Skin Color Measurements in Terms of CIELAB Color Space Values

Ian L. Weatherall and Bernard D. Coombs

School of Consumer and Applied Sciences (ILW) and Department of Preventative and Social Medicine (BDC), University of Otago, Dunedin, New Zealand

The principles of color measurement established by the Commission International d'Eclairage have been applied to skin and the results expressed in terms of color space L*, hue angle, and chroma values. The distribution of these values for the ventral forearm skin of a sample of healthy volunteers is presented. The skin-color characteristics of a European subgroup is summarized and briefly compared with others. Color differences between individuals were identified in terms of one, two, or all three color-space parameters. Because the method is quantitative and the principles internationally recognized, these color-space parameters are proposed for the unambiguous communication of skin-color information that relates directly to visual observations of clinical importance or scientific interest. *J Invest Dermatol 99: 468–473, 1992*

The appearance of human skin is a major descriptive parameter in both clinical and scientific evaluations. Skin color may be associated with susceptibility to the development of skin cancer [1,2], changes in color characterize erythema [3–6], and the observation of color variegation is an important clinical criterion for differentiating between cutaneous malignant melanoma and benign nevi [7].

Visual observations and subjective assessments however, lack precision with respect to the communication of color information. Therefore, recent scientific investigations have relied on the instrumental measurement of the optical properties of skin by means of reflectance spectroscopy [8,9], and the resulting spectral data used to provide quantitative information on the constituents of skin, usually in terms of erythemal or melanin indices [10–12]. The chromophores in skin have been referred to, somewhat loosely, as "skin colors" [12], but this terminology can be misleading in a scientific context because it does not distinguish between the pigmented substances in skin and the actual visual sensation of colors. Both are important in clinical and scientific studies and both can be quantified by means of reflectance spectroscopy. However the latter, i.e., the measurement of appearance, has received much less clinical attention than the former.

Reflectance methods have been widely applied in studies of the chromatic characteristics of skin in the context of human genetics [1,13,14]. Filter colorimetry has been used to a limited extent for designating the extent of erythema [4,5,15], but for complete color measurements it has been shown that such methods can give results that differ systematically from those based on scanning spectrophotometry [16,17]. There appear to have been no reports of the evaluation of the color of skin by applying reflectance spectroscopy according to the principles laid down by the Commission Internationale d'Eclairage (CIE) for the measurement of the color of surfaces with the results given in terms of CIE 1976 L* a* b* (CIELAB) color space parameters [16,18]. The description of the appearance of skin in these terms would give an objective measure of the visual perception of the colors and would have the additional advantage of enabling quantitative specifications of the magnitude of perceived color differences or changes [16,19].

The CIE system applies solely to the measurement of appearance and makes no assumptions about the nature or amounts of any pigments that may be present. It has international recognition so the specification of the CIELAB color space parameters for skin would have particular value for clinicians who make visual assessments of various phenomena that, although they may be readily apparent, may be difficult to describe reliably in diagnostic communications [11]. Because CIELAB color space parameters are calculated from measured reflectance spectra, the same spectral data may also be used in physiologic and biochemical studies to determine the concentration of the chromophores in skin.

The present article summarizes color assessment and specification and describes the application of the CIE system to the determination of the CIELAB color space parameters of the skin of a sample of healthy volunteers as a demonstration of a methodology that might be usefully applied in studies on possible relationships between observed skin color and matters of clinical importance or scientific interest.

COLOR ASSESSMENT

Color information may be acquired and communicated in various ways; however, in a scientific context there are requirements for consistency independent of time, distance, and language.

Although the average person may be able to distinguish several thousands of colors, the description of visual observations by the use of general color terms is the least satisfactory in terms of precision. The range of names upon which people can be relied to agree is very limited and there is no simple way of using visual observations to describe the differences between colors [16].

Color assessments based on visual comparisons with sets of col-

Manuscript received August 7, 1991; accepted for publication March 9, 1992.

Reprint requests to: Dr. Ian L. Weatherall, School of Consumer and Applied Sciences, University of Otago, P.O. Box 56, Dunedin, New Zealand.

This work was supported by the Cancer Society of New Zealand Inc., the University of Otago Medical School bequest funds for cancer research, and a New Zealand Lottery Science Research grant.

Part of this work was presented to the Otago Medical School Research Society, University of Otago, Dunedin, New Zealand, October 1989.

