31 chapter

Color Analysis

R.E. Wrolstad (✉) • D.E. Smith
Department of Food Science and Technology,
Oregon State University,
Corvallis, OR 97331-6602, USA
e-mail: ron.wrolstad@oregonstate.edu; dan.smith@oregonstate.edu

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31.1 INTRODUCTION

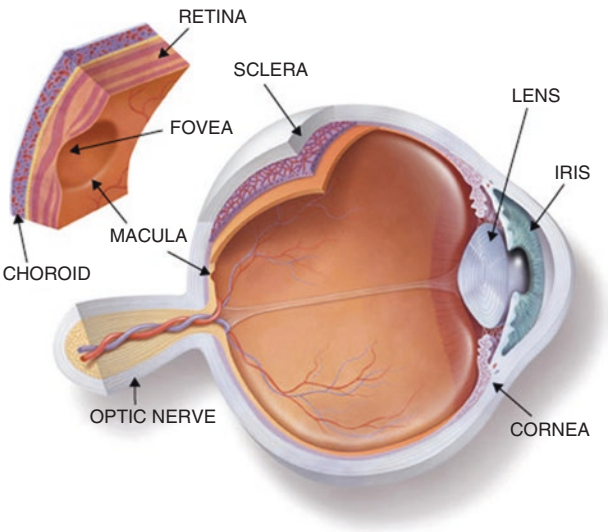
Color, flavor, and texture are the three principal quality attributes that determine food acceptance, and color has a far greater influence on our judgment than most of us appreciate. We use color to determine if a banana is at our preferred ripeness level, and a discolored meat product can warn us that the product may be spoiled. The marketing departments of our food corporations know that, for their customers, the color must be "right." The University of California Davis scorecard for wine quality designates 4 points out of 20, or 20% of the total score, for color and appearance [1]. Food scientists who establish quality control specifications for their product are very aware of the importance of color and appearance. While subjective visual assessment and use of visual color standards are still used in the food industry, instrumental color measurements are extensively employed. Objective measurement of color is desirable for both research and industrial applications, and the ruggedness, stability, and ease of use of today's color measurement instruments have resulted in their widespread adoption.

Color can be defined as the sensation that is experienced by an individual when radiant energy within the visible spectrum (380–770 nm) falls upon the retina of the eye [2], and a **colorant** is a pigment that is used to color a product. For the phenomenon of color to occur, there must be: (1) a colored object, (2) light in the visible region of the spectrum, and (3) an observer. All three of these factors must be taken into account when assessing and measuring color. When white light strikes an object, it can be absorbed, reflected, and/or scattered. Selective absorption of certain wavelengths of light is the primary basis for the color of an object. Color, as seen by the eye, is an interpretation by the brain of the character of light coming from an object. **Colorimetry** is the science of color measurement [3]. It is possible to define color in mathematical units; however, those numbers do not easily relate to the observed color. A number of color-ordering systems and color spaces have been developed that better agree with visual assessment. In food research and quality control, instruments are needed which provide repeatable data that correspond to how the eye sees color. This chapter will provide a brief description of human physiology of vision and an overview of the different color-ordering and color-measuring systems. The chapter is limited to presenting the basic underlying principles that will hopefully allow for an understanding of how color of food products should be measured. Color measurement is a very complex subject, and for more detailed exploration of the subject, the following references are recommended [2–7].

31.2 PHYSIOLOGICAL BASIS OF COLOR

Humans have excellent color perception and they can detect up to 10,000,000 different colors [8]. They have very poor color memory, however, and cannot accurately recall colors of objects previously observed [5, 9], hence the need for objective measurement of color. While color perception varies somewhat with humans, it is much less variable than that for the senses of taste and smell. Color perception is comparatively uniform for people with normal color vision; however, 8% of males and 0.5% of females have physiological defects and perceive colors in a markedly different way [2, 5].

Figure 31.1 is a simplified diagram of the human eye. Light enters the eye through the cornea, passes through the aqueous and vitreous humor, and is focused on the **retina**, which contains the receptor system [10]. The **macula** is a small (approximately 5 mm in diameter) and highly sensitive part of the retina that is responsible for detailed central vision. It is located roughly in the center of the retina. It is yellow-orange colored and contains a high concentration of the carotenoid pigments, lutein and zeaxanthin. It is believed that these dietary antioxidants may protect the retina from photo damage [11]. Age-related macular degeneration results in loss of central vision and is a major health issue in our aging population. The **fovea**, the very center of the macula, is about 2 mm in diameter and contains a high concentration of **cones**, which are responsible for daylight and color vision, known as "**photopic**" vision. The cones contain receptors that

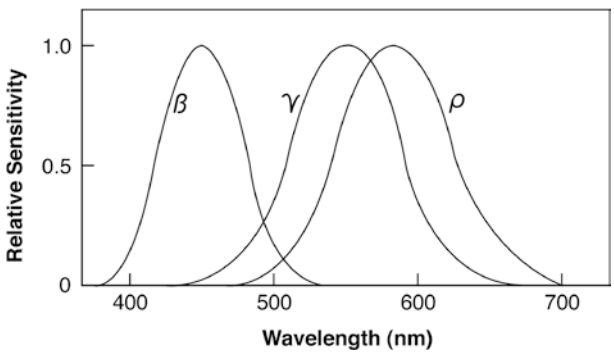


31.1 figure

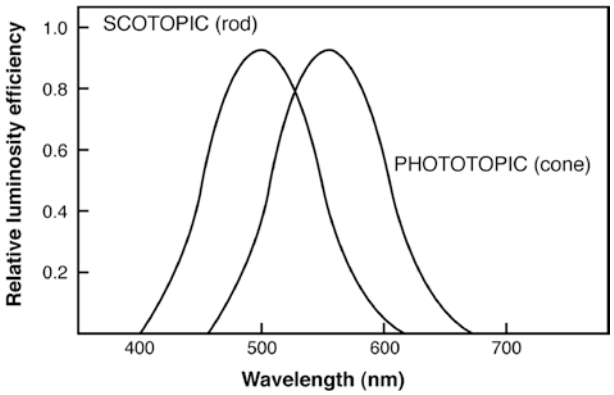
Diagram of the human eye. http://www.amdcanada.com/template.php?lang=eng&section=4&subSec=2d&content=4_2

are sensitive to red, green, and blue light. Figure 31.2 shows the spectral sensitivity curves for the three respective cones. **Rods** are more widely distributed in the retina and are sensitive to low-intensity light. They have no color discrimination and are responsible for night or "**scotopic**" vision. Figure 31.3 shows the spectral sensitivity curves for scotopic (rod) and photopic (cone) vision, the latter being an integration of the curves shown in Fig. 31.2. Note the sensitivity maximum is at 510 nm for scotopic vision and 580 nm for photopic vision. This accounts for blues appearing to be brighter and reds darker at twilight when both scotopic vision and photopic vision are functioning.

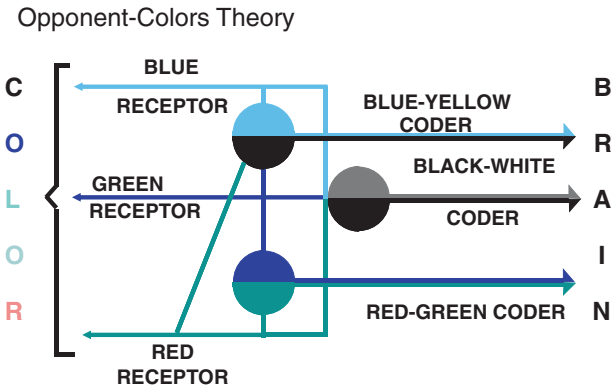
Signals are sent via the optic nerve to the brain, where "vision" occurs. According to the "Color Opponent Theory" [4], the signals from the red, green, and blue receptors are transformed to one brightness signal indicating darkness and lightness and two hue signals, red vs. green and blue vs. yellow. Figure 31.4 shows a diagram of the opponent color model. The



31.2 figure Spectral sensitivity curves of the three types of cones comprising photopic vision (From Hutchings [5], with kind permission of Springer + Business Media)



31.3 figure Spectral sensitivity curves for scotopic (rods) and photopic (cones) vision (From Hutchings [5], with kind permission of Springer + Business Media)



31.4 figure The color opponent model (Courtesy of HunterLab, Reston, VA)

brain's interpretation of signals is a complex phenomenon and is influenced by a variety of psychological aspects. One such aspect is **color constancy**. The same sheet of white paper will appear white when seen in bright sunlight and also when it is viewed indoors under dim light. The physical stimuli in each case are obviously quite different, but the brain knows that the paper should be white and draws on its experience. A second aspect occurs when a large expanse of color appears brighter than the same color in a small area. One only needs the experience of painting a whole wall of a room and then seeing how different it appears from the small color chip obtained from the paint store.

31.3 COLOR SPECIFICATION SYSTEMS

There are verbal, visual matching, and instrumental methods for describing and specifying color. Color is three-dimensional, and any color-order system will need to address **hue**, what we instinctively think of as color (e.g., red, blue, green); **value**, which represents lightness and darkness; and **chroma** or **saturation** which indicates intensity. When attempting to verbally describe a color defect or problem, one should attempt to use these three qualities in formulating a color description.

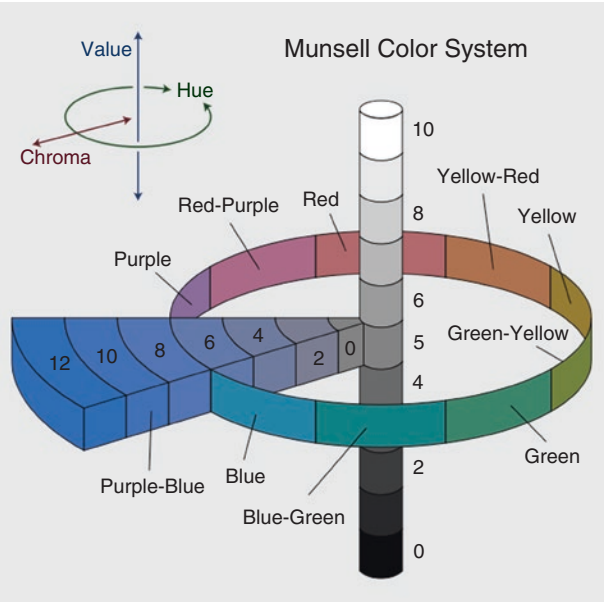
31.3.1 Visual Systems

The **Munsell** system is probably the best known and most widely used visual color-ordering system. It was developed by A.H. Munsell, a Boston art teacher, in 1905. In this system red, yellow, green, blue, and purple plus five adjacent pairs, green yellow, yellow red, red purple, purple blue, and blue green, describe **hue**. **Value** is that quality of color described by lightness and darkness, from white to grey to black. Value is designated from 0 (absolute black) to 10 (absolute white). **Chroma** is that

quality that describes the extent a color differs from a gray of the same value. It is designated in increasing numbers starting with 0 (neutral grey) and extending to /16 or even higher. A change from pink to red is an example of an increase in chroma. In Munsell notation, hue is listed first and designated by a number and letter combination. Numbers run from 1 to 100, and the letters are taken from the ten major hue names, e.g., 10 GY. Value follows with a number from 0 to 10 followed by a slash mark, which is followed by a number for chroma (e.g., 5R 5/10).

One of Munsell's objectives was to develop a system based on equal visual perception, with equal steps of perception for each of the coordinates. For example, the difference in value between 2 and 3 is visually equivalent to the difference between 5 and 6. This visual linearity applies to the other coordinates as well. The Munsell systems' visual linearity undoubtedly contributes to its success and wide popularity in many different fields. Figure 31.5 illustrates the Munsell color system, showing a circle of hues at value 5 and chroma 6, the neutral values from 0 to 10, and the chroma of purple-blue (5PB) at value 5. The ten named hues are shown with additional intermediate hues interspersed. The distance from the core to the edge shows increasing chroma, the maximum chroma differing considerably for different hues (e.g., R5 has a maximum of 12 and yellow has a maximum of 6). Interactive kits that demonstrate the relationships between Munsell hue, value, and chroma are available for purchase [12]. Also available is the Munsell Book of Color with 1,605 colored chips, each with a numerical designation.

Assessing color of foods by visual comparison with color standards is an option for a number of food products. USDA color standards are available for honey, frozen French fried potatoes, peanut butter, and canned ripe olives, for example [12]. This method is simple, convenient, and easy to understand; however, it is subjective.



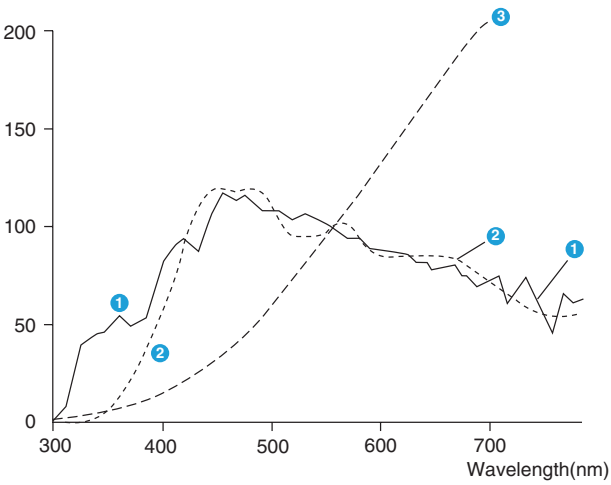
31.5 figure

Diagram of the Munsell color system, showing a circle of hues at value 5 chroma 6, the neutral values from 0 to 10, and the chromas of purple-blue (5PB) at value 5 (Source, Wikipedia: Jacobolus (http://en.wikipedia.org/wiki/User:Jacobolus))

31.3.2 Instrumental Measurement of Color

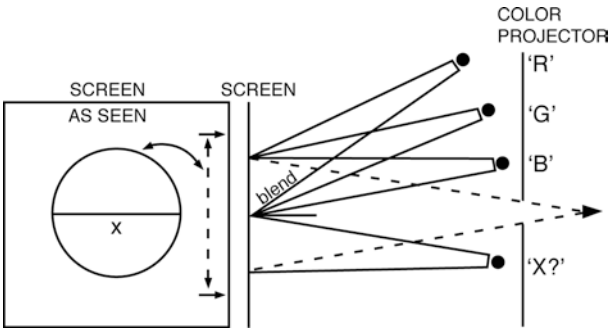
31.3.2.1 *Historical Development*

For a more detailed discussion of the historical development, refer to the 4th edition of this text [14]. The **CIE** (**Commission Internationale de l'Eclairage**, or the **International Commission on Illumination**) is the main international organization concerned with color and color measurement [3]. Standard illuminants for color measurement were first established in 1931 by the CIE. Figure 31.6 shows the spectral power distribution curves of three standard CIE illuminants, A, C, and D_{65}. **Illuminant C** was adopted in 1931 and represents overcast daylight, while **illuminant D_{65}**, which was adopted in 1965, also represents average daylight but includes the ultraviolet wavelength region. **Illuminant A**, adopted in 1931, represents an incandescent light bulb. Objects will appear to have different colors when viewed under illuminants A and C. Because of the



31.6 figure

The spectral power distribution curves of three standard CIE illuminants. Standard illuminant D_{65}, average daylight including ultraviolet wavelength [1]; standard illuminant C, average daylight (not including ultraviolet wavelength region) [2]; and standard illuminant A, incandescent light [3] (Courtesy of Konica Minolta Sensing Americas, Inc., Ramsey, NJ)



31.7 figure

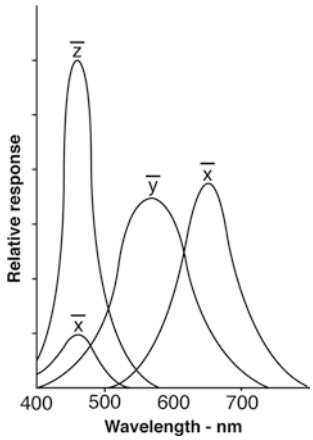
Diagram showing three projectors focused on the upper half of a *circle* on the screen. The color to be measured is projected on the lower half and the eye can see both halves simultaneously

predominance of long wavelength light and lesser amounts of shorter wavelength light of illuminant A, one can predict that objects will appear to have a "warmer" color under illuminant A than under other illuminants. **Metamerism** occurs when two objects appear to have the same color under one light source but exhibit different colors under another source.

Scientists knew that a color sensation could be matched by mixing three colored lights [3]. W.D. Wright in 1928 and J. Guild in 1931 conducted independent experiments in which people with normal color vision visually matched spectral (single wavelength) light by mixing different amounts of three primary lights (red, green, and blue) using rheostats (Fig. 31.7). The process was repeated for test colors covering the entire visible spectrum. The **field of view** for these experiments is described as **2°**, which is similar to viewing a dime at an arm's length. The purpose of these viewing conditions was to have primary involvement of the fovea, the retinal area of greatest visual acuity. The red, green, and blue response factors were averaged and mathematically converted to x, y, and z functions that quantify the red, green, and blue cone sensitivity of the average human observer. The observer functions were standardized and adopted by CIE in 1931 as the **CIE 2° Standard Color Observer**. The standard observer curves provide human sensory response factors that are used in color measurement worldwide (Fig. 31.8). Subsequently it was realized that more realistic data could be obtained from a larger field of view. The experiment was repeated using a 10° field of view and adopted by CIE in 1964 as the **10° Standard Observer**. Both sets of data are used today, but the 10° standard observer is preferable because it better correlates to visual assessments.

31.3.2.2 *The CIE Tristimulus System*

With the adoption of standard observer functions and standard illuminants, it became possible to convert the spectral transmission or reflectance curve of any object to three numerical values. These numbers are known



31.8 figure

Standard observer curves showing the relationship between the *red* (x), *blue* (z), and *green* (y) cone sensitivity and the visible spectrum

as the **CIE tristimulus values**, X, Y, and Z, the amounts of red, green, and blue primaries required to give a color match. The data values for a standard illuminant and the standard observer functions are multiplied by the % reflectance or % transmission values for the object at selected wavelengths. Summation of the products for the wavelengths in the visible spectrum (essentially integrating the areas under the three curves) gives the resulting X, Y, and Z tristimulus values. This can mathematically be represented as follows:

$$X = \int_{380}^{750} RE\bar{x}\,dx \tag{31.1}$$

$$Y = \int_{380}^{750} RE\bar{y}\,dy \tag{31.2}$$

$$Z = \int_{380}^{750} RE\bar{z}\,dz \tag{31.3}$$

where:

R = sample spectrum
E = source light spectrum
$\bar{x}, \bar{y}, \bar{z}$ = standard observer curves.

With the objective of plotting the three coordinates in two dimensions, the CIE converted the X, Y, and Z tristimulus values to x, y, and z coordinates by the following mathematical operation:

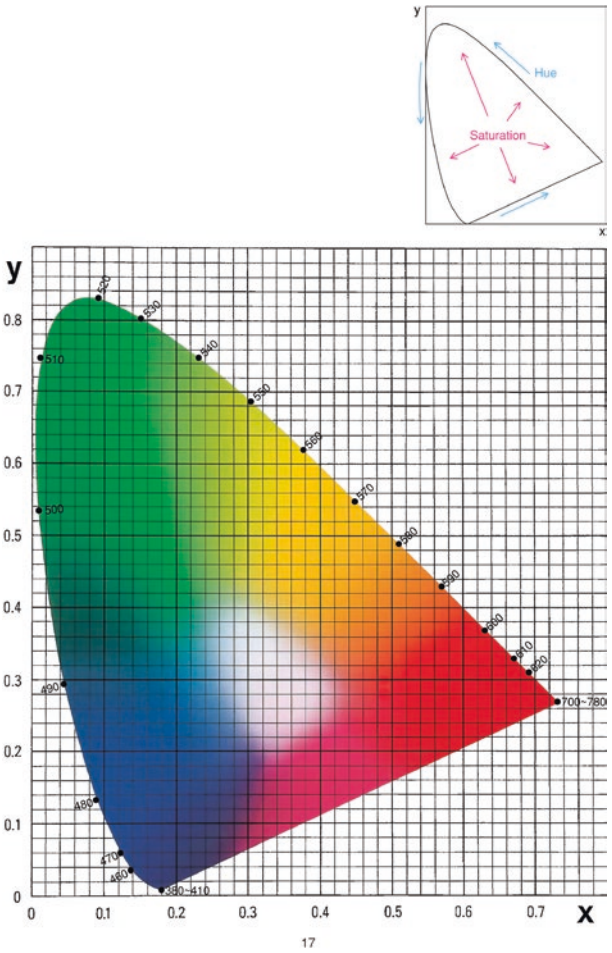
$$x = \frac{X}{X+Y+Z} \tag{31.4}$$

$$y = \frac{Y}{X+Y+Z} \tag{31.5}$$

$$z = \frac{Z}{X+Y+Z} \tag{31.6}$$

Since $x + y + z = 1$, only two coordinates are needed to describe color as $z = 1-(x + y)$.

Figure 31.9 shows the 1931 **chromaticity diagram** where x vs. y are plotted to give the horseshoe-shaped locus. Spectral colors lie around the perimeter and white light (illuminant D_{65}) has the coordinates $x = 0.314$, $y = 0.331$. With the aid of a ruler, a line can be drawn from the coordinates for white light through the object coordinates to the edge, which gives the **dominant wavelength**, λd. Dominant wavelength is analogous to hue in the Munsell system. The distance from the white light coordinates to the object coordinates, relative to the distance from the white light coordinates to λ_d, is described as % **purity** and is analogous to chroma in the Munsell system. The standard observer curve for y (green) shown in Fig. 31.8 is very similar to the sensitivity curve for human photopic vision shown in Fig. 31.3. Because of this, tristimulus value Y is known as **luminosity** and is analogous to value in the Munsell system.



