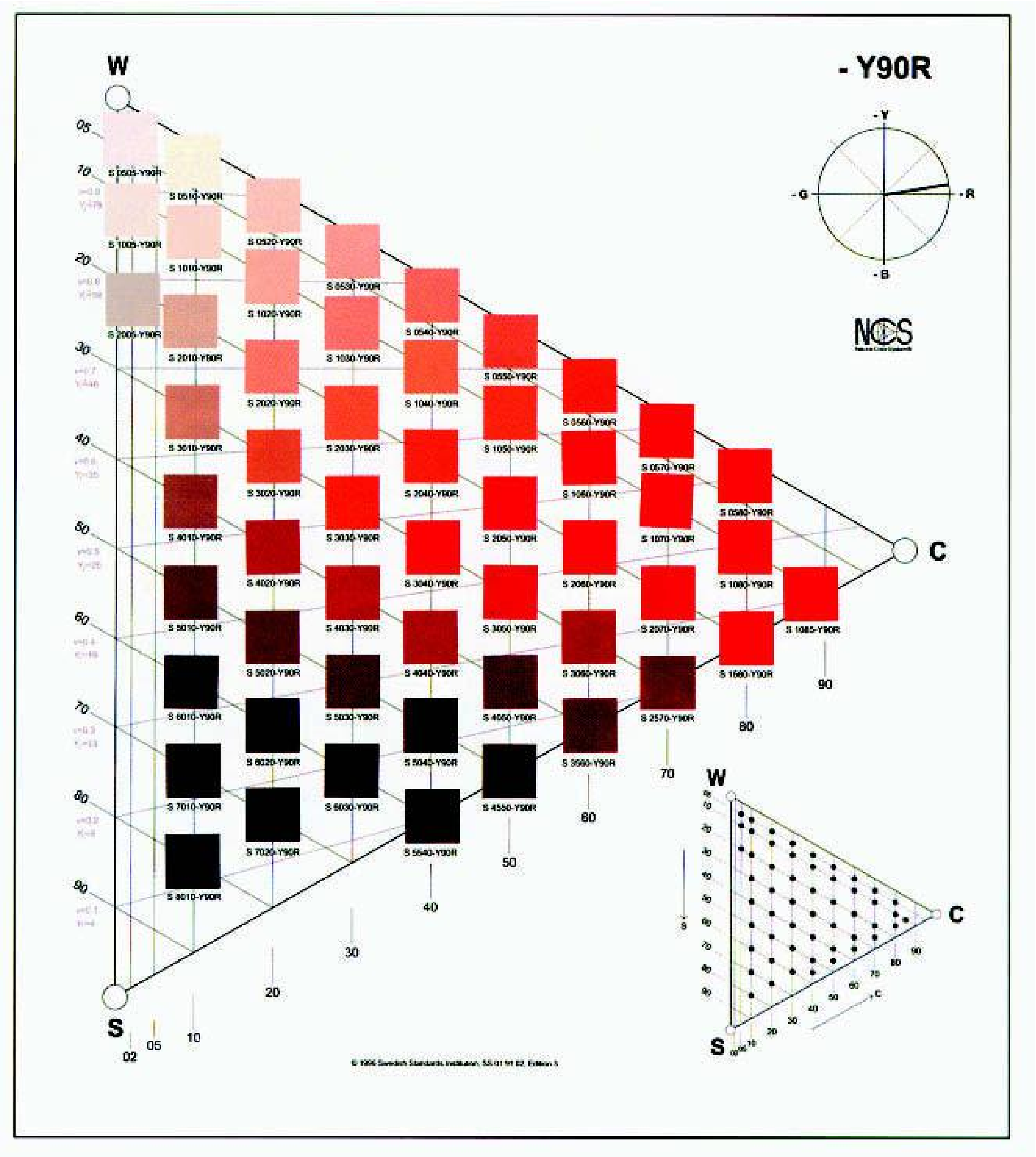
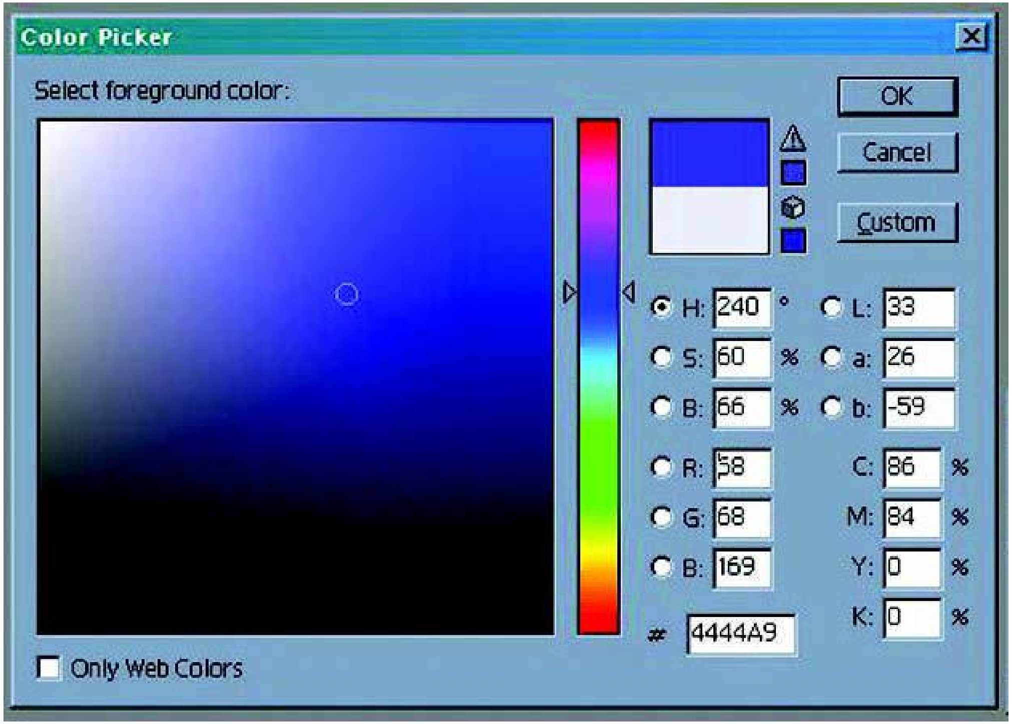


Fig. 2-53 *NCS constant hue triangle of hue Y90R with full color C, white W, and black S. Colors of constant blackness s are located on lines parallel to W–C, colors of constant chromaticness c fall on lines parallel to W–S. Courtesy NCS.*



● H: 240 °
○ S: 60 %
○ B: 66 %
○ R: 58
○ G: 68
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○ L: 33
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○ b: -59
C: 86 %
M: 84 %
Y: 0 %
K: 0 %
☐ Only Web Colors

Fig. 2-54 *Color Picker screen from Adobe® Photoshop showing specification of a given reddish blue color in four systems: HSB, Lab (=L*, a*, b*), RGB, and CMYK.*

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.*