Chapter 4

Color Attributes and Perceptual Attribute Scaling

4.1 THEORIES OF VISION

Vision is defined as the sense, mediated by the eyes, by which the positions, qualities, and movements of objects are perceived. The generally accepted view is that patterns of light energy are absorbed by light sensitive cells in the eye. The resulting electrochemical signals are passed into the brain where they cause activation of other cell types eventually resulting in sensations and perceptions of form, color, and movement. A representation of the outside world is generated in the retina and eventually in the brain. There are standard relationships between stimulus and resulting perception for which, presumably, neural correlates exist in the brain. Exceptions to these standard relationships are just that. They are caused by limitations in the neural apparatus. Much of the efforts of visual science in the 1980s and 1990s have been attempts at elucidation of these standard relationships and exceptions and finding their neural correlates (e.g., see De Valois, 2000). But parts of this view face serious problems from a slew of perceptual responses that are not explained by standard models.

Already Helmholtz thought that perception is the result of the interaction of the neural messages from the eyes with stored memories from past experiences (Helmholtz, 1866). With the wider acceptance of Darwin's ideas about evolution in the twentieth century, some researchers began to look at senses

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as tools of animals to cope with challenges in their particular ecological niches. In the second half of the twentieth century the American psychologist J. J. Gibson developed what he called an ecological approach to visual perception. He believed that the important rules of vision are found in natural viewing environments and not in fixed laboratory situations. Indeed, both are realities and ultimately must find meshing explanations. But it appears quite clearly wrong to assume that there is a simple standard relationship between states of retinal and early neural cells of the visual system and percepts. There is no doubt that vision has provided its bearers with an important tool to help make decisions affecting their own life and that of their offspring. Vision, implemented in many different ways in the animal kingdom, is undoubtedly shaped by evolutionary forces. It remains to be determined how.

4.2 HISTORICAL DEVELOPMENT OF VIEWS ON ATTRIBUTES

Regardless of how a particular color experience is generated, it can be said to have certain attributes, that is, inherent characteristics. The idea of color attributes has developed slowly over an extended period of time. As shown in Chapter 2, ancient Greeks appear not to have had a clear concept of chromatic color attributes. Only the concepts of light and dark and of hue were familiar to them. The simple linear color scales of the philosophers, originally seemingly in random order, later implied an ordering by lightness, without regard to hue ordering in the sense of the spectrum. In Aristotle's seven-color scale white precedes yellow followed by crimson, violet, green, and blue which precedes black. The red-centered five-color scale, found in descriptions until the sixteenth century, is that of Chalcidius: white–yellow–red–blue–black. From observations in nature and the work of artists the lightening and darkening of full colors (or of pure highly chromatic pigments) was well known in artist's circles of the twelfth century, as the text by Theophilus demonstrates. A painting technique of the early Italian Renaissance, described by Cennini in 1390, involved the use of pure chromatic pigments for the darkest areas and dilutions with a white pigment for lighter areas. In 1435 Alberti advised his fellow painters as follows: ". . . you may change the color with a little white applied as sparingly as possible in the appropriate place within the outlines of the surface, and likewise add some black in the place opposite to it. With such balancing, as one might say, of black and white, a surface rising in relief becomes still more evident. Go on making similar sparing additions until you feel you have arrived at what is required." The full complement of tonal colors began to be exploited by some artists wanting to avoid a certain garishness that can arise when painting with pure chromatic pigments. Chief among them was Leonardo da Vinci who developed the *sfumato* (smoky) style of painting and who is credited by some art historians as having distinguished between lightness (*chiarezza* in Leonardo's terminology) and chroma (*bellezza*) (Ackerman, 1980). Quantitative estimates of the natural lightness of full object colors were provided in print first by Cardanus in 1563, as seen in Chapter 2.

As has been discussed earlier, it is reasonably certain that Forsius and Glisson did not have a concept of a third attribute, beyond hue and lightness.

The concept of saturation as an attribute of prismatic color makes its definitive appearance with Newton. It is clearly based on his experiments with overlays of various wavebands of light. He described points on a radial line in his diagram (see Fig. 2-10) as indicating colors "proportional to the fullness or intenseness of the [prismatic] Colour, that is, to its distance from whiteness." Newton recognized seven primary and an indefinite number of intermediate hues. He described lightness in connection with colorants as follows: "Now considering that these grey and dun Colours may also be produced by mixing whites and blacks, and by consequence differ from perfect whites not in Species of Colours but only in degree of luminousness, it is manifest that there is nothing more requisite to make them perfectly white than to increase their Light sufficiently . . ." (Newton, 1704, p. 112). Here we see for the first time (if not in the same place in the book) mention of three attributes describing color perceptions.

Mayer, who in the mideighteenth century developed the first plan for a three-dimensional color order system, did not distinguish color series from the most saturated colors on the surface of his double triangular pyramid through the interior of the triangle. A possible reason is that in his own efforts with pigments he ended up with a neutral gray quite removed from the gravimetric center of the triangle, according to his own information at $r^3\ g^2\ b^7$, indicating that his scheme of determining relative strength of pigments was less than perfect.

Also Lambert did not recognize saturation or chroma as a separate color attribute, even though it can be seen as implicit in his single pyramid. The reason is similar to the one applicable in the case of Mayer. His three primary colors are placed on the same level regardless of their lightness, and his choice of colorants and mixture ratios did not result in black falling onto the gravimetric center of his basis triangle but, again, not far from the blue corner.

The painter Runge provided clear and explicit discussion of the general idea of saturation, but without using such a term. Because he placed the full colors on the circumference of the central horizontal plane of his color sphere, its vertical dimension does not refer to brightness or lightness. But Runge understood clearly the desaturation of a full color, by the admixture of appropriately selected complementary colors or combinations: "When we add to pure green, a product of yellow and blue, the smallest amount of red as the third color, we learn that it simply destroys and dirties the pleasant appearance of green without adding the appearance of redness. Therefore, through a stronger admixture of red, green is dissolved into completely colorless smut, or gray, and assumes a reddish hue only through an even stronger admixture. . . . All diametrically opposed colors and mixtures on the circle are (in the center point of the circle) dissolved (into gray)" (Runge, 1810). In the colored figure of the equatorial cross section of his sphere (see Fig. 2-22) Runge shows four desaturation steps toward the central gray for each full color.[1]

Grassmann, as we have seen in Chapter 2, supplied Newton's diagram with a mathematical foundation based on Helmholtz's and Maxwell's ideas of three fundamental color processes. He also, for the first time, explicitly referred to three attributes that combine to form a color perception: "If, finally, we consider a light of arbitrary composition, the eye can distinguish in it only the three mentioned attributes, that is, any impression by a light can be imitated by mixing a homogeneous color of a certain intensity with white light of a certain intensity. Therefore, we have to distinguish three things in each impression: intensity of color, hue, and intensity of the admixed colorless light" (Grassmann, 1853, pp. 70–71). Grassmann provided a general connection between perceptual color attributes and physical magnitudes.[2]

In his *Physiologische Optik*, preceding the *Handbook*, Helmholtz slightly modified Grassmann's definition:[3]

> Every impression on the eye made by an arbitrarily mixed light can always be represented as a function of three variables that can be expressed in numbers, that is,
>
> 1. Quantity of saturated colored light,
> 2. Quantity of white light that when admixed results in the same color impression,
> 3. Wavelength of the colored light. (Helmholtz 1860)

In the *Handbook* he described the three attributes in the form still in use:

> Accordingly, with all possible combinations of systems of aether-waves of different frequencies of vibration, there is after all a comparatively small number of different states of stimulation of the organ of vision which can be recognized as different colour sensations. First of these are the series of *saturated* colours, composed of the colours on the spectrum, along with purple which links the ends of the series. Each of these hues again may occur more or less pale in different gradations. The paler it is the less saturated it appears. . . . Thus, we have here two kinds of differences between colours, namely, first, differences of *hue*, and second, differences of *saturation*. . . . Lastly, in ordinary speech we are wont to describe differences of luminosity as differences of colour, however, only in case colour is considered as a characteristic of bodies. (italics in the original)

In 1866 Brücke presented a schematic color sphere and a cross-sectional view in which he showed presumed lines of constant saturation (Fig. 4-1). He viewed constant saturation contours as representing the surfaces of spindle shapes, with varying ratios of length to width, ending in the sphere shape at maximum saturation for a given level of lightness.

In Wundt's color sphere of 1874 hue (*Farbton*), saturation (*Sättigung*), and brightness (*Lichtintensität*) are established concepts. His student Kirschmann published in 1895 a paper "Color-saturation and its quantitative relations" in which he described the design of a color disk that, when spun with sufficient speed, displayed what was described as fifteen perceptually equally different saturation steps of the test color of the disk (Fig. 4-2). The heart-shaped figure A is colored with the test color (e.g., an approximation of a Hering type full

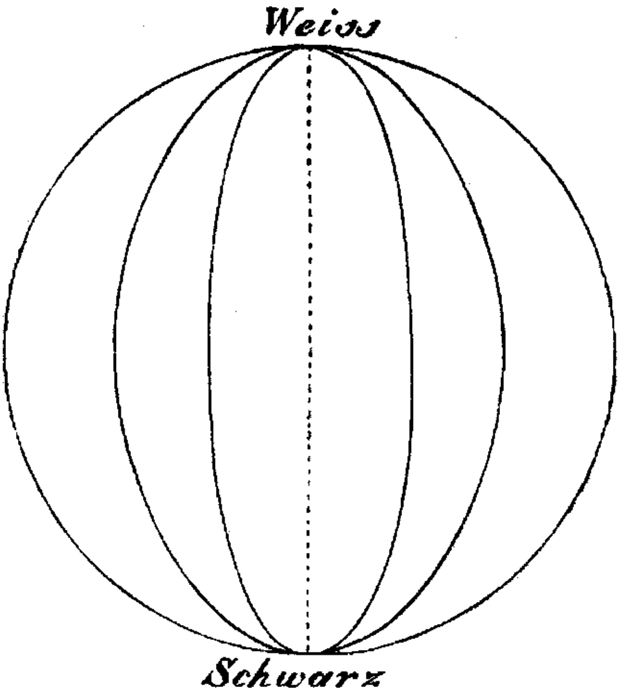

Fig. 4-1 *Brücke's vertical section through the color sphere with white on top and black on the bottom, 1866. The full interior lines are meant to be lines of constant saturation.*

color). The shapes of B and C are designed to produce from black and white the appropriate level of gray to be added to the full color so that all resulting saturation steps have identical lightness (thus representing a chroma scale when seen as object colors). The exact shape of B and C depends on the photometrically measured luminosity of the color of A. With this method Kirschmann investigated the validity of the Weber-Fechner law in regard to saturation.

