Chapter 1

The Concept of Color Space and Color Solid

1.1 INTRODUCTION

Attempting to understand our place in the world and classifying things and experiences is a well-known human trait. Already ancient Greek philosophers thought about the multitude of color perceptions, but they despaired of finding a system in which to place them. First, colors were logically sorted according to lightness, regardless of hue. Early in the second millennium we begin to find descriptions of tonal scales of individual hues or mixed tones, like flesh color. They were achieved by adding lighter or darker pigments of similar hue, even black or white, to saturated chromatic pigments. Systematic hue circles began to appear in the late seventeenth century. The concept of a three-dimensional logical arrangement of color perceptions began to take shape only in the eighteenth century.

Color space is a three-dimensional geometric space with axes appropriately defined so that symbols for all possible color perceptions of humans or other animals fit into it in an order corresponding to the psychological order. In this space each color perception is represented as a point. The symbolic representations of color perceptions in this space form the color solid. The earliest proposals for color solids had simple geometrical forms: triangular double pyramid, sphere, cone, and so forth. There is, of course, no a priori reason why a systematic arrangement of color perceptions should fit into a simple geometrical solid. What controls the form of the solid is the definition of the axes of the space and their divisions.

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There is ample evidence that the colors we experience in various conditions from a given spectral stimulus can vary widely. According to one view they are determined by empirical rules derived on an evolutionary basis for our species and for each individual. There is strong evidence that the color attributed to an object depends on the nature and complexity of the surround in which the object is seen. In scientific experiments the complexity of surrounds usually is minimized (elementaristic approach).[1] Color experiences from given stimuli under elementaristic conditions depend on the exact conditions and change to a smaller or larger extent as quality and complexity of the surround and lighting change. Only under closely controlled conditions can a color space for the average color normal human observer be represented by spectral stimuli. In these relativized circumstances terms such as *color stimulus* and *object color* have applicability restricted to the experimental conditions and cannot claim the level of universality that has generally been assumed from the eighteenth to the twentieth century. Critics of the idea of color space have pointed to its lack of solid foundation. While this is ultimately true in the end such criticism appears simply to address the fact that at this point in time we do not have an understanding of consciousness. Color perceptions are the result of brain activity; they are subjective and private. As for all other sensory feelings and beliefs we do not know how in a given situation a given light stimulus can result in our seeing an object, and this object to have the appearance of red. It is not clear that humans will ever gain an understanding of this process. Color scientists have over the years built conjectural models based on what must, in the absence of true knowledge, be called coincidental relationships between stimuli as viewed in controlled circumstances and visual perceptions. In a perfect world this is not an acceptable process. Given the lack of fundamental understanding of consciousness it is an empirical approach having produced many reasonably well established, coincidental or otherwise, relationships.

Within the framework of an evolutionary development model, some key questions concern what forces in our early history shaped the development of visual sense and what strategies were implemented during its evolution by neurochemistry to deal successfully with the pressures of these forces. The simplistic color perceptions and attributes on which color scaling is based are doubted by some psychologists as having anything to do with the fundamental perceptual processes embedded in our visual system as a result of interactions with the environment. We appear to be only at the beginning of a process to find answers. Questions such as why color space is (at least) three-dimensional and why there are four psychologically fundamental hues and not more or less have started to be asked only recently.

The issue of a systematic arrangement of color perceptions under simplified viewing conditions is a relatively abstract matter, removed from such considerations. It is probably not surprising that it took shape in the age of Enlightenment with its belief in a universal rational order. In the twentieth century, aside from fundamental considerations of trying to understand our place in the world, the quest was shaped by technical and economic issues of color control of manufactured colored goods.

A color space belongs in the domain of psychology. The description of stimuli that under standard conditions result in perception of colors in that space is an aspect of physics. Together they form the uneasy domain of psychophysics that attempts to connect stimuli with perceptions (see Chapter 3). The stimuli are messages to us from the outside world. An alternative view is that we actively search for them when viewing the world. They enter through the pupils of the eyes and are absorbed by the retinal layer. There they trigger a complex chain of events that result in our perceptions. These events belong into the domain of neuroscience and are part of the conundrum of consciousness.

The number of different color experiences we can have is unknown, but large. Given a particular starting point in color space the finest perceptual division of color space is represented by visual threshold increments deviating from that point in all directions. A color space of given definition can only be expressed in terms of differences within the related color solid against a chosen surround because it is only applicable to those conditions. The smallest difference in a color solid as related to a given starting point, therefore, consists of a pair of different color stimuli displayed against a particular (usually neutral) surround and seen as having a just perceptible difference.

Generally, a color space and the related color solid may be defined as an economic systematic description of subjective color experiences, and as such it is not subject to engineering precision. It is indicative of our visual strategies vis-à-vis the world.

