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Color Matching Function

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 λ.

From: Encyclopedia of Spectroscopy and Spectrometry, 1999

Related terms:

Color Matching, Linear Transformation, Wavelength, Chromaticity Diagram, Illuminant, Reflectance, Spectral Sensitivity

Colour representation and colour gamuts

Marcelo Bertalