Review of the CIE System of Colorimetry and Its Use in Dentistry

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ABSTRACT

When we observe the light reflected from surfaces in a scene or look directly at light emitted by light sources, we experience the sensation of color. Color is just one attribute of a complex and not fully understood set of properties that define the appearance of our surroundings. To measure or specify the color of an object, we need to take into account the nature of the light under which the object is viewed, the spectral reflectance properties of the surface, and the properties of the human color vision system.

CLINICAL SIGNIFICANCE

In this article the CIE system of colorimetry is briefly reviewed and its limitations are described. The consequences of these limitations for color measurement in dentistry are discussed.

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PHYSICS OF COLOR

Light is a form of energy. Specifically, it is that part of the spectrum of electromagnetic radiation to which our eyes are sensitive. Radio waves and x-rays as well as ultra violet and infrared radiation are all part of the family of electromagnetic radiation, but the human visual system is only capable of sensing a very narrow band of wavelengths in the approximate range of 360 to 780 nm (a nanometer is 10^{-9} m). The light from any source can be described in terms of the relative power emitted by the source at each wavelength in the visible spectrum.

The spectral power distribution of daylight varies with geographic position and the time of day and year, but the set of daylight power distributions is similar to that emitted by a blackbody heated at different temperatures.[1] A blackbody is a hollow heated chamber with a small hole; as the blackbody is heated, the spectral power distribution of the light emitted from the hole varies. For many light sources it is useful to refer to the temperature (expressed in degrees Kelvin) of the blackbody for which the radiation most closely resembles that of the light source. This temperature is called the correlated color temperature (CCT). The radiation of north sky daylight on a cloudy day has a CCT of about 6500°K, whereas the light from a tungsten filament bulb has relatively more power at the long wavelengths, which gives it a much lower CCT. Note that if two light sources have the same CCT, they do not necessarily have identical spectral power distributions. Figure 1 shows the spectral power distribution for a number of different illuminants. Illuminants A, B, and C were introduced in 1931 and refer to tungsten light and two phases of daylight, respectively.

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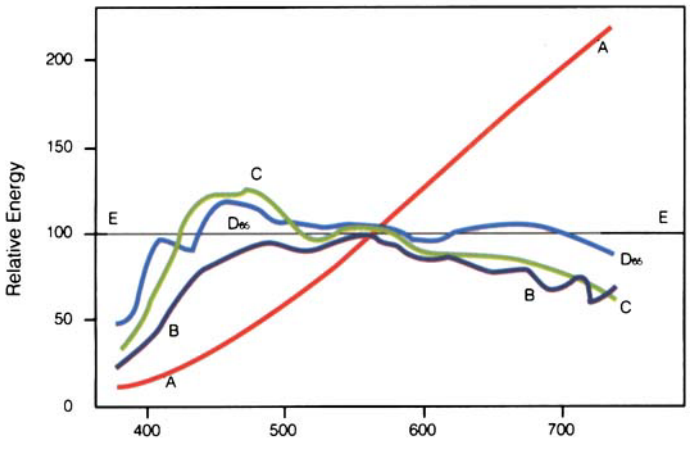


*Figure 1. The spectral power distribution of illuminants A (*red line*), B (*light blue line*), C (*green line*), D65 (*dark blue line*), and E (*black line*). Illuminant D65 is the spectral power distribution of a blackbody radiator at 6500°K.*

Illuminants B and C have largely been replaced, however, by illuminant D65, which was introduced in 1964. Illuminant D65 represents blackbody radiation at 6500°K; other illuminants such as D55 and D50 are used to represent blackbody radiation at other CCTs. Illuminant E is an equal-energy illuminant, in which the amount of power is consistent across all wavelengths. For further information about spectral power distributions and CCTs, readers are directed to the texts by Berns and Sinclair.[2,3]