31.9 figure

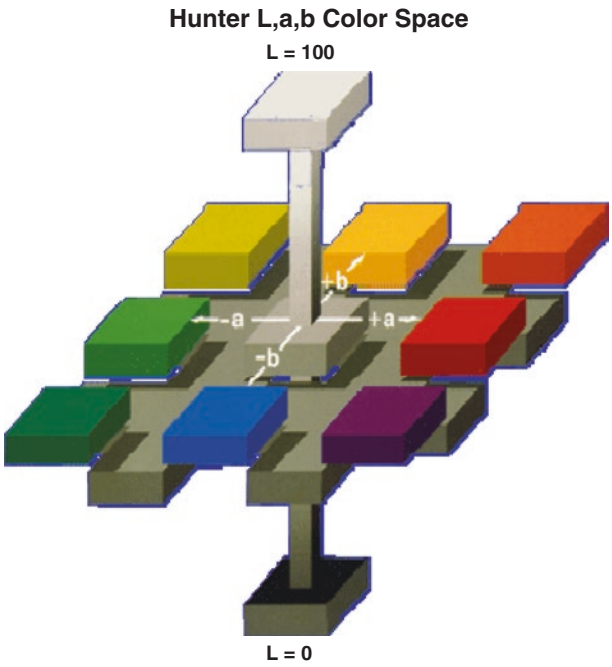
The 1931 x, y chromaticity diagram (Courtesy of Konica Minolta Sensing Americas, Inc., Ramsey, NJ)

Manual calculation of XYZ tristimulus values from reflectance/transmission spectra is a tedious operation. Modern colorimetric spectrophotometers measure the light reflected or transmitted from an object, and the data are sent to a processor where it is multiplied by standard illuminant and standard observer functions to give the XYZ tristimulus values. Since objects with identical XYZ tristimulus values will provide a color match, they find application in the paper, paint, and textile industries. Unfortunately, the XYZ numbers do not easily relate to observed color, and they have the limitation of not having equivalent visual spacing. [Referral to Fig. 31.9 reveals that the wavelength spacing in the green region (500–540 nm) is much larger than that in the red (600–700 nm) or blue (380–480 nm) regions.] The same numerical color differences between colors will not equate to the same visual difference for all colors. This is a severe limitation in measurement of color of food products, as major interest is in how food product color deviates from a standard or changes during processing and storage. Statistical analysis of color data for which numerical units were nonequivalent would be problematic.

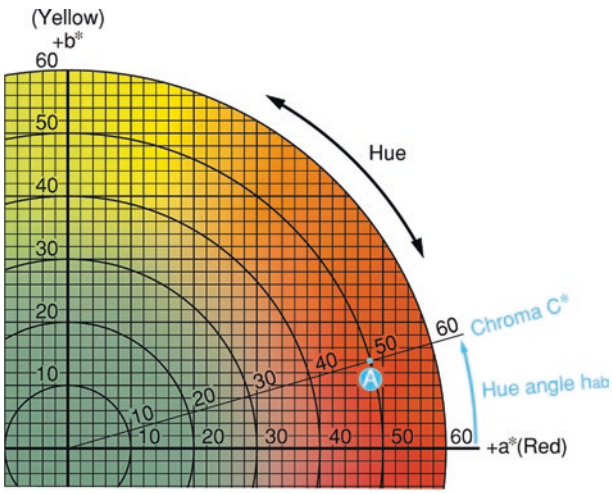
31.3.3 Tristimulus Colorimeters and Color Spaces

Richard S. Hunter, Deane B. Judd, and Henry A. Gardner were among the pioneering scientists who in the 1940s were working to develop color-measuring instruments that would overcome the disadvantages of the CIE spectrophotometric tristimulus system [2, 5, 6]. Light sources that were similar to illuminant C were used, along with filter systems that approximated the sensitivity of the cones in the human eye. Empirical approaches were taken to get more equivalent visual spacing. In an effort to get numerical values that better related to observed color, a system that applied the color opponent theory of color perception was developed [3].

The **Hunter color solid** (Fig. 31.10) was first published in 1942 where L indicated **lightness**; a, the **red** (+) or **green** (−) coordinate; and b, the **yellow** (+) or **blue** (−) coordinate. The **Hunter L a b color space** has been widely adopted by the food industry. It is very effective for measuring color differences. The *Lab* system was subsequently improved to give more uniform color spacing. In 1976, the CIE officially adopted the modified system as **CIELAB** with the parameters $L^*a^*b^*$. L^* indicates **lightness** (0–100) with 0 being black and 100 being white. The coordinate a^* is for **red** (+) and **green** (−), and b^* is for **yellow** (+) and **blue** (−). The limits for a^* and b^* are approximately + or − 80. Figure 31.11 shows a portion of the a^*, b^* chromaticity diagram where a^* and b^* are both positive, representing a color range from red to yellow. Point A



31.10 figure The Hunter *L*, *a*, *b* color solid (Courtesy of HunterLab, Reston, VA)