Personal Color Spaces and Color Solids

Each person with normal color vision has individual, personal (relativized) color spaces and related color solids (depending on the conditions under which they were established). Such individual solids vary within limits, based on the detailed implementation in an individual of his/her color vision apparatus. (Relativized personal spaces generally are at least in ordinal if not in interval order compared to that of the average observer.)[2] What it means is that if the reader and the writer sense the spectral power distribution representing a particular object color field in a particular surround and illumination, the resulting experience is likely to be somewhat different. Such a statement assumes that both observers are "color normal" and that color normal individuals have in essence the same fundamental color experiences. It does not consider the possibility, raised by some philosophers, of what is loosely called "spectrum inversion." It cannot be excluded with certainty that, for example, the reader actually experiences as green what the writer experiences as red, regardless of how it is named.

How different the experience resulting from a given spectral power distribution might be in terms of hue can be judged from individual determination of unique hues and, to less extent, from color perceptions judged to be intermediate between unique hues. Unique hues are those four primary hues that do not contain perceptual components of other hues. A unique red hue is neither yellowish nor bluish: it is just red. Color stimuli resulting in unique hue perception vary among color normal observers.[3] This variation depends on the hue in question. It ranges approximately from 5% to 12% of the total hue variation in a hue circle experienced under standard viewing conditions (i.e., approximately two to five Munsell 40-hue steps; see Chapters 2 and 7 for information on the Munsell system). Because of the absence of unambiguous criteria, it is not possible to meaningfully assess the stimulus variability for other hues. It is quite evident that there is also variability in the experience of gray scale steps, in adaptation and constancy response and other visual mechanisms, resulting in considerable variability of individual experience when looking at a given scene of color stimuli. Persons with impaired color vision have implicit color spaces significantly different from those of color normal observers. Their nature cannot be conveyed with certainty. Theoretical considerations of the genetics of color vision indicate that as much as 50% of the female population have the potential for four rather than the normal three cone types even though none has so far been identified as having four cone types.[4] Richer color experiences than those had by standard trichromatic observers have recently been determined for females with the genetic potential for four cone types. In how many ways their color experiences are richer remains to be determined.

Adaptation and Conspicuousness of Differences

Color experiences, in the normal case, result from the impact of light energy on the retina in our eyes. They are known to depend on the absolute level of light energy. This level can differ by a ratio of 1 million to 1 (on a retinal illumination basis). There are mechanical (pupil size) and neurochemical processes to manage such large variation, known under the general term of adaptation.[5] The complete process adjusts the range of incoming light to an output capability with a range of approximately 100:1. The adaptation process works to map the energy pattern in a given viewing situation to the total output range so that contrasts between different areas are seen roughly as the same under a wide range of illumination. At very low intensities of light we see no hued colors and neither do we at very high intensities. Probably because of the importance of very low light levels (night) in the lives of some early ancestors, we have a separate set of receptors for that situation, the rods. Rod signals pass through the same postreceptoral cells into the brain as cone signals. If they have any effect on daylight color vision, it is very small. The response pattern as a function of light intensity of our daylight-level sensors, the cones, is S-shaped, but the response has a considerable range that is approximately linear in the center region. There are issues at low and high levels of response of cones that cannot be of concern in this discussion. This text is largely limited to color spaces and solids represented by reflecting materials at mid levels of illumination, say 500 to 1500 lux.[6]

Earlier, mention was made of the lack of constancy of color perceptions resulting from most stimuli as a function of surround or illumination changes. Chromatic adaptation is a seemingly opposite process. Its purpose appears to be to provide a considerable level of color constancy for reflecting objects with certain spectral signatures. Among terrestrial nonhuman mammals trichromatic color vision is limited largely to fruit eaters and pollinators. For them it is important to recognize their objects of interest in all natural lighting conditions. Color is an important part of the stored memory of the appearance of objects and helps to recognize them rapidly when encountered again. Without chromatic adaptation, colored objects in the natural world might change their appearance significantly over time as a result of changes in ambient illumination. With independent adaptation capabilities for each cone type, likely together with additional processes, our ancestors could recognize the colors of most natural objects as essentially the same regardless of the quality of illumination and surround. This is less true today than it was at a time when there were only natural objects and all light was sunlight, direct, scattered, or reflected. Today we have a large number of artificial colorants and various artificial light sources that have complicated the issue considerably, resulting in smaller or larger changes in the appearance of objects as a function of surround and illuminant. This text does not consider most issues of chromatic adaptation but considers color spaces and related solids only in terms of colored objects as viewed against achromatic backgrounds of varying levels of lightness under a standard light source.

The visual system has developed in a way that favors the conspicuousness of small differences in reflectance signatures of objects. Its cause may have been an escalating battle between camouflage and detection, a matter of life and death. Highest discrimination of small reflectance differences between objects is provided in a surround with reflectance intermediate to those of the objects compared. This results in improved detection of highly camouflaged predators or prey in natural surroundings. The principle also applies when the number of objects with different color increases and/or the differences between them become larger. Best discrimination is provided in this case by an average (i.e., mid-level) achromatic surround. The best surround to view a complete color atlas, by this reasoning, is a mid-level gray.

Mathematical Color Appearance Models

Our complete color experience is much wider than what was just discussed. We view natural scenes, color television, computer monitors, projected slides, projected digital images, the output of many coloration devices under many different light sources, metameric objects under different light sources, and so on. It has become important to be able to predict for an average observer the appearance of colored objects in many different conditions. This is the province of color appearance modeling, evolving rapidly in the last ten years and having developed several mathematical models that are still comparatively simple and correspondingly only modestly accurate. This is expressed to some extent by the fact that several different modeling approaches can result in about the same level of prediction accuracy. An excellent survey of color appearance modeling has recently been provided by MD. Fairchild (1998). As indicated, the present text is concerned with color appearance under limited conditions only.

1.2 DIVISIONS OF COLOR SPACES AND SOLIDS

Color spaces and solids are always expressed in terms of differences of some kind between color perceptions. As will be shown, there are various kinds of differences that have been proposed for color spaces. A kind of color space of particular interest is one in which distances in the solid in all directions are proportional to the magnitude of perceived differences between the related color experiences. Such a space can be built from (or divided into) threshold differences or larger differences. Differences imply scales, and there are several different kinds of scales possible. The primary scales are psychological or perceptual. Such scales are built on the basis of perceptual attributes. A logical expectation is that the perceptual attributes form the axes of the space. For simple observation situations (uniform achromatic surround and defined light source) three attributes are sufficient to define the perceived color of an object. If its dependence on surround and illumination is to be considered quantitatively, additional attributes are required (see Chapter 4). We will find, however, that all possible hue perceptions are best ordered in a circle and that the hue attribute, therefore, is a function of two dimensions of the space.

A psychological color solid and the space into which it fits can be built from a very large number of color samples. It requires picking the appropriate samples to represent the chosen type and size of difference. Once the task is complete, the selected samples represent the solid and the space. This is not a generally satisfactory solution because producing many copies of the solid requires large sheets of uniformly colored materials. Our inability to define color experiences from an object verbally or by some other subjective means with a high degree of accuracy and precision makes it desirable to use objective means of defining the color samples. Weight of colorants in a mixture has been used in the earliest attempts at illustrating color scales, (e.g., F. Glisson, Chapter 2). With the development of photometry in the eighteenth century and colorimetry in the late nineteenth century, physical and psychophysical means of specifying color stimuli became available. It quickly was learned that in a given set of conditions the relationship between measured stimuli and perceptions is not linear, and the next task was to develop models of the relationship between physical properties of stimuli and resulting perceived color. This is the domain of psychophysics. This branch of psychology developed as a quantitative science in the mid-nineteenth century. Both psychological color scaling and psychophysical color modeling continue to be incomplete activities.

The simplest kind of scale applicable to the universe of color experiences is the ordinal scale. It describes the order of entities that form the scale. An example of an ordinal scale is a random series of gray papers, arranged in terms of perceived lightness. The differences between steps are also random in perceived size. A psychophysical example is a gray scale in which the steps differ by 10% in luminous reflectance. It is not a perceptually uniform scale. There are an infinite number of possible color spaces based on such ordinal scales and encompassing three dimensions. Examples are cone sensitivity spaces, the CIE tristimulus X, Y, Z and x, y, Y spaces, the Luther-Nyberg space, or spaces based on color matching functions different from the standard CIE functions (see Chapter 5).[7]

Of historically greater interest have been interval scales of object color perceptions and the psychological space derived from them. Interval scales, as defined in Chapter 3, are scales where the meaning of the size of the interval is the same regardless of where on the scale the interval is located. Interval scales are known as psychometric scales. Typical interval scales are lightness, hue, and chroma scales—or scales of complex color differences—based on perceived total color difference. An example of approximation of a uniform psychological color solid based on interval scales is the Munsell "tree" of colors, a three-dimensional logical arrangement of color chips forming interval scales in certain directions. However, equal geometrical distances in the Munsell system do not correspond in all directions to equal perceived differences.

A different approach has been pursued in the development of the Optical Society of America Uniform Color Scales (OSA-UCS; see Chapters 2 and 7). Here no attributes have been scaled, but uniformity in size of complex chromatic color differences in a triangular grid was determined at approximately constant lightness, as was the magnitude of combined chromatic and lightness differences. A fitted formula was then used to tile the corresponding space so that colors in twelve directions were defined from a central color approximately perceptually equally distant. The result is a space with a square grid pattern for colors of equal perceptual lightness rather than the radial grid of the Munsell system. It turns out that also here a uniform solid has not been formed. Uniformity of color space and the related color solid has been a goal since the earliest attempts at building color appearance spaces. Its importance increased with the capabilities of accurately and inexpensively measuring reflectance properties and the related opportunities for objective color quality control in the mid-twentieth century. This text, while discussing many different kinds of color spaces, pays particular attention to the issues of uniform color spaces.

Ratio scales represent the next higher level of scale complexity. Here not only are the intervals quantitatively the same, but ratios are also fully valid. Historically ratio scales for colors have been controversial. Many observers do not agree that it is possible to make a judgment that a given color is twice as

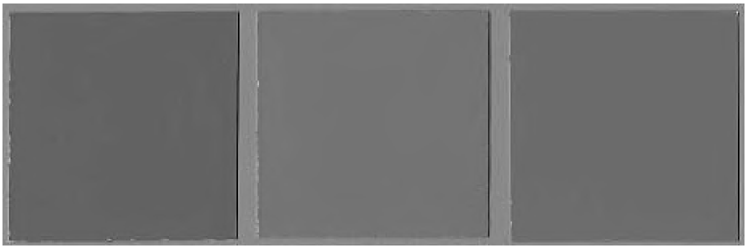

Fig. 1-1 *Images of chips of the OSA-UCS system.* Left*: Color 000;* center*: color 00-4;* right*: color 00-8. (See color plate.)*

red or twice as black as another color. The difficulties involved can be visualized by comparing, say, OSA-UCS chips 000, 00-4, and 00-8 (Fig. 1-1). If the OSA-UCS greenness–redness scale could be considered a ratio scale, the statement describing the *g*-8 chip as twice as red as the *g*-4 chip should apply. But many observers, including the author, are not prepared to agree with such a statement.

Once a color solid has been perceptually developed for a specific set of conditions, the selected stimuli/samples can be defined physically by spectral power or reflectance measurements. The next step is to build a mathematical model connecting the physical with the psychological data in a manner resulting in perfect or near perfect agreement between the two sets. As will be seen in Chapter 6, much effort has been devoted to finding the mathematical definition of a uniform psychophysical color space. There are a number of problems and difficulties with such efforts. They begin with the difficulties or impossibility of creating an euclidean geometrical model of a uniform psychological color space. In addition the physical definition of samples and spectral power distributions, representative of the observed objects, is not without problems.

1.3 UNIFORM AND REGULAR COLOR SPACES

The Oxford English Dictionary's definition of *uniform* in regard to motion or dimensions is "free from fluctuation or variation in respect to quantity or amount." In regard to color space the term *uniformity* has historically had two different uses: (1) Absence of variation in terms of a single concept: perceived color difference between two grades in any direction in space. (2) Absence of variation in terms of attributes that are perceptually significant but do not result in perceptually uniform differences, such as blackness or relative content of unique hues. In the former case the space is uniform in terms of the magnitude of perceived differences but not uniform in terms of blackness or redness. In the latter case the space is uniform only in terms of the chosen attributes but not in terms of perceived differences. It is useful to reserve the term "uniform" for the former situation and use another term, perhaps "regular color space" (Hering space for the Hering-inspired version), for the latter.

As will be seen in Chapter 2, the concept of uniform color solid has a long history. In the seventeenth century Glisson attempted to develop a gray (lightness) scale and three tonal color scales with visually equidistant steps with which to specify the colors of objects. T. Mayer, J. H. Lambert, and P. O. Runge in the eighteenth and nineteenth centuries were already thinking in terms of visually uniform steps between the scale points of their color solids. Mayer appears to have been the first to propose a three-dimensional color solid. H. von Helmholtz was the first to attempt to find the relationship between physical measurements of the stimulus and a perceptually uniform space.

W. Ostwald, apparently through a misunderstanding of Helmholtz's concept of brightness, decided to use Hering's blackness and whiteness as the two attributes that together with chromatic color, form the color perception. He used Hering's equilateral triangular template to arrange all color perceptions of a given hue. In this template, in the tradition of Runge, W. Wundt, and Hering, lightness is not an attribute and chromaticness of all full colors (pure pigment or maximal color) is considered perceptually equal. In regard to chromaticness the result is that the perceptual magnitude of chromaticness steps depends on hue. In addition Ostwald decided that the Weber-Fechner law was applicable regardless of size of color difference, and he scaled the grades in the hue triangle accordingly.

Munsell introduced a radical philosophical departure from the German school by using the three attributes lightness, hue, and chroma. His chromaticness measure, the chroma unit, is in principle of equal perceptual magnitude regardless of hue, and it is defined in terms of (imperfectly defined) constant perceived lightness. While he originally constrained his color solid into the form of a sphere, Munsell soon learned from experiments that when building his system from the central gray midpoint perceptual uniformity was not compatible with the complete color solid having a spherical form. The result was the irregular shape of the Munsell "color tree." Munsell's successors continued to refine the scaling of the three attributes, the last accepted revision being the Munsell Renotations. In the Renotations perceptual data were "smoothed" to some degree in terms of psychophysical data.

A major reason for the development of early forms of color solids, as Chapter 2 will show, was to have a basis for discovering systematic rules of color harmony. This desire was behind the efforts of Runge, O. N. Rood, Munsell, Ostwald, and others (Schwarz, 1999). An American version of Ostwald's system was called *Color Harmony Manual*. Even though claims of having discovered universal rules of color harmony have been discredited, there has been a continuing discussion on the usefulness of the various systems for the purposes of art and design. Ostwald strove to make his system derivable from additive color mixture data, thus developing a system that attempted to combine perceptual psychology, psychophysics, and harmony.

The Swedish Natural Color System (NCS) is a modern interpretation of Hering's ideas. It was derived on a purely psychological basis using presumed innate concepts of Hering type *Vollfarben* (full colors) with unique hues, blackness, and whiteness. Psychophysical measures were used only to specify color grade samples exemplifying the system under a specific set of conditions. The attributes of this Hering or Ostwald type of system are hue, expressed by quadrant in terms of one or two unique hues, blackness, and whiteness (or hue, blackness, and chromaticness). The double-cone geometrical form of systems such as Ostwald's and NCS's appears to imply conventional definitions of the geometrical dimensions. But by placing all full colors on the periphery of the central disk of the double cone and a perceptually uniform gray scale on the central vertical axis, the meaning of the vertical dimension in these systems is not defined. As a result the steps are not uniform in the sense defined above but regular. The practical value of such systems must be found in principles other than uniformity of difference.

The Munsell system on the other hand, as mentioned, is based on the psychological attributes hue, as expressed in terms of five primary hues, value (lightness), and chroma (saturation). Munsell's original intent was to represent a uniform color space. However, by concentrating on planes of constant hue, he neglected the changes in hue difference as a function of chroma and lightness between adjacent constant hue planes. A uniform version of the Munsell system is impossible to fit into a euclidean system as will be shown. By disregarding the issue of relative perceptual size of hue and chroma difference steps, the Munsell system is simply accepted as fitting a polar system. In this system the polar angle, radial distance, and distance from the origin in the third dimension have defined meanings: hue, chroma, and lightness; but the units are of different perceptual size (in the case of hue also as a function of chroma). This was experimentally determined in the 1930s. According to D. Nickerson's index of fading formula (1936), one unit of value difference is equal to two units of chroma difference and, at chroma 5, to three 100-step units of hue difference.

In 1943, based on the then newly available calculations by D. L. MacAdam of the object color limits, Nickerson and S. Newhall calculated two three-dimensional models of the psychological Munsells solid (Fig. 1-2).[8] They are approximations of a uniform psychological solid under two different observational conditions without among other things, considering the matter of the relationship between unit hue and chroma differences. They were described as fulfilling the following requirements: "Dimensional scales . . . calibrated in perceptually uniform steps; units of the several scales . . . equated; the surface of the solid . . . represents all colors of maximum saturation; the difference and volume . . . representative of all colors which are perceptibly different; conditions of stimulation or viewing . . . described; and, finally, the scales . . . stan-

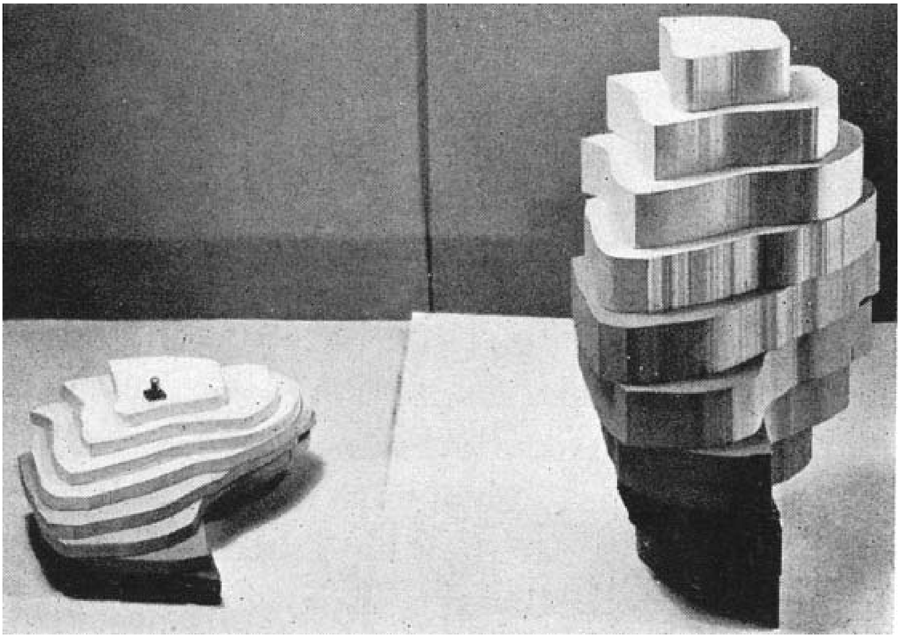

Fig. 1-2 *Models of Nickerson and Newhall's psychological color solid, based on the Munsell system. The two figures represent color solids based on large and small perceived differences.* Left*: At the level of Munsell Book of Color differences.* Right*: At the just noticeable difference level.*

dardized in terms of a generally recognized psychophysical system." B. Bellamy and Newhall (1942) investigated differences at the threshold level and reported them in terms of the Munsell attributes. Their results, surprisingly, indicated one unit of value to be equal to eight units of chroma and, at chroma 6, to 22 units of hue difference, thus indicating a vast change in relative importance as the differences became small. The shorter version of the model represents space proportions when viewing differences of the magnitude of chroma or value steps. The taller version has the vertical dimension increased by a factor 4 to indicate the scales when judging samples differing at the just noticeable difference level. Figure 1-3 illustrates cross sections at the five basic Munsell hues through the solid, with the inner contours representing areas covered by actual Munsell color samples. These figures, seemingly, are the first attempt at realistic (but euclidean) geometrical representation of the universe of (relativized) human object color perceptions in approximations of perceptually uniform spaces.

D. B. Judd and I. H. Godlove, investigating the relationship between hue and chroma differences used by Nickerson in her formula, discovered that it is not possible to map the results onto a flat plane. According to this formula the radial distance covered by the hue differences at any given chroma level is approximately twice that of a circle, meaning the total hue angle is approx-

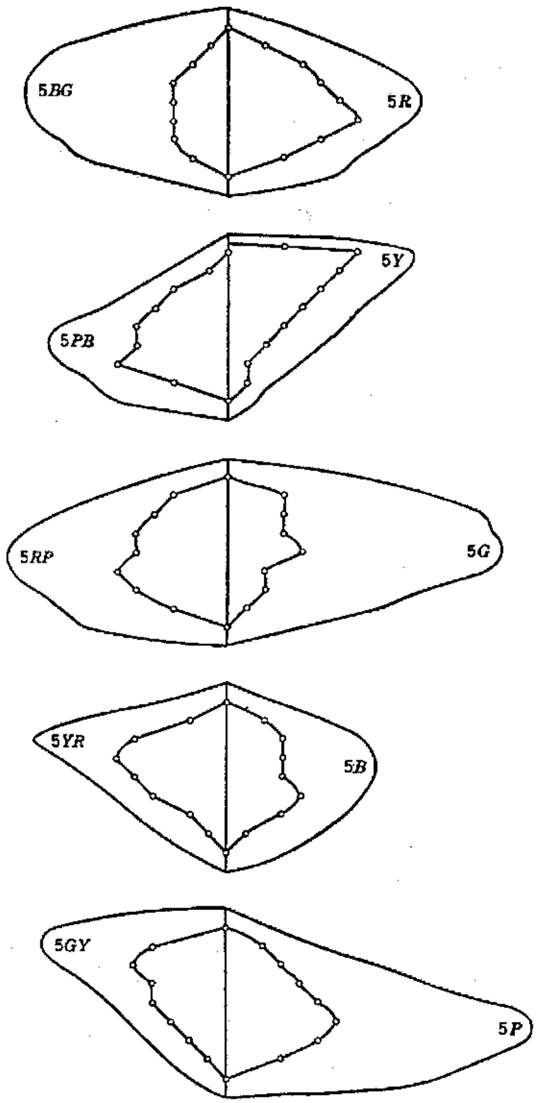

Fig. 1-3 *Vertical sections in five different hue planes through the color solid that represents the Munsell system extrapolated to the optimal color limits. The inner borders delineate the space filled by samples of the system.*

imately 720 degrees. Judd attributed this result to experimental error, and Godlove (1951) wrote a formula that reduces the magnitude of hue differences so that the Munsell equal lightness psychological data map onto a plane. Toward the end of his life Judd reconsidered his view, and there is now significant additional evidence indicating that the Nickerson formula is approximately correct. Full clarification requires further psychological scaling.

As will be shown in Chapter 5, three sets of extensive chroma spacing data, determined at different times, are not in good agreement, and the implicit chroma scale of the Optical Society of America Unform Color Scales (OSA-UCS) system does not agree with any of the three. The psychophysical chroma scale implicit in the widely used CIELAB color space formula is not in good agreement with any of the above.[9] It is fair to say that we do not have a reliable chroma scale. Similarly there are no data of hue scaling around a hue circle at constant chroma and lightness that can be considered reliable and replicated. Different formulas have been proposed for the weighting of CIELAB hue differences in recent years and formulas optimal for one set of data usually perform significantly less well for another. We also do not have a psychophysical model with known scientific validity for uniform hue spacing.

Similary, elementaristic lightness scales are found to depend on surround conditions and there is poor agreement between perceived lightness of chromatic color patches and measured luminous reflectance.

In 1969 Judd wrote an essay on the subject of ideal color space. His initial definition of an ideal color space was: "Ideal color space is a tridimensional array of points, each representing a color, so located that the length of the straight line between any two points is proportional to the perceived size of the difference between the colors represented by the points." A number of experimental facts, however, led him to conclude that ideal color space by this definition is impossible. He listed these facts as:

1. Evidence for curvature of color space from the MacAdam ellipse data.
2. Superimportance of hue as indicated in the Nickerson formula.
3. Diminishing returns in color difference perception.
4. Influence of surround color.

Accounting for these problems, he offered the following redefinition of the concept of ideal color space: "Ideal color space redefined is a tridimensional array of points, each representing a color, such that all pairs of points separated by any fixed distance correspond to pairs of color perceived to differ by the same amount provided that the appraisal of the perceived size be carried out with optimal surround colors chosen in accord with Schönfelder's law[10] that the surround be the average of the two colors being compared." It is evident that uniformity of difference is the central principle behind both definitions.

In the 1970s R. M. Evans and B. Swenholt extensively investigated psychological color space and concluded that to accommodate achromatic surrounds of varying brightness or lightness, five attributes require consideration and that, therefore, a euclidean map of color space is a simplification applying to one surround only.

In its work the Uniform Color Scales Committee of the Optical Society of America was well aware of the problem of hue superimportance. As mentioned, it abandoned separate scaling of color attributes in favor of scaling complex chromatic and chromatic/lightness differences. Based on a euclidean formula fitted to the visual data it proceeded to tile, according to a proposal by I. Balinkin and C. E. Foss, the implicit space uniformly in twelve directions from a central midgray. The resulting space combines an irregular shape with a crystalline interior structure (see Chapters 2 and 7). As a result hue superimportance was purposely neglected, and the space is not visually uniform in all directions.

In 1981 G. Wyszecki defined uniform color space as follows: "A uniform color space is a geometrical representation of color perceptions in a three-dimensional space in which the distance between any two points can be taken as a measure of the magnitude of the difference between the two color perceptions that are represented by the two points." It appears that the concerns of Judd and Evans about surround and other issues had been shelved.

Today it is evident that there is no single uniform color space and no simple geometrical model of perceptually uniform space that is more than an approximation. In addition different surrounds and different sizes of intervals on which the space may be based result in different geometrical forms of the space and different selections of color chips within the space to represent visually uniform steps.

A goal of sensory psychophysics is to determine the relationship between physical stimuli and psychological response. In the case of colors seen as those of objects, this requires discovering the relationship between the spectral return of light, reflected from objects, and the psychological response of the observer. Given the variability in response of observers, this is usually done for an average color normal observer. Quantitative description of human color vision used in models consists either of functions representing the average sensitivity of the three cones or color-matching functions that predict if two different spectral power distributions are seen as matching by the standard observer for whom the color-matching functions apply. The two sets of functions are considered linearly related. Many color space formulas contain additional suppositions concerning the color vision apparatus, in particular, an opponent color theory. In the last fifty years the CIE has proposed several color space and color difference formulas (see chapter 6). Other formulas have been proposed by other organizations and by individuals. The best of these formulas explain 65% to 80% of the average variation in perceived differences of the visual data on which they are based. Significant further improvement is unlikely without reliable visual hue, chroma and lightness scales and understanding of how size of difference affects the implicit color space. Most formulas for object colors developed in the last twenty years are based on the CIELAB formula, recommended by the CIE in 1976 as a compromise formula for unification of practice. As will be demonstrated, this formula is quite clearly not a good basis for color difference calculation. Improvements in the fit of the formula to visual data since then have been based on statistically determined mathematical fixes. This text presents new, more detailed understanding of the relationship between stimuli conventionally taken as color stimuli and color perceptions associated with objects, with the potential to provide a basis for improved formulas.

1.4 COLOR SPACE, SENSATION, PERCEPTION, AND AWARENESS

The terms sensation and perception[11] have traditionally referred to immediate and direct qualitative experiences such as "hard," "cold," and "green" in the former case and complete psychological processes involving implied meaning, past experience, memory, and strategy in the latter. This view of the visual system descended from ideas by Descartes who described "three grades of sensory response. The first is limited to the immediate stimulation of the bodily organs by external objects. . . . The second grade comprises all the immediate effects produced in the mind . . . such effects include pain, pleasure, hunger, colors, sound, taste . . . The third grade includes all the judgments about things outside us . . ." In recent years it has become quite clear that such a distinction has little connection with reality. In order to form a perception, we now understand that it is necessary to pay attention to a stimulus and thereby become aware of it. Experiments have shown that the visual system continuously senses a large number of stimuli arriving at the retina without the owner of the system becoming aware of them or having recollection of them. It seems useful to use the term perception for what results from a given local stimulus after it has received attention and it has undergone the complete processing resulting in awareness. A step taken in connection with color scaling is to form judgments based on perception.

Color perception and the concept of color space and solid are important components of the not well-defined concepts of awareness and consciousness. Consciousness remains a mystery but is now being investigated intensively by neuroscientists, physicists, psychologists, and philosophers. There is a growing corpus of neurological information regarding the functioning of the visual system. At the same time we have more than 200 years of investigations of psychological color space. But there continues to be a black box into which biologically produced correlates of physical stimuli disappear and out of which color experiences appear. This situation prevents the development of a convincing model of human color vision and has resulted in the use of growing numbers of mathematical variables to fit cone sensitivity or color matching function data to perceptual data. It is generally accepted that all information derived from radiant energy required for us to experience form, color, and motion passes through the filter of the three cones. If this is an ultimate truth, then we must look to neurophysiology of the retina and pathways in the brain to provide more information on the processes as a basis for better models. What we have seems promising and, at the same time, is unsatisfactory. This assessment is based on the unproved assumption that color experiences are directly derivable from the neurophysiological functioning of certain cells in our visual system, an idea that has, more or less directly, informed efforts toward a uniform psychophysical color space for the last century. However, there is a significant group of scientists and philosophers disagreeing with it, and the issue must be considered open.

