Chapter 12

Color and Appearance

Abstract In this chapter we discuss what color is and then go on to describe color vision. We pay attention to variations in normal color vision due to genetic variations in the color receptor genes as well as to color blindness. We then discuss the measurement of appearance with attention to turbidity and glossiness. Instrumental color measurements are briefly described with special attention to the Munsell, RGB, and various CIE color systems.

Some days are yellow.
Some days are blue.
On different days I'm different too.
You'd be surprised how many ways
I change on different colored days.
On bright RED days how good it feels
to be a horse and kick my heels!

—(My Many Colored Days by Dr. Seuss)

Contents

12.1 Color and Appearance

In food products, especially meats, fruits, and vegetables, the consumer often assesses the initial quality of the product by its color and appearance. The appearance and color of these products are thus the primary indicators of perceived quality. The importance of color and appearance can be demonstrated when we think of drinking milk from a Coca-Cola bottle, when we choose bananas in the grocery store (a green–yellow–black continuum that indicates ripeness), when a friend serves green-colored bread and beer on St. Patrick's day, and when someone serves us a watermelon with yellow flesh instead of the more usual red. In food processing and cooking, color serves as a cue for the doneness of foods and is correlated with changes in aroma and flavor. Simple examples include the browning of baked and fried foods. For other foods, color or lightness is important to identity and to grading as in the lightness of canned tuna fish.

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Scientific studies have also shown that the color of the product affects our perception of other attributes, such as aroma, taste, and flavor. For example, DuBose et al. (1980) found that the number of correct identification of fruit-flavored beverage flavors decreased significantly when the beverage was atypically colored and that the number of correct identifications increased when the beverage was colored correctly. Shankar et al. (2009) studied the effect of color and label on perceived chocolate intensity and likability of brown and green milk and dark chocolate M&Ms (candy-coated chocolate buttons) and found that the color and the label affected the perceived chocolate intensity but not the likability. Additionally, they found no interaction effect of label and color. Christensen (1983) found that when sighted panelists scored the aroma intensity of appropriately and inappropriately colored cheese, soy analog bacon, margarine, raspberry-flavored gelatin and orange drink, the perceived intensity of the appropriately colored product was higher than for the inappropriately colored product. Interestingly, the bacon analog was a notable exception. The effect on perceived flavor intensity was less pronounced and there was no effect on perceived texture of the products.

Osterbauer et al. (2005) showed through functional magnetic resonance imaging (fMRI) of the brains of their subjects that as these subjects increased their rating of color–odor matches their brain activity in the caudal regions of the orbitofrontal cortex and in the insular cortex increased progressively with their perceptions of color-odor congruency. Therefore, these color–flavor interactions are likely "real."

Based on these studies and others (Dematte et al., 2009; Stevenson and Oaten, 2008) we can conclude that not only is the color and appearance of foods and products important to the consumer in and of themselves, but that color and appearance affect the consumers' perceptions of other sensory modalities in that food or product as well. Therefore it is very important that the sensory specialist knows how to ask panelists to evaluate product appearance and color and how to perform sensory tests to minimize the subjects' color and appearance biases from affecting the sensory results of other modalities.

12.2 What Is Color?

Color is the perception in the brain that results from the detection of light after it has interacted with an object. The perceived color of an object is affected by three entities: the physical and chemical composition of the object, the spectral composition of the light source illuminating the object, and the spectral sensitivity of the viewer's eye(s). As we will see in the following discussion changing any one of these entities can change the perceived color of the object.

The light striking an object may be refracted, reflected, transmitted, or absorbed by that object. If nearly all the radiant energy in the visible range of the electromagnetic spectrum is reflected from an opaque surface then the object appears white. If light through entire visible range of the electromagnetic spectrum is absorbed in part then the object appears gray. If light from the visible spectrum is absorbed almost completely then the object appears black. This also depends upon the surrounding conditions. The black type from this book in direct sunlight reflects more light than the white page under a reading lamp, yet they appear black and white under both conditions due to their relative reflectance of light.

The color of an object can vary in three dimensions, namely hue, this is typically what the consumer refers to as the "color" of the object (for example, green); lightness, also called the brightness of the object (light versus dark green); and saturation, also called the purity or chroma of the color (pure green versus grayish green). The perceived hue of an object is the perception of the color of the object and results from differences in the absorption of radiant energy at various wavelengths by the object. Thus if the object absorbs more of the longer wavelengths and reflects more of the shorter wavelengths (400–500 nm) then the object will be described as blue. An object with maximum light reflection in the medium wavelengths results in an object described as yellow-green in color and an object with maximal light reflection in the longer wavelengths (600–700 nm) will be described as red in color. The lightness (value) of the perceived color of an object indicates the relationship between reflected and absorbed light with no regard to specific wavelength(s) involved. The chroma (saturation

or purity) of the color indicates how much a specified color differs from gray.

The visual perception of color arises from stimulation of photoreceptors in the retina by light in greater intensities at some wavelengths than others in the visible region (380–770 nm; Table 12.1) of the electromagnetic spectrum. The entire electromagnetic spectrum encompasses gamma rays (wavelengths of 10^{-5} nm) to radio waves (wavelengths at 10^{13} nm). However, the photoreceptors in the human eye only respond to a small range of this energy. Thus, color is an appearance property attributable to the spectral distribution of light interacting with the photoreceptors in the eye and visual color perception is the brain's response to this stimulus of the photoreceptors that results from the detection of light after it has interacted with an object. Or stated differently, wavelengths in the visual portion of the electromagnetic spectrum not absorbed by the viewed object are seen by the eye and interpreted by the brain as color.

Table 12.1 Visible portion of the electromagnetic spectrum

Color	Wavelength range (nm)
Violet	380–400
Blue	400–475
Green	500–570
Yellow	570–590
Orange	590–700
Red	700–770

Certainly color is an appearance property of an object attributable to the spectral distribution of light emanating from that object. However, gloss, transparency, haziness, and turbidity are appearance properties of materials attributable to the geometric manner in which light is reflected and transmitted. Something as simple as uneven reflection of light from a surface can make the object appear dull or matte. If the reflection is stronger at a specific angle or in a beam, then the resultant perception of gloss or sheen is a result of specular and/or directional reflectance. The reflectance is caused by the surface of the object. Smooth objects reflect in a directional manner and irregular, patterned, or particulate objects reflect light diffusely. The appearance of an object is affected by the optical properties associated with the object, namely the geometric light distribution, over the surface of the object and within the object if it is not opaque, the translucence of the object, the gloss, the size, shape, viscosity (Hutchings, 1999).

12.3 Vision

The light reflected from an object, or the light passing through an object, falls on the cornea of the viewer's eye(s), travels through the aqueous humor to the lens, and from there travels through the vitreous humor to the retina, where most of the light falls on or near a small hollow in the retina, the foveal pit. The visual receptors, the rods and cones, are located in the retina of the eye. These receptors contain light-sensitive pigments which change shape when stimulated by light energy, leading to the generation of electrical nerve impulses which travel along the optic nerves to the brain. There are approximately 120 million rods in the retina and the rods are capable of operating at extremely low light intensities (less than 1 lux). The rods yield only achromatic (black/white) information and under low-light conditions humans have scotopic vision with no color perception. This is why we cannot see colors by moonlight ("all cats are gray in the dark") although we can usually see well enough to move around. The maximum rod concentration is approximately 20° from the foveal area, this area is called the parafovea. Thus under low levels of illumination an object is more likely to be perceived when viewed slightly from the side than directly, called averted vision (Hutchings, 2002).