Abbreviations:

CIE: Commission International d'Eclairage

CIELAB: CIE 1976 L* a* b* color space

ored samples, known as color-order systems, can increase the range and reliability of color designations significantly [16]. The Munsell color-order system [19] is the oldest and perhaps the most widely recognized, but there are several others [20], including one based on the Munsell system and specifically designed for use in differentiating skin colors [15]. There is no agreed international standard color-order system and in only a few cases have relationships been established between the various systems [20].

Even if agreement exists on the application of any one system, its usefulness depends on its availability and continuity of publication without alteration over time. Color comparisons may also involve the problem of metamerism. This occurs when two colors match under one set of conditions, but fail to match under a second set of conditions [16]. Illuminant metamerism is the most important type and can occur, for example, when two metameric colors match under "daylight" but fail to match under "artificial" light. Observer metamerism is exhibited when two metameric colors appear to match for one person but not another. The color vision of individuals differs to a greater or lesser extent and is also known to change with a person's age. Color blindness in various forms is not uncommon and those so affected cannot participate in visual color matching and have limited comprehension of color information based on color-order systems. Geometric metamerism occurs when viewing geometry changes and the physical surface structure of a sample differs from that of the reference. Color-order systems are most reliable when used under fixed conditions of illumination to match colors of relatively flat surfaces that are uniformly pigmented. They are less appropriate for samples that are heterogeneous in surface structure. A particular limitation of color-order systems is that they only identify single colors and do not provide a way of specifying the nature or magnitude of color differences.

The limitations of visual observations may, in principle, be overcome by the instrumental evaluation of colors and color differences according to the system of color measurement established by the CIE [16,18,21,22]. This system has become widely used with the availability of reliable reflectance spectrophotometric instrumentation that conforms to the recommendation of the CIE for the measurement of the color of surfaces [23–25].

CIE COLOR SYSTEM

The perceived color of an object depends on 1) the nature of the illuminating light, 2) its modification by interaction with the object, and 3) the characteristics of the observer response. The CIE system defines these conditions as follows. 1) The relative spectral energy distributions of various illuminants, known as CIE standard illuminants, are specified and available as published tables [16,18,21–24] (see also the *Appendix* to this paper). 2) The modification of an illuminant by interaction with the object is measured with a reflectance spectrophotometer having an optical configuration that conforms to CIE recommendations [18], and provides a visible spectrum expressed as the fractions of incident light intensity reflected in the wavelength range 400–700 nm. 3) The nature of human color vision has been quantified for the purposes of color measurement in terms of three color matching functions $\bar{x}$, $\bar{y}$, and $\bar{z}$. Three are required because color vision has been found to be trichromatic: a single perceived color may be regarded as resulting from the effect of three separate stimuli on the visual cortex [22]. Their numerical values are available as published tables and are known collectively as a CIE standard observer [16,18,21–24] (see also the *Appendix*). They may be regarded simply as a numerical description of human color vision. From a practical viewpoint their use has been made more convenient by incorportation of the tabulated values within the software provided with color-measuring reflectance spectrophotometers. Similarly, the tabulated values of the relative spectral-energy distributions of various CIE illuminants are provided within the software because they do not exist as actual physical sources of light within the instrumentation.

Colors are measured in terms of their tristimulus values X, Y, and Z by combining a selected table of illuminant data, the measured

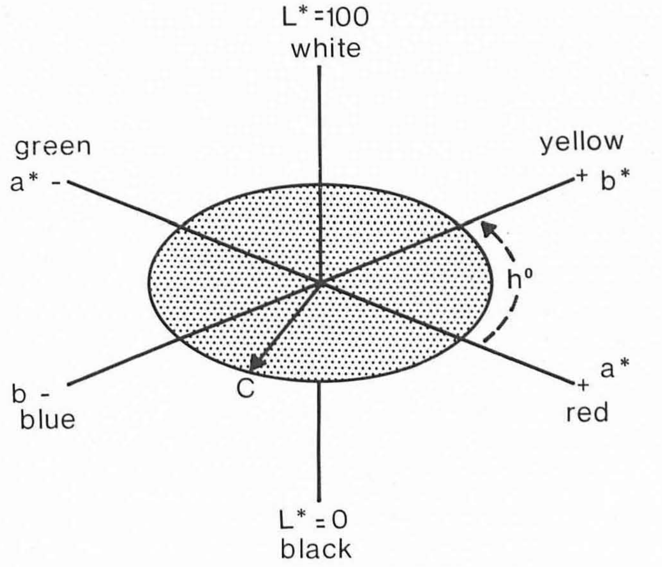

Figure 1. CIELAB color space.

