An Introduction to Appearance Analysis

by Richard W. Harold

Printers and graphic arts service providers who deal daily with such practices as color correcting images, "matching" proofs and press sheets, controlling register, or using densitometers, spectrophotometers, or profiles and color management are already familiar with the concept of appearance analysis. They are also familiar with that very subjective aspect of appearance analysis that comes from a customer who says, "Well, it just doesn't look right to me."

While the judgment of a product's appearance inevitably includes subjective opinion and contextual issues, an element of science, technology, and numbers and measurements also applies, especially when it comes to color and the factors that affect it. And that is what author Richard Harold clarifies in this article. Harold, who has been involved with appearance analysis for over 30 years and with GATF for two years, first describes the interaction of light with objects, which results in the human perception of appearance. He then goes on to connect this perception to the instruments and measurements that have been developed to analyze appearance attributes.

The appearance of an object is the result of a complex interaction of the light incident on the object, the optical characteristics of the object, and human perception. Given that manufactured products are meant to fulfill an intended purpose, their appearance is one of their most important commercial attributes. Appearance often determines the acceptability of a product to its seller, and ultimately to the consumer or end-user. The quality of a product's appearance is psychologically related to its expected performance and useful life. It therefore determines its reception (or rejection) by potential purchasers.

All manufacturing industries are concerned with the appearance of their products. Appearance involves all visual phenomena such as color, gloss, shape, texture, shininess, haze, and translucency that characterize objects. All other things being equal, when consumers have a choice, they buy what looks best. Appearance is the foremost and most impressive product message.

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Buyers also expect uniformity of appearance in any group of the same product. When consumers see a difference among the same products on display, that difference is associated with poor quality or out-of-date packaging. Visual appeal and uniformity of appearance have such importance that quantitative identifications of appearance are demanded by every marketplace.

Durability and resistance to fading or degradation are also important factors when considering the expected life of a product. Subjective comments about light fastness and durability are often looked upon with great skepticism, but standardized testing procedures and quantitative measurements before and after exposure testing can serve as a basis for comparison and help educated consumers make more informed purchase decisions.

The behavior of light interacting with products such as inks, paints, coatings, papers, textiles, plastics, metals, ceramics, pharmaceuticals, cosmetics, and food varies depending on many physical characteristics. Using the right instrumentation and problem-solving techniques, it is possible to measure the distinctive appearance attributes of a wide variety of products.

Interaction of Objects and Materials

While light sources are visible by their own emitted light, objects and materials appear to the eye according to how they affect the light that falls on them (incident light). The objects or materials may be a printed surface, a sheet of paper, an apple, or any of a great variety of different things.

Light (Figure 1) is defined as visually evaluated radiant energy of wavelengths from about 380 to 770 nm.

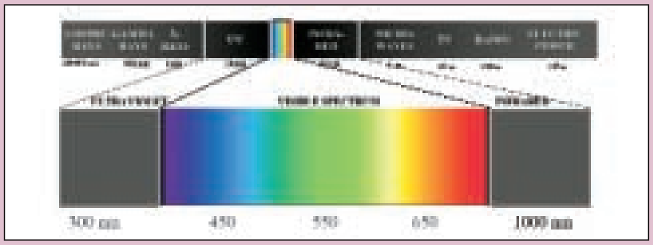


Figure 1. The electromagnetic spectrum. Our eyes are sensitive to a limited range of the electromagnetic spectrum, the wavelengths from about 380 to 780 nm, which contain all the colors we know.

