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# Colorimetry, Theory

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**ELECTRONIC SPECTROSCOPY**
**Theory**

Colorimetry is the science of the measurement of colour. It involves the replacement of subjective responses, such as ‘light blue’, ‘rich dark purple’, ‘bright gold’, with an objective numerical system. This study began with the work of Young, Helmholtz and Maxwell in the early nineteenth century, who recognized the principles of additive and subtractive colour mixing, and proposed the trichromatic nature of human colour vision. The science began to be formalized in 1931, when the Commission International de l’Eclairage (CIE) recommended a system of colour specification based on the three tristimulus values *X*, *Y* and *Z*. The current CIE reference document relating to colorimetry is CIE Publication 15.2-1986 (Edition 3 is in preparation); for more practical information on colorimetric measurement, ASTM document E308-96 should be consulted.

## Illumination, object, observer

Three things contribute to our perception of the colour of an object: the nature of the illumination, the optical properties of the object itself and the response of the human eye (**Figure 1**). The nature of the illumination can be characterized by the spectral power distribution $S(\lambda)$ of the light source, the relative intensity of the illumination at each wavelength in the visible spectrum. The object reflects a certain fraction of the incident light and this can be characterized by the reflectance spectrum $R(\lambda)$. The intensity of light entering the eye, $I(\lambda)$, is the product of these terms. Thus in order to measure colour, and to specify colour by numbers, it is necessary to specify each of these three components of the colour trio. In 1931, the CIE recommended standard illuminants for use in colorimetry, published data representing the standard observer and recommended standard optical geometries for use in colour-measuring instruments.

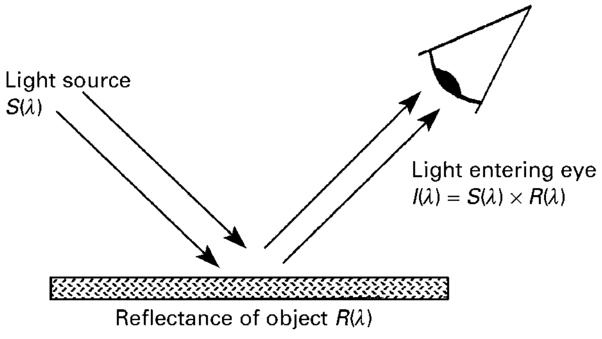

**Figure 1** How colour reaches the eye.

## Standard illuminants (A, C, D65, F)

In 1931 the CIE recommended three standard sources and Illuminants (A, B and C) where a source is a physically realizable light source and an illuminant is a table of data (spectral power distribution) representing a source. A is intended to represent an incandescent tungsten filament lamp (colour temperature 2856 K); B and C may be produced by filtering the light from source A to produce a representation of noon sunlight (B) or average daylight (C). More recently, the CIE has recommended the D series as illuminants only, representing daylight in various phases. D75 (colour temperature 7500 K) represents north sky daylight, D65 (colour temperature 6500 K) represents average daylight and D55 (colour temperature 5500 K) represents sunlight plus skylight. D65 is now the reference illuminant for use in colorimetry (although the graphic arts industry tends to prefer D55) and so should be included in any colour specification. Unfortunately, illuminant D65 is not realizable in practice, and so colour-matching cabinets generally contain a daylight simulator (a filtered fluorescent lamp). A further series of florescent lamps, the F series, were also defined, although none is specified as a standard illuminant. There are three types: normal, broad-band and three-band. The most important are F2 (normal, known as ‘cool white’), F7 (broad-band, known as ‘artificial daylight’ and commonly used for colour matching) and F12 (three-band, with high energy efficiency, and so often used in shops). **Figure 2** shows the relative spectral power distribution of the more commonly used illuminants.

## Standard observers (2-degree, 10-degree)

The experiments that established the basis of colorimetry were carried out separately by J. Guild at the

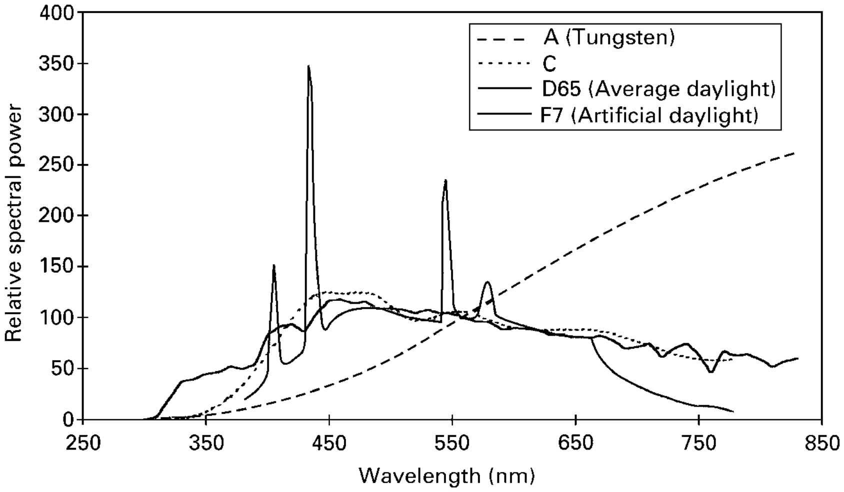

**Figure 2** Relative spectral power distributions of common CIE illuminants.

National Physical Laboratory (UK) and W.D. Wright at Imperial College London in a famous series of experiments in the late 1920s. These experiments were dedicated to characterizing the response of the human eye to different wavelengths of light, and were carried out by colour matching using red, green and blue lights. A set of red, green and blue light sources are often called primary sources since the appearance of any one of the sources cannot be matched by blending together light from the other two. A possible experimental arrangement is illustrated in **Figure 3**. Each worker used several observers (Guild 7 and Wright 10) who adjusted the mixture of light from three primaries until it matched the appearance of the monochromatic light.

These early experiments were carried out using the central area of the retina, the fovea. This region contains the highest concentration of colour-sensitive cells, and occupies the central 2° field (based on the angle to the line of sight, drawn from the centre of the lens to the foveal pit). The standard observer derived from Guild's and Wright's experiments is therefore known as the 2° standard observer (1931). The colour matching functions $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$ represent the amounts of light from the red, green and blue primaries, in tristimulus units, needed to match unit intensity of light with a narrow band of wavelengths centred on $\lambda$. Tristimulus units are defined such that a mixture of equal units of the red, green and blue primaries will match an equal-energy white. The values of the colour-matching functions are normalized so that there is an equal area under each of the spectral curves. The values are plotted against wavelength in **Figure 4**.

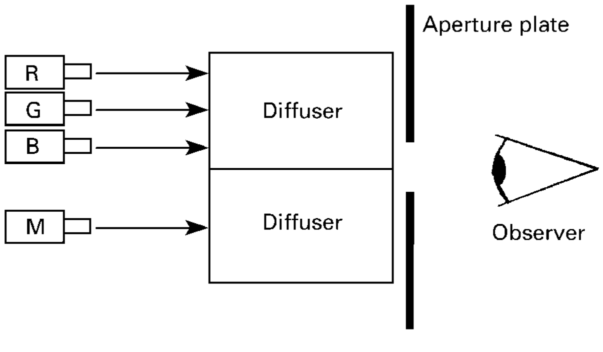

**Figure 3** Possible arrangements of Guild's and Wright's experiments.

It was found that not all the colours produced by monochromatic light could be matched by a simple additive mixture of light from three primaries. For some wavelengths it was necessary to add light from one of the primaries to the monochromatic light, reducing the colour saturation of the monochromatic light. The appearance of the desaturated mixture could then be matched by a combination of the other two primaries. When this occurs, the amount of the primary added to the monochromatic light appears as a negative number in the colour specification.

Later workers observed that although the fovea is the region most sensitive to colour, most everyday objects occupy a larger area of the retina. The 10° standard observer (1964) was thus derived in a similar manner and is now the preferred observer function. The true cone sensitivities were not measured directly until 1979, but correspond very well to those expected from the colour-matching functions found by Guild and Wright.