In Hering's system full colors occupy one corner of equilateral triangles. The remaining colors in a triangle consist of those of the gray scale and the veiled (*verhüllte*) colors with the same hue as the full color. As mentioned in Chapter 2, Hering was fully aware of the varying lightness of full colors but never explicitly described how lightness as an attribute was to fit into his "natural color system." Any color could be described as the sum of one or two primary colors, white and black. Thus, in the majority of cases, colors had four attributes, for example, for a brown yellowness, redness, whiteness, and blackness. Hering abandoned use of the term saturation because he believed its meaning to be "contaminated" by Helmholtz. He defined colors of "equally strong veiling" as those falling on lines parallel to the line connecting white and black in his triangle,[4] those having the same ratio of full color to total color

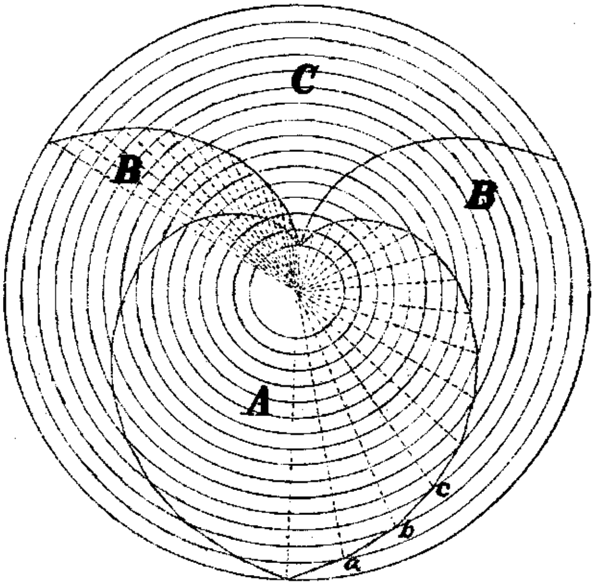

Fig. 4-2 *Construction of a disk arrangement for the spinning disk mixture resulting in fifteen concentric circles at equal luminance with perceptually equally (according to the Weber-Fechner law) different steps of saturation of the color displayed on shape A. From Kirschmann (1895).*

content. He commented on the difficulty of comparing degree of veiling for differently hued colors and does not seem to have regarded it as a primary attribute of color perception.

Later the Hering pupil E. G. Müller and the psychologist D. Katz suggested replacement of the term saturation with *Eindringlichkeit* (penetrance). In 1917 the psychologist C. Stumpf completely rejected saturation as an attribute and believed it to be a cognitive abstraction for the resemblance of a color perception to its ideal.

Munsell, in his effort to develop a useful teaching tool, first relied on the form of a new kind of color sphere, developed by him in 1898. This sphere differed from Runge's in that the vertical dimension has an unambiguous definition as lightness (value) with the result that on this sphere Hering's full colors are not located on the equatorial plane. Munsell had studied art in Paris around 1880 and, perhaps influenced by the French use of *valeur* in tonal painting, settled on the term value for lightness. The Greek term *chroma* (surface skin, color) was also in use as a general term for color in French art literature at the time of his studies (e.g., George Seurat's *chromo-luminarisme* painting style[5]) and it appeared in the title of Rood's influential *Modern chromatics*. It seems intuitive to use it in a quantitative sense to indicate how much chromatic color is present. Munsell's three color attributes, principally in agreement with those of Helmholtz, were thus named hue, value, and chroma. Munsell, intrigued with the decimal system, selected a 100-part hue circle and five primary colors rather than Hering's four (he thought Hering to be wrong because Hering's claims for the operation of his opponent-color system were not in accord with contemporary knowledge about the retinal structure). His value scale consisted of ten steps. The chroma scale was open ended because Munsell soon found that he could not fit all colors with uniform chroma spacing into a sphere form. As described below and in Chapter 7, scales for all three attributes were intensively investigated before finding their final form in the Munsell Renotations.

Ostwald, working in isolation during the First World War, erroneously believed Helmholtz had made no distinction between what we now call brightness and lightness.[6] For this reason he rejected lightness as an attribute for his system and followed Hering in using full color content, whiteness and blackness. But unlike Hering, he based his hue circle on three primary colors, yellow, red, and blue. Object colors were defined as the sum of full color perceptions and perceptions of white and black. Hering's colors of equally strong veiling were termed by Ostwald *Reingleiche* (colors of equal purity). Analysis of Ostwald's system in 1944 indicated that:

1. The system did not cover the full range of object colors as defined by the Rösch-MacAdam limits.
2. Ostwald's claims for complementarity and visual uniformity in terms of hue differences around the hue circle have not been met and cannot be met.
3. Various compromises have been made by Ostwald in physically implementing his system (Foss, Nickerson, and Granville, 1944).

Basic ideas of Hering were also used by Johannsson and Hesselgren and resulted in the development of the Swedish Natural Color System (see Chapters 2 and 7).

4.3 WHITENESS AND BLACKNESS

In Chapter 2 it was mentioned that white and black have been considered colors for some 3000 years or more. But there has been a certain amount of controversy about this subject. Non-hued visual percepts are often called achromatic colors, that is, colorless colors. Truly achromatic colors differ from chromatic colors in the lack of the key perceptual attribute of hue. While hued colors are well defined, unique blue is a bluish color that is neither greenish nor reddish, neither black nor white are well defined in a similar sense. This becomes apparent if one looks, for example, at a collection of white and black textiles. Generally preferred white and black both have a slightly bluish tinge. But the preferences differ among individuals and cultures. In addition, while not any chromatic stimulus can appear unique red, any neutrally reflecting surface can be made to look white or black or any gray in between depending on illumination and surround. Perceptions of white and black as the achromatic extremes are outputs of our color vision system, just as perceptions of hue and chroma are. It appears entirely justified to consider achromatic colors to be on an equivalent level with chromatic colors.

Helmholtz defined black as the absence of light energy, while Hering, correctly, defined it as an indirect manifestation of light in terms of contrast. When looking at reflectance data of pigmented black and white paint layers, it is obvious that while the white layer reflects most light the black layer reflects very little. But the small amount it reflects is responsible for the fact that a black pigment layer, selectively illuminated with high intensity white light, can be made to look white (as demonstrated by A. Gelb in 1929). Contrast plays a key role in the perception of black, as is well known from the demonstrations of the effect of surround brightness by Evans and from the fact that an unpowered television screen is gray and not black in appearance. The blackness we see in images on the screen must come from contrast effects.

The perception of blackness has been studied in considerable detail (e.g., see Volbrecht and Kliegl 1998). The blackness induction curve is somewhat similar to the heterochromatic flicker brightness curve (see Chapter 5). However, it varies significantly depending on the design of the experiment. If a monochromatic ring surrounds a white center, the agreement with the flicker brightness curve is relatively high. If center and ring are reversed, the function appears to have a chromatic opponent color component added, reminiscent of the Helmholtz-Kohlrausch effect. A detailed model of blackness perception based on cone sensitivities and assumptions about the physiology of color vision has been developed by K. Shinomori and co-workers (Shinomori, 1997).

As we have seen, whiteness as a psychological attribute has been defined in terms of a perceptually uniform gray scale by Hering and Ostwald. The psychophysical description of whiteness has been of interest since the mid-1930s. The definition of the portion of color space that most observers call white or near white, and its description in terms of a psychophysical formula, have been driven by industrial interest in measuring whiteness of papers or textiles. Several formulas were developed around 1960, and in 1979 the CIE recommended a whiteness formula to be used in the interest of uniformity (CIE 1979; for a bibliography until 1976, see Sève, 1979). An improved formula is under development. It is of interest to note that the preferred psychological optimal white is not one representing perfect 100% reflectance across the spectrum, nor an equal energy distribution, but one with a slight bluish tint and achieved with the addition of fluorescent whitening agents. This indicates that whiteness and lightness are different psychological and psychophysical concepts.

4.4 EVANS'S FIVE COLOR ATTRIBUTES

In 1974 R. M. Evans published his interpretation of the results of many years of study of the appearance of color. He concluded that there are five attributes that require consideration for a full description of color appearance. These are brightness, brilliance, lightness, saturation, and hue. Brightness is conventionally defined in terms of luminosity. Brilliance is a term that encompasses the scale of perception from grayish colors, through the zero grayness (G_0) point to fluorent colors (a term proposed by Evans). Object colors are seen to contain grayness up to a certain level of luminous reflectance (dependent on the surround luminous reflectance) where the zero grayness point is located. At this point they are seen as equally light as the surround. When the luminous reflectance increases further, the colors are seen as lights (weaker or stronger, depending on the degree of fluorence). The spectral zero grayness function (Fig. 4-3) bears close resemblance to the saturation discrimination function, a function describing, based on dominant wavelength, the purity of Munsell samples at constant chroma, as well as to MacAdam's color moment per lumen function (MacAdam, 1981). Evans defined lightness as relative luminance and saturation in a form comparable to colorimetric purity (see Glossary). In his system saturation is the perception of the brilliance of the hue component in relation to the total brilliance of the color. Evans defined Munsell chroma as brilliance difference from a gray of the same value. He

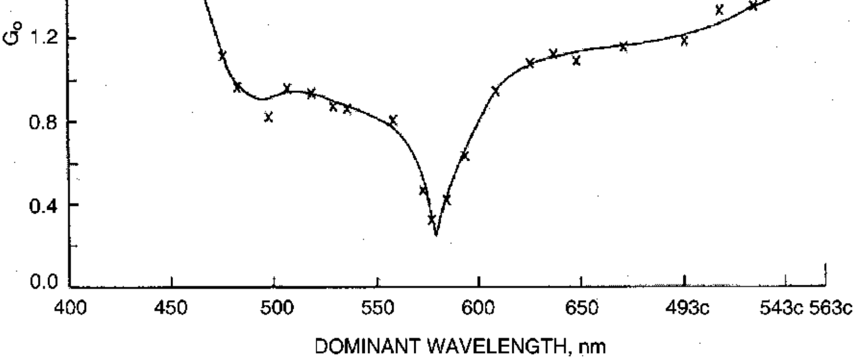

Fig. 4-3 *Zero grayness (G_0) of object colors as a function of dominant wavelength. From Evans (1974).*

described the problems with Judd's original uniform color space definition as due to the need for four dimensions of such a space. When defining uniform color space in terms of surrounds that are always intermediate to the two colors compared, as Judd did in his re-definition, the four-dimensional space can be reduced to three dimensions. This minimizes the required stimulus increment or decrement for color differences. Evans believed the spacing of the Munsell system to be a good approximation of Judd's re-defined uniform color space. The usual approach, however, is to base an attempted uniform color space on a single achromatic surround of a given lightness.