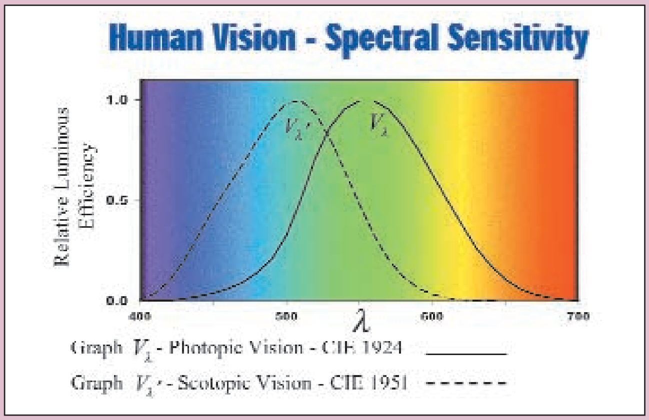


Figure 2. Relative spectral sensitivity of human vision. We see light in the yellow-green portion of the spectrum around 550 nm much more easily than elsewhere. The 1924 Photopic Vision curve represents the eye's sensitivity under daylight viewing conditions. The 1951 Scotopic Vision curve shows nighttime vision sensitivity with a shift toward the blue end of the spectrum.

Different wavelengths have different colors, and some wavelengths are visibly more intense than others. The eye's varying response to the same amount of energy at different wavelengths can be represented by the luminosity curve of the human eye (Figure 2). These graphical representations, known as "spectral curves," can describe the amount of light or radiation at each wavelength, or our response to it, as in the luminosity curve.

Light can be produced by heating objects (e.g., the filament in a light bulb) to incandescence or by the excitation of atoms and molecules (e.g., when the heating coil in a electric stove begins to glow red). Fluorescence, where light is converted from one spectral region to another, is a special case.

A completely radiating source, called a "blackbody radiator," can be used as a reference standard for identifying the color of incandescent light sources. The correlated color temperature (CCT) of a light source is the temperature of a blackbody radiator visually closest to the appearance of the light source. For example, a typical incandescent (tungsten filament) lamp would have a CCT of about 2856 K.

Although the appearance of materials, including printed ones, results from very complex factors, the problem can be simplified for analysis by separating chromatic (color) attributes from geometric (gloss, haze, texture, etc.) attributes, and by separating diffuse from specular light distributions. With the help of this breakdown, it is possible to identify nearly any attribute and prescribe the measuring instrument and techniques needed to analyze it.

The light striking an object will be affected by its interaction with the object in several ways. The light distributions (types of reflection or transmission) that result after light strikes an object give us our impressions of what the object looks like. Specular reflection, for example, makes an object look glossy or shiny. Metals are usually distinguished by stronger specular reflection than that from other materials, and smooth surfaces are always shinier than rough ones.

Geometric Attributes of Appearance

Unlike color, the geometric attributes of appearance, often associated with surface properties, cannot be completely defined in any simple coordinate arrangement. Fortunately, if only relatively flat, uniform, surface areas and over-simplified specular and diffuse distributions of light are considered, some meaningful simplification of geometric attributes is possible.

First, light may be characterized as reflected or transmitted by an object. Reflected light is light that rebounds from an illuminated surface. Transmitted light is light that passes through the object and is viewed from the exit side. Transmitted and reflected light may each be further divided into diffused and undiffused light, giving four main kinds of light distribution from objects: diffuse reflection, specular reflection, diffuse transmission, and regular transmission (see Figure 3). This separation into diffuse and specular components provides a good approximation (adequate for many analyses) of the geometric distribution of reflected or transmitted light.

Selective absorption of certain wavelengths is what results in our perception of color. When absorption is the dominant process, the resulting colors are not intense. If all wavelengths are absorbed, black results. And if all wavelengths are reflected, white results.

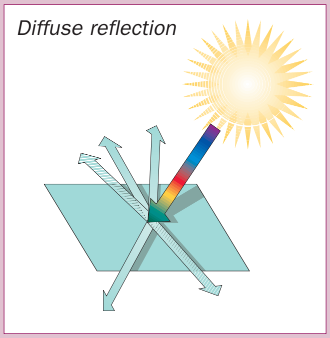
All the following processes operate on the majority of objects:

- Specular (shiny) reflection
- Diffuse reflection
- Regular transmission
- Diffuse transmission by scattering, and absorption.

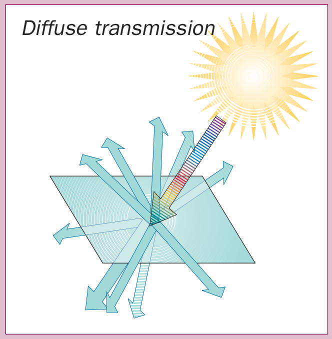
Physical analyses of the combined results of these processes are made using measurements from spectrophotometers and goniophotometers (see Figure 4).

Spectrophotometric curves are a measure of the reflection or transmission of light, wavelength by wavelength, over the visible spectrum.

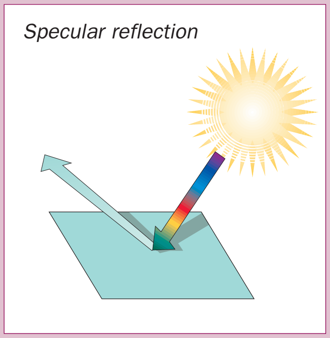
Figure 3. Types of light reflection and transmission.



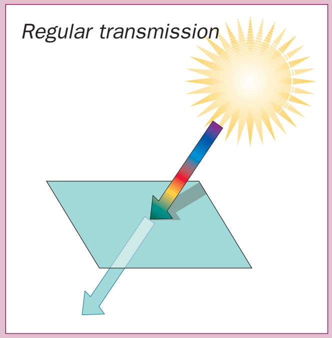
Diffuse reflection is characteristic of light that is redirected (scattered) over a range of angles from a surface on which it is incident. Diffuse reflection accounts for more of the color than any other type of distribution because most objects are opaque and reflect light diffusely.



Diffuse transmission occurs when light penetrates an object, scatters, and emerges diffusely on the other side. As with diffusely reflected light, diffusely transmitted light leaves the object surface in all directions. Diffuse transmission is seen visually as cloudiness, haze or translucency, each of which is of interest in appearance measurement.



Specular reflection is reflection as from a mirror. It is highly directional instead of diffuse, and the angle of reflection is the same as the angle of the incident light striking the object. Specular reflection is what gives objects a glossy or mirrorlike appearance. There are a variety of ways to assess or "see" this glossy appearance.



Regular transmission refers to light passing through an object without diffusion. Regular transmission measurements are widely used in chemical analysis and color measurement of liquids. Potential appearance attributes important for regular transmission should be roughly analogous with gloss attributes associated with specular reflection.

Spectral curves thus relate to color and can be used to help identify the component dyes or pigments used to produce the color.

Goniophotometric curves describe how light is reflected from or transmitted through objects as a function of varying angles, and they relate to geometric attributes such as gloss and haze. Although spectrophotometric and goniophotometric measurements do not provide conclusive values describing appearance, they quantify the light-object interaction part of the observing situation.

Chromatic Attributes of Appearance

The Physics of Color

Color is associated with light waves, specifically, their wavelength distributions. These distributions are most often referred to as the spectrophotometric characteristics. Visible wavelengths are those between the violet and red ends of the spectrum, near 400 and 700 nm, respectively (see Figure 1). The selective absorption of different amounts of the wavelengths within these limits ordinarily determines the colors of objects. Wavelengths not absorbed are reflected or transmitted (scattered) by objects and thus visible to observers. In other

Figure 4. Instruments used for physical analysis of light reflection and transmission. The goniophotometer (left) measures light scatter as a function of variable angles of illumination or observation. This instrument is useful for studies of gloss, luster, surface smoothness (or roughness), haze, and distinctness of image. A spectrophotometer measures and analyzes the reflected light from a surface wavelength by wavelength as a means of determining the color of that surface. The unit shown here (right) is an automated scanning spectrophotometer that measures both reflected and transmitted light. Handheld spectrophotometers about the size of densitometers are also available.

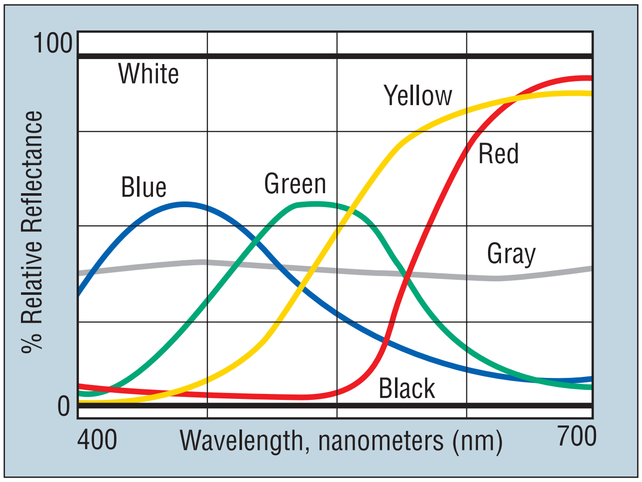


Figure 5. Spectrophotometric curves for some typical colored surfaces. The white, gray, and black curves are nearly horizontal lines, while each of the curves representing a chromatic color is highest in the part of the spectrum associated with that color.

words, yellow objects characteristically absorb blue light; red objects absorb green light, and so on.

Physically, the color of an object is measured and represented by spectrophotometric curves, which are plots of fractions of incident light (that is reflected or transmitted) as a function of wavelength throughout the visible spectrum relative to a reference. The typical reference is a white standard that has been calibrated relative to the perfect white reflecting diffuser (100% reflectance at all wavelengths). Figure 5 shows spectrophotometric curves for some typical colored surfaces.

The white, gray, and black curves are nearly straight, horizontal lines at the top, middle, and bottom of the graph, respectively, while each of the curves representing chromatic colors is highest in that part of the spectrum associated with that color (i.e., light that is scattered) and drops to lower values at other wavelengths (i.e., light that is absorbed).

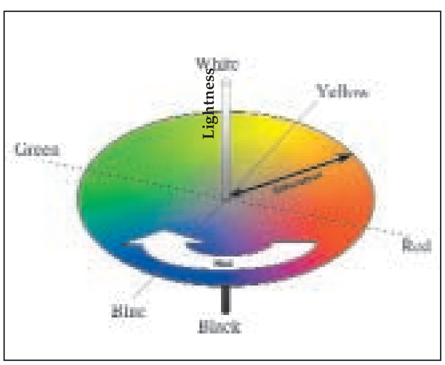


Figure 6. How hue, saturation, and lightness are related to each other in a three-dimensional color system.

Physiology of Color

Psychologically and physiologically, color is a perception in the brain, resulting from signals brought to it by light receptors in the eyes. The color of any material results from the effect that the pigments, dyes, or other absorbing materials in the perceived object have on light. The eye does not see wavelength analyses, such as the curves in Figure 5; rather, it synthesizes the responses of three color receptors (for red, green, and blue light) in the eye. A skilled colorimetrist can estimate from curves, such as those in Figure 5, what a specimen's color will look like, but an unskilled person cannot.

Attributes of Color As Seen by an Observer

What an artist sees when examining a color is neither its spectrophotometric curve nor the separate responses of the eye's red, green, and blue light receptors. If asked to identify the color of an object, the artist will speak first of its hue. Hue is the attribute that corresponds to whether the object is red, orange, yellow, green, blue, or violet. This attribute is often related to the hue circle, which has been recognized by artists, color technologists, and decorators for years.

A second attribute of color, and a readily appreciated one, is saturation. Saturation is determined by how far from the gray (lightness) axis toward the pure hue at the outer edge that a color is perceived to be. A pastel tint, for example, is said to have a low saturation while a pure color is said to have high saturation.

A third attribute or dimension of color is associated with an object's luminous intensity (usually light-reflecting or transmitting capacity). This attribute is variously called lightness, value, and sometimes, although incorrectly, "brightness."

The three attributes of an object's color, then, are hue, saturation, and lightness. They are related to each other as shown in Figure 6. One of the best-known surface-color systems is the Munsell System of Color Notation illustrated in Figure 7. In this system, the three visually perceived dimensions of color appearance are designated as hue, value (lightness), and chroma (saturation). In color communication, particularly when discussing color differences, lightness, chroma and hue (LCH) are the most frequently used terms.

Illuminants

The light source (the illuminant) will affect the perception of color. Both natural daylight and artificial simulated daylight are commonly used for visually examining the color difference between materials. A window facing north (to be free of direct sunshine) is the natural illuminant normally employed. Artists are known for their preference for studios with "north" light. However, natural daylight varies greatly in spectral quality with time of day, weather conditions, direction of view, time of year, and geographical location. Because of this variability, the trend in industrial testing has been toward using a simulated daylight source that can be standardized and remain relatively stable in spectral quality.

In order to define the artificial light sources used in appearance evaluation, the Commission Internationale de l'Eclairage (CIE) established standard illuminants, which have spectral characteristics similar to natural light sources and are reproducible in the laboratory (CIE, 1931): Illuminant A defines light typical of that from an

Figure 7. The Munsell system of color notation.

incandescent lamp, Illuminant B represents direct sunlight, and Illuminant C represents average daylight from the total sky. See Figure 8 for examples of some CIE illuminants.

In 1963 a "D" series of illuminants was proposed to the CIE and later adopted. The D Illuminants represent daylight more completely and accurately than do Illuminants B and C because the spectral distributions for the D Illuminants have been defined across the ultraviolet (UV), visible, and near-infrared (IR) wavelengths (300–830 nm).

The D Illuminants are usually identified by the first two digits of their correlated color temperature (CCT); for example, D_{65} represents average daylight with a CCT of 6504 K. Most industries now specify Illuminant D_{65} when "daylight" is required for visual evaluations and color measurement. The only exception is the graphic arts industry, which specifies Illuminant D_{50} (5000 K) for prints and transparencies because it is more spectrally balanced across the entire visible spectrum. The low-temperature light emitted by a candle, for example, is weighted to longer wavelengths (mainly reds and yellows). It is difficult to judge blue and violet colors by candlelight.

Within recent years, interest in the UV content of any illuminants used for visual evaluation and color measurement has increased. The major reason is an increase in the commercial use, chiefly in papers and textiles, of fluorescent whitening agents (FWAs) that are activated by UV light. For the proper visual examination and color measurement of these materials, it is necessary to control not only the visible but also the UV energy that impinges upon them.

Color Measurement Scales

CIE Standard Observer

Scientific color measurement is based on numerical representations or quantifications of the three color-response mechanisms in the human eye. The response of the light receptors in the eye to different wavelengths of light is widely known. In order to make measurements that correspond to the way the eye sees color, specific numerical values for the responses of the average human eye to different wavelengths of light are required.

The delineation of the three color-matching response functions of the human observer is called the 1931 CIE Standard Observer (also known as the 2° Observer). This international standard can also be shown as a table of weighting factors from which a specification of color by CIE X, Y, Z tristimulus values can be derived. The 2° Observer is intended to be used when viewing smaller samples (typical of printed materials) that create an angle of view at the eye between about 1° and less than about 4° (similar to looking at an object through a small hole about the size of a U.S. dime).

In 1960, the CIE proposed a 10° Supplementary Standard Observer (see Figure 9) in an effort to obtain a better correlation with commercial judgments when viewing larger samples with larger fields of view (e.g., when viewing a pair of painted test panels that are 4 in. [100 mm] square). The functions finally adopted in 1964 give more weight to the shorter wavelengths and are believed to more adequately represent the object-color response function of human observers. Using the 10° Observer is recommended whenever the pairs of specimens being viewed create an angle subtended at the eye greater than about 4°. Imagine drawing two lines to your eye from the opposite sides of the samples being examined. That conical dimension would probably be larger than 4° for most of the larger sized samples typically evaluated for paints, plastics, etc.