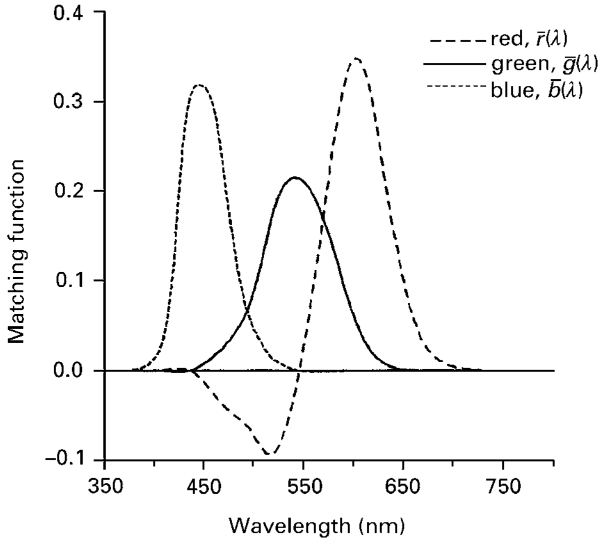

**Figure 4** Guild's and Wright's colour-matching functions.

## RGB specification

The RGB system of colour specification was based on the trichromatic theory of colour vision and the colour-matching experiments carried out by Guild and Wright. It had been suggested by Maxwell in 1860 that if the specifications of the red, green and blue lamps used in such experiments were known, then the amounts of each light required to match a sample colour would provide a numerical specification of that colour. These amounts may be found either by passing the light from the sample through filters matching the RGB primaries, or by calculation from the reflectance values of the sample at a series of wavelengths through the visible spectrum:

$$
\begin{aligned}
R &= k\left[I(\lambda_1)\,\bar{r}(\lambda_1) + I(\lambda_2)\,\bar{r}(\lambda_2) + \cdots\right] \\
\text{or} \quad R &= k\sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{r}(\lambda) \\
G &= k\left[I(\lambda_1)\,\bar{g}(\lambda_1) + I(\lambda_2)\,\bar{g}(\lambda_2) + \cdots\right] \\
\text{or} \quad G &= k\sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{g}(\lambda) \\
B &= k\left[I(\lambda_1)\,\bar{b}(\lambda_1) + I(\lambda_2)\,\bar{b}(\lambda_2) + \cdots\right] \\
\text{or} \quad B &= k\sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{b}(\lambda) \qquad [1]
\end{aligned}
$$

Although RGB values are a valid representation of the colour of an object viewed under specified conditions, for practical reasons these values are rarely used. For a significant proportion of colours one of the three values is negative, and this was considered a distinct disadvantage.

## *XYZ* specification (1931)

The *XYZ* system of colour specification was recommended by the CIE in 1931 and was closely based on the RGB system. The difference lies in the fact that *R*, *G* and *B* were real light sources of known specifications. *X*, *Y* and *Z* are theoretical sources which are more saturated than any real light source, and allow matching of any real colour using positive amounts of the three primary sources. The *X*, *Y* and *Z* stimuli are defined so that:

- The *XYZ* tristimulus values of all real colours are positive.
- The *Y* tristimulus value is proportional to the luminance.
- A mixture of equal amounts of *X*,*Y* and *Z* has the same colour appearance as an equal-energy white.
- The *X*, *Y*, *Z* values of the visible colours have the widest possible range of values.
- The *X* stimulus represents a red more saturated than any spectral red.
- The *Y* stimulus represents a green more saturated than any spectral green.
- The *Z* stimulus represents a blue more saturated than any spectral blue.

*X*, *Y*, *Z* values for the 2° observer may be calculated from RGB values using the equations

$$
\begin{aligned}
X &= 0.49R + 0.31G + 0.20B \\
Y &= 0.17697R + 0.81240G + 0.01063B \\
Z &= 0.00R + 0.01G + 0.99B \qquad [2]
\end{aligned}
$$

Alternatively, *XYZ* values may be calculated from reflectance values using similar equations to those for RGB, but using weighting functions $\bar{x}(\lambda$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$ in place of $\bar{r}(\lambda)$, $\bar{g}(\lambda)$ and $\bar{b}(\lambda)$. The CIE nomenclature is to denote the 10° observer function with a subscripted '10' (Eqn (3)). The *XYZ* system is an improvement over the RGB system in that it eliminates negative numbers in colour specification. However, it is still based on the mixing of coloured lights and not on the visual appreciation of colour. In particular, the visual colour difference between two samples is not linearly related to the difference in *XYZ* values:

$$X_{10} = k\big[I(\lambda_1)\,\bar{x}_{10}(\lambda_1) + I(\lambda_2)\,\bar{x}_{10}(\lambda_2) + \cdots\big]$$

$$\text{or} \quad X_{10} = k \sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{x}_{10}(\lambda)$$

$$Y_{10} = k\big[I(\lambda_1)\,\bar{y}_{10}(\lambda_1) + I(\lambda_2)\,\bar{y}_{10}(\lambda_2) + \cdots\big]$$

$$\text{or} \quad Y_{10} = k \sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{y}_{10}(\lambda)$$

$$Z_{10} = k\big[I(\lambda_1)\,\bar{z}_{10}(\lambda_1) + I(\lambda_2)\,\bar{z}_{10}(\lambda_2) + \cdots\big]$$

$$\text{or} \quad Z_{10} = k \sum_{\lambda=380}^{\lambda=780} I(\lambda)\,\bar{z}_{10}(\lambda) \qquad [3]$$

## *L*a*b** colour space (1976)

CIE $L^*a^*b^*$ colour space is based on the opponent theory of colour vision, which arose from the ideas of Hering. Hering pointed out that of the thousands of words used to describe hue, only four are unique; red, green, yellow and blue. They are unique because they cannot be described without using their own colour name, yet any other hue can be described using one or more words from this set. When taken together with white and black, they form a group of six basic colour properties that can be grouped into three opponent pairs, white/black, red/green and yellow/blue. The concept of opponency arises from the observation that no colour could be described as having attributes of both redness and greenness, or of both yellowness and blueness. A red shade of green just does not exist.

It seems sensible to associate these three opponent pairs with the three axes of a three dimensional colour space. On a colour chart, the amount of redness or greenness of a colour sensation could be represented by the distance along a single axis, with pure red lying at one extremity and pure green lying at the other. In a similar way yellow and blue are opposite extremities of a second axis that could be placed perpendicular to the red/green direction. The third axis would go from white to black and lie in the plane normal to the other two. CIE $L^*a^*b^*$ (1976) space uses three terms $L^*$, $a^*$ and $b^*$ to represent colour, as shown in **Figure 5** and described below.

- $L^*$ The vertical axis represents lightness; 100 represents a perfect white sample and 0 a perfect black.
- $a^*$ The axis in the plane normal to $L^*$ represents the redness–greenness quality of the colour. Positive values denote redness and negative values denote greenness.
- $b^*$ The axis normal to both $L^*$ and $a^*$ represents the yellowness–blueness quality of the colour. Positive values denote yellowness and negative values denote blueness.

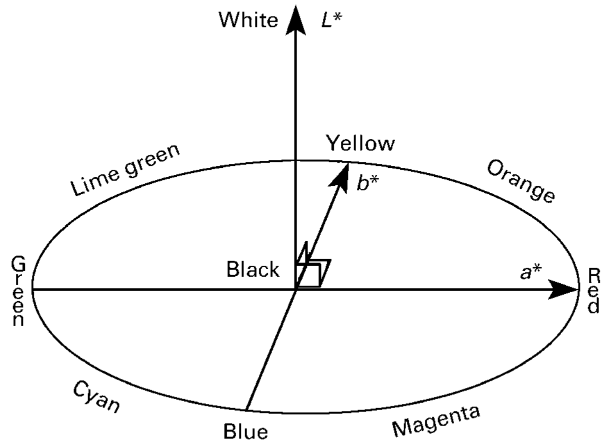

**Figure 5** CIE $L^*a^*b^*$ colour space.

$L^*a^*b^*$ values are calculated from $XYZ$ values using the following equations:

$$F_X = \left(\frac{X}{X_0}\right)^{1/3} \qquad [4a]$$

unless

$$\left(\frac{X}{X_0}\right) \leqslant 0.008\,856$$

when

$$F_X = 7.787\left(\frac{X}{X_0}\right) + \frac{16}{116} \qquad [4b]$$

where $X_0$ is the $X$ tristimulus value of a perfect white sample under the chosen illuminant. Values of $F_Y$ and $F_Z$ are calculated in a similar manner. Then:

$$\begin{aligned} L^* &= 116F_Y - 16 \\ a^* &= 500[F_X - F_Y] \\ b^* &= 200[F_Y - F_Z] \end{aligned} \qquad [5]$$

Since $L^*a^*b^*$ values for a sample may change for a different illuminant and observer combination, any colour specification must always include the illuminant and observer for which the values were calculated.

## CIE $L^*C^*h°$ coordinates

The coordinates of the points representing the colour of a sample can also be expressed in cylindrical coordinates of lightness $L^*$, chroma $C^*$ and hue $h°$, as illustrated in **Figure 6**. This system corresponds more closely to the natural description of colour.

$L^*$ Lightness (see above)
$C^*$ Chroma:

$$C^* = \sqrt{\left(a^{*2} + b^{*2}\right)}$$

$h°$ Hue angle:

$$h° = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad [6]$$

Neutral grey samples would have $C^*$ values between 0 and about 5 units. The hue angle is always measured anticlockwise from the positive $a^*$ axis. It is traditional to associate one of the psychological primary hues with each axis direction, as shown in the diagram, although in reality the angles of the pure hues do not lie exactly along the axis directions.

## Colour difference

As the CIE $L^*a^*b^*$ system was designed to be visually uniform, it is fairly simple to devise an equation for the total colour difference between a trial and standard sample. The total colour difference is the distance between the two points representing those colours in the colour space, as shown in **Figure 7**. The distance, expressed as $\Delta E^*_{ab}$, is determined using the laws of right-angle triangles:

$$\Delta E^*_{ab} = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \qquad [7]$$

where

$$\begin{aligned} \Delta L^* &= L^*_{\mathrm{trl}} - L^*_{\mathrm{std}} \\ \Delta a^* &= a^*_{\mathrm{trl}} - a^*_{\mathrm{std}} \\ \Delta b^* &= b^*_{\mathrm{trl}} - b^*_{\mathrm{std}} \end{aligned} \qquad [8]$$

The overall colour difference may also be split into lightness, chroma and hue terms, which again correspond more closely to the natural description of colour:

$$\Delta C^* = C^*_{\mathrm{trl}} - C^*_{\mathrm{std}} \qquad [9]$$

$$\Delta H^* = \sqrt{\Delta E^{*\,2}_{ab} - \Delta L^{*2} - \Delta C^{*2}} \qquad [10]$$

It is worth remembering that the scaling of the colour space was set so that a value of $\Delta E^*_{ab} = 1$ between the colour of two samples should be just visually perceptible. This means that if a large

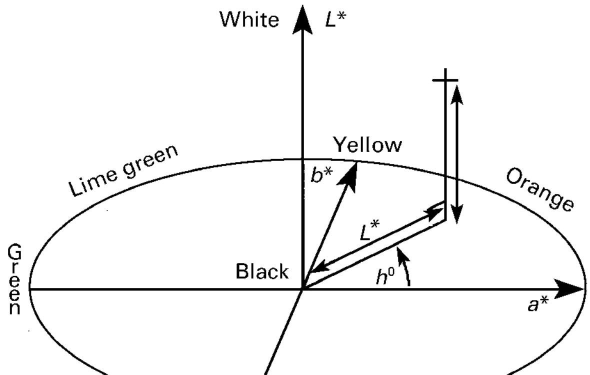

**Figure 6** CIE $L^*C^*h°$ colour coordinates.

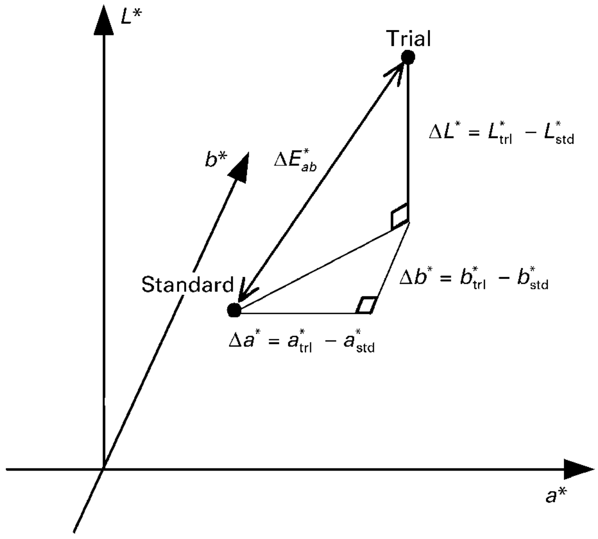

**Figure 7** The CIE $L^*a^*b^*$ colour difference calculation.

number of people were asked to judge the colour difference between the two samples, about 50% of observers would say that there was a difference in colour, the other 50% would say the two colours matched. This is the point of maximum argument.