values of reflectance, and a selected table of color-matching functions with three summations, each having the form

$$\Sigma E \cdot R \cdot \bar{x} - = X$$

At selected intervals in the wavelength range 400–700 nm the relative energy (E) of the chosen illuminant is multiplied by the fraction reflected (R) and the numerical value of the standard observer ($\bar{x}$ or $\bar{y}$ or $\bar{z}$). A wavelength interval of 10 nm, which requires 31 terms in each summation, gives adequate precision for most purposes. Modern color-measurement instrumentation normally incorporates microcomputer hardware and software so that the spectral measurements and subsequent calculations are integrated so as to produce a copy of the results within a few seconds. However, the tristimulus values of colors are difficult to relate to the experience of seeing them. In addition, in any study involving comparisons, contrasts, or changes, tristimulus values do not directly enable measurement of the difference between two colors. This concern has now been overcome by using the tristimulus values to calculate the CIE 1976 L* a* b* (CIELAB) color space values [16,18,23,24,25] (see also the *Appendix*). The mathematical manipulations that convert tristimulus values to CIELAB color space values enable colors to be regarded as existing in an approximately uniform three-dimensional space in which each particular color has a unique location defined in terms of its cartesian coordinates with respect to the axes L*, a*, and b*, as shown in Fig 1. Modern computer-controlled reflectance spectrophotometers, such as that used in the present study, provide for automatic calculation of CIELAB values from the spectral data they produce.

The measured L* value of a color has been recommended by the CIE as the psychometric correlate of the visually perceived color attribute of "lightness" [18,23], to which the descriptive terms assigned might include the words "light," "dark," etc. In other words, L* would measure the change along a grey scale from black to white that visually varied in a perceptually uniform manner. The L* scale, which ranges from 0 for a theoretical black to 100 for a perfect white, corresponds to the notion of the value attribute in the Munsell color order system.

The a* and b* coordinates may be conceptually related to Hering's opponent color theory [24], which was based on the proposition that the retina of the eye contains opponent color channels that distinguish colors according to their red-versus-green and yellow-versus-blue attributes. In CIELAB space they are more useful when converted into polar coordinates. This enables definition of a hue angle, h° = arctan(b*/a*), which is recommended by the CIE as the psychometric correlate of the visually perceived attribute of hue (e.g., red, orange, yellow, etc.) [18,24]. Measured hue angles make the use of visually assigned hue terms unnecessary, although it is simple and often convenient to relate them in a general way. The general angular position of some of the main generic hues are shown in Fig 1. CIE hue angle corresponds conceptually to the attribute of Hue in the Munsell color-order system but no simple relationship has been found between measured hue-angle values and Munsell hue designations [20]. Colors for which both a* and b* are zero, and therefore lie on the L* axis, are termed achromatic and would be perceived as grey, white, or black. The visually perceived color attribute of "saturation," which might be described by the use of the terms "weak," "strong," etc., may be measured in terms of its distance away from the L* axis in the a*b* plane. This is the length of the line C in the diagram. It is termed the CIE [1976] a, b chroma and is calculated using coordinate geometry as $C = [(a^*)^2 + (b^*)^2]^{1/2}$. It corresponds conceptually to the attribute of chroma in the Munsell system but the measured values do not relate in any simple way to Munsell designations [20]. Thus the use of CIELAB coordinates enables measurement of the three attributes of a color by which it is visually distinguished [19].

CIELAB space is not only more convenient than tristimulus values with respect to its conceptual relationship to the actual experience of seeing the colors but it has the important advantage of providing a means of measuring the differences between any two colors [16,24]. Their color difference (ΔE) is calculated, using coordinate geometry, as the length of the line joining their coordinate positions:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}.$$

In some circumstances the differences between two colors may also be considered in terms of differences in hue angle and/or chroma.

Modern computer-controlled reflectance spectrophotometers used for color measurement often include the software necessary for automatic calculation of color differences from two sets of spectral data.

MATERIALS AND METHODS

Volunteers Ninety-nine medical students in the second year of their studies took part in the survey. The ages ranged from 18 to 29 years with a mean of 20.9 years. There was close to half of each gender. They were informed of the details of the experimental process and their consent was obtained prior to the measurements being made. Individuals volunteered information as to their racial origin in cases for which this was known and the subsequent skin-color data grouped accordingly. Eighty-one classified themselves as being of European ethnicity. The remainder were Chinese, Indian, Polynesian, or mixed race.