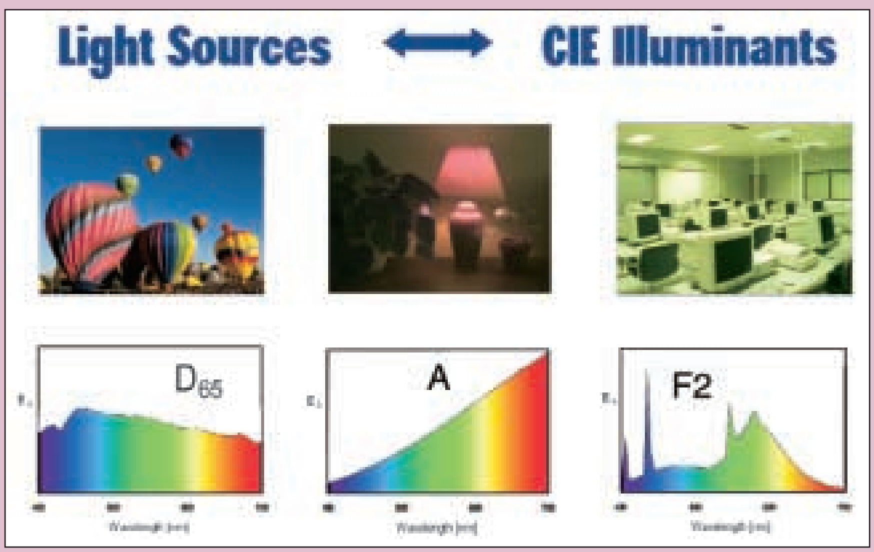


Figure 8. Examples of illumination along with graphs showing the spectral power distributions (SPDs) of the related CIE-designated Illuminants: D_{65} – average daylight, A – incandescent light, and F2 – cool white fluorescent light. Because different illuminants affect our perception of color, it is important to use standard viewing conditions (see Refs. 10–12) and a viewing booth when judging printed color.

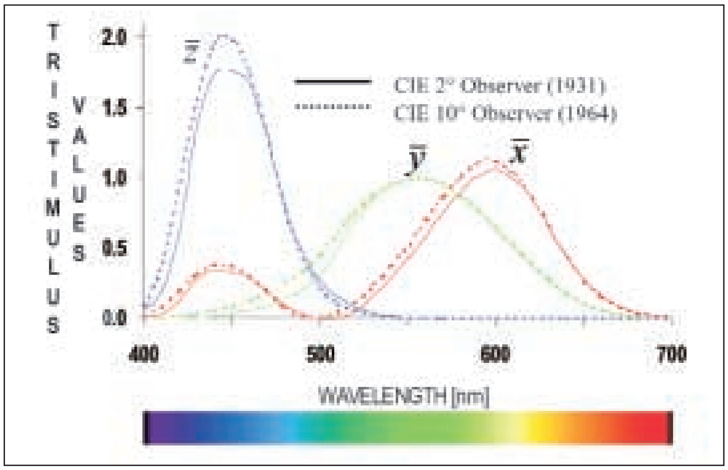


Figure 9. Comparison of CIE 2° and 10° Standard Observer.

Opponent-Colors (L, a, b-type) Color Scales

Because the CIE scales do not provide even reasonably uniform estimates of perceived color differences or color and relationships, scientists have developed so-called uniform color scales. Most, although not all, are opponent-colors (L,a,b-type) scales.

The opponent-colors theory of color vision had its beginnings with Thomas Young in 1807, Hermann Von Helmholtz in 1857, and Ewald Hering in 1878. It was refined in 1930 by G.E. Müeller, and since then, those who have applied Müeller's principles have created several highly useful techniques.