Comparisons between the majority visual decision and a numerical assessment, based on the condition that $\Delta E^*_{ab}$ must be less that 1 for a match, show that the instrument decision will disagree with the majority visual decision about 19% of the time. On average, an individual colourist will disagree with the majority decision about 17% of the time when judging pairs of panels with fairly small colour differences. Pass/fail decisions based on the CIE $L^*a^*b^*$ (1976) equation with a limit of $\Delta E^*_{ab} = 1$ are, on average, slightly less reliable than visual judgements made by a single colourist. However, a colour-measuring instrument has the great advantage of giving much more repeatable decisions.

A number of scientists have devised more reliable or optimized colour difference equations. The simplest method of improvement is to assign individual tolerances to $\Delta L^*$, $\Delta a^*$ and $\Delta b^*$. Alternatively, individual tolerances can be assigned to $\Delta L^*$, $\Delta C^*$ and $\Delta H^*$ (differences in lightness, chroma and hue). The most successful equations are based on the $\Delta L^*$, $\Delta C^*$, $\Delta H^*$ system of colour splitting and the CMC ($l$, $c$) and CIE 94 equations are of this type. The CMC equation was developed by the Colour Measurement Committee of the Society of Dyers and Colourists (Bradford, UK) and has been adopted as the ISO standard for small colour difference assessment of textile materials. In 1994 the CIE suggested the simpler CIE 94 equation for evaluation. The published evidence collected so far by the CIE suggests that pass/fail decisions made using either of the optimized colour difference equations are considerably more reliable than those based on $\Delta E^*_{ab}$ or on the judgement of a single human colourist. Comparison with decisions made by panels of observers show that the equations disagree with the majority decision about 13% of the time. Neither equation has yet been adopted as a CIE standard as it has been shown that further improvements can still be made.

## Colour and appearance

The systems of colorimetry described above can only specify the colour of an isolated sample viewed against a neutral grey background. However, almost all colours are viewed against different backgrounds, with different fields of view, viewing environments, and states of adaptation to that environment. The surrounding colours or patterns will affect the perceived colour of the sample in ways which cannot be predicted using the CIE $L^*a^*b^*$ system. More complicated models have been developed that take these factors into account; the CIE have recently recommended the CIECAM97s model for further testing. Colour appearance models are becoming increasingly important in these days of digital images and global communication. The faithful reproduction of an image from computer screen to printed hard copy requires an effective colour appearance model at the heart of the colour management system.

## Summary

The use of colour-measuring instruments allows specification and communication of colour by means of international standard terms such as CIE $L^*a^*b^*C^*h^\circ$. Colour difference values can also be determined instrumentally and, if optimized colour difference equations are used, can out-perform a single trained colourist. However, the visual appreciation of colour and colour difference is still a subjective response, affected by many factors. Care must be taken to include measurement conditions in the interpretation of colour measurement data. The gold standard answer must always be that which agrees with the majority of a group of human observers. Whether this can be achieved by optimized equations based on CIE $L^*a^*b^*$ colour space or by colour appearance models remains to be established.

## List of symbols

$a^*$ = redness/greenness; $b^*$ = yellowness/blueness; $c^*$ = chroma; $F_X F_Y F_Z$ = functions of $XYZ$ values used in deriving $L^*a^*b^*$ values; $h^\circ$ = line angle; $I(\lambda)$ = intensity of light entering the eye; $k$ = normalization constant; $L^*$ = lightness; $L^*, a^*, b^*$ = values in the CIE $L^*a^*b^*$ system; $L^*, C^*, h^\circ$ = values in the CIE $L^*C^*h^\circ$ system; $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ = Guild/Wright colour-matching functions; $R(\lambda)$ = reflectance; $R,G,B$ = values in the RGB system; $S(\lambda)$ = spectral power distribution of light source; $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ = weighting functions replacing $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ in the $XYZ$ system; $X,Y,Z$ = tristimulus values in the $XYZ$ system; $\Delta E^*_{ab}$ = distance function in the CIE $L^*a^*b^*$ system.

*See also:* **Art Works Studied Using IR and Raman Spectroscopy; Colorimetry Theory; Dyes and Indicators, Use of UV-Visible Absorption Spectroscopy.**

## Further reading

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