In the 1940s color space and difference research in the United States profited from the historical curiosity of a search for work not directly connected with war effort (Nickerson, 1977). Early results generated their own momentum, and work continued in the 1950s and 1960s through the efforts of a few dedicated individuals in a committee of the Optical Society of America. In the 1960s, with growing capabilities for industrial reflectance measurement and color calculation, color technologists in colorant producing and using industries around the world became increasingly interested in the possibilities of objective color quality control and provided impetus for new work. These efforts have resulted in the level of success mentioned above, based on reliable reflectance measurement techniques and the developments in color science to be discussed below. Since the mid-1980s the major activity has shifted to academic institutions. More recently lack of funding and new and seemingly more exciting fields of research in color have slowed the pace of color space and difference research work appreciably. It seems that we must rely again on a few dedicated individuals, interested in pushing the frontier in this field for the sake of advancing toward the distant goal of understanding qualitatively and quantitatively, in very limited situations, the relationship between visual stimuli and the resulting color and color difference perceptions.

1.5 PLAN OF THE BOOK

Chapter 2 begins with an attempt at a general definition of the meaning of color space and color solid. It is followed by a historical survey of ideas about color order beginning with ancient Greek philosophers. Given the paucity of surviving documents, our knowledge in this area is likely incomplete. The survey continues through the Middle Ages and the Renaissance into the Age of Enlightenment. Three-dimensional color solids began making an appearance in the eighteenth century. The contributions of psychophysics, starting in the midnineteenth century, to the matter at hand are discussed as are development in understanding of human color vision and of the colorimetric system. Brief discussions of the systems of Hering, Munsell, Ostwald, the German DIN 6164, the Optical Society of America Uniform Color Scales, the Swedish Natural Color System, and others, including systems used in video display, are presented to bring the reader to the present in this multimillennia pursuit of ordering our color perceptions.

Chapter 3 offers a survey of psychophysics as relevant to the color-ordering enterprise. Many of the problems and complexities of psychophysics are touched on including theories of categorization, relationship of differences and magnitudes, uni- and multidimensional scaling methods, and the relationship between psychological and psychophysical color spaces.

The theme of Chapter 4 is perceptual color attributes and how they are scaled. It concentrates on perceptual scaling only. Views regarding color attributes have a history of their own. On the one hand is the physics inspired set of hue, saturation, and brightness or lightness introduced by Newton and Helmholtz, on the other, Herings "natural" system of hue, whiteness, and blackness. A large portion of the chapter is given to data of perceptual scaling of color attributes, including location of unique hues and distances between them. The paucity of extensive sets of global scaling data and the lack (for unknown reasons) of close agreement among those few that exist is commented on.

In Chapter 5 the perceptual scales of Chapter 4 are related to physical definitions of color stimuli such as reflectance or spectral power distribution data. This requires brief discussions of photometry and colorimetry as well as psychophysical spaces such as cone response, tristimulus, and opponent color spaces. The relationship between color matching and color appearance is touched on, as is placement of unique hues in psychophysical spaces and curvature of lines connecting blues of constant hue in CIE-based opponent color diagrams. The chapter closes with a discussion of the number of colors we can distinguish.

Chapter 6 contains all major historical steps in the effort of finding psychophysical formulas attempting to describe uniform color space, beginning with Helmholtz' line element and ending in the present. The chapter ends with a brief comparison of color and spectral spaces as well as a comparison of performance of various formulas against the Munsell system and the RIT-DuPont data exemplifying global color and small color difference data.

Chapter 7 contains more extensive descriptions and comparative analysis of three major color order systems: the Munsell and OSA-UCS system and the NCS system. The former two are attempts at a uniform color space while the latter is an implementation of Herings "natural color system." It is demonstrated that neither constant value planes of the Munsell system nor constant lightness planes of the (experimental results of the) OSA-UCS can be isomorphically plotted on a euclidean plane.

In Chapter 8 color differences have been scaled at many different levels, from color-matching error and threshold differences to small and large suprathreshold differences. In this chapter important data from each category are compared in the cone sensitivity and the tristimulus spaces for agreement and discrepancies. One of the comparisons involves the magnitude of Weber fractions, another the direction of the unit chromatic contours in the spaces. Many issues are found to be unresolved because of lack of reliable, replicated data.

Chapter 9 draws conclusions from the facts of the previous chapters by attempting to answer 13 questions related to color scaling and uniform and regular color spaces. An approximation of a uniform color space at the level of small color differences is shown as a counterpoint to the figure of the Nickerson-Newhall uniform color space in this chapter (Fig. 1-2). A research program is proposed in some detail to establish reliable, replicated data that can be used to determine the properties of uniform color spaces for a given viewing and surround situation at different levels of size of difference.