Measurements Reflectance measurements were made with a Labscan 6000 (Hunter Associates Inc.) scanning reflectance visible spectrophotometer having 0° illumination and 45° viewing geometry with the specular component excluded. The instrument was calibrated with a supplied white standard traceable to the National Bureau of Standard's perfect white diffuser. The spectrophotomer was controlled by an IBM XT microcomputer, which performed all color calculations from the digitized spectral data by means of a menu-driven suite of programs supplied with the instrument. Each subject placed the ventral surface of the forearm, at a region midway between the wrist and the elbow, over a 30-mm–diameter open circular port with a 26-mm illuminated area in the horizontal upper surface of the sensor module. Ten reflectance spectra over the wavelength range 400–700 nm, each requiring about 3 seconds for measurement, were obtained for different but overlapping regions a few millimeters apart and computer averaged. Tabulated data for CIE illuminant D65 and the CIE 1964 10° standard observer were selected under software control and combined with the spectral data at 10-nm intervals to compute the CIELAB L*, a*, and b* values. The latter two values were then further converted to CIELAB color space hue angles and chromas.

RESULTS AND DISCUSSION

The skin colors for the 81 European subjects in terms of the CIELAB color parameters L*, hue angle, and chroma are shown in Fig 2 as histograms and the values for selected individuals are given in Table I. The CIELAB parameters for any individual measure skin color as it would have been visually perceived. The skin of the lower forearm has characteristics determined by both hereditary skin color and environmentally induced melanotic pigmentation [13]. The ventral forearm, however, is relatively infrequently exposed to ultraviolet radiation and provided a readily accessible site to place over the viewing port of the spectrophotometer. The distribution of CIELAB parameters for the 81 subjects represents objectively the ventral forearm skin-color phenotype of the group. The range of each color space parameter within the group provides a numerical specification of the distribution of the corresponding color attribute as it would have been visually perceived.

The L* values ranged from 59.7 to 73.4 and for the histogram in Fig 2 a class interval of 3 was chosen on the basis that it was over twice the mean within-sample standard deviation and because it represented a difference in this color attribute that would have been just visually apparent for two colors that were otherwise similar with respect to hue angle and chroma. For example, the skin colors of subjects 33 and 80 shown in Table I differ in this way. The apparent asymmetry of the distribution within the group was confirmed by a goodness of fit test that showed that the hypothesis that the L* values were normally distributed about a mean of 68.2 could be rejected at the 95% level of confidence. This meant that there were a few individuals whose skin was much lighter than would be expected from a normally distributed range of L* values.

The hue angles (h°) ranged from 54.0° to 77.8° and for the histogram in Fig 2 a class interval 4° was used because a difference of this magnitude would be visually apparent. A goodness of fit test applied to the distribution of hue angle values showed that the hypothesis that it was normal about a mean of 64.9° could not be rejected at the 95% level of confidence. A difference in hue angle was noted between some subjects as the only color attribute that distinguished them because they were otherwise similar with respect to L* and C. An example is the CIELAB values for subjects 33 and 38 in Table I.

The chroma (C) values ranged from 13.2 to 21.6. A goodness of fit test of the hypothesis that the values were normally distributed about a mean of 16.5 could not be rejected at the 95% level of confidence. The CIELAB parameters for subjects 74 and 78 were similar with respect to L* and h°, and differed only in the value for C, so that this color attribute alone distinguished them.

Differences in the skin color between individuals could be identified where both the L* and h° values differed but the values for C were similar (subjects 5 and 15), or where the values for both the C and h° differed but the L* values were similar (subjects 19 and 44). A further possibility was identified where differences in both L* and C were evident but the hue angles were similar (subjects 5 and 75). For many randomly selected pairs of individuals all three CIELAB values were different (subjects 5 and 44).

The other racial groups were insufficiently represented to justify a similar analysis. There were five individuals who classified themselves as Indian; their skin color could be described as brown to black. The mean L*, h°, and C values for this group were 51.8, 61.4°, and 22.1, respectively, which indicates the nature of the differences in the three color space parameters compared to the European group. However, a larger sample size would be required for proper characterization. The same consideration applied to the measurements made on the seven individuals who classified themselves as Chinese. Their skin color could be described as olive and the mean values of L*, h°, and C were 64.8, 67.6°, and 19.5 respec-