The 6 million cones operate at higher light intensities (levels of illumination) and provide chromatic information (color), allowing photopic vision. The cones are concentrated on the fovea, a small (2 mm diameter) depression located in a yellow colored spot (*macula lutea*) on the retina, where the highest color resolution occurs. When viewing an object, the unconscious movement of our eyes serves to bring the image of the object onto the foveal areas. The cones contain three color-sensitive pigments each responding most sensitively to red (two polymorphic variants at ~560 nm), the L-pigment also known as the ρ-receptors; to green (at ~530 nm), the M-pigment

also known as the γ-receptors; or to blue (at ~420 nm), the S-pigment also known as the β-receptors (Deeb, 2006; Hutchings, 2002). A phenomenon called the Purkinje shift occurs under decreasing light conditions when humans become more sensitive to blue-green, with blues seemingly becoming brighter and reds relatively darker. Due to the Purkinje shift at very low light intensities the reds will appear almost black and the blues will appear gray.

12.3.1 Normal Human Color Vision Variations

It has been shown that variations in normal color vision are due to polymorphisms in the L- and M-pigments with amino acid substitutions at position 180 (alanine versus serine) accounting for most of the variations (Merbs and Nathans, 1992, 1993). There are additional amino acid substitutions at positions 277 and 285 but these are not as well studied, yet. In humans with normal color vision, Deeb (2005) found that among Caucasian males, 62% have serine at position 180 in the L-pigments (L_{serine}) and 38% have alanine ($L_{alanine}$). Using a color-matching test (the Rayleigh test) they asked their subjects to match a standard yellow (590 nm) light with a mixture of red (644 nm) and green (541 nm) lights. They found that males needing less red light to make the match (hence ones that were more sensitive to red light) were much more likely to have serine at position 180 of the L-pigment. The L-pigments are linked to the X-chromosome, thus men have two variants (about 60% express L_{serine} and about 40% $L_{alanine}$) and women have three variants (about 50% of women are heterozygous and express both L_{serine} and $L_{alanine}$; and the other 50% of women homozygously express either $L_{alanine}$ or L_{serine}). Pardo et al. (2007) showed that due to the above gender-related L-pigment expressions, on average women perceive some colors significantly differently from men. Jameson et al. (2001) specifically showed those women who were homozygous for the L- or M-pigments did not perform differently from men but those women who were heterozygous to L- and/or M-pigments had a relatively richer color experience. Additionally, ageing, glaucoma, and cataracts affect color vision. Older subjects (60–70 years old) perceive colored surfaces to be less chromatic ("colored") than subjects under 30 years of age (Hutchings, 2002).

12.3.2 Human Color Blindness

Humans either lacking one or more of the L-, M-, and S-pigments or having specific mutations in these pigments fall in various color-blind categories and comprise about 8% of males and 0.44% of females. Color-blind individuals are classified into different groups. The first group is the protanopes or protoanomalous trichromats who have no or a reduced ability, respectively, to see red due to absence or anomaly with ρ-receptors (L-pigments) and comprise about 1/4 of the color-blind population. The second group is the deuteranopes or deuteranomalous trichromats who have no or a reduced ability, respectively, to see green due to absence or anomaly with γ-receptors (M-pigments) and comprise about 3/4 of the color-blind population. The last and by far the smallest group is the tritanopes who have no or a reduced ability to see blue due to absence or anomaly with β-receptors (S-pigments). The genes for the more common forms of color blindness are recessive and carried on the X-chromosome. Thus the trait is seen much more frequently with men than with women.

It is possible to test panelists for color blindness and all panelists should be screened if they will be evaluating the color of samples. Techniques include pseudo-isochromatic plates such as the Ishihara plates, created in 1917, the Farnsworth Dichotomous Test for Color Blindness, or the Farnsworth–Munsell 110 Hue test (Farnsworth, 1943). Ishihara pseudo-isochromatic plates and the various Farnsworth tests can be obtained from any reputable optometric supply company.

12.4 Measurement of Appearance and Color Attributes

12.4.1 Appearance

Some scientists (Hutchings, 1999) maintain that product appearance is inclusive of product color and other appearance properties such as physical form (shape, size, and surface texture), temporal aspects (movement, etc.), and optical properties (reflectance, transmission, glossiness, etc.) For our purpose we will discuss color and appearance as separate entities, while

keeping in mind that appearance attributes clearly affect perceived color.

Usually, physical appearance characteristics can easily be measured through sensory techniques. Standard descriptive techniques can quantify size, shape, and visual surface textures using simple intensity scales. An example would be "amount of chocolate chips visible on the surface of the cookie." In this case, "amount" might be rated from none to many, with examples being given in training to anchor the high and low ends of the scale. Visual texture is another example that lends itself well to simple intensity scales, such as apparent roughness of the surface, size or number of surface indentations, and density or amount of sediment in a container of a liquid product. Most of these simple and concrete attributes require little training and can be easily worked into a descriptive profile of the product. Of course, as in any other descriptive technique, the scale becomes more calibrated and there is better agreement among panelists if the low and high ranges are shown to provide the frame of reference that anchors the scale.

In food, temporal appearance characteristics are more rarely measured, even though they exist. Examples would be the viscosity of molasses as it drips from a spoon, the jiggle of JellO®, or the stringiness of pizza cheese. Optical properties (reflectance, transmission, glossiness, etc.) have been called "cesia" (Caivano et al., 2004); however, this term has not yet been widely used in the appearance research world. In the following section we will discuss few food-relevant appearance optical properties such as turbidity, translucency, and glossiness.

12.4.1.1 Turbidity (Cloudiness)

An important characteristic of many beverages is how clear versus how cloudy they appear. Turbidity (cloudiness or haze) occurs when small suspended particles divert light from a straight path through the material and scatter it in different directions. In physical terms, turbidity is the total light scattered from an incident beam as it transverses a suspension (Carrasco and Siebert, 1999). Consumers often expect beverages such as beer, fruit juices, and wines to be clear. In other beverages, for example, cider, cloudiness is expected and here again particulate matter is responsible for the light scattering. Various steps in beverage processing may be aimed at reduction in turbidity and increasing the clarity, such as the use of fining agents in wine making. In some products such as beer, cider, and fruit juices, haze development is a function of polyphenol–protein interactions; others are due to carbohydrates and yet others are due to the growth of microorganisms (Siebert, 2009). Haze can also result from colloidal or larger particles that may precipitate in a container.

Instrumental methods for turbidity, such as nephelometers, use a focused light beam to measure light scattering at several angles. It is always prudent to cross-reference instrumental values to human perception. It is fairly simple to train a panel to evaluate turbidity. If the relationship between perceived turbidity and instrumental turbidity is not well known for a product, it is recommended that one performs the human testing to understand their sensory reactions to the product (Carrasco and Siebert, 1999). In other words, light scattering as a physically measured phenomenon may not tell you what you need to know about perceived turbidity. Relationships between instrumental measures of light scattering and human sensory ratings have been determined. Malcolmson et al. (1989) found a linear relationship between instrumentally measured turbidity and perceived clarity for commercial apple juices. Other studies have found relationships between physical measurements of cloudiness and sensory evaluations in different media including coffee (Pangborn, 1982) and beer (Hough et al., 1982; Leedham and Carpenter, 1977; Venkatasubramanian et al., 1975). Pieczonka and Cwiekala (1974, cited in Carrasco and Siebert, 1999) obtained an instrumental–sensory correlation between nephelometer values and a 5-point sensory scale of –0.81 in juices. Since light scattering is dependent upon particle size, it should be possible to measure a direct relationship between sensory clarity and the size and distribution of suspended matter in a product.

Clarity arises from the transmission of light, and fluids that transmit more light will appear more translucent. However, the relationship may be complicated by other factors such as the color of the medium (Siebert, 2009). Carrasco and Siebert (1999) addressed these issues in model systems and beverages, comparing turbidimeter results to those of human sensory panels. Haze perception thresholds were measured and while they varied with particle size and concentration depending upon the medium, the human sensory

threshold was in a small range of instrumental haze values of about 0.5 Nephelos Turbidity Units. This suggested a good sensory–instrumental relationship at low levels. At ranges above threshold, perceived intensity followed the instrumental response until a saturation level was reached. After this point the instrument determined values continued to increase, but the sensory response was flat, even if panelists were allowed to use an open-ended magnitude estimation method of scaling (see Fig. 12.1). Sensory response (scaled intensity) was predicted on the basis of particle size, particle concentration, and suspension color.

Two situations arise when sensory–instrumental correlations break down. The most common example is when the human responds but the instrument does not, as in the case of olfactory sensitivities to some compounds which exceed the sensitivity of common analytical methods in chemistry. Another situation arises when the instrument responds, but the human does not. The scaling results in Carrasco and Siebert's study provide an interesting example of where the machine response has a broader dynamic range than the sensory judge. However, the upper range of turbidity becomes irrelevant when the sensory response does not change. This obviously imposes an upper limit on the utility of turbidimeter responses when a high level of cloudiness has been reached and the human eye no longer sees any further increase.

12.4.1.2 Glossiness (Shine)

Another important visual attribute is gloss or shine. Once again there are a variety of physical instruments to measure light reflectance, but the sensory data are still important to determine what humans will perceive in a specific situation. This becomes more important if the surface is non-uniform, since most instrumental reflectance measures are designed to work with uniform surfaces such as paints, waxes, and finishes. Many foods and consumer products will not conform well to these conditions. For example, the glaze on a cake or other baked product may not be a smooth surface or the shine on an apple may vary across the surface of the fruit. Just asking panelists about overall shine without appropriate training with reference standards may lead to different interpretations by different panelists, since there are two primary types of light reflectance. Specular reflectance refers to the mirror-like shine perceived when the actual image of a light source appears on the surface of the product (Beck and Prazdny, 1981). Obviously, standard angles and viewing conditions are necessary in order to test this in a reliable manner. Another important type of shine arises from diffuse reflectance. In this case the light is reflected, but it is scattered by the surface over such different angles that the reflected image of the light source is not seen. Buffing a metal surface with an abrasive cloth to produce many fine scratches will result in a good example of a surface with diffuse reflectance. The surface may seem quite shiny, but there is no mirror-like image, only the brightness of the light source. This type of shininess is also quite common with foods such as glazed doughnuts and egg-washed bread. A few example of studies on glossiness are Obein et al. (2004) and Xiao and Brainard (2008) where objects and pictures were used to determine

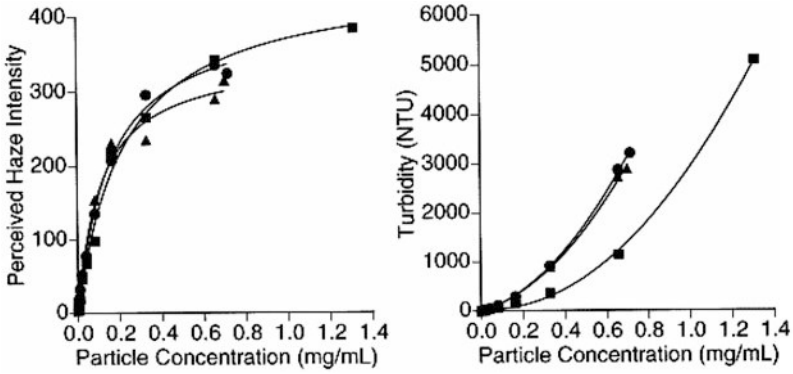

Fig. 12.1 Haze intensities (geometric means) perceived by sensory panelists using non-modulus magnitude estimation (*left*) and instrumentally measured turbidity (*right*) versus particle concentration for medium (2.600 mm diameter) particles in clear (■), yellow (●), and red (▲) liquids (Reprinted with permission from Carrasco and Siebert, 1999).

perceived glossiness. Chong et al. (2008) created a machine vision system to evaluate the surface gloss of eggplant fruit.

Translucency

Translucency is defined as the property of a specimen by which it transmits light diffusely without permitting a clear view of objects beyond the specimen (ASTM, 1987). Joshi and Brimelow (2002) gave a simple test to determine whether a sample is translucent or not. They suggest measuring the sample with a reflectance spectrophotometer at maximum area of illumination and with the maximum viewing aperture. Then repeat the measurement with the same viewing aperture but with a smaller area of illumination. If there is a large increase in the lightness reading (L^* in CIELAB, see below) then the sample is translucent.

This property is important in orange juice (MacDougall, 2002), tomato skins (Hetherington et al., 1990), fresh-cut tomatoes (Lana et al., 2006), and pineapples (Chen and Paull, 2001) where flesh translucency is a defect associated with off-flavors and fruit fragility during harvest. Hetherington et al. (1990) found that increased sensory translucency scores of tomatoes were associated with increased opacity and that the translucency scores were inversely related to the L^* values (r=0.774). Standard sensory techniques are used in the sensory assessment of translucency and instrumentally a reflectance spectrophotometer followed by the Kubelka-Munk data analysis is used (Talens et al., 2002).

The Kubelka-Munk theory is a relatively crude model to describe light scattering and its effect on translucency (see Nobbs (1985) as well as Vargas and Niklasson (1997) for excellent overviews of the theory and its applicability). Simply put a "scattering" coefficient (S) and an "adsorption" coefficient (K) are calculated and the ratio (K/S) is related to translucency of the object. For example, Lana et al. (2006) found that during storage the pericarp of tomato slices but not that of intact tomatoes became more translucent. The sensory translucency scores were related to changes in the K/S ratio of the Kubelka-Munk analysis of the reflection spectra of the sliced tomatoes. Additionally they found that removing the locular gel inhibited the development of translucency in the pericarp.

MacDougall (2002) gives an example that makes it very clear that only using instrumental values in measurement of translucent samples can give results that are totally inconsistent with visually observed values. In his example, 4-fold orange juice concentrate is diluted to a concentration of 0.2 and 4. When glasses of these oranges juices are viewed with overhead illumination they range from pale yellow (concentration less than 1) to deep orange (concentration of 4). Instrumentally, the most dilute juice had the lowest L^* and it was the darkest according to the instrument. On the other hand, the most concentrated juice had the highest L^* and was the lightest according to the instrument. This occurred due to the loss of light scatter in the more diluted samples. He cautions that one should remember that the instrument only sees light reflected from a limited solid angle while the human "is influenced by the multidirectionality of illumination, which makes coloured translucent materials glow."

One can do a simple experiment to visually demonstrate the above effect. Pour an equal amount of orange juice into two identical transparent glasses. Cover both glasses completely with white paper. The paper covering the side of one glass should have a circular hole cut into it the size of a dime (approximately 1.5 cm in diameter). The paper covering the side of the other glass should have a circular hole cut into it the size of a quarter (approximately 2.5 cm in diameter). Then evaluate the color of the juices by viewing the visible juice through the holes at a 90° angle. The juice in the glass covered with the paper with the small hole seems darker because much of the scattered light is "trapped" within the glass and not seen by the viewer.

12.4.2 Visual Color Measurement

Sensory evaluation of color is frequently performed. Sensory scientists have used the whole range of sensory testing tools to do visual color measurements. For example, Whiting et al. (2004) used triangle and two-out-of-five difference tests to investigate perceived color differences in liquid foundation cosmetics; and Eterradossi et al. (2009) used descriptive analysis and consumer satisfaction scales to evaluate red and blue automotive paints with different levels of quality.

When doing sensory color evaluation it is even more important than usual to standardize all factors that can affect the perceived color. In general the sensory scientist performing color assessment should carefully standardize, control, and report the following:

(a) the background color in the viewing area. Ideally the background color should be non-reflective and neutral, usually a matte gray, cream, or off-white is used (ASTM 1982).
(b) the light source (Table 12.2) in Kelvin and its intensity (in lux or foot candles) at the product surface. Eggert and Zook (2008) recommend a light intensity between 750 and 1,200 lux. Also, the light source (if it is not a standard illuminant) should be chosen to have a high color rendering index (R_a, see below) (Hutchings, 1999).
(c) the panelists' viewing angle and the angle of light incidence on the sample. These should not be the same since that leads to specular reflection of the incident light and a potential glossiness that may be an artifact of the method. Usually the booth area is set up with the light source vertically above the samples and the panelists viewing angle when they are seated is about 45° to the sample, this minimizes specular reflection effects.

Table 12.2 Light sources, color temperatures, and color rendering indices[a]

Light source	Color temperature (K)	Ambiance description	Color rendering	
			Index (R_a)	Quality
Candle	1,800	Very warm		
High-pressure sodium lamp	2,100	Very warm	22	Poor
40 watt incandescent light bulb	2,770	Warm	Close to 100	Excellent
100 watt incandescent light bulb	2,870	Warm	Close to 100	Excellent
CIE source A	2,856	Warm	Close to 100	Excellent
Warm white fluorescent light				
Sylvania T5-warm	3,000	Warm	82	Very good
Metal halide lamp				
Sylvania MetalArc ProTech	3,000	Warm	85+	Very good
GroLux Wide Spectrum lamp	3400	Neutral	89	Excellent
Neutral fluorescent light				
PureLite	3,500	Neutral	85	Very good
Cool white fluorescent light				
Sylvania T5-cool	4,100	Cool	82	Very good
Tungsten/halogen light				
SoLux	4,700	Cool	99	Excellent
CIE source B (direct sunlight)	4,870	Cool		
Full spectrum fluorescent light				
DuroTest Vitalite	5,500	Cool	90	Excellent
Daylight fluorescent light				
Sylvania F40D	6,300	Cool-blue	76	Good
CIE source D_{65}	6,500	Cool-blue	100	Excellent
Daylight fluorescent light				
DuroTest DayLite 65	6,500	Cool-blue	92	Excellent
CIE source C (overcast daylight)	6,774	Cool-blue		
CIE source D (daylight)	7,500	Cool-blue		

[a]Values collated from commercial literature and Hutchings (1999)

(d) the distance from the light source and the product. This will affect the amount of light incident on the sample. The light intensity should be measured at the product surface.
(e) whether the sample is lit with reflected or transmitted light.

Frequently, very little or none of the above information appears in the literature associated with food or personal care product color evaluations. Whiting et al. (2004) were exceptional in explicitly indicating the color of the sensory booth wall and table (gray with specified color system values); the color of the sample tray bottoms (a gray-woven fabric with specified color system values); the light source (D_{65} at 1,000 lux); the viewing distance (60 cm); and the viewing angle (each sample was subtended at 6º).

In color and appearance evaluations the light source is usually specified by its color temperature. The color temperature is determined from the temperature in Kelvin to which a black body that absorbs all energy that falls onto it needs to be heated to emit light of a spectral distribution characteristic of the specific light source (Table 12.2). The light emitted by the black body changes as the color temperature changes. At lower temperatures (2,000 K) the light emitted is redder, at higher temperatures (about 4,000–5,000 K) the light is whiter, and at high temperatures (8,000–10,000 K) the light becomes bluer (1999). Standard lights used in food color evaluation tend to be illuminants A (with a color temperature of 2,856 K), C (6,774 K), D_{65} (6,500 K), and D (7,500 K). These illuminants are all based on tungsten filaments. The spectral distribution of illuminant A is very different from the spectral distribution of illuminants B and C (Fig. 12.2). The spectral distribution of illuminant A is high in red-yellow wavelengths while it is low in blue-violet wavelengths. Illuminants C and D_{50}, through D_{65}, are high in blue wavelengths. Illuminants C, D_{65}, and the other D variants are designed to mimic variations of daylight. Standard fluorescent lights have very different spectral distributions (they tend to be more spiky and less smooth, see F11 in Fig. 12.2) than those from tungsten and incandescent lamps. The result is that objects viewed under fluorescent and tungsten lights often have differences in perceived color than when the same objects are viewed under say illuminant C. These differences in perceived color occur because the color depends on the absorption of light by the product and the incident spectrum's wavelengths. For example, under a standard illuminant if the product absorbs red wavelengths and not those in the green area of the spectrum the object would look green. However, if the incident light only has red wavelengths then the object would not appear green since there were no green wavelengths to reflect to the eye. Depending on the light source this object may appear black.

The color rendering index (R_a) is a measure of the effect of an illuminant on the perceived color of an object (CIE, 1995a). The R_a is measured by assessing the size of the color change of eight Munsell color samples under the light of interest versus a reference light, usually an incandescent light (a 60 W tungsten lamp, 2,900 K). Lights with a 100 R_a index exactly reproduce the perceived color of the reference light (Table 12.2).

Panelists should be tested for color blindness (see above). If reference color standards are desired they can be paint chips, Munsell spinning disks, model products, or digital images (Hernández et al., 2004; Kane et al., 2003). However, when using these standards the sensory specialist should keep in mind that the color of the standard and the sample may only be a metameric match. A metameric match is an apparent match in the colors of two objects when viewed under one light source but the colors of the objects are not matched when viewed under most other light sources (MacKinney and Little, 1962). Metameric matches also occur when two objects match under a specified light source when viewed by one observer but not when viewed by a second observer (Kuo and Luo, 1996).

Recently, a number of studies have been published on the use of digital images as reference standards or the use of virtual product images to evaluate color differences in foods. It could be very useful if it were possible to obtain accurate reproductions of color and appearance of products as images. These can then be displayed to the panelists (anywhere in the world) as long as they are viewed using the identical reference display and viewing conditions. Kane et al. (2003) studied the possibility of using digital references for the brownness of cookies and found that the panelists' scores when using either digital references or physical references led to the same trends in differences among cookie formulations but in some cases the panelists' scores were lower when using the digital references than when using the physical references. Hernández et al. (2004) created digitally processed color charts of

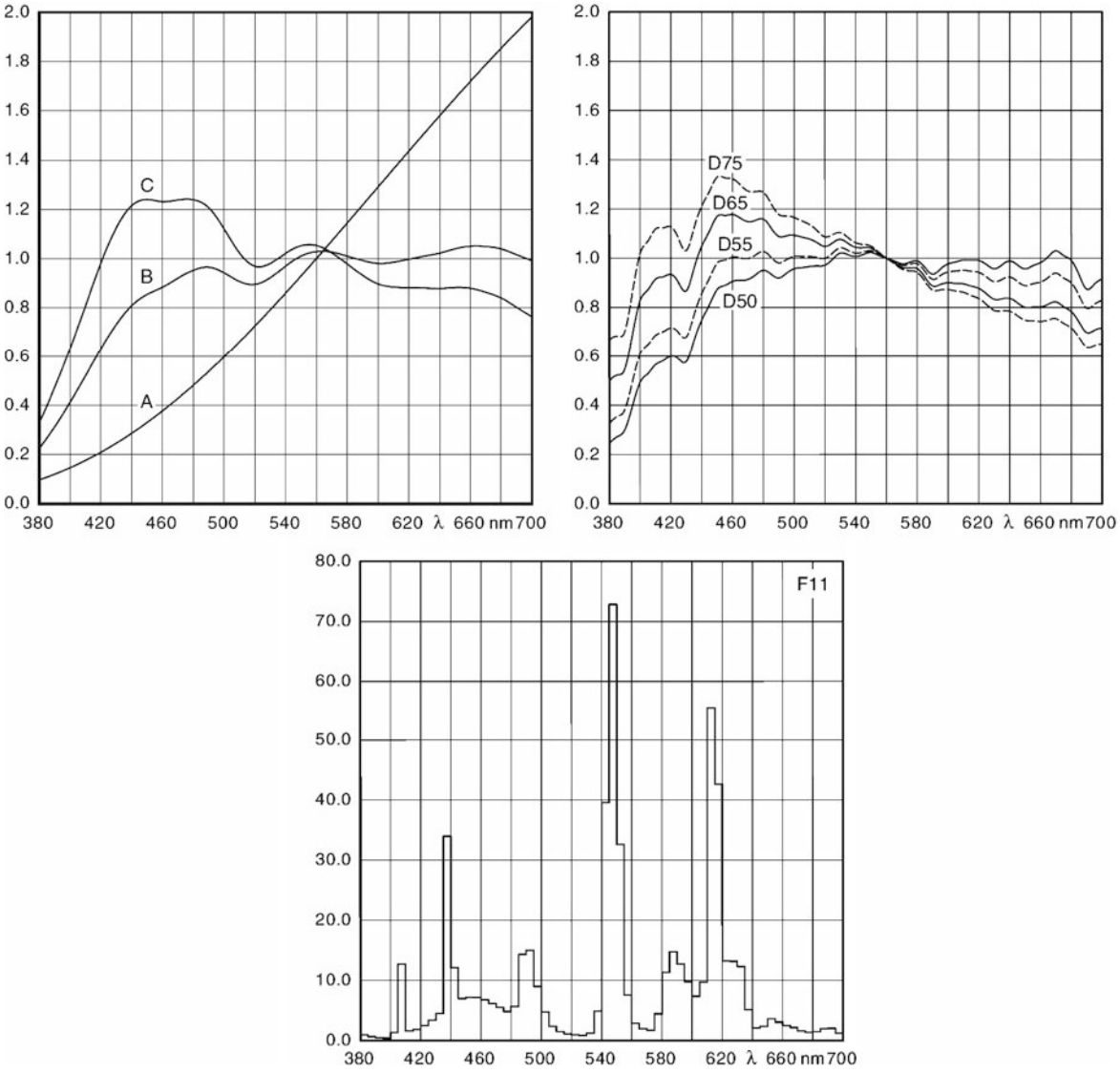

Fig. 12.2 The relative wavelength distributions for CIE standard illuminants A, B, C, D_{65}, and D variants and F11. Illuminant A has more yellow-red wavelengths, illuminant D_{65} and the D variants have more blue wavelengths, and illuminant F11 (a fluorescent light) has a more spiky distribution in terms of wavelengths (Reprinted with permission from Gernot Hoffman, University of Applied Sciences, Emden, Germany).

Piquillo peppers to use as a color reference standard and they found that the repeatability of the visual color chart scores was satisfactory. Examples of digital images used as reference standards: Pointer et al. (2002) successfully used digital images of bananas, tomatoes, oranges, peas, and biscuits (cookies) that had been perturbed in terms of lightness or color in triangle tests; Valous et al. (2009) similarly used digital images of ham slices and successfully determined the CIE color characterization of these slices from the digital images using a computer vision system; Kang et al. (2008) successfully did something similar with a more complex product—bicolor mango fruit.

When asking panelists to evaluate color the sensory scientist has to keep in mind that humans are very good at evaluating color differences when samples are side by side or when they have access to color standards but

humans are not good at evaluating color differences from memory. Additionally, research has shown that humans are quite good at evaluating hue (see Munsell color solid) and lightness (value) changes in objects but not good at discriminating chroma (saturation of color) changes (Melgosa et al., 2000). Additionally, Zhang and Montag (2006) confirmed Melgosa and coworkers' results and conclude with the following statement: "...people do not have ready access to the lower level color descriptors such as the common attributes used to define color spaces, and that higher level psychological processing involving cognition and language may be necessary for even apparently simple tasks involving color matching and describing color differences."

12.5 Instrumental Color Measurement

"There are a bewildering variety of methods and instruments available to the food technologist in the field of colour measurement. When one is approaching the subject for the first time or when attempting to devise a method for a material outside the normal experience the wealth of possibilities available sometimes makes the choice difficult" (Joshi and Brimelow, 2002). In the next section we will endeavor to shed some light on color measurement. For additional information the following are suggested: Hutchings (1999, 2003), MacDougall (2002), and Lee (2005).

12.5.1 Munsell Color Solid

Prior to the advent of instrumental techniques, several visual color solids were developed to describe color; one of the more famous was the Munsell color solid. The Munsell color solid was developed by A.H. Munsell around 1900 (Clydesdale, 1978). The Munsell system had three attributes: hue (H), value (V), and chroma (C). A specific color was described as a point in the three-dimensional hue–value–chroma space. In the Munsell color solid (or color space) the hue–value and chroma values for each color were arranged in a sphere composed of individual color "plates" separated by equal visual steps (Fig. 12.3). Hues are spaced around the circumference with ten major hues (grouped into major divisions of red, yellow-red, yellow, green-yellow, green, blue-green, blue, purple-blue, purple, and red-purple), each being ten hue steps apart. These hue steps were supposed to be equal but research has shown that the hue spacing in the yellow-red, yellow-green, and blue regions is actually not equally spaced (Oleari, 2001). The value is a darkness or lightness scale with absolute black (at the bottom of the sphere) to absolute white (at the top of the sphere).The chromatic colors are positioned at the value that is equally spaced between absolute black and absolute white. The chroma is the amount by which a given hue deviates from a neutral gray of the same value. The chroma of a hue is imagined as a line of constant hue drawn from the center of the sphere to the edge of the sphere at a constant value.

Visual color solid systems are useful when one wants to specify a color but one always needs a human to do the matching of the sample color to the color solid (usually a color chip). However, due to the idiosyncratic nature of color vision, it was not possible to have an instrument measure color as specified in Munsell

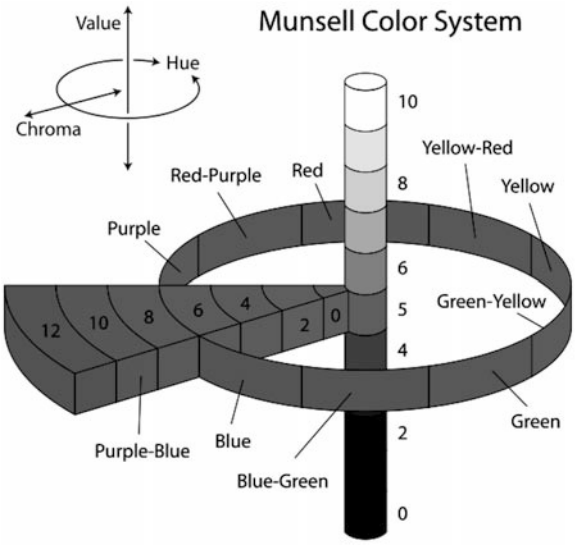

Fig. 12.3 A schematic of the Munsell color solid indicating the three dimensions of hue, chroma, and lightness (From Jacobolus, Wikimedia Commons, http://en.wikipedia.org/wiki/File:Munsell-system.svg. This file is licensed under the Creative Commons Attribution ShareAlike 2.5 License. In short: you are free to share and make derivative works of the file under the conditions that you appropriately attribute it and that you distribute it only under a license identical to this one).

notation. In order to develop instrumentation that could measure color, it was necessary to devise mathematical relationships to describe color (the so-called mathematical color solids).

12.5.2 Mathematical Color Systems

In order to develop meaningful mathematical color systems the approach used by Munsell had to be changed. Mathematical color systems are based on the physical laws related to the addition of lights and these are based on the existence of L-, M-, and S-receptor cones and rods in the human eye. The most used mathematical color systems are the CIE versions. The CIE acronym is based on the French name for the International Commission on Illumination or "La Commission Internationale de l'Eclairage" (CIE, 1978, 1986). In order to explain the CIE system it is easier to start with a less complex version, the so-called three lights system. The three lights system simply specifies color in terms of how colors are perceived by the human eye.

12.5.2.1 The R, G, B Mathematical Color System

Three projectors, one with a red filter (R), one with a green filter (G), and one with a blue filter (B), are set up to shine on a screen in such a way that they completely overlap. The sum of the wavelengths hitting the screen, the so-called spectral radiant flux, is perceived by an observer as a single color. Then, another projector with an unknown color filter is projected onto a separate portion of the same screen. It is now possible to adjust the energy (radiant flux) projected through the R, G, and B filters on the first three projectors until the combined radiant flux from these projectors matches the unknown color. One can then specify the unknown color as the energy combination from R, G, and B. The amounts of energy required to match the unknown from each of the three lights are the so-called tristimulus values. These values may be expressed as radiant flux (watts), luminous flux (lumens), or, more usually, in arbitrary psychophysical scales of red, blue, and green.

In practice this approach is overly simple leading to a number of problems. Some colors are too bright to match because no light source can project the required radiant flux. Other colors are too saturated. For example, some yellows cannot be matched using just red and green filters even if the blue filter is eliminated. "Matchable colors" are within the color gamut (or the acceptable color range) of a specific mathematical color system while "non-matchable colors" are outside the color range. Even if different filters had been chosen for the three projectors in this simple system it is still not possible to match all colors. In theory, the three lights system is based on the physiological response of the three cone types of the eye. In practice, it is further simplified by isolating the responses that are analogous to actual physiological responses. This simplification results in the unfortunate effect that there are always some colors outside the color gamut because nearly all parts of the color magnetic spectrum excite more than one of the cones to some extent. If it were possible to find a part of the spectrum that excited only one cone type while having no effect on the other two cone types, then a color gamut based on the three lights system would include all perceived colors. Despite its limitations, the three color system has been used extensively as the basis for other tristimulus color systems.

It is possible to express the color matching produced by the three lights algebraically (Clydesdale, 1978). If we assume that C is a color in the three-dimensional color space and its color is matched by the three lights red, green, and blue with tristimulus values R, G and B, then the following equation describes the color match:

$$C_{(\mathrm{R,G,B})} = R + G + B \tag{12.1}$$

Based on the physical law of additivity of luminances, the intensity of color C (also known as the luminance L) in the three-dimensional space can be described by the next equation:

$$L = l_{\mathrm{R}} + l_{\mathrm{G}} + l_{\mathrm{B}} \tag{12.2}$$

where l_{R}, l_{B}, and l_{G} are the luminances (intensities) of the corresponding light primaries in their unit amount with $R = B = G = 1$. If the tristimulus values R, G, and B of color C are changed by a constant factor "a" then the luminance of C changes to "aL." If color D with tristimulus values R_{D}, G_{D}, and B_{D} is added to color C with tristimulus values G_{C}, B_{C}, and $\underline{R_{\mathrm{C}}}$ then the new

color E has tristimulus values of R_E, G_E, and B_E. This can be expressed algebraically:

$$E_{(R_E,G_E,B_E)} = (R_C + R_D) + (G_C + G_D) + (B_C + B_D) \tag{12.3}$$

So, the tristimulus values of a mixture of colors are equal to the sum of the tristimulus values of the component colors. Based on the above explanation it is possible to describe both the luminance (l) and tristimulus values r, g, b of a color in terms of three colored lights, if the color falls within the color gamut of the mathematical color solid.

It is also possible to define a unit plane within the three-dimensional mathematical color solid which has within it all colors with the same luminance. This unit plane is a plane of constant luminance in the three-dimensional mathematical color space and is similar to the plane of constant value in the Munsell color solid. Differences in colors within this plane are a function of hue and chroma of the specified colors. This unit plane is called a chromaticity diagram and a color point within the chromaticity diagram is not specified by the arbitrary tristimulus values R, G, and B but by fractions of their total:

$$r = \frac{R}{R+G+B} \tag{12.4}$$

$$g = \frac{G}{R+G+B} \tag{12.5}$$

$$b = \frac{B}{R+G+B} \tag{12.6}$$

A color may be therefore specified in the three-dimensional color by description of the luminance (l) and two of the color's three chromaticity coordinates. This will be illustrated in the next section (Fig. 12.4) for the CIExyz tristimulus system. This simple three-light system is the basis for all mathematical color solids like the CIE tristimulus system. However, this simple system does not work in reality because (1) some colors are outside the color gamut and a negative amount of radiant flux is needed to match these colors, (2) the color solid is not visually uniform, (3) a vector analysis is needed to calculate the luminance. The CIE system eliminates all of these problems.