The opponent-colors theory presumes that, in the human eye, there is an intermediate signal-switching stage between when the light receptors in the retina receive color signals and when the optic nerve takes those color signals to the brain (see Figure 10). During this switching stage, it is presumed that red responses are compared with green to generate a red-to-green color dimension. The green response (or red and green together, depending on the theory) is compared in a similar manner with the blue to generate a yellow-to-blue dimension. These two dimensions are widely, although not always, associated with the symbols "a" and "b," respectively. The necessary third dimension, "L" for lightness, is a nonlinear function such as the square or cube root of the CIE Y value, which is percent reflectance (or transmission).

The scientific validity of the opponent-colors system is strongly supported by experimental evidence. For example, in 1966 Russell L. De Valois of the Primate Vision Laboratory at the University of California (Berkeley) attached electrodes to individual optic nerve fibers of monkeys and identified L, a, and b correlating signals, rather than X, Y, and Z correlating signals. The wide acceptance and use of the opponent-colors system by practicing color technologists also supports its validity.

Figure 11 shows the dimensions of the L, a, b opponent-colors coordinate system. The earliest of these L, a, b-type scales was the original Hunter L, a, b scale developed and refined by Richard S. Hunter between 1942 and 1958. Many other opponent-colors-type scales were developed between 1958 and the early 1970s, but they are rarely used today.

In 1976, the CIE adopted another L, a, b-type scale identified as the CIE 1976 L*a*b* scale. Often abbreviated as the "CIELAB" scale, it is the current recommended color scale in almost all domestic and international color measurement test methods and specifications.

Communicating Color by Numbers: Color and Color Difference Scales

The industrial use of color measurement, formulation, and specification has become a common practice to ensure more consistent production without visible variation. Customers have come to expect to see the same color every time they purchase the same product, whether it is days or months between purchases. To achieve this degree of color control, numerical tolerances are developed to ensure that if production falls within the specified tolerance, there will be minimal chance of

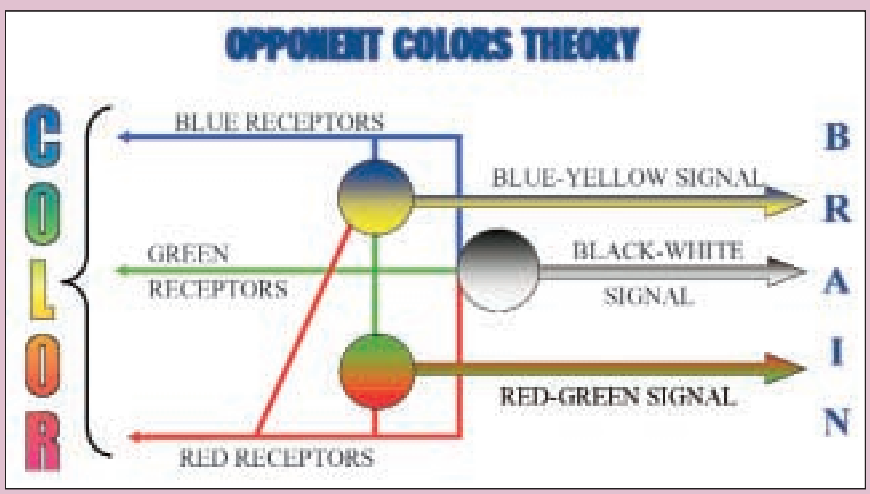


Figure 10. The opponent-colors theory presumes, that, in the human eye, there is an intermediate signal-switching stage between when the light receptors in the retina receive color signals and when the optic nerve takes those color signals to the brain. During this switching stage, it is presumed that red responses are compared with green to generate a red-to-green color dimension. The green response (or red and green together, depending on the theory) is compared in a similar manner with the blue to generate a blue-to-yellow signal.