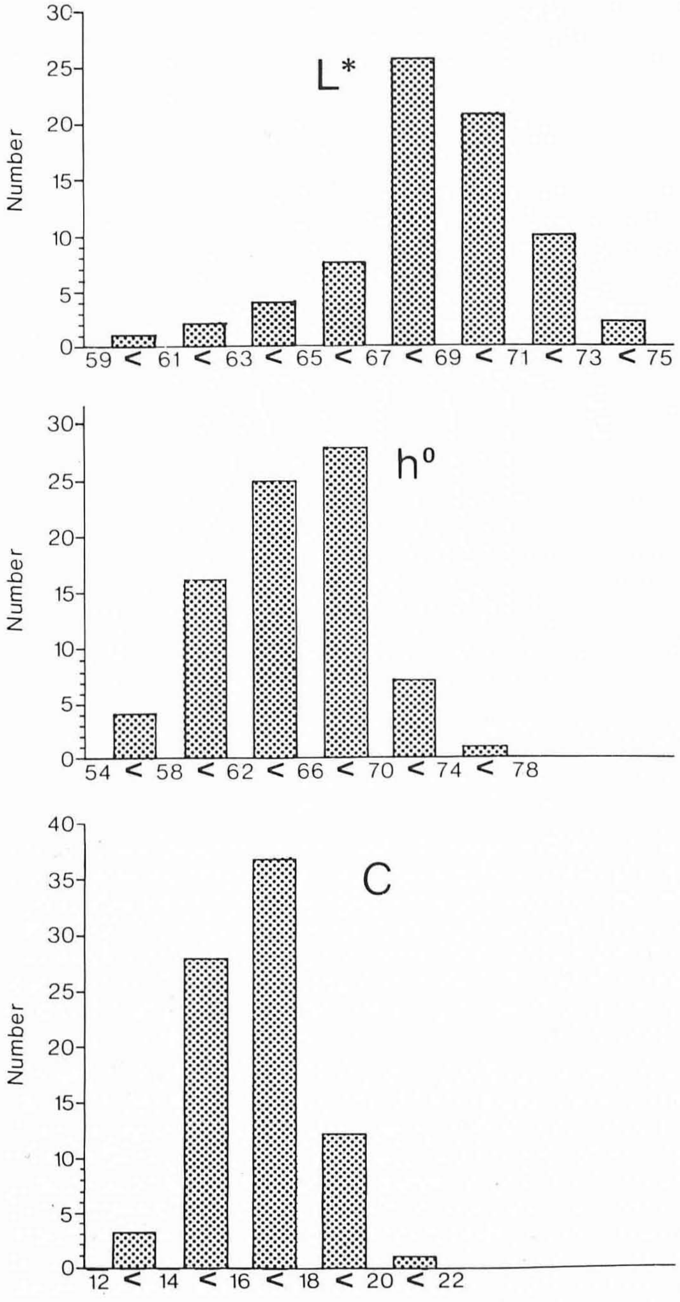

Figure 2. Distribution ventral forearm skin colors of 81 volunteers of European ethnicity, expressed as the measured values of CIELAB L* (*top*), hue angle (h°) (*middle*), and chroma (C) (*bottom*).

tively, again indicating the nature and magnitude of the difference in skin color compared to the other two groups.

CONCLUSION

Measurement of the visible reflectance spectrum of skin and the calculation of CIELAB values provides a practical numerical basis for quantifying the perceived color of human skin. The excess of data in a full spectrum can be reduced to a set of color space parameters that relate directly to the appearance of the color as it would be clinically observed and without making any assumptions about the nature of the pigments involved. However the same spectral data could be used if there was a requirement beyond the simple numerical specification of appearance as in the determination of the concentration of chromophores in physiologic studies. The use of CIELAB color space parameters has potential cosmetic applications, such as the design of prosthetic devices and use in anthropologic studies of human population genetics. Differences in skin CIELAB values enable a distinction to be made between individuals within a group in terms of differences in one, two, or three color space parameters. This may have application in relating skin color to susceptibility to the development of skin cancer or other diseases. An extension of the methodology would enable the comparison of the color of a cutaneous lesion and that of adjacent normal skin, or even of the color at various positions on the surface of a single lesion. Either extension might provide a quantitative adjunct for the diagnosis of melanomas. Instrumentally this now appears feasible through the use of fiber-optic cables to obtain the reflectance spectrum of areas only a few millimeters across [8,12,26].

Measured CIELAB color space parameters enable the unique identification of every color that may be visually distinguished and their use is proposed for the unambiguous communication of skin-color information for clinical or scientific purposes.

APPENDIX

The CIE system for the measurement of color starts with the premise that the stimulus for color is provided by the proper combination of a source of light, an object, and an observer, and the methodology to derive numbers that provide a measure of a color seen under a source of illumination by an observer. In 1931 the CIE introduced the element of standardization of illuminant and observer.

Standard Sources and Illuminants There is a distinction, in CIE terminology, between a source and an illuminant. A source is a real physical light. Its spectral power distribution can be determined by experiment and once this is known the source is referred to as a standard source. An illuminant, on the other hand, is defined by a spectral power distribution, and it may or may not be possible to make a source representing it. All standard sources today have their corresponding standard illuminants, but not all standard illuminants have corresponding sources. For example, CIE standard source A is a tungsten-filament lamp operated at a specified temperature; its spectral power distribution curve is known and is a standard illuminant. Standard sources B and C, representing noon sunlight and average daylight, respectively, also have their corresponding standard illuminants. In 1965 the CIE introduced the D series of illuminants to supplement A, B and C based on new studies of the spectral power distribution of natural daylight. The most important of these, and the most widely used, is D65. Despite extensive efforts, no sources simulating it have been developed. Such a source is not needed, however, because for the purposes of color measurement only the tabulated values of its relative power distribution curve are required, and these are available in many standard texts as well as being incorporated in the software of modern color-measuring reflectance spectrophotometers. The general form of D65 is shown in Fig 3.

Table I. L*, Hue Angle (h°), and Chroma (C) Values for Ventral Forearm Skin Color of Selected Subjects of European Ethnicity

Subject	L*	h°	C
5	71.8	71.0	15.9
15	67.7	58.8	15.9
19	66.1	55.7	16.6
33	71.4	65.5	15.2
38	71.3	70.5	14.8
44	66.3	62.6	19.5
74	68.0	66.8	13.2
75	67.8	70.7	18.7
78	67.8	66.1	16.2
80	68.4	64.8	15.9

Color-Matching Functions, Tristimulus Values, and Standard Observers It has been shown experimentally that the appearance of any individual color [C] can be matched by using three primaries in the form of single wavelengths representing the red [R], green [G], and blue [B] regions of the spectrum. The relative proportions of the three primaries required to match each of the pure spectrum wavelengths are known as the distribution coefficients, or color-matching functions for the equal energy spectrum, and designated $\bar{r}$, $\bar{g}$, and $\bar{b}$. Using these it is possible to calculate the relative proportions of the primaries required to match a color consisting of a mixture of wavelengths. These relative proportions are called the tristimulus values (R, G, and B) for the color.

Color-matching algebra represents the process of additive mixing with equations of the following form:

$$C[C] = R[R] + G[G] + B[B].$$

The fact that only three primaries are required implies that there are three types of receptors in the eye, but color vision does not necessarily involve only additive responses, because for some colors a match can only be obtained by adding one of the primaries, say [R], to it and matching the result to a mixture of the other two primaries. This process could be represented by

$$C[C] + R[R] = G[G] + B[B]$$

or, by rearrangement,

$$C[C] = -R[R] + G[G] + B[B]$$

and the set of tristimulus values (−R, G, B) includes a negative value. No set of real primaries that avoids the occurrence of negative numbers has been found. The mathematics of color mixing and the algebra of color matching enables color-matching functions and tristimulus values derived from one set of primaries to be converted into other values based on another set of primaries. The CIE used this fact to resolve the problem of negative numbers, with its awkward implication of negative responses, by adopting a set of hypothetical primaries [X], [Y], and [Z] that, although they lay outside the realm of real stimuli, enabled the specification of any color in terms of its tristimulus values X, Y, and Z, such that no negative numbers appeared. The corresponding set of color-matching functions are $\bar{x}$, $\bar{y}$, and $\bar{z}$ and are known collectively as a CIE standard observer. The original color-matching experiments were conducted using a group of people believed to have normal color vision and were performed in such a way that the subjects made their observations over a narrow (2°) field of view. For this reason the first color-matching functions are referred to as the CIE (1931) 2° standard observer. Subsequent studies revealed that the geometry of the eye is such that, when the field of view is larger, colors appear slightly different. More recent color-matching experiments using a 10° field of view led to the publication of the currently recommended color-matching functions known as the CIE (1965) 10° standard observer. Their numerical values are published in many standard texts and are incorporated in the software of modern color-measuring reflectance spectrophotometers. Their general form is shown in Fig 4.

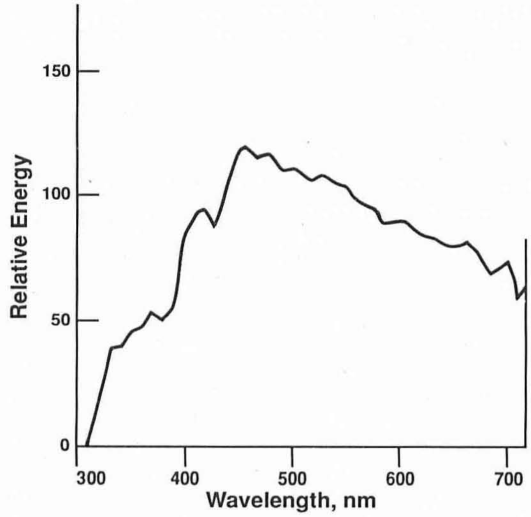

Figure 3. CIE standard illuminant D65.

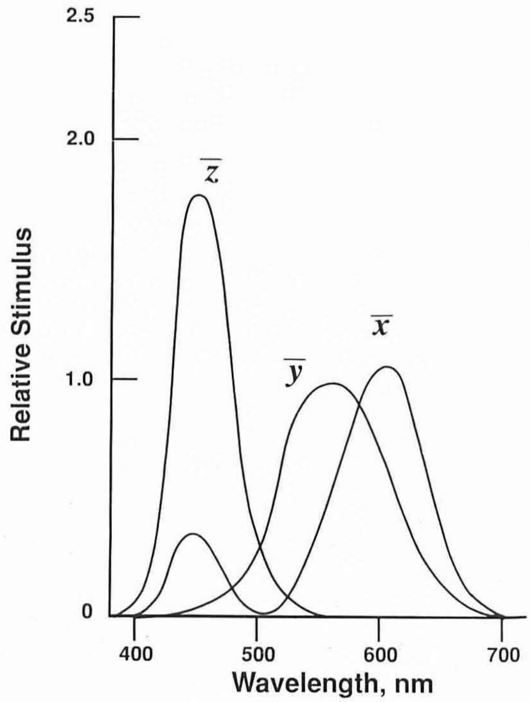

Figure 4. CIE 10° standard observer.

Color Space and Color Difference The tristimulus values of a surface color are obtained by combining selected illuminant and observer data with the experimentally determined reflectance spectrum of the surface using calculations of the form described in the main text of this paper. Although the tristimulus values are the basic measure of a color, they are difficult to relate to the experience of actually seeing it, even for an experienced colorist. In addition, they do not directly provide a way of quantifying the difference between two colors. This is important because in many instances it is color differences that are of principal interest. Since the publication of the CIE system in 1931 a great many investigations have been conducted with the objective of overcoming these deficiencies. In essence these investigations sought mathematical transformations of tristimulus values that would place colors in a hypothetically uniform three-dimensional color space. The uniformity sought relates to perceptual uniformity, in the sense that when the difference between any two colors is perceived to be just noticeable, then the measured difference in terms of the length of the line joining their coordinate positions in color space should always be the same irrespective of where the two colors are within the color space. In other words, all adjacent colors that are perceived to be just noticeably different would be a constant measured distance apart, so that the entire gamut of colors would exist in a color space that was not only perceptually uniform, but also measurably so. The CIE (1976) L*a*b* (CIELAB) color space approaches the required ideal for a uniform color space and, although it is not perfect, it is currently widely used for specifying color differences as described in the main text of this article. CIELAB parameters, in contrast to tristimulus values, also enable ready comprehension of the visual attributes of a color. The way in which L*, a*, and b* relate to the actual experience of seeing colors is described in detail in the main text of this article. The mathematical transformations of tristimulus values to CIELAB coordinates were developed by trial and error. They are

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

where X_n, Y_n, and Z_n are the tristimulus values for a particular standard illuminant and observer, for a sample reflecting 100% of light at all wavelengths. Their values are available in many standard texts and are incorporated in the software of modern color-measuring reflectance spectrophotometers. Because of the recognized deviations of CIELAB space from perceptual uniformity, other transformations of tristimulus values are available for the specification of color differences, but with a concomitant loss of the conceptual simplicity of CIELAB space.