4.5 COMMON COLOR ATTRIBUTE DEFINITIONS

The three psychological Munsell attributes have become generally accepted for object colors. Wyszecki termed the empirical evidence of three attributes being sufficient for an observer with normal color vision to describe any perceived color "overwhelming." His terms for the three attributes were hue, lightness, and chromaticness (Wyszecki, 1981).

Hue

The term hue is defined as "attribute of visual perception according to which an area appears to be similar to one of the colors red, yellow, green, and blue, or to a combination of adjacent pairs of colors considered in a closed ring" (CIE, 1987). Essentially this definition indicates that hues represent the variable one experiences when looking at a Munsell (or other system) hue circle. As mentioned earlier, such hue circles derive their legitimacy from the arrangement of hues in the spectrum, as well as systematic mixtures of stimuli from the beginning and end of the visible spectrum (see Fig. 3-6).

Brightness, Lightness

Lightness is an attribute related to brightness, the definition of which is: "attribute of a visual perception according to which an area appears to emit, or reflect, more or less light" (CIE, 1987). Brightness is generally taken to apply to light sources. Lightness is defined as: "the brightness of an area judged relative to the brightness of a similar area that appears to be white." Lightness thus can be said to be relative brightness and is generally taken to apply to object colors. Brightness and lightness have been controversial since their definitions because they have been defined based on additive functions using an experimental method that is far from natural. As will be shown in Chapter 5, brightness and lightness of chromatic lights, respectively objects, when viewed in natural or strongly relativized conditions have additional components, not contained in the additive function.

Saturation, Chroma

Over the years there has been considerable discussion concerning the term used for the third attribute. Helmholtz's *Sättigung*, or saturation, is now an "attribute of a visual sensation that permits a judgment to be made of the proportion of pure chromatic color in the total sensation" (CIE, 1987). The term chroma is closely related to Munsell chroma and refers to an "attribute of visual sensation that permits a judgment to be made of the amount of pure chromatic color present, regardless of the amount of achromatic color." A differently worded definition is: "attribute of color used to indicate the degree of departure of the color from the gray of the same lightness" (ASTM E284). This definition relates directly to the Munsell system. As discussed next, chroma can be seen as related to an attribute termed "colorfulness," as lightness is related to brightness. Chroma and saturation are identical for two colors having the same hue and lightness. Saturation remains constant regardless of brightness or lightness. Chroma, on the other hand, increases as lightness increases. Saturation relates to an inverted cone arrangement of colors, for example, the DIN system, while chroma refers to a cylindrical arrangement.

The question as to how intuitive the concept of chroma is to the average observer is an interesting one. We have seen that as a well-defined concept, as introduced by Munsell, it is only approximately 100 years old. Seemingly there are no terms of folk psychology that directly refer to it. Empirical evidence of the author with more than 100 untrained observers in experiments where they had to sort Munsell chips of constant hue into a Munsell value/chroma template indicates that many had considerable difficulty to do so because of uncertainty about the concepts of lightness and chroma. A recent investigation has confirmed the higher uncertainty of judgments of assessing color differences as chroma differences, compared to lightness and hue differences (Melgosa et al., 2000).

Hunt's 1977 Proposals

In 1977 R. W. G. Hunt proposed new systematic terminology for color attributes at four levels:

1. Perceptual (psychological)
2. Psychophysical (related to stimulus)
3. Psychometric (interval scales)
4. Psychoquantitative (ratio scales)

Perceptual terms include brightness, lightness, hue, saturation, and perceived chroma. The psychometric terms have the modifier "metric" before them. It changes to "quantitative" for the psychoquantitative terms. The psychoquantitative terms are controversial because of the philosophical problems surrounding them. Hunt also proposed revised definitions for chroma and a new attribute: colorfulness. It is defined as the "attribute of a visual sensation according to which an area appears to exhibit more or less chromatic color." Colorfulness refers to chromatic power perceived regardless of the magnitude of the stimulus. Hunt has used, for example, theatrical lights of varying intensity to demonstrate the meaning of colorfulness. Hunt proposed the definition of perceived chroma as amount of chromatic color in related colors judged in proportion to the average brightness of the surroundings. His proposals for metric hue and chroma are as, for example, defined in the CIELAB formula (see Chapter 6).

4.6 CONFIRMATION OF THREE ATTRIBUTES

The attributes hue, lightness, and chroma for surface colors in simplified viewing conditions have received confirmation from multidimensional scaling experiments. In 1988 Indow reported on the results of nineteen multidimensional difference scaling studies using Munsell color chips. Because of difficulties in comparing chromatic differences of colors with greatly differing hue scaling was only done in overlapping, comparatively small regions of the Munsell chromatic plane. Indow drew the following key conclusions:

1. In a three-dimensional euclidean space the points representing Munsell colors form layers according to the order of Munsell value.
2. In each of the planes colors of the same Munsell hue are located along line segments in the order of Munsell chroma; all lines converge at a single point in the center, corresponding to the gray of the same Munsell value. The circular order of the radial lines agrees with the sequence of Munsell hue.
3. Interpoint euclidean distances between colors are closely related to scaled perceptual distances that were used as the data in the multidimensional scaling experiment.
4. Chroma and value are clearly orthogonal.
5. There are many irregularities in the resulting structure, the main ones being anomaly of hue spacing in sectors B to P, and the first chroma step from neutral is always larger than successive steps.

The result of one multidimensional scaling analysis of Munsell colors at different value levels is shown in Fig. 4-4. Taken together, the findings help support the Munsell system as a systematic perceptual arrangement of colors and the psychological validity of the three attributes.

The perceptual significance of the three Munsell attributes is also indirectly supported by subjecting the reflectance functions of the Munsell chips to dimensionality reduction using a neural network (Usui et al., 1992). The

Fig. 4-4 *Multidimensional scaling analysis of Munsell colors involving samples at four different value levels (From Indow, 1988). The results are shown in an elliptic space. Colors of constant hue are connected with approximately radial lines, colors of equal chroma fall on approximate circles.*

reflectance data of 1596 chips were subjected to a five-layer wineglass type of neural network. Of the three middle-layer units one was found to approximately correspond to value and the other two roughly to opponent responses with red-green and yellow-blue orientation. Lines of constant hue are approximately radial and lines of constant chroma jaggedly oval but placing the hues in proper ordinal order. When reducing the network to two internal layers, yellow and blue colors overlap. On the other hand, of four layers one was found to be redundant, two layers of the four being highly negatively correlated ($r = -0.991$). The most efficient representation involves three internal layers and reconstructs the Munsell color solid roughly as in the X, Y, Z tristimulus space (Fig. 4-5; compare to Fig. 5-30).

Because of the diurnal cycle, to whose effects we are exposed already in the womb, the ideas of bright (or light) and dark are deeply embedded in us. In their simplest form they are achromatic experiences, and all but congenitally blind people know them. As to chromatic colors, the preeminent fact is hue. This is also indicated by our monolexemic names for what we regard as the most significant colors. They generally refer to hue. Level 2 of the Universal Color Language consists of 26 hue-related names (Kelly and Judd, 1976). On

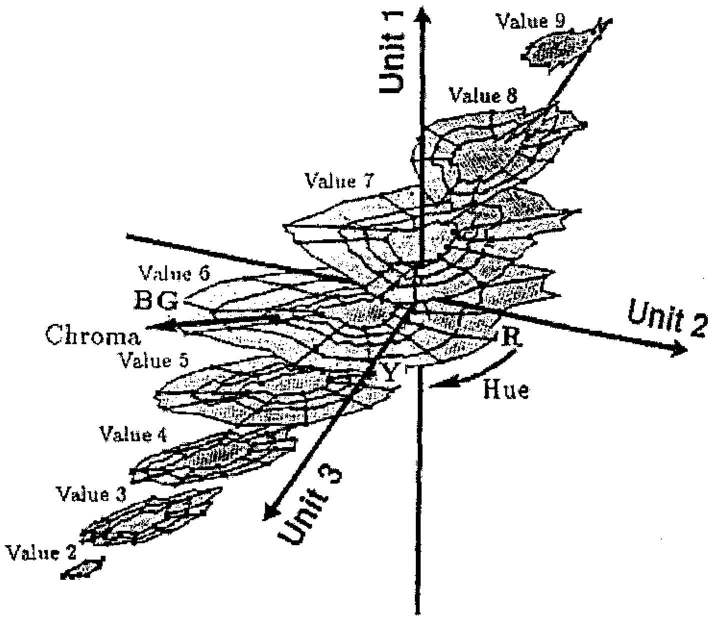

Fig. 4-5 Reconstruction of the Munsell color solid from 1280 reflectance functions of Munsell chips with a five-layer neural network (From Usui et al., 1992). Colors of constant value fall approximately on planes of constant unit 3 values. Constant hue colors fall on approximately radial lines and colors of constant chroma are connected by jagged ellipsoidal contours. The arrangement is similar to one of Munsell colors in the CIE X, Y, Z *space.*

the other hand, the number of modifiers added in level 3 that describe lightness and chroma (e.g., light, strong, vivid, dark, and deep) is only 13. These, together with the 26 hue terms of level 2 and the achromatic terms form the 267 terms of level 3. From this and other facts it is evident that hue is the primary attribute of our normal color experiences. In evolutionary terms light and dark are older, but they encompass one dimension. Hue, on the other hand, has, in a manner of speaking, four dimensions and therefore provides a much larger range of experiences. The general idea of a third attribute of object colors, now named chroma, developed beginning in the nineteenth century with people professionally involved with color, namely painters. In the general population today, even in well-educated segments, it is not yet a commonly understood concept.

The attributes of the Hering-NCS systems are claimed to be intuitive by their creators and to be introspectively determinable with a high degree of precision. The author is not aware of an extensive independent test of this claim. The clear expectation is that in a multidimensional scaling experiment based on uniformity of perceived differences NCS color chips would be placed into a Munsell type color solid.

4.7 CONTRAST VERSUS SIMILITUDE

Given an arrangement of two test fields against a surround sending different spectral power distributions to our eyes, the color experiences resulting from the test fields depend on the spatial proximity of those fields. There are two results possible: either the perceived difference between the test fields becomes larger if the fields are adjacent compared with widely separated or it becomes smaller. In the former case we speak of contrast, in the latter of similitude (also known as the spreading effect; Bezold, 1874). Such effects are usually interpreted as due to lateral interaction between retinal cells (but see Purves and Lotto, 2002). As a result the relationship between stimulus and resulting perception depends on the composition of the visual field.

Contrast has a somewhat different meaning in photography or printing and is defined as the difference between the lightest and the darkest area in the image expressed perceptually or in terms of physical measurements. Aside from lightness contrast there is also chromatic contrast.

Discovery and quantification of contrast as a function of spectral energy is a key aspect of operation of our visual system. As will be shown in Chapter 5, perceptions of white and black do not depend on absolute values of spectral power but are related according to complex, not yet fully understood rules. Similarly it appears that colors are assigned by the visual system to fields of given spectral power, and not by that power but by the relationship of that power to that of neighboring fields according to rules not yet fully understood.

Colors may be said to exist only as contrasts since in a so-called (extreme) *Ganzfeld* where our eyes are individually exposed to uniform light from all directions color experience fades quickly regardless of the spectral power distribution of the light. While contrast effect rules are comparatively simple in case of two fields only, the more articulated the visual field is, the more complex the rules become. Contrast effects resulting in colored shadows were described in the eighteenth century by the Count of Rumford and others. Chevreul famously developed empirical rules of contrast in the nineteenth century. Contrast effects are temporally dependent. When viewing two contrasting fields in a neutral surround, the *simultaneous contrast* is immediately apparent. When the two fields are replaced after some time by the surround color, their images remain still visible, however, with appearances usually changed according to the rules of *successive contrast*.

4.8 NEURAL CORRELATES OF COLOR ATTRIBUTES

Color attributes are phenomenological entities that have as yet no firm basis in neurology. Current answers to the question of neural correlates of color attributes are speculative. According to the opponent color theory, there are six primary object color perceptions: unique yellow, red, blue, green, and white and black. A chromatic object color stimulus invokes one or two of the unique hues, and perhaps white and/or black. It is not yet known what the neural correlates of the unique hue perceptions are. Known opponent color cells in the lateral geniculate nucleus (LGN) and beyond in the cortical visual system do not have outputs correlated with unique hue perceptions, as discussed in Chapter 5 (see also Webster et al., 2000; Valberg, 2001). It appears less and less likely that there are two simple subtractive chromatic opponent color systems as proposed by Hering. Multiple hue detection and discrimination systems have been proposed as an alternative to a two-component opponent color process (e.g., see Krauskopf, 1999). There is a large amount of literature relating to the operation of a neural opponent color system, a subject outside the scope of this text (relevant citations are found in Gegenfurtner and Sharpe, 1999).

Brightness-related signals are transferred from the retina through at least two different neural pathways. Brightness and lightness perception is very complex, for example, as the work by A. L. Gilchrist and co-workers shows (Gilchrist, 1994; Gilchrist et al., 1999), and the Munsell value and similar lightness functions are only simple approximations. Recently Lotto and Purves (1999) have argued that brightness/lightness perception of fields may be guided by our past experiences as a species and as individuals, and interpretation of clues in an image in regard to its likely illumination.

Hue and brightness/lightness perceived in contrast to a surround are affected by a complex set of adaptations whose neural machinery is not well known. As will be seen in Chapter 5, the neural machinery of hue and chroma detection and discrimination is also not known, but signs point to a complex system.

4.9 PSYCHOLOGICAL (PERCEPTUAL) SCALING OF COLOR ATTRIBUTES

This section contains a discussion of various scaling attempts of the three fundamental color attributes hue, chroma, and lightness. The section on hue includes the issue of the number of uniform hue difference steps between unique hues at a given level of chroma. The chroma section includes a discussion of the determination of the magnitude of the first steps from gray, presumably an indication of the coloring power of the unique hues and their combinations. Lightness scaling is briefly touched upon, but most of the discussion of lightness scaling is postponed until Chapter 5.

Hue

Newton's hue circle was shown to be a parsimonious solution to representing the common desaturation effect on all spectral hues. When scaling hue differences of fourteen spectral colors and performing multidimensional analysis of the results, Shepard (1962) obtained data points that are fitted with good accuracy by a circle, with a considerable space between spectral violet and red, as one would expect (see Fig. 3-6). With availability of purple hues in object colors the hue circle is naturally closed, as Hering has pointed out.

Unlike lightness and chroma, hue cannot easily be envisaged by reference to simple numbers. To have a concept of hues based on hue angles as determined in a given system is too abstract to be of practical use. One can have a mental image of what a value 6 gray scale chip looks like, and it may even be possible to have a mental image of a given hue identified by Munsell hue name at chroma 8, but this is no longer possible with any reasonable accuracy for a hue with a hue angle of 165° unless intensive training has taken place.

In general, it is easier to assign unique hue, chroma, and lightness values to a given color stimulus than to mentally synthesize it based on such numbers. Without extensive practical experience I can more easily estimate the content of yellow, red, and gray in a brown than create a mental image of a brown from numbers of yellow, red, and gray given to me. Our color names are relatively vague and most have considerable extension around focal points. Only the unique hues give us a comparatively solid mental reference point (however individually variable as to the required stimulus, as will be seen below). Midpoints between unique hues also can be fixed relatively well, though less well than unique hues. On the other hand, "purplish pink" or "turquoise" can apply to five or more (individually varying) Munsell 40-hue steps. In general, color names are least well defined in the yellow-green segment, probably because of the lack of widely present exemplars during the time period when color terms developed.

As mentioned, division of Newton's hue circle is proportional to the intervals between the musical sounds of an octave, thereby implying a relationship between sound and color (Newton, 1704). Newton's circle did not explicitly include extraspectral (purple) hues. Grassmann's circle is essentially identical to Newton's. Helmholtz's circle, at highest saturation, includes extraspectral hues and is divided into ten equal segments with the middle color of each segment diametrically opposed to its complementary color. Hue circles based on complementary hues being diametrically opposed were common after Helmholtz. However, there is no simple information on which to base the placing of complementary diametrical lines relative to each other. In both his earlier sphere and later cone models Wundt placed complementary hues opposite. In case of the sphere model they were placed in such a manner that the largest segments are occupied by yellow and blue. Rood studied this matter and concluded that there was no objective way of placing the diametrical hue lines relative to each other. His ten-hue chromatic circle has uneven division between the hue lines and is apparently based on a placement using distances along the spectrum scale with arbitrary placement of the nonspectral reds and purples (Rood, 1879). There seem to be only two methods by which to place hues with perceptually meaningful distances into a circle.

Hering was, as mentioned, the first basing a hue diagram on four unique hues. His psychological hue circle (Fig. 2-32) has conceptually equal perceptual increments/decrements of unique hues. As shown below, hue coefficients describing the relative perceptual amounts of unique hues in Hering's system form by definition an × pattern. The NCS system represents a practical implementation of Hering's hue circle.

Munsell's approach to scaling a hue circle was based on uniformity of the size of hue differences along the hue circuit. As a result complementary colors as expressed by optimal colors of Munsell Renotations in the CIE chromaticity diagram do not plot diametrically opposed in the Munsell psychological diagram. We can conclude from this that chromatic circles based on complementary colors are not uniform in terms of perceived hue differences. As we will see below, the Hering/NCS circle also is not uniform in terms of perceived hue differences, indicating that constancy of perceived unique hue increment does not equal uniform size of perceived hue difference in the four quadrants.

An interesting issue in connection with hue scaling is the psychophysical identity of the four unique hues, given an achromatic surround. Historically these have been determined in the spectrum, using optical equipment. Individual results have varied to a surprising degree (e.g., see Ayama, Nakatsue, and Kaiser, 1987). For example, the wavelength of unique green has been determined in various experiments as anywhere from 488 to 561 nm. Similar results have more recently been reported by Webster and co-workers (2000). Unique hues can also be determined, with considerably reduced variability, using object color samples (Hård, Sivik, and Tonnquist, 1997; Kuehni, 2001a). The mean choices of 40 observers that directly selected their unique hues from arrays of Munsell hues were found to be 3.0R, 3.5Y, 2.5BG, 2.75PB. Indow, based on his principal hue scaling method, obtained the following locations: 3.75R, 5Y, 6G, 3PB (Indow, 1999b). Note the discrepancy in the green unique hue. In a recent, as yet unpublished, study using Munsell chip arrays with 75 observers average unique green was found to be 7.0G. Webster's group (Webster et al., 2000) found green to have the largest individual variation among unique hues. This was also the case for Kuehni's original experiment as well as the experiment with 75 observers. It is evident from results with Munsell chips that the range of dominant wavelengths in such experiments is much narrower than the reported range of spectral wavelengths for determinations using optical equipment. Recently it was shown that there is no relationship, as previously surmised, between the ratio of *L* and *M* cones in an individual's retinas and the perception of unique yellow (Yamauchi et al., 2002). There is currently no model with good explanatory power for the relationship between stimulus and perceived unique hues.

Conceptually the geometrical image of a perceptually uniform hue circle of constant chroma is a perfect circle with each hue placed at uniform hue angle increments around it (Fig. 4-6). The location of each hue can be described in terms of ordinate (*b*) and abscissa (*a*) values relative to the center of the circle. Logically it might be expected that these values represent the content of unique hues in each hue. But, as we will see, this is not the case if hue steps are perceptually uniform. When plotting these absolute coordinates against the hue

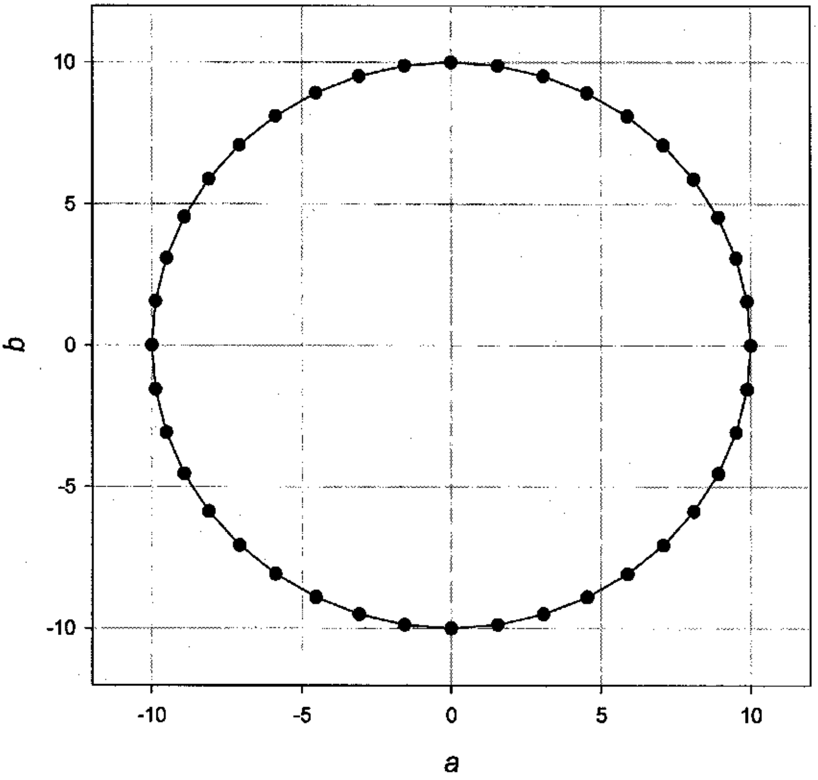

Fig. 4-6 *Idealized uniform chroma circle with forty colors representing identical hue differences in an* a, b *opponent color diagram.*

angle, sine wave curves are obtained (Fig. 4-7). When these are converted to relative values (percentages, called hue coefficients) × pattern functions result (Fig. 4-8). An × pattern in agreement with Fig. 4-8 is also obtained when plotting the forty NCS hue steps, conceptually based on uniform changes in unique hue components. In its psychological diagram the NCS atlas hue circle plots as forty equal hue angle increments of 9°. The Munsell atlas hue steps, involving constant hue differences, plot in the same way. However, this diagram is not based on the four unique hues and has no preferred axis system. In the standard presentation of the Munsell hue circle the *x* axis is formed by hues 10PB and 10Y, the *y* axis by 5BG and 5R (as can be seen in Fig. 4-11 below). All four are, to a greater or lesser extent, hues that are mixed in terms of unique hues. But while a step along the NCS hue circle means a 10% change in unique hue content, a step along the Munsell hue circle means a constant hue difference 1/40th of the total hue circuit. As a result the two diagrams are quite different.

The hue scales of the Munsell system up to and including the Munsell Rerenotations are briefly described in Chapter 7. Various hue scaling experiments

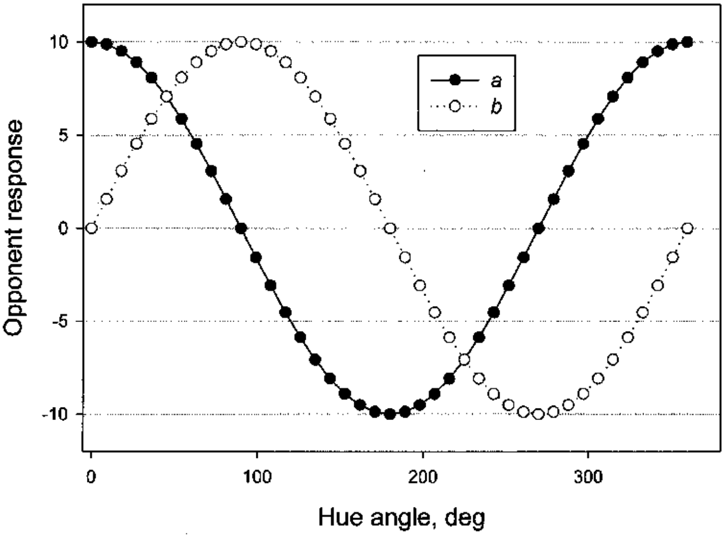

Fig. 4-7 *Plot of* a *and* b *values of the ideal color circle of Fig. 4-6 as a function of hue angle. The points form sinusoidal curves.*

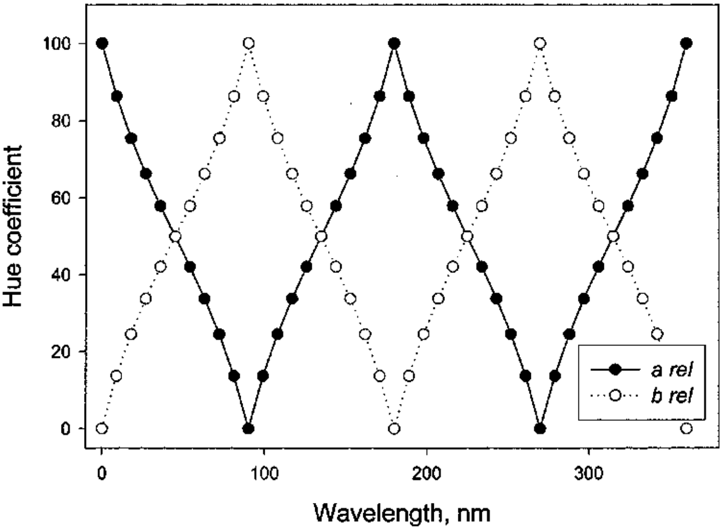

Fig. 4-8 *Hue coefficients (relative* a *and* b *values) as a function of hue angle, calculated from the absolute values of Fig. 4-6.*

using Munsell *Book of Color* chips have been performed by Indow and his colleagues. In 1972 Indow and Ohsumi published the results of multidimensional scaling involving 60 samples. The corresponding hue circle was considerably distorted compared to the Munsell circle. The hue angle between 5PB and 5P, 36° in the psychological diagram, was found to be 80°. In a later more extensive multidimensional scaling experiment involving 176 Munsell chips, a hue circle much more in geometrical agreement with the conceptual Munsell circle was found (Indow and Aoki, 1983). The difference, in the most recent analysis of the results (Indow, 1988), between 5PB and 5P at the highest chroma level is 45°. In a later study Indow and co-workers had observers assess the principal hue components in Munsell chips at different chroma and value levels (Indow, 1999b). They had observers mark on a paper scale the estimated amount of achromatic (gray) color in the total color. Next observers determined the content of one or two principal hues in the color and marked them separately. Average absolute principal hue components at chroma 8 and value 6 are illustrated in Fig. 4-9; There is a reasonable resemblance to Fig. 4-8; however, yellowness is undervalued compared to the other three principal hue components (presumably because observers disagreed on what represents 100% yellow). The resulting implicit, considerably distorted, hue circle is illustrated in Fig. 4-10. Implied chroma varies substantially, as do the hue angle differences. Somewhat different results have been obtained at other levels of chroma and value. The changes in absolute hue components are more linear

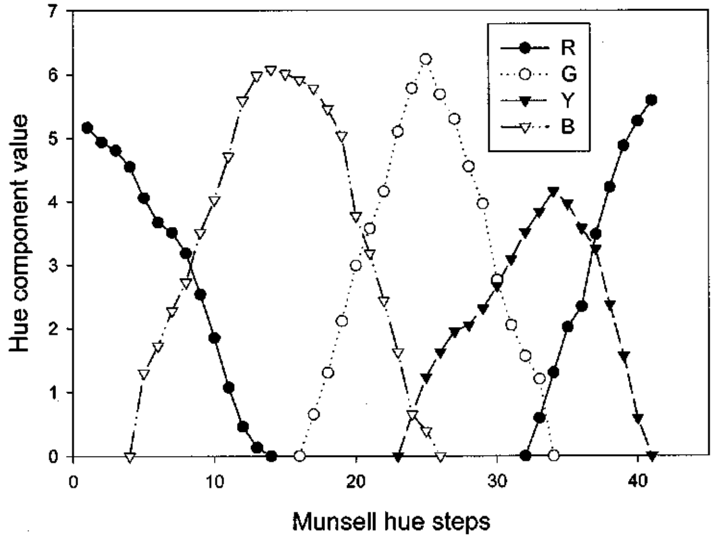

Fig. 4-9 Average absolute principal hue components of Munsell colors at chroma 8 and value 6 (after Indow, 1999b). The curves have a resemblance to those of Fig. 4-8. The biggest deviation is for yellow, presumably because the observers could not agree on which color represents unique yellow.

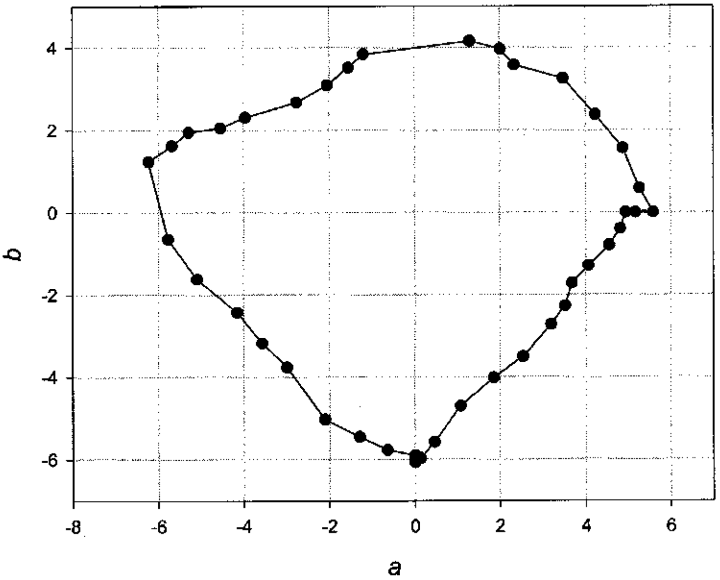

Fig. 4-10 Hue circle derived from the absolute hue components of Fig. 4-9.

than sinusoidal between unique hues, indicating that the observers judged the chromatic content of mixed hue colors lower than that of unique hue colors, most severely so for 1 : 1 mixes (compare Fig. 4-10 and Fig. 4-6).

Number of Uniform Steps between Unique Hues

In the hue circle of his atlas Hesselgren placed different numbers of equal-sized hue steps between his unique hues (Hesselgren, 1952). There are eight steps from blue to red, six from red to yellow, and five each from yellow to green and from green to blue.

Somewhat different results were obtained by Kuehni who investigated the perceptual distance between unique hues. Six observers scaled the Munsell hue circle at value 6, chroma 8 by using the difference between 5PB and 10B as the reference difference. The five Munsell 100-hue steps difference of the reference pair was seen as equal in difference to between 3.0 and 5.8 steps around the hue circle. On average, a total of 22 (rather than the expected 20) hue steps of the size of the reference step was found. In the four sectors between the unique hues the number of equal sized steps was found to be different: R–Y: 5; Y–G: 6; G–B: 4; B–R: 7 (Kuehni, 1999).

When plotting the average unique hues of Kuehni's 40 observers (green adjusted to the results of the 75 observers) on the ideal psychological Munsell hue circle (Fig. 4-11), the yellow and blue unique hues fall on a straight line passing through the center while red and green do not. The lines do not sep-

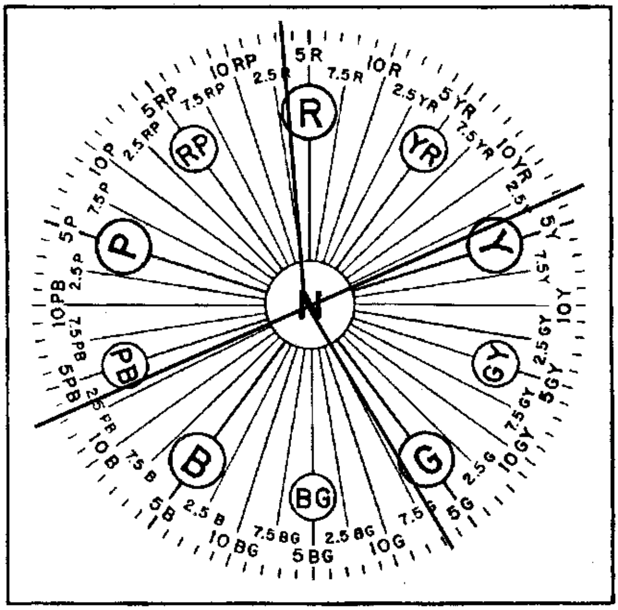

Fig. 4-11 *Ideal Munsell hue circle with the average unique hues determined by the author (and an additional experiment for unique green) represented by heavy full lines.*

arate the hue circle into four equal segments. Rounded to the nearest half-step on the 40-step Munsell hue scale the number of steps in each sector is as follows: R–Y: 8.0; Y–G: 9.5; G–B: 10.5; B-R: 12.0. If there are four primary hues and all other hues are mixtures of two of them, one might, sensibly and logically expect the primary hues to fall on the axes of a Cartesian diagram. Only then, as we saw above, can the content of primary hues in any given hue be expressed in terms of the axis coordinates. The Munsell system indicates, however, that in such a diagram there is a nonproportional relationship between hue angle and perceived hue difference. For reasons presented in the next chapter we cannot absolutely rely on the Munsell hue differences at a given chroma level having all exactly identical perceived magnitude and additional constant hue difference scaling work is desirable.

A nearly identical figure results when locating the same unique hues in Indow and Aoki's multidimensional euclidean scaling grid of the Munsell hue plane (fig. 6 in Indow 1988). The conclusion here also is that the number of unit-sized hue differences in the four sectors between unique hues differs.

In addition to the experimental results above the following relevant data are available:

1. Based on published information for the DIN color system, it is possible to translate the same unique hues into that system. The number of

TABLE 4-1 Comparison of hue angle segments in the psychological chromatic diagram between unique hues from different psychological experiments

Data set	Angle of segment, Degrees			
	R–Y	Y–G	G–B	B–R
Munsell Renotations	71	84	96	109
Hesselgren	90	75	75	120
DIN system	90	75	60	135
Newhall experiment	63	89	82	126
OSA-UCS	66	83	85	126
Kuehni experiment	82	98	65	115
Qiao et al. experiment	76	76	86	122
Berns function	65	82	87	126
Mean	75.4	82.8	79.5	122.4
CV, %	14.5	9.6	15.2	6.5

uniform hue steps between the unique hues in the DIN system is R–Y: 6; Y–G: 5; G–B: 4; B–R: 9.

2. As part of a preliminary effort during the development of OSA-UCS Newhall scaled a constant chroma circle at value 6 into 40 visually equally sized hue differences (102 observers, 142 pairs, 14,484 judgments; Judd, 1965). Unique hues have been plotted into an optimized model of the Newhall results.
3. They also have been plotted into the *g*, *j* diagram of the OSA-UCS system, regarding it as an optimized psychophysical model of the psychological diagram.
4. A hue difference scaling experiment for the purposes of establishing a hue difference weighting function has been performed by Y. Qiao et al. in 1998. The resulting CIELAB weighting function can be integrated and the number of equal hue steps between the unique hues determined.
5. R. S. Berns has proposed a somewhat modified hue function, taking into account suprathreshold small color difference data (Berns, 2001).

In Table 4-1 the hue angle segments in the psychological chromatic diagram between the four unique hues of the various experiments are compared (Kuehni, 2001e). As Table 4-1 shows, there is considerable variation in the results, but the trend is uniform (except for the yellow sector in the Hesselgren and DIN systems). The variation coefficients (CV) indicate greatest agreement for the R–B sector and significant disagreement in the R–Y and G–B sectors. Additional high-reliability hue-scaling experiments to provide a clearer picture of this important issue are very desirable.

In addition a linear model was fitted to the MacAdam color-matching error ellipses resulting in a coefficient of variation of 15% for 100 color differences (four per ellipse; Kuehni 2001d). By this formula the number of hue color matching error steps between the average unique hues was calculated with the following results: R–Y: 52; Y–G: 77; G–B: 72; B–R: 127. The trend is the same as that shown in Table 4-1, but the differences in the segments (after scaling the numbers for a total of 360) are more distinct.

In the NCS system unique hues form by definition equal sized quadrants in their hue circle. The NCS unique hues are well within the observer variability of those of Kuehni's unique hue determination experiment (and the additional experiment on unique green). As mentioned earlier, the implication is that the psychological unit differences are not the same in the different quadrants of that system. This has been mentioned by Tonnquist (1966). It follows that equal numerical changes in perceived content of unique hues do not result in equal perceived hue differences in the four segments.

Chroma

While hue has four comparatively easy to locate psychological markers, the unique hues, chroma has none. Different chroma scales (the results of different experiments) can therefore only be compared in terms of physical or psychophysical scales. Such comparisons will be made in Chapter 6.

Chroma steps have been investigated extensively as part of the development of the Munsell system as described in Chapter 7 and the results codified in the Munsell Renotations. The Renotations represent a considerable change of chroma scaling compared to the 1915 *Atlas* and the 1929 *Book of Color*. Few explicit studies of chroma scaling have appeared since then. In 1957, in preparation for the development of the Optical Society of America Uniform Color Scales (OSA-UCS), Judd, Nickerson, and Nimeroff determined a constant chroma circle at value 6 and chroma 8 (384 chroma differences, 60 observers, 23,040 observations; Judd 1965). As Chapter 5 will show, it differs significantly from the Renotation constant chroma circle. Implicit chroma scales along the chromatic axes were also developed for the OSA-UCS system. The four chroma scales, when compared in a common psychophysical system, are found to differ considerably, as shown in Chapter 5.

In the DIN system saturation rather than chroma was scaled. The constant saturation contours of that system in the CIE chromaticity diagram differ significantly from the constant chroma contours of the Munsell system. DIN saturation is independent of lightness and the relationship between chroma and DIN saturation differs as a function of lightness.

NCS chromaticness is different from Munsell chroma. There has been no recognition in that system of the varying chromatic power of optimal colors as all implied full colors arbitrarily have been set at chromaticness 100. When transforming Munsell colors of constant chroma to NCS notation the resulting chromaticness varies with hue in roughly sinusoidal fashion, as one would expect from the definition of NCS chromaticness.

Chroma scales are also an implied result of Indow's principal hue and chromatic versus achromatic color component determination as well as of his multidimensional scaling work. The scales from the two experimental efforts differ significantly. In the principal hue component work the implied chroma scales are often severely compressed at higher chroma levels, indicating the difficulty observers had in assessing the relative amount of achromatic and chromatic components (see Fig. 4-9). There was also some compression of the chroma scale at high chroma levels in the multidimensional scaling experiment, when compared to the Munsell system. However, when chroma scales of the *Book of Color* atlas are viewed, the higher chroma steps do not generally appear somewhat smaller than those at lower chroma. Indow also appeared to accept the Munsell chroma scales as essentially valid since he fitted a Riemannian model to his MDS data to improve the evenness in regard to chroma. The results raise doubt that chroma can be accurately assessed by determination of principal hue and achromatic components in a color or by multidimensional scaling.

Chromaticness scaling used in all cases, for sensible reasons, an achromatic surround. Chromatic surrounds change chromaticness scaling. However, this subject is outside the scope of this text and an issue for general appearance modeling. As will be argued later in this text, chromaticness depends on the magnitude of the unit chromaticness difference used to scale it (see also the related comment in the next section).