12.5.2.2 CIE Mathematical Color Systems

In the CIE mathematical color system theoretical primaries were developed to remove the disadvantages of the actual lights (R, G, and B) while still retaining the advantages of the simple three-light system. The primaries are X, Y, and Z and their chromaticity coordinates are x, y, and z. The developers mathematically included luminance into one of the primaries (Y) and thus avoided the problem of needing vector analysis to calculate luminance. This was possible because the cones of the eyes are most sensitive to luminance in the green region of the spectrum. Careful choice allowed the theoretical primaries X, Y, and Z to cover the entire color gamut with positive values, thus the horseshoe-shaped CIE spectrum locus has a color gamut that includes all colors (Fig. 12.4).

In the CIE system it is possible to locate a color in the three-dimensional color space by specifying Y and two of the three possible chromaticity coordinates (x, y, and z). The chromaticity coordinates are related to each other by the following equation: $x+y+z = 1$. Thus, knowledge of two of the three possible values will define a specific color.

The CIE data are usually expressed as tristimulus values (X, Y, and Z) or as chromaticity coordinates (x, y, and z). The x, y chromaticity coordinates are often plotted on the horseshoe-shaped CIE spectrum locus with $\%Y$ superimposed (Fig. 12.5, please note that not all colors are present at all levels of $\%Y$). The color can then be specified as x, y, and $\%Y$. Since CIE spectrum locus is not based on Cartesian coordinates, it is difficult to express mathematically and even more difficult to explain to most people. One attempt to simplify the CIE system plots the CIE spectrum locus at constant $\%Y$. Then x and y chromaticity coordinates, at a given Y value, appear on a unit plane.

The problem with the x, y, z chromaticity system is that the space looks like a horseshoe which makes any linear relationship calculations between these values and say sensory scales very difficult. Other color systems have been developed with more uniform diagrammatic representations of color spaces than the horseshoe-shaped CIE space. Early versions of these color spaces were the Gardner and the Hunter L,A,B spaces (which were associated with specific instruments) where the value (also known as the degree of whiteness or blackness) is represented by L. The

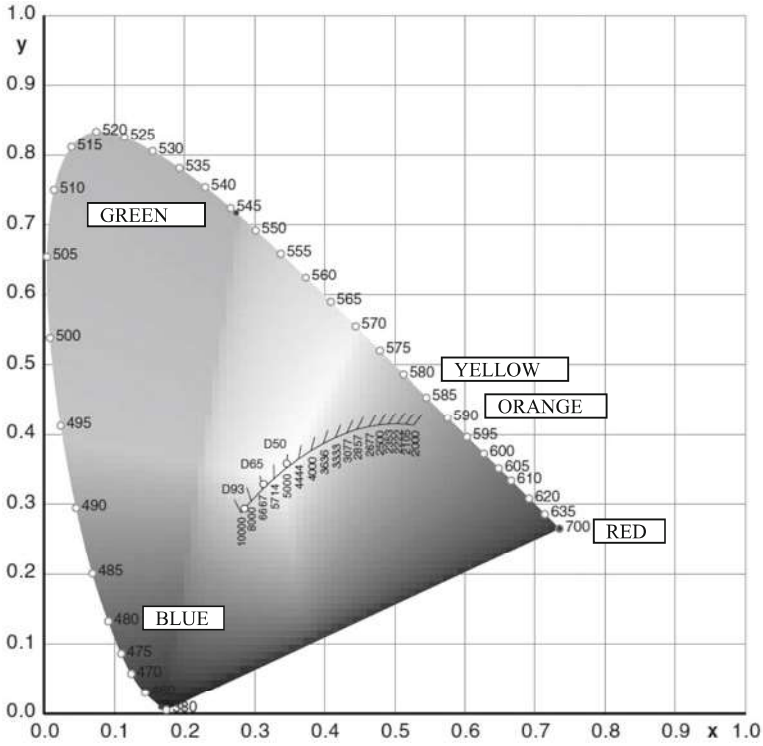

Fig. 12.4 Horseshoe-shaped chromaticity diagram (Reprinted with permission from Gernot Hoffman, University of Applied Sciences, Emden, Germany).

chromatic portion of the color space is based on rectangular Cartesian coordinates (a, b) with red represented by $+a$, green represented by $-a$, yellow represented by $+b$, and blue represented by $-b$. These systems made it easier to meaningfully communicate color data. Subsequently other spaces that were instrument invariant, like the CIELAB and CIELUV, also known as the L*a*b* and L*u*v*, respectively, were developed by CIE to improve the linearity of the CIE system (CIE, 1986). The L*u*v* system has been applied to food but was primarily devised for color additive mixing such as television and lighting. The L*a*b* space approximates the Munsell space. For both the L*u*v* and L*a*b* systems the three axes are mutually perpendicular. An increase in the value of $+a$ indicates an increase in red; a larger $-a$ value indicates an increase in green. An increase in $+b$ indicates an increase in yellow and an increase in $-b$ indicates an increase in blue. Increasing L* values indicate increasing lightness (or whiteness). One has to be careful not to oversimplify the space—this occurs when authors incorrectly describe a as redness and b as yellowness. In actuality (a b) are Cartesian coordinates that *together* describe a point in space (Hutchings, 1999; Wrolstad et al., 2005).

In an effort to make the color coordinate values more intuitive the L*C*h* color space was devised (Sharma, 2003). This space uses the same diagram as the L*a*b* color space but uses angles rather than Cartesian coordinates for a and b. The L* in L*C*h* is identical to the L* in the L*a*b*. The C* indicates chroma (an indication of color saturation) and is equal to zero at the center of the color space and increases based on the distance from the center. The h* is the hue angle and it is expressed in degrees. Starting from the $+a^*$ axis, 0° is $+a$ (red), 90° is $+b$ (yellow), 180° is $-a$ (green), and 270° is $-b$ (blue).

The above color systems are helpful in specifying a color but are not very useful when one wants to specify the differences between colors. Color difference can be calculated in the L*a*b*, the L*u*v*, and the L*C*h* systems. For the L*a*b* the equation for color difference between two samples is as follows:

$$\Delta E^* = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2} + (b_1 - b_2)^2 \tag{12.7}$$