Objects interact with light in a complex and varied way that includes processes of absorption, scattering, refraction, and diffraction, but it is the light that is reflected by the objects in a scene that we use to identify those objects by their color. The reflectance properties of objects can be defined by the spectral reflectance factors that are normally measured at regular intervals in the visible spectrum of radiation. Typical reflectance spectrophotometers are able to measure the reflectance factors at intervals of 10 nm in the range 400 to 700 nm (although some instruments extend their measurement to shorter or longer wavelengths). Reflectance factors are normally in the range of 0 to 1 and represent the proportional amount of light reflected in each wavelength interval. The light that we see when we look at a point in a scene clearly depends upon the spectral power distribution of the illuminating source and the reflectance properties of the scene at that point. For nonfluorescent objects the reflectance spectrum obtained is independent of the light source that was used in the spectrophotometer for the measurement. Thus, we can compute the color signal for any object under any illuminant by performing a simple multiplication at each wavelength of the reflectance with the illuminant power at that wavelength.

The reflectance spectra for most objects (Figure 2) are smooth functions of wavelength.[4,5] The smoothness of these functions reflects something about the way in which matter and light interact. Although most spectrophotometers measure reflectance at 31 equally spaced intervals in the visible spectrum, the true dimensionality of reflectance spectra is probably < 12 intervals.[4]

COLOR VISION

Our visual system detects the reflected light in a scene using the light-sensitive sense organs in the retina, which forms the inner lining of the back of the eyeball. Light enters the eye through the pupil and is focused onto the retina by the lens. The retina consists of a mosaic of specialized cells called rods and cones that contain pigments that respond to light. The chemical changes that take place when the visual pigments in the rods and cones absorb light initiate electrical impulses that are subsequently processed by a neural network of brain cells and that eventually lead to excitation of cells in various specialized areas of the outer region of the brain known as the cortex. It is still unknown where in the brain color perception actually occurs, if indeed it occurs in any localized area, but activity in the visual cortex at the back of the

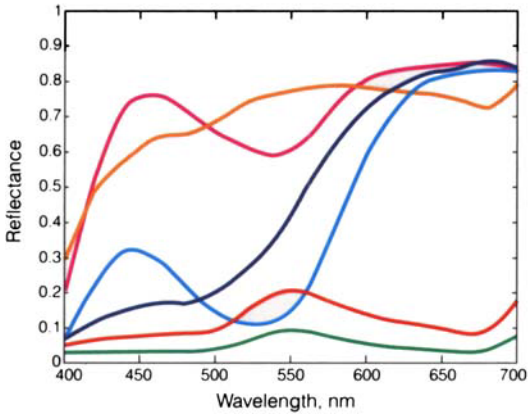


Figure 2. The spectral reflectance factors are shown for a small number of objects. The spectra are all smooth functions of wavelength, and this is typical of the color statistics of objects more widely.

brain is strongly implicated. The properties of the visual system have been reviewed elsewhere,[6] and only a minimal summary of retinal processes is presented here before methods for the measurement of color are outlined.

The rods are responsible for our vision at low levels of illumination under conditions referred to as scotopic or night vision. At higher or photopic levels of illumination, color vision is mediated by the responses of the cones. There are three types of these cones, with sensitivities peaking at 420 nm (short wavelengths), 530 nm (medium wavelengths), and 560 nm (long wavelengths), termed S, M, and L cones, respectively.[7] The three classes of cones are not distributed evenly throughout the retina. In the central or foveal region, for example, only L and M cones are present and there are approximately twice as many L cones as there are M cones. The S cones are rare throughout the retina but are more concentrated in a ring around the fovea. The retina contains several layers of cells, and the signals generated by the transduction of light into chemical and electrical energy in the cones activate the bipolar and ganglion cells before leaving the eye via the optic nerve. The cones and rods each provide a univariant response,[6] and the consequence of this is that the individual classes of cones and rods are color blind. That is, the scotopic visual system can only perceive shades of gray, and the three classes of cones considered separately are also incapable of wavelength discrimination. At least two classes of cones are required for color vision. The photopic visual system achieves color vision by analyzing the relative responses of the three classes of cones in the eye. An important consequence of the univariance of cone responses is metamerism. Two color signals may be spectrally dissimilar and yet elicit the same cone responses. Indeed, most methods of color-image reproduction (eg, printers, televisions) exploit this phenomenon to generate color sensations from three primaries.

The cone responses are combined in the retina in such a way that retinal ganglion cells are found that respond to luminance, red-green, and yellow-blue color signals. We can represent the transformation from cone responses to opponent processes with the following equations:

$$Lum = L + M$$
$$O_{RG} = L - M$$
$$O_{YB} = L + M - S$$

where *Lum* is the luminance channel, O_{RG} is the red-green channel, O_{YB} is the yellow-blue channel, and L, M, and S represent the cone responses. Whereas the existence of three cone classes can essentially explain the phenomenon of trichromacy, the opponent representation explains other aspects of the nature of color perception, including why there seem psychologically to be four primaries: red, yellow, green, and blue. The opponent signals leave the retina via the optic nerve and pass, via a structure in the central brain called the lateral geniculate nucleus, to the visual cortex, which is located at the back of the head. Further processing of the color information takes place in the cortex, where it is combined with spatial and temporal information to generate the unified percept of vision

in a way that is not completely understood. Psychophysically we can determine that the three axes of our internal perceptual color representation are brightness, colorfulness, and hue (Figure 3).

CIE SYSTEM OF COLOR SPECIFICATION

The Commission Internationale de l'Eclairage (CIE) developed a system for the visual specification of color signals that was recommended for widespread use in 1931.[5,8] The most important principle that allowed this development was additive color mixing. Thus, all color signals can be matched by the additive mixture of three appropriately chosen primaries. It had long been recognized that the amounts or intensities of the primaries required to match a given color stimulus effectively form a specification of the stimulus in terms of the primaries that are used. The amounts of the primaries used for any given stimulus are commonly known as the tristimulus values. It is possible to determine the tristimulus values for any given stimulus using a device known as a split-field or bipartite colorimeter. In such a device an observer views a bipartite field. On one side of the field the stimulus is displayed; on the other side the additive mixture of the three primaries is displayed. The observer adjusts the intensities of each of the three primaries until the additive mixture is indistinguishable from the stimulus. Under the matching condition the field appears uniform to the observer and the tristimulus values can be read off the device and recorded.

The measurement of the color-matching functions of observers was a critical feature in the development of the 1931 CIE system of colorimetry since it allowed the computation of the tristimulus values for a known color signal without the need to view the stimulus in a bipartite colorimeter. The color-matching functions are the amounts of three primaries required to visually match one unit of intensity of a single wavelength of light; they were recorded for small wavelength intervals throughout the visible spectrum (Figure 4).

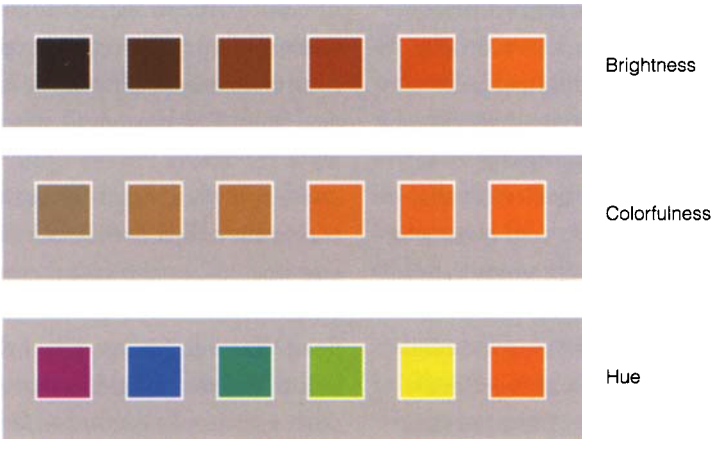


Figure 3. The perceptual dimensions of color space are brightness, colorfulness, and hue.

In fact, experiments were carried out prior to the publication of the CIE system by two groups of workers headed by Wright in 1929 and Guild in 1931 to determine color-matching functions. The two groups of workers used different primaries; consequently the two sets of color-matching functions were different. The CIE transformed the two sets of color-matching functions obtained from the two groups of workers into a single set of color-matching functions and reassuringly found good agreement between the two sets of data. The CIE system as we know it today is based upon a transformation of the original color-matching functions averaged from Guild and Wright to a set of primaries known as X, Y, and Z. The color-matching functions are known for each wavelength and are therefore represented by $x(\lambda)$, $y(\lambda)$, $z(\lambda)$. Since any real color signal can be considered to be the sum of energy at many different wavelengths, it is possible to predict the tristimulus values for any stimulus.