Chromatic thresholds, the first steps from the neutral point, have been studied since the 1920s. Typical saturation thresholds (amount of spectral light to be added to white light to result in a just perceptible color) as determined in 1938 by I. G. Priest and F. G. Brickwedde are shown in Fig. 4-12. Results by other investigators differ in detail but agree in the general features. Such thresholds are, presumably, indicators of chromatic strength of spectral colors. Evans defined spectral chromatic strength as the factor by which the luminance of a stimulus has to be multiplied in a brilliance match to equal the brilliance of the achromatic surround (Evans, 1974). Recall that a brilliance match against the surround is achieved when the stimulus field looks neither grayish nor fluorent against the surround. In 1968 Evans and Swenholt investigated chromatic strength using the Munsell system. In plotting the reciprocal CIE colorimetric purity against the dominant (or complementary) wavelength for chroma circles 2, 4, 6, 8, and 16 at value 5, they obtained curves essentially parallel to each other and reciprocal to the saturation threshold curve (see Fig. 4-13). These curves provide another kind of support for the salience of the chroma attribute.

In an experiment with 35 observers Kuehni investigated the relative sizes of the first steps from gray of the colors nearest to the respective axes in the *a**, *b** diagram in the Munsell as well as the OSA-UCS systems (Kuehni, 2000c). The results indicated that the average observer judged, in the Munsell system at value 6/chroma 8, the first step toward yellow to be about 2.5 times the magnitude of the first step toward blue. In the red/green direction the

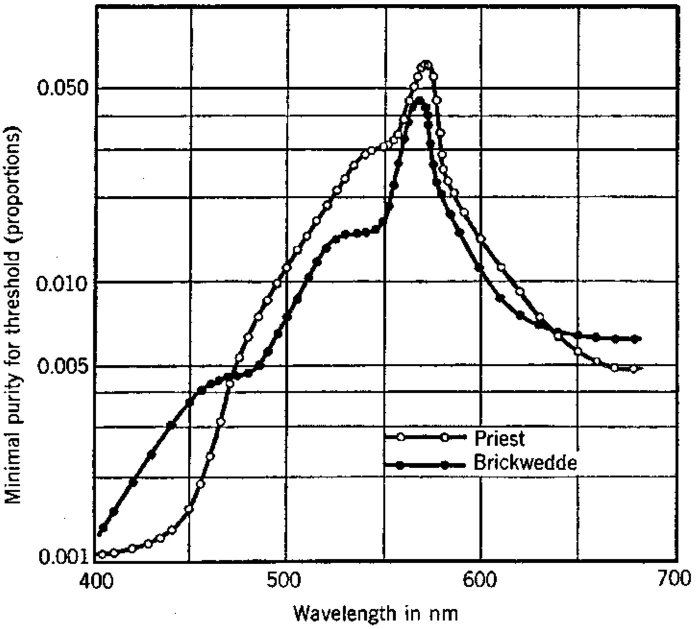

Fig. 4-12 Spectral saturation thresholds determined in 1938 by Priest and Brickwedde. From Osgood (1953).

green step was seen as about 10% larger than the red step. For OSA-UCS the first step toward yellow was seen as about 20% larger than the first step toward blue. In that system the first steps toward red and green were seen as of about equal size. Somewhat different results have been obtained by Indow (2001).

The results of Priest and Brickwedde and many later researchers were obtained monocularly with optical apparatus. M. De Matiello and co-workers investigated the difference between monocular and binocular saturation discrimination at the threshold level as well as for suprathreshold saturation differences (2001). They found the changes in colorimetric purity for threshold steps to be considerably larger for the first step from gray than for the first step from the spectral color. For suprathreshold saturation differences they found power relationships varying by wavelength with exponents from 0.61 to 0.97. Interestingly they found exponents of binocularly determined data to be lower than those obtained for monocular data.

Relationship between Hue and Chroma Differences

This matter created considerable discussion in the 1950s and 1960s (Judd, 1969). As mentioned previously, in 1936 Nickerson developed the first formula, on a psychological basis, that could result in predictions of the perceptual

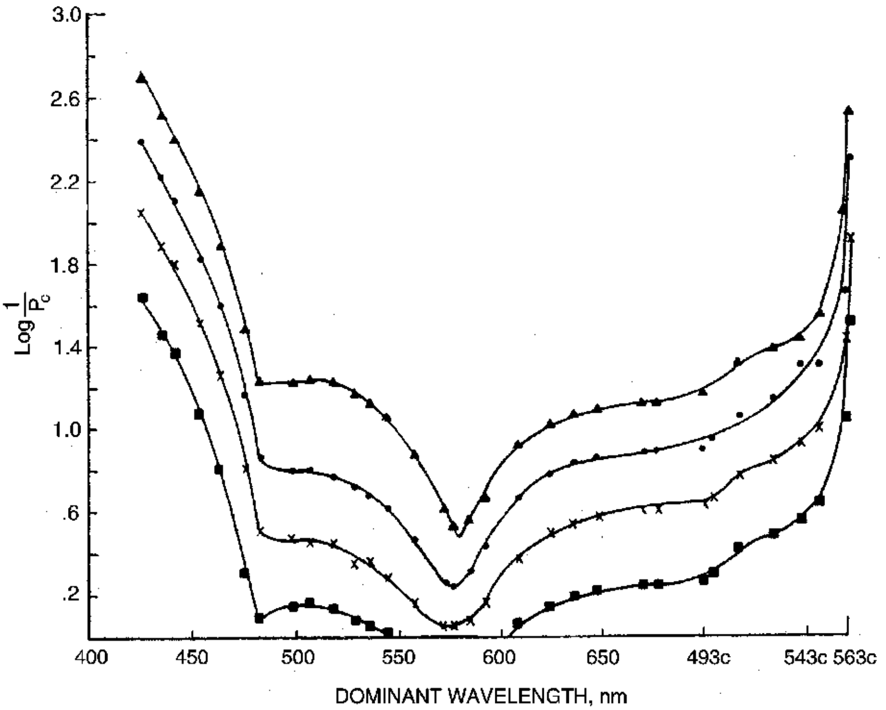

Fig. 4-13 Reciprocal CIE colorimetric purity as a function of dominant wavelength for Munsell colors at five levels of chroma (represented by different symbols) and value 6. From Evans and Swenholdt (1968).

magnitude of color differences, the Index of Fading. It was based on the Munsell system and reads as follows:

$$I = \left(\frac{C}{5}\right)(2\Delta H) + 6\Delta V + 3\Delta C, \tag{4-1}$$

where I is the index value, C is Munsell chroma, V is value, and H is hue expressed in terms of the Munsell 100-hue circle. For two colors being compared, perceptual differences according to this formula are equal to the simple sum of weighted differences between the index values. Note that this formula predicts hue differences between colors of neighboring Munsell hues to grow linearly in magnitude as a function of chroma.

As Judd showed, for colors of equal V one hue step is, according to the Nickerson formula, equal to $2C/15 = 0.133C$ chroma steps. When expressing the total hue angle of all 100 hue differences the result is found to be $13.33C$. This is slightly more than twice the theoretical total hue angle of a circle that in a euclidean system is $6.28C$. While initially skeptical of this result and believing it to be due to experimental error, Judd later found support for what he called the “superimportance of hue” in experiments involving large hue differences. If the Nickerson formula is factual, perceptual color space is not euclidean. Judd used a crinkled fan model to account for hue superimportance (see Fig. 7-15).

Hue superimportance was also detected in the experimental basis data for the OSA-UCS system. In 1964 the Committee on Uniform Color Scales of the Optical Society of America completed a basic experiment eventually resulting in the OSA-UCS scales. Forty-three samples were viewed in 102 pairs by 71 observers and compared for size of difference against other pairs. After psychometric scale values were calculated, the correlation between these and various formulas was determined. The correlation coefficient obtained, for example, for the Glasser cube root formula was 0.34 while the Nickerson formula resulted in a value of 0.61. When, instead of sums, the square root of the sum of the squares of the component differences was calculated, the correlation increased to 0.65 (perhaps merely a fortuitous result). An optimal value of 0.80 was obtained with (1) revised Munsell spacings in regard to hue and chroma and (2) use of the following formula, which derives from a formula developed earlier by Godlove as a description of the ideal Munsell system in a euclidean space in place of the Nickerson formula:[7]

$$\Delta E = \left\{\left[f_g f_h (C_1 C_2)^{0.5} \Delta H\right]^2 + (\Delta C)^2 + (4\Delta V)^2\right\}^{0.5}, \tag{4-2}$$

where C_1 and C_2 are the Munsell chromas of the two colors compared, ΔH is the hue difference in Munsell 100-hue steps, ΔV is the difference in Munsell value, and

$$f_g = \frac{[2(1-\cos 3.6\,°\Delta H)]^{0.5}}{\Delta H},$$

$$f_h = \frac{2-k+4(k-1)}{3-\cos 3.6\,°\Delta H},$$

where k is the hue superweight factor with a value from 1 to 2. If the value is 1, then $f_h = 1$. For optimal correlation the value of k was selected as 1.7 (Judd and Nickerson, 1967), this being indicative of hue superimportance. This experiment supported the idea of a relationship between perceptual hue differences and chroma differences that does not fit into a euclidean system. This matter is further discussed in Chapters 7 and 8.

Lightness

The first “qualitative” verbal gray scale, seemingly, is the one by Forsius, with seven grades including black and white (see Chapter 2). Glisson described quantitatively (in terms of weights of black and white pigment to be used) a

24-grade gray scale that is reasonably uniform through the middle portion. Mayer envisaged 23 grades of different lightness in his double pyramid, while Lambert reduced that to 8 grades. Runge's color sphere has a 10-grade gray scale.