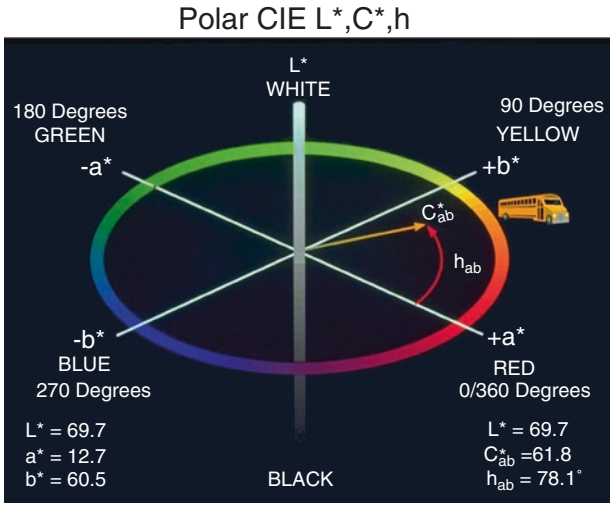
$$\text{Chroma } C^* = \sqrt{(a^*)^2 + (b^*)^2}$$

$$\text{Hue angle } h_{ab} = \tan^{-1}\left\{\frac{b^*}{a^*}\right\}$$

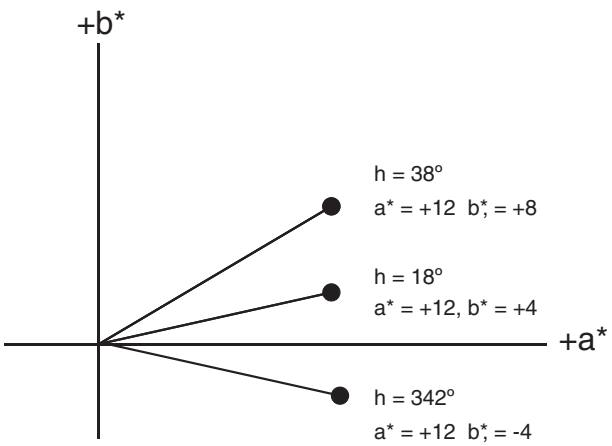
31.11 figure A portion of an *a**, *b** chromaticity diagram showing the position A for a red apple (Courtesy of Konica Minolta Sensing Americas, Inc., Ramsey, NJ)

is the plot of *a** and *b** for a red apple. The angle from the start of the $+a^*$ axis to point A can be calculated as **arctan** b^*/a^* and is known as **hue angle**, h or H^*. The distance from the center to point A is **chroma**, which is calculated as the hypotenuse of the right triangle formed by the origin and the values of coordinates a and b. $\left(a^{*2} + b^{*2}\right)^{1/2} = C^*$.

The CIE has also recommended adoption of this color scale known as **CIELCH** or ***L*C*H*****. This color space (which is illustrated in Fig. 31.12) designates hue (*H**) as one of the three dimensions, the other two being lightness (*L**) and chroma (*C**), which have an obvious parallel to Munsell hue, value, and chroma. This color space is advantageous as hue is most critical to humans with normal color vision for perception and acceptability. In this system, 0° represents red, 90°—yellow, 180°—green, and 270°—blue. Figure 31.13 shows plots of *a** and *b** for three hypothetical objects



31.12 figure The CIE *L*C*H** color space showing the location of "school bus yellow" (Courtesy of HunterLab, Reston, VA)



31.13 figure Plots of *a**and *b** for three hypothetical samples

having the following a^*b^* coordinates: $a^* = +12$ and $b^* = +8$; $a^* = +12$ and $b^* = +4$; $a^* = +12$ and $b^* = -4$. While all objects have identical a^* values, their colors range from purplish red ($H^* = 342°$) to red ($H^* = 18°$) to orange ($H^* = 34°$). A common error in interpretation of color measurements is to use only the coordinate a^* as a measure of "redness." Monitoring color change is more understandable if one measures lightness (L^*), hue angle (H^* from 0 to 360°), and chroma. Chroma will increase with increasing pigment concentration and then decrease as the sample becomes darker. Thus, it is possible for one light and one dark sample to have the same hue angle and the same chroma. They will readily be distinguished, however, because of their different L^* values.

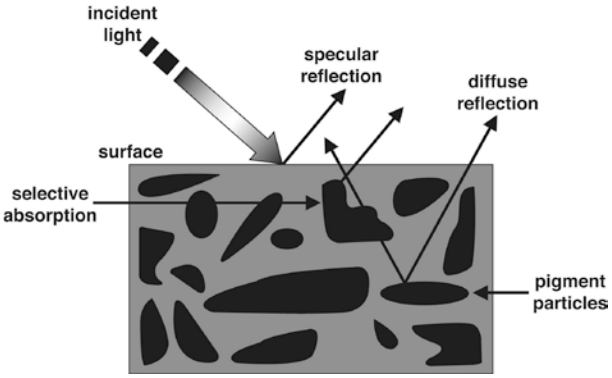
The colorimeters that are available in the market today have vastly improved from earlier models with respect to stability, ruggedness, and ease of use. There are handheld instruments that are portable for use in the field, online instruments for process control, and specialized colorimeters for specific commodities. They vary with respect to operating in transmission or reflectance mode and size of sample viewing area. Colorimeters have a high degree of precision, but do not have a high degree of accuracy with respect to identifying or matching colors. Most colorimeters used in research are color spectrophotometers with a diffraction grating for scanning the visible spectrum, with the data being sent to a microprocessor for conversion of reflectance or transmission data to tristimulus numbers. In operating the instrument, choices must be made as to **illuminant, viewing angle** (2° or 10°), and data presentation as **XYZ**, ***Lab***, **CIEL*a*b***, or $L^*C^*H^*$. Illuminant D_{65}, 10° viewing angle, and $L^*C^*H^*$ are appropriate for most food applications. It should be obvious that different numbers will be obtained with different illuminants, viewing angles, and color scales. It is critical that the illuminant, viewing angle, and color scale used in color measurement be specified in technical reports and research publications.

31.4 PRACTICAL CONSIDERATIONS IN COLOR MEASUREMENT

Choice of an appropriate instrument, sample preparation, sample presentation, and handling of data are issues that must be dealt with in color measurement.