The CIE also defined standard illuminants—tables of spectral power distributions—that can be used to compute the color signal for a surface given the spectral reflectance

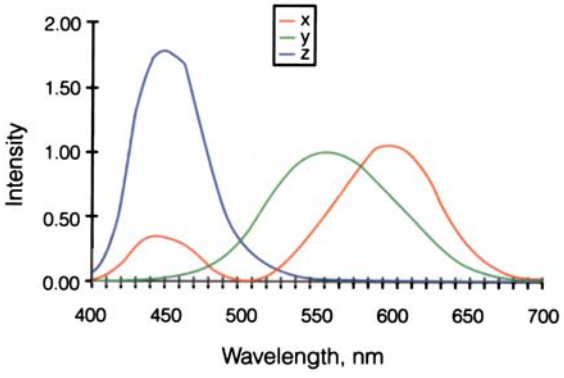


Figure 4. The CIE color-matching functions are shown. At each wavelength the intensities of the color-matching functions are the relative amounts of the XYZ primaries that an observer would use in an additive mixture to match one unit of light at that wavelength.

factor of the surface. The introduction of tables of illuminants allowed the computation of tristimulus values for surface colors as well as for self-luminous colors. A practical formula for computing the CIE 1931 tristimulus values for a surface with spectral reflectance $P(\lambda)$ under an illuminant of relative spectral power $E(\lambda)$ is as follows:

$$X = k \sum E(\lambda)P(\lambda)x(\lambda)$$
$$Y = k \sum E(\lambda)P(\lambda)y(\lambda)$$
$$Z = k \sum E(\lambda)P(\lambda)z(\lambda)$$

where k is $100/[\sum y(\lambda)E(\lambda)]$. At each wavelength interval the product $E(\lambda)P(\lambda)$ gives the amount of energy in the stimulus at wavelength λ, and the amount of the primary required to match this is given by multiplying this product by the color-matching function at that wavelength. To arrive at the amount of the primary required to match the stimulus as a whole, it is only necessary to sum across all wavelengths. Note that the implication of the normalizing factor k is that the *absolute* spectral power distribution for the illuminant is not required so that, for surface colors at least, $Y = 100$ for a perfect white surface, irrespective of the intensity of the illuminant. Further, note that a perfect white surface will give $Y = 100$ for *any* illuminant E. This normalization is reasonable given the processes of adaptation that take place in our everyday vision.[5]

The CIE 1931 color-matching functions were derived from color-matching experiments that used a bipartite field that subtended 2° (in terms of visual angle) at the retina. A second set of color-matching functions was measured in 1964 using a larger (10°) field size. The 1931 and 1964 color-matching functions are based on the same XYZ primaries but exhibit some marked differences. One reason for this is that the spatial distribution of cones (the light-sensitive cells in the eye) is not uniform across the retina. For example, it is known that there are no cones that contain short wavelength–sensitive pigment in the central region of the retina known as the fovea.

The CIE XYZ tristimulus values specify a color stimulus in terms of the visual system. It is often useful, however, to compute chromaticity coordinates x and y from the tristimulus values as follows:

$$x = X/(X + Y + Z)$$
$$y = Y/(X + Y + Z)$$

The chromaticity diagram is derived by plotting y against x, and this provides a useful map of color space. However, it should be noted that stimuli of identical chromaticity but different luminance are collapsed onto the same point in the two-dimensional plane of the chromaticity diagram (Figure 5).