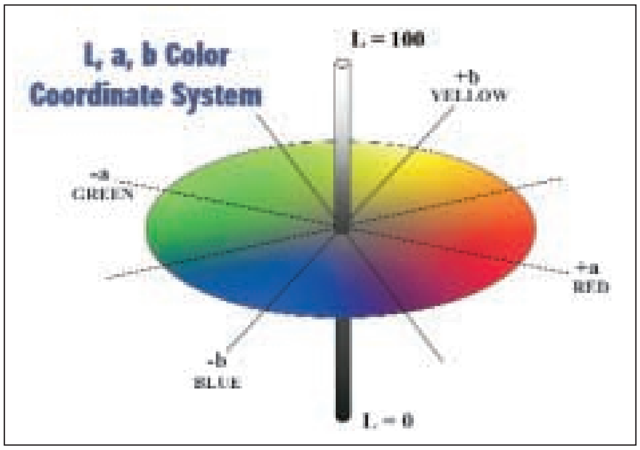


Figure 11. Example of an opponent-colors L,a,b-type color system.

customer complaints about color matching.

Although there are numerous ways to specify color tolerances, one increasingly popular method involves using a total color difference formula based on the CIELAB color scale and differences in lightness, chroma, and hue called ΔE CMC *(l:c).* The CMC formula has appeared in several different domestic and ISO (International Standards Organization) standards.

The CMC formula is being used in many industries, including paints, plastics, graphic arts, paper, textiles, inks, and food products to name just a few. CMC values for an "acceptable" color match typically range from about 0.4 (for some paints and textiles) to 2 to 4 units (for some graphic arts applications). The size depends, of course, on the nature of the product, the application, and customer requirements and expectations.

A new total color difference formula, CIE ΔE 2000, reportedly with significant improvements over the previous ΔE formulas (ΔE* CIELAB and ΔE CMC), is being considered in CIE Committee for eventual public release.

Conclusions

This overview is intended to clarify the basic concepts of the science and technology of appearance measurement. Proper application of these principles to industrial and printing situations can quantify appearance and thus enable its precise control.

Many color and appearance instrument manufacturers can provide assistance in applying this technology for specific applications. Several leading universities and some instrument manufacturers offer courses in appearance analysis and color measurement. See the references for further information. ■

References and Resources

1. R.S. Hunter, and R.W. Harold, *The Measurement of Appearance,* 2nd Edition. Wiley-Interscience, New York, 1987.

2. F.W. Billmeyer Jr. and M. Saltzman, *Principles of Color Technology,* 2nd Edition. Wiley-Interscience, New York, 1981.

3. *Colorimetry,* 2nd Edition., CIE Publication No. 15.2, Bureau Central de la CIE, Vienna, Austria, 1986.

4. *The Science and Technology of Appearance Measurement,* Hunter Associates Laboratory, Inc., Marketing Publication, Reston, Virginia, 1981.

5. R.L. De Valois, *Physiological Basis of Color Vision,* Color 69, Vol. 1, p. 29, Muster-Schmidt, Göttingen, 1970.

6. *Colour Physics for Industry,* 2nd Ed., edited by R. McDonald, Society of Dyers and Colourists, England, 1997.

7. *ASTM Standards on Color and Appearance Measurement,* Sixth Edition, American Society for Testing and Materials, Conshohocken, PA, 2000.

8. R.W. Harold and Gerald M. Kraai, "Legal Protection for Color," *GATFWorld,* March/April 1999, p. 31–36

9. Akihiro Kondo with R.W. Harold, "Measuring the Effect of Substrate Properties on Color Inkjet Images, *GATFWorld,* Sep/Oct 1999, p. 31–36.

10. R.W. Harold and D.Q. McDowell, "Standard Viewing Conditions for the Graphic Arts," GATF SecondSight reprint (Cat. No. SS72), 1999, 7 pages.

11. D.Q. McDowell and L. Warter, "Viewing Conditions: What's New? Should We Care?" *IPA Prepress Bulletin,* Nov/Dec 1997, p. 17-20.

12. *ISO3664:2000, Standard Viewing Conditions for Prints,* is available from NPES at *www.npes.org/standards/order.htm.*

13. Gary G. Field, *Color and its Reproduction,* 2nd Edition, GATFPress, Pittsburgh, 1999, chap. 2–6.

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