31.4.1 Interaction of Light with Sample

When a sample is illuminated with light, a number of things occur that are illustrated in Fig. 31.14. Light for which the angle of reflection is equal to the angle of incidence is described as **specular light**. Smooth polished surfaces will appear **glossy** because of the high degree of **specular reflection**. Rough surfaces will have a great deal of **diffuse reflection** and will have a dull or **matte** appearance. Selective absorption of light will result in the appearance of color. **Opaque** samples will **reflect** light. **Transparent** samples will primarily **transmit** light, and **translucent** samples will both **reflect** and **transmit** light. Ideal samples for color measurement will be flat, smooth, uniform, matte, and either opaque or transparent. A brick of colored Cheddar cheese is one of the few food examples that come close to having those characteristics.



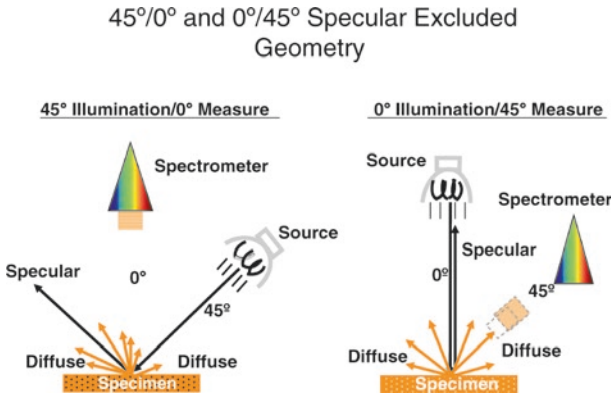
31.14 figure Interaction of light with an object (From Loughry [4], used with permission)

31.4.2 Instrument Choice

Instrument geometry refers to the **arrangement of light source**, **sample placement**, and **detector**. The CIE recognizes the following instrument geometries: **45°/0°** where the specimen is illuminated at 45° and measured at 0° and, the inverse, **0°/45°** where the specimen is illuminated at 0° and measured at 45°. Diffuse reflectance is measured since specular light is excluded. These are illustrated in Fig. 31.15. **Diffuse sphere geometry** is the third type where a white-coated sphere is used to illuminate a sample. With some sphere geometry instruments, measurements can either include or exclude specular reflectance. These instruments are versatile in that they can measure in transmission for transparent samples and in reflectance for opaque samples. Some can also measure the amount of light scattering, turbidity or haze in liquid samples, and the amount of gloss in solid samples. Instruments with 45°/0° and 0°/45° geometries can only measure reflectance.

31.4.3 Color Difference Equations and Color Tolerances

When colorimeter measurements are conducted under carefully controlled conditions, data with a high degree of precision can be obtained. In both industrial and research applications, the interest is primarily in how color dimensions deviate from a standard



31.15 figure CIE standardized geometries for 45°/0° and 0°/45° instruments (Courtesy of HunterLab, Reston, VA)

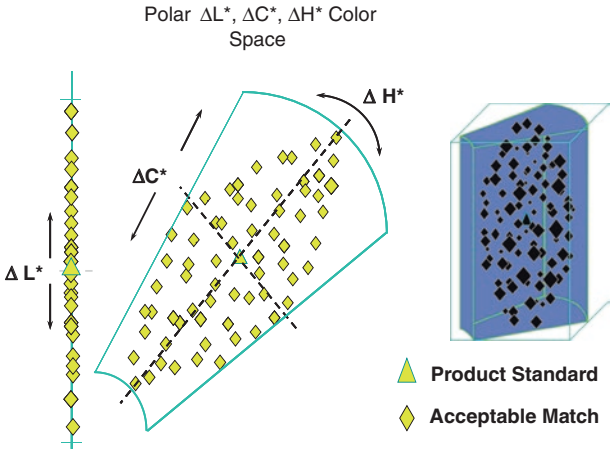
or how they change from batch to batch, year to year, or during processing and storage. Color differences are calculated by subtracting $L^*a^*b^*$ and $L^*C^*H^*$ values for the sample from the standard, e.g.,

Delta L* = $L^*_{sample} - L^*_{standard}$. Positive ΔL^* numbers will be lighter than the standard, and negative ΔL^* numbers will be darker.
Delta a* = $a^*_{sample} - a^*_{standard}$. Positive Δa^* numbers will be more "red" (or less "green") than the standard, and negative Δa^* numbers will be more "green" (or less "red").
Delta b* = $b^*_{sample} - b^*_{standard}$. Positive Δb^* numbers will be more "yellow" (or less "blue"), and negative Δb^* numbers will be more "blue" (or less "yellow").
Delta C* = $C^*_{sample} - C^*_{standard}$. Positive ΔC^* numbers mean the sample has greater intensity or is more saturated, and negative ΔC^* numbers mean that the sample is less saturated.
Delta H* = $H^*_{sample} - H^*_{standard}$. Positive H^* numbers indicate the hue angle is in the counterclockwise direction from the standard, and negative numbers are in the clockwise direction. If the standard has a hue angle of 90°, a positive ΔH^* is a shift in the green direction, and a negative ΔH^* number is a shift in the red direction.

A single number is often desired in industry for establishing pass/fail acceptability limits. **Total color difference** (ΔE^*) is calculated by the following equation:

$$\Delta E^* = \left(\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}\right)^{1/2} \qquad (31.7)$$

A limitation of ΔE^* is that the single number will only indicate the magnitude of color difference, not the direction. Samples with identical ΔE^* numbers will not necessarily have the same visual appearance.