The CIE system of colorimetry is a system of color specification. It allows us to predict the matching condition, that is, when two stimuli will be a visual match (under standard viewing conditions) even if they are spectrally dissimilar. However, it has two limitations that are important to understand. First, the system was designed for color specification, rather than to predict color appearance. The chromaticities of a perfect reflecting diffuser change as the illumination changes. However, the color appearance of

such a surface would be expected to remain approximately constant under quite large changes in illumination intensity and/or color. Second, the system is perceptually nonuniform. For a given Euclidean distance between two points in XYZ space, the perceptual color difference between the two stimuli represented by those points can vary by an order of magnitude. This second limitation, in particular, has presented industrial practitioners of colorimetry with serious problems, and even today those problems have not all been resolved. Although it is useful to be able to state that two stimuli are a visual match if they have the same tristimulus values, it would also be useful to be able to predict the visual difference between two stimuli for which tristimulus values are not identical. Ideally, we would like a uniform color space in which equal distances in that space correspond to equal perceptual differences. The MacAdam ellipses shown in Figure 5 demonstrate that the chromaticity space is far from being perceptually uniform. If the center of each ellipse represents a color standard, then each elliptic locus represents samples that are just noticeably different than the standard at the center of the ellipse. If the space were perceptually uniform, then these ellipses would be circles of the same size throughout the color space.

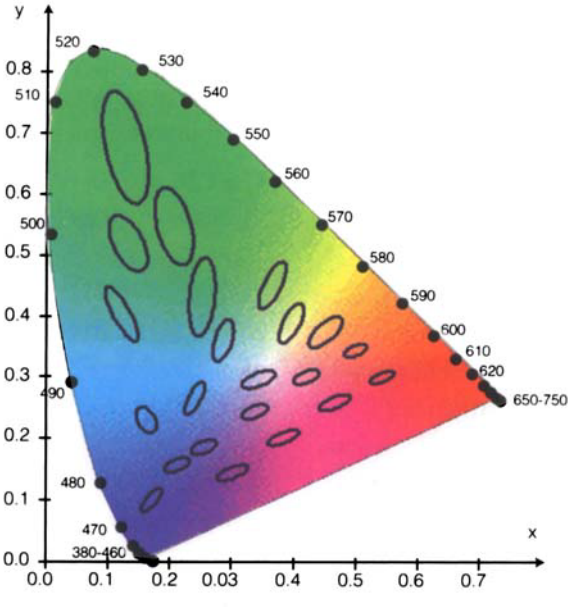


Figure 5. The CIE chromaticity diagram is shown. The MacAdam ellipses (magnified ×10) represent the nonuniformity of the space in perceptual terms.

Cielab Color Space

A major advance was made by the CIE in 1976 with the introduction of the CIELAB system of color specification. This nonlinear transform of the XYZ values provided partial solutions to both the problems of color appearance and color difference. The transformation from tristimulus values to L* a* b* coordinates is given by the following equations:

$$L^* = 116(Y/Y_n)^{1/3} - 16$$
$$a^* = 500[(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$$
$$b^* = 200[(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$$

where X_n, Y_n, and Z_n are the tristimulus values of a specified white achromatic stimulus. (Note that under certain conditions a modified set of equations is used.)

CIELAB provides a three-dimensional color space where the a*-b* axes form one plane to which the L^* axis is orthogonal. The CIELAB transform was intended to be used for surface colors (a separate transform, CIELUV, was provided for use with self-luminous color stimuli such as those generated using additive color-reproduction devices) and includes several interesting features.

First, the inclusion of difference signals crudely models processes that are believed to take place in the human visual system. Thus, whereas the retina initially captures responses derived from the cone spectral sensitivities, these responses are combined at an early (retinal) stage of visual processing to provide a luminance signal and two opponent signals that can be described as being yellow-blue and

red-green. Similarly, CIELAB represents color stimuli as an achromatic signal (L*) and two chromatic channels representing yellow-blue (b*) and red-green (a*).

Second, the normalization by the specified white achieves a color space that makes better predictions of color appearance than the tristimulus space from which it is derived. Thus, whereas the x and y chromaticities of a perfect white surface vary with the illuminant, the CIELAB coordinates remain constant at L* = 100, and a* = b* = 0. CIELAB also allows the representation of a color stimulus by dimensions of lightness, chroma, and hue, and it is therefore reasonable to describe CIELAB as a color-appearance space, whereas this label is not appropriate for a tristimulus space, which is strictly for color specification. However, if predictions of color constancy using CIELAB are compared with empiric measurements of color constancy, then it is found that the predictions are quite poor in general.

Third, the nonlinear transform of tristimulus values in the CIELAB equations allows the Euclidean distance between two points in the new space to better predict the visual color difference between the color stimuli represented by two points. Consequently, the color difference metric known as ΔE^*_{ab} has been used effectively to quantify color difference in a wide range of industries. It is computed by the following formula:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5}$$

where ΔL^*, for example, denotes the difference in L^* between the two samples. The values of ΔL^*, Δa^*, and Δb^* are given by the following equations:

$$\Delta L^* = L^*_1 - L^*_2$$
$$\Delta a^* = a^*_1 - a^*_2$$
$$\Delta b^* = b^*_1 - b^*_2$$

where the subscripts refer to the two stimuli concerned.

Unfortunately, although CIELAB is *more* perceptually uniform than is XYZ space, it is still a long way from *being* perceptually uniform. Industrial practitioners of color science would like to be able apply a single tolerance on the value of ΔE^*_{ab} that defines the perceptibility or acceptability boundaries throughout color space, but this is not yet possible.

Advanced Color-Appearance and Color-Difference Metrics

The requirements of dentistry for colorimetry are rather similar to those for many other fields. We would like to be able to predict when two teeth will match and, if there is a mismatch, the degree of color difference between the two teeth. We would also like to predict the color appearance of teeth to be able to state whether one tooth is whiter or yellower than another or, more specifically, to be able to deduce the efficacy of a whitening treatment in terms of color appearance.

Unfortunately, the CIELAB color space is not suitable for either the prediction of color differences or color appearance. In Figure 6 the two small gray squares are physically identical and therefore have the same XYZ and L*a*b* values; however, they do not look the same.

The field of color appearance has been actively researched over the past decade in particular, and several advanced color spaces (eg, CIECAT94 and CIECAM97s) are now available for predicting color appearance.[9,10] For teeth we are normally concerned with the prediction of whiteness or yellowness, and these percepts are particularly elusive to measurement. A large number of special indices are available (eg, the CIE Whiteness Index), but it has not been proven that

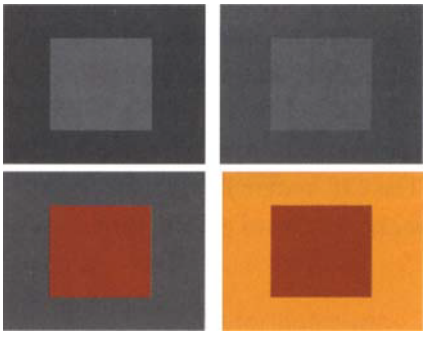


Figure 6. These two small gray squares are physically identical, as are the two red squares. However, physically identical stimuli do not necessarily have the same color appearance. The CIELAB color space cannot predict this phenomenon.

these indices can accurately predict the whiteness or yellowness of teeth.

The last two decades of the twentieth century saw a great deal of research into the development of effective color-difference formulas. CIELAB is not a perceptually uniform color space, and fixed changes in a* or b*, for example, are more visible in some parts of the space than in others. The CMC formula (named after the Colour Measurement Committee of the Society of Dyers and Colourists) was introduced in 1983 and has been widely used in industry. However, a new color difference formula was recently recommended for trial by the CIE and is known as CIEDE2000.[11] CIEDE2000, like its predecessor CMC, is not, in itself, a color space (it computes color difference starting from differences in CIELAB space) but rather describes a method for combining and weighting the differences that is more complex, and certainly more effective, than simply measuring the Euclidean distance.

SUMMARY

The CIE system of colorimetry is well established as a method for color specification. However, the demands of users have exceeded the capabilities of the original system. Models that are able to better predict color difference and color appearance are currently active areas of research for color scientists in academia and industry. One of the factors that is actively driving research in these areas is the need to be able to effectively communicate color between image-capture and image-reproduction devices. The proliferation of inexpensive color capture and display systems, in addition to the increasing commercial use of color on the Internet, requires increased understanding of and ability to predict color difference and color appearance. In dentistry the percepts of whiteness and yellowness are of particular importance. Further work is required to ascertain the effectiveness of existing colorimetric formulas to predict whiteness and yellowness and, if necessary, to develop better formulas.

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