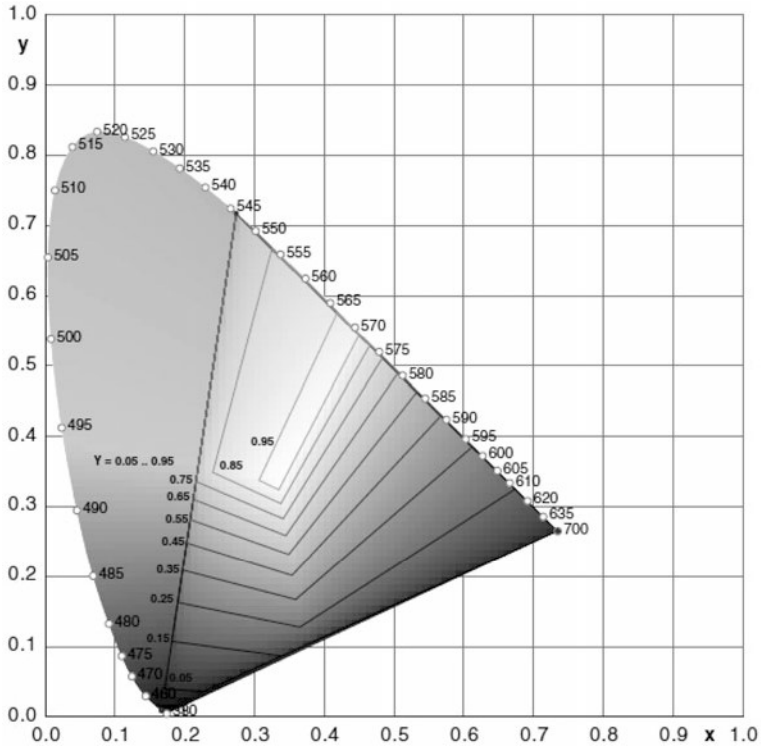

Fig. 12.5 Horseshoe-shaped chromaticity diagram with third dimension (Y). The third dimension is indicated by the tristimulus value Y. As previously mentioned, this value indicates the lightness or luminance of the color. The scale for Y extends from the white spot in a line perpendicular to the plane formed by x and y using a scale that runs from 0 to 1. The fullest range of color exists at 0 where the white point is equal to CIE illuminant C. As the Y value increases and the color becomes lighter, the range of color, or gamut, decreases so that the color space at 1 is just a sliver of the original area (Reprinted with permission from Gernot Hoffman, University of Applied Sciences, Emden, Germany).

It is important to note that once the ΔE is calculated the size of the difference is known but not whether it is due to L, a, b singly or in some combinations (Sharma, 2003). Because the L, a, b space is not uniform the ΔE is more accurate in some parts of the color space than others. In an attempt to improve the situation a number of other color difference equations have been proposed. The most popular are the CIE94 (also known as ΔE_{94}, CIE 1995b) and the CIEDE2000 (Luo et al., 2001; Sharma et al., 2005). The CIEDE2000 has been extensively studied and seems to be an improvement over the standard ΔE and CIE94 (Melgosa et al., 2008; Xu et al., 2002).

There are also mathematical color systems that may be less familiar to North American readers but very familiar to others, for example, the Swedish Natural Color System (NCS, Hard and Sivik, 1981), the DIN99 (Cui et al., 2002), and the CMC (AATCC, 2005). Fortunately, values derived from any of these systems can be interconverted, provided conditions are appropriately specified. A few examples of color conversion tables and equations are listed in Table 12.3.

Interconversion between color systems can have problems. In food matrices there are frequently discrepancies when converting from the other systems to the CIE XYZ system, because the conversion calculations are based on the responses of opaque standards. Food systems, on the other hand, are often somewhat translucent and do not behave exactly as would be predicted by the standards.

Angela Little (MacKinney and Little, 1962) stated "Once we accept that color belongs to the realm of sensory perception, we must also accept that is can only be measured directly in psychological terms. From physical measurements, nevertheless, we can obtain

Table 12.3 Conversion equations and tables for some common color systems

Convert CIE *XYZ* to CIELUV L*u*v*[a]

$L^* = 116(Y/Y_n)^{1/3} - 16$ for $Y/Y_n > 0.008856$ where Y_n is the value for reference white

$L^* = 903.3(Y/Y_n)^{1/3}$ for $Y/Y_n \leq 0.008856$ where Y_n is the value for reference white

$u^* = 13L^*(u'-u'_n)$ where u' is calculated as described below and u'_n is for reference white

$v^* = 13L^*(v'-v'_n)$ where v' is calculated as described below and v'_n is for reference white

Calculation of u' and v':

$u' = (4X)/(X+15Y+3Z) = (4x)/(-2x+12y+3)$

$v' = (9Y)/(X+15Y+3Z) = (9y)/(-2x+12y+3)$

Convert CIE *XYZ* to CIELAB L*a*b*[b]

$L^* = 116(Y/Y_n)^{1/3}$ for $Y/Y_n > 0.008856$ where Y_n is the value for reference white

$a^* = 500\{(X/X_n)^{1/3} - (Y/Y_n)^{1/3}\}$ where X_n is the value for reference white

$b^* = 200\ \{(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}\}$ where Z_n is the value for reference white

Convert CIELAB L*a*b* to CIE *XYZ*[c]

$Y^{1/3} = (L^* + 16)/24.99$ if illuminant C was used

$X\%^{1/3} = (a^*/107.72) + Y^{1/2}$ if illuminant C was used

$Z\%^{1/3} = Y^{1/3} - (b^*/43.09)$ if illuminant C was used

Convert CIELAB L*a*b* to HunterLAB[c]

$L = 10Y^{1/2}$ if illuminant C was used

$a = 17(X\%-Y)/Y^{1/2}$ if illuminant C was used

$b = 7.0(Y-Z\%)/Y^{1/2}$ if illuminant C was used

Convert CIE *XYZ* to HunterLAB[d]

$L = 10Y^{1/2}$

$a = 175(1.02X-Y)/(Y^{1/2})$

$b = 70(Y-0.847Z)/(Y^{1/2})$

Convert Munsell values to CIE *XYZ*

Use tables by Glenn and Killian (1940)

Convert Munsell values to CIE *xy*

Use tables by Glenn and Killian (1940)

[a] Hutchings (1999) (CIELUV was intended for color additive mixing in the television and lighting industries, but it has been used in food color measurements)
[b] ASTM (1991)
[c] Pattee et al. (1991)
[d] Clydesdale (1978)

data which provide the basis for establishing psychophysical scales, from which we can predict visual color appearance." She suggests that usually the primary concern in color measurement is to measure what the eyes see. Thus it is necessary to produce data that correlate with human visual perception. Often the instrumental data (tristimulus values) do not correlate well with the data derived from panelists and further manipulation of the instrumental data may be needed to improve the correlation.

When the color of foods is measured instrumentally the scientist should keep in mind that the instrument was designed to measure the reflectance color of ideal samples, namely samples that are homogeneously pigmented, opaque, flat, and evenly light scattering (Clydesdale, 1975, 1978). Foods are far from the ideal sample. Nearly all foods have shape and texture irregularities and surface characteristics that scatter and transmit light. Additionally, the pigment distribution in most foods is also irregular. Instruments are also designed to measure the transmittance color of ideal samples, and in this case the ideal sample is clear and moderately light absorbing. Real liquids (where one usually measures transmittance color) tend to have hazes and may be very light absorbing (Clydesdale, 1978).

It is possible to obtain an approximate ideal reflectance color measuring surface for dry powders, such as flour and cocoa, by compressing the dry powdered sample into a pellet. Other dry foods such as instant coffee, potato flakes, dry gelatin crystals (dry Jell-O®) can be pressed into very thin wafers between

Teflon disks. When measuring the color of translucent liquids the area exposed should be much larger than the area illuminated. This allows any light entering the sample and traveling laterally within the sample to emerge in the direction where it will be measured. This minimizes the selective absorption effect that can change the hue of the liquid (see above under translucency).

12.6 Conclusions

Sensory color measurement is frequently neglected by sensory specialists or they add this measurement as an afterthought. We hope that this chapter has made the reader realize that the measurement of color, whether visually or by instrument, is no simple task. The sensory specialist should be very careful to standardize all possible conditions associated with these measurements and to carefully report the specific conditions used in a test. Additionally, it is important to realize that most (if not all) visual and appearance characteristics can be evaluated using standard descriptive analysis techniques.

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