31.16 figure Diagram showing acceptable ΔL^*, ΔC^*, ΔH^* tolerance limits for a product (Courtesy of HunterLab, Reston VA)

In establishing color tolerances, ΔL^*, ΔC^*, and ΔH^* numbers are preferred since they correlate well with visual appearance. A diagram showing acceptable tolerances based on ΔL^*, ΔC^*, and ΔH^* numbers is shown in Fig. 31.16. The elliptical shape of the solid arises since tolerances for ΔH^* are considerably narrower than for ΔC^* and ΔL^*.

31.4.4 Sample Preparation and Presentation

For color measurement data to be at all useful, the numbers must be consistent and repeatable. Sampling of product must be done so that it is representative of the product and prepared so that it represents the product's color characteristics. Many food samples are far from ideal in that they may be partially transmitting and partially reflecting. Rather than being uniform, they may be mottled or highly variable in color. The number of readings that need to be taken for acceptable repeatability is dependent on the nature of the sample. Another problem is that often the only instrument available is one that is less than ideal for the sample. Gordon Leggett [15] provides some practical tips and a systematic protocol for consistent color measurement of different food categories. Transparent liquids should be measured with a sphere instrument, using a clear glass or plastic cell. A cell filled with distilled water can be used as a blank to negate the effects of cell and solvent. Cell path length is selected based on color intensity. A 20 mm cell is used for most colored liquids, with 10 mm cells for highly absorbing liquids. A very thin 2 mm cell may be appropriate for highly absorbent transparent liquids such as soy sauce. For nearly colorless liquids, a 50 mm cell may be necessary. For clear transparent liquids, a single measurement using a viewing area of 15 mm diameter or greater may be sufficient for good repeatability.

For hazy transparent liquids, two to four readings with replacement of the liquid between readings is necessary to get acceptable repeatability when using a 10 mm path length cell and a sphere instrument.

Liquid samples with high solids are translucent rather than transparent. They can be measured by transmission using a very thin 2 mm path length cell, or measured in reflectance. Here it is necessary to control the thickness of the sample so that it is effectively opaque. Solid foods vary with respect to size, geometry, and uniformity. With some colorimeters, reflectance measurements can be taken directly on the sample. Ideally the surface should be flat. Readings of an apple or orange may be distorted because of the "pillowing" effect, which is a result of the distorted reflectance values from the uneven surface. Pureeing nonuniform materials such as strawberries will give a uniform sample; however, the incorporation of air renders a color extremely different from the sample of interest. For opaque foods, instruments with 45*/0° and 0°/45° geometries are recommended as the measurements correlate better with visual assessment than those obtained with sphere instruments. Instruments with a large area of view, e.g., 25–50 mm, are helpful for area-averaging nonuniform color. For powders, two readings with replacement of the powder between readings may be sufficient, but for flakes, chunks, and large particulates, a large field of view (40 mm or larger) with three to six readings and sample replacement between readings is recommended.

Different commodities present their own peculiarities when it comes to measuring color and appearance. In the proceedings of an American Chemical Society symposium [16], various authors discuss methodology for color measurement of meat, fish, wine, beer, and several fruits and vegetables.

31.5 SUMMARY

Color is three-dimensional, and any color-ordering or color-measuring system needs to address that fact. The Munsell system is a visual system that designates color in terms of hue, value, and chroma. Each of these dimensions has equivalent visual spacing, which is advantageous. The physiology of color vision has been long understood, and it provided the necessary background information for development of the CIE tristimulus system. Standardization of illuminants and experiments using humans with normal color version was necessary to develop color-matching functions that corresponded to the color sensitivity of the human eye. The system permits calculation of numerical *XYZ* tristimulus values that can accurately represent a color and are useful in color matching. The system does not have equivalent visual spacing, which is a disadvantage when measuring how a sample differs from a standard or changes during processing and storage. Color-order systems have been developed that are more suitable for measuring color differences. These include the Hunter*Lab* system, the *CIEL*a*b** system, and the *L*C*H** system. The latter two systems are recommended by the CIE, the International Association with responsibility for standardization and measurement of light. They have been widely adopted by the food industry for color measurement. There are many colorimeters available for industrial and research applications that are rugged, easy to standardize, and user friendly. They vary with respect to presentation of sample, size of viewing area, portability, and the ability to measure by transmittance or reflectance. Many food samples are less than ideal for color measurements because they may be partial transmitting and partial reflecting, nonuniform, and of varying size and shape. A number of factors need to be considered with respect to sample preparation and presentation to get measurements that are repeatable and that correspond to visual appearance.

There are a number of excellent illustrative tutorials dealing with color measurement that are available on various websites that have been developed by organizations and commercial companies. The following are recommended: HunterLab [17], Konica Minolta [18], CIE [19], Munsell [20], Color Models Technical Guides [21], A Review of RGB Color Spaces [22], and Beer Color Laboratories [23].

31.6 STUDY QUESTIONS

1. Dominant wavelength (λ_d), % purity, and luminosity (Y) in the CIE *XYZ* system correspond to what indices in the Munsell system? In the CIE *L*C*H** system?
2. Using a calculator, determine hue angle and chroma for the following sets of *a**, *b** data: *a** = +12 and *b** = +8, *a** = +12 and *b** = +4, and *a** = 12 and *b** = -4.
3. If one wants to use a colorimeter to measure of the amount of browning in maple syrup, what indices would you expect to correspond well with visual assessment?
4. How variable is human color perception when compared with that of taste and smell? What are the human capabilities for color perception and color memory?
5. Why is CIE tristimulus Y used as a measure of luminosity?
6. Give examples where it is appropriate to use a colorimeter with diffuse sphere geometry and, conversely, a colorimeter with 0°/45° reflectance geometry.
7. How can you determine how many readings should be taken for a given sample?

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