In 1729 the French mathematician Bouguer published *Essai d'optique sur la gradation de la lumière* (Optical treatise on the gradation of light) in which he described experiments using shadows of rods made by the light of two candles on a white screen. He found that the distance ratio of the two candles needed to be about 8:1 to result in a just noticeable difference between the two shadows. Thus he initiated the study of brightness thresholds. In 1845 his compatriot V. Masson described a white disk on which a black radial line segment was inscribed. When spinning the disk the line segment darkened a ring of the disk (the spinning disk method was invented by Pieter van Musschenbroek in 1768[8]). The width of the line segment as a fraction of the total disk circumference is an indicator of the fractional change in luminosity required to see a difference. Masson found that the ratio, depending on circumstances of illumination and viewing distance, was between 1/50 to 1/120. In 1850 the French astronomer D. F. Arago (1786–1853) repeated the shadow experiment with improved equipment and found a ratio of 1/133. Masson's experiment was repeated in 1858 by Fechner and Volkmann, who found a ratio of 1/100 and by Helmholtz in 1860 who, under optimal conditions, could see a ratio of 1:167. In 1888/9 König and Brodhun used Masson's technique to determine brightness as well as chromatic thresholds.

Attacking the problem of a uniform gray scale from another angle Plateau in 1872 asked several painters to paint a color halfway between black and white (as described in Chapter 2), thus performing an equisection. Independently Delboeuf developed a detailed uniform gray scale using successive equisection, as well as by adjusting black and white disk segments to obtain perceptually equal steps.

In 1874 Hering, as part of his psychological color triangle, described a "nuanced" series of grays from black to white that was to have uniform increments/decrements of blackness and whiteness. Ebbinhaus described in 1887 an eight-grade gray scale (see Chapter 5). In 1899 Munsell began to develop his color order system of which an eleven-grade (ten-step) value scale was an integral part. The Munsell value scale underwent development until the 1930s and was finalized in the Munsell Renotations. In the final experiments gray scales were visually measured against a white, gray, and black background. They were found to differ, and the results were averaged into the value scale (see Chapter 5, Section 5.7). Ostwald selected a logarithmic relationship between the stimulus and the response for his gray scale. In the 1960s Kaneko and Takasaki confirmed and further quantified W. Schönfelder's finding that color differences between two stimuli are perceived best if the surround is intermediate between the two stimuli. This makes a gray scale and its steps dependent on the surround. Surround dependence had been found in 1922 by Adams and Cobb and was also investigated by Evans. The effect was included into the definition of the OSA-UCS lightness scale, otherwise based on the Munsell value scale. The NCS whiteness/blackness scale is derived from average judgments of the content of whiteness and blackness in gray samples. The atlas scale has eleven grades (including black and white) resulting in ten steps, the numerical scale has 100 steps.

From the beginning with Bouguer the development of lightness scales has run parallel with the development in photometry. While work with the Masson disk or Delboeuf's equisection method and others did not explicitly require photometry, their results were best interpretable in quantitative terms when compared to the corresponding stimulus strength. The development of lightness scales is therefore further discussed in Chapter 5.

A fundamental issue involving lightness is how brightness and lightness are connected. As has been demonstrated by many researchers over the last 100 years, a source of achromatic color with any given luminance value can, depending on the conditions it is seen in, be perceived as any grade of gray from white to black. The question arises how the human visual system decides to assign a given lightness value to a given luminance value. Among the early researchers investigating this matter was D. Katz who was a student of G. E. Müller. In 1909 he published a book-length paper, *Die Erscheinungsweisen der Farben und ihre Beinflussung durch die individuelle Erfahrung* (translated in 1935 as *The world of colour*) in which he discussed his investigations of different appearance modes of colors, including the relationship of brightness, lightness, and luminance. In a dramatic experiment Gelb showed in 1929 that if a black piece of paper is suspended in midair and illuminated with a strong beam of white light, its appearance is white. If a paper of higher luminous reflectance than that of the black paper is placed next to it, the original paper no longer appears white but a shade of gray or black, depending on the luminous reflectance of the second paper. Thus lightness perception is dependent on the relative luminous reflectance of adjacent fields. A few years later gestalt psychology theorists postulated that the visual system compares the luminance of a target against the weighted average of the luminance of the total scene. In 1948 H. Wallach proposed that lightness is decided by the ratio of the luminances of two adjacent fields. The so-called intrinsic image model of lightness was developed in the last twenty years. It had been found that when a gray paper is successively viewed against backgrounds of different lightness, the ratio of luminous reflectances changes significantly but the perceived lightness of the paper changes little. Similarly there is considerable lightness constancy when viewing the arrangement of paper and background under different kinds of illumination. The intrinsic image model analyzes the image as it appears on the retina according to three components: surface reflectance, illumination, and three-dimensional form clues. However, significant disagreements between the predictions of theory and the experimental results remained in certain situations. As Gilchrist and colleagues (1999) describe it, a fundamental question is that of the anchoring problem. It relates to the question "where to locate the range of luminance values (in a given situation) on the scale of perceived gray shades." Once it is solved, the next question is "how the range of luminance values is distributed on the scale of perceived gray shades." Many researchers have contributed to the current answers: in simple images (two fields of different luminance filling the entire visual space) the highest luminance is seen as white unless the relative area of the darker field is more than half of the total field. Then an area rule applies. As the darker side grows in relative size, it appears lighter and lighter, making the smaller, lighter area appear more and more white, eventually fluorent and then self-luminous.

In more complex images Gilchrist and his group propose to separate the image into components, called frameworks, that belong together according to gestalt principles (an exact definition of framework is difficult, so coplanarity of the elements appears to be a good start). For each local framework the anchoring and area rules of the simple situation approximately apply. The entire visual field is called the global framework. Within a local framework a veridical, or 1:1 scaling between lightness and luminance, is found to apply if the luminance ratio between white and black is less than 30:1. If it is larger, some luminance scale compression occurs. Gilchrist et al. have tested their model on many classical lightness test results and "illusions," such as the Benary effect (1924) or White's illusion (White, 1981) and found good explanatory power. In cases where the information from local frameworks appears contradictory, Gilchrist et al. believe that our visual system makes a compromise between the results or alternately displays one or the other. It is evident that much work remains to be done.

4.10 PERCEPTION OF COLOR DIFFERENCES

A formula that mathematically describes the relationship between attribute component differences and total perceived difference is Nickerson's formula of 1936 encountered above and expressed in terms of the attributes as defined in the Munsell system. The investigation by Bellamy and Newhall (1942) showed that the definition of the formula depends on the size of the differences; that is to say the quantitative relationship between the Munsell attributes changed significantly when tested at the JND level.

In current practice the results of small color difference calculation are usually expressed in terms of total color difference and its hue, chroma, and lightness difference components. The visual small color difference data have in all cases been determined as total differences. The split of the total difference into components is achieved mathematically, based on the assumption that color space is euclidean. The correlation between visual and calculated data has been improved by adding empirical functions. Because of the lack of visual small color difference component data, the degree to which calculated components are in agreement with visual data is unknown. This is an area that requires attention.

Surprisingly it appears that the assumption that perceived, properly scaled attribute differences add up by euclidean summation has never been explicitly tested and confirmed. One problem is that, as seen earlier, there are no reliable, replicated scales of perceptual hue, chroma, and lightness, a prerequisite for such a test.

Another effort in developing a color difference formula based on visually determined components has been made by Indow (1999a, 2002). Using visual judgments of Munsell differences determined for the purpose of multidimensional scaling analysis (as described in Indow, 1988), he attempted to find the form of geometrical space that would result in the best agreement between interpoint distances of colors in that space and of those visually determined. Indow found that the formula he developed resulted in smaller root mean square (RMS) error than that of Adams-Nickerson but larger than the CIE94 formula. This is surprising because the differences judged were rather large, involving Munsell chips. In the same year Indow (1999c) also investigated the accuracy of prediction of Munsell type color differences from the judged differences in their principal hue components and lightness differences. Indow obtained the lowest RMS error with a formula that is the sum of weighted value difference and individually weighted principal hue component differences:

$$\tilde{d}(\Delta V, \Delta\bar{\xi}) = a_V \Delta V + (d_0 + \Sigma a_a \Delta\bar{\xi}_a), \tag{4-3}$$

where $\tilde{d}$ is the predictor of the color difference, ΔV is the Munsell value difference, $\Delta\bar{\xi}_a$ is the difference in a principal hue component, and a_a is the corresponding weight for the principal component difference, with the values $a_R = 0.199$, $a_Y = 0.031$, $a_G = 0.098$, $a_B = 0.136$, $d_0 = 0.610$, and $a_V = 0.459$. The principal hue components are functions of value and chroma.

Also in Indow's work, with different data and using principal hue components, simple addition of the component differences was found to give best results. Because of the normalization of perceived principal hue components to a maximum value of ten different weighting of the individual components is required. In differences the red principal component has the strongest effect. It takes 1.5 units of blue principal hue component (PHC) to equal in a difference one unit red PHC, 2.2 of green PHC, and, adjusted for the lower absolute yellow maximum, 3.4 units yellow PHC.

Indow's work with principal hue components implies, unsurprisingly, that they are the psychological fundamentals constituting hue. At the same time they implicitly constitute an aspect of chroma. The achromatic difference to the maximum value of 10 is also a conflation, in this case of an achromatic portion of chroma and lightness differences. The lightness difference (presumably including the Helmholtz-Kohlrausch effect) is, in addition, separately judged. As mentioned above, Indow's observers, however, had difficulties distinguishing in terms of principal hue components between different Munsell chroma levels at the same lightness.

In this chapter it was demonstrated that for purposes of an object color space uniform in color differences, hue, lightness, and chroma appear to be the essential color attributes. Other attributes can replace lightness and chroma if uniformity in terms of difference is not the guiding principle. Historically two sets of fundamental attributes of color perceptions have been proposed. Hue is common to both. In Hering's approach veiling is described by the relative amounts of blackness and whiteness in the perception. But veiling can also be described in terms of lightness and chroma. It has not been determined how under comparable conditions the two sets of veiling attributes compare. Various experimental scales of constant chroma and equal-sized hue differences vary considerably for unclear reasons. It has also been shown that a psychological color space with the unique hues on the chromatic axes is not uniform because there are varying numbers of equal-sized hue differences in the four quadrants. The relationship between chroma and hue differences appears to change significantly as a function of the size of the differences. In the next chapter these and other issues are investigated in terms of quantitative stimulus differences.