REFERENCES

1. Little MA, Wolf ME: Skin and hair reflectance of women with red hair. Ann Human Biol 8(3):231–241, 1981
2. Holman CDJ, Armstrong BK: Pigmentary traits, ethnic origin, benign nevi, and family history as risk factors for cutaneous malignant melanoma. J Natl Cancer Inst 72:257–266, 1984
3. Feather JW, Ryatt KS, Dawson JB, Cotterill JA, Barker DJ, Ellis DJ: Reflectance spectrophotometric quantification of skin color changes induced by topical corticosteroid preparations. Br J Dermatol 106:437–444, 1982
4. Babulak SW, Rhein LD, Scala DD, Simion FA, Grove GL: Quantitation of erythema in a soap chamber test using the Minolta Chroma (Reflectance) Meter: comparison of instrumental results with visual assessments. J Soc Cosmet Chem 37:475–479, 1986
5. Westerhof W, van Hasselt BAAM, Kammeijer A: Quantification of UV-induced erythema with a portable computer controlled chromameter. Photodermatol 3:310–314, 1986
6. Hacham H, Freeman SE, Gange RW, Maytum DJ, Sutherland JC, Sutherland BM: Do pyridine dimer yields correlate with erythema induction in human skin irradiated in situ with ultraviolet light (275–365 nm)? Photochem Photobiol 53(4):559–563, 1991
7. Fitzpatrick TB, Rhodes AR, Sober AJ, Mihm MC: Primary malignant melanoma of the skin: the call for action to identify persons at risk; to discover precursor lesions; to detect early melanomas. In: Elwood JM (ed.). Naevi and Melanoma: Incidence, Interrelationships and Implications; Pigment Cell, No. 9. Basle, Karger, 1988
8. Marchesini R, Brambilla M, Clemente C, Maniezzo M, Sichirollo AE, Testori A, Venturoli DR, Cascinelli N: In vivo spectrophotometric evaluation of neoplastic and non-neoplastic skin pigmented lesions. I. Reflectance measurements. Photochem Photobiol 53(1):77–84, 1991
9. Feather JW, Hajizadeh-Saffiar M, Leslie G, Dawson JB: A portable scanning spectrophotometer using visible wavelengths for the rapid measurement of skin pigments. Phys Med Biol 34:807–820, 1989
10. Kollias N, Baqer A: Quantitative assessment of UV-induced pigmentation and erythema. Photodermatol 5:53–60, 1988
11. Anderson PH, Bjerring P: Spectral reflectance of human skin in vivo. Photodermatol 7:5–12, 1990
12. Kollias N, Baqer A: Spectroscopic characteristics of human melanin in vivo. J Invest Dermatol 85:38–42, 1985
13. Clarke P, Stark AE, Walsh RJ: A twin study of skin reflectance. Ann Human Biol 8:529–541, 1981
14. Towne B, Hulse FS: Generational change in skin color variation among Habbani Yemeni Jews. Human Biol 62(1):85–100, 1990
15. Gibson IM: Measurement of skin color in vivo. J Soc Cosmet Chem 22:725–740, 1971
16. Billmeyer FW, Saltzman M: Principles of Color Technology, 2nd ed. Wiley-Interscience, New York, 1981
17. Stevenson JM, Weatherall IL, Littlejohn RP, Seman DL: A comparison of two different instruments for measuring venison CIELAB values and color assessment by a trained panel. N Z J Agr Res 34:207–211, 1991
18. Colorimetry, 2nd ed. (CIE publications No. 15.2); Colorimetric Illuminants (CIE S001); Colorimetric Observers (CIES002). Central Bureau of the CIE, Vienna, 1986
19. Munsell AH: A Color Notation, 14th ed. Munsell Color Co., Macbeth Division of Kollmorgen Co., Baltimore, Maryland, 1981
20. Billmeyer FW: Survey of color order systems. Color Res Appl 12:173–186, 1987
21. Wyszecki G, Stiles WS: Color Science: Concepts and Methods, Quantitative Data and Formulas, 2nd ed. John Wiley and Sons, Inc., New York, 1967
22. Wright WD: The Measurement of Color, 4th ed. Adam Hilger Ltd., London, 1969
23. Hunter RS, Harold RW: The Measurement of Appearance, 2nd ed. Wiley-Interscience, New York, 1987
24. McDonald R: Color Physics for Industry. Society of Dyers and Colorists, Bradford, 1987
25. Chong TF: Instrumental measurement and control of color. Rev. Prog Coloration 18:47–55, 1988
26. Rosen CF, Jacques SL, Stuart ME, Gange RW: Immediate pigment darkening: visual and reflectance spectrophotometric analysis of action spectrum. Photochem Photobiol 51(3):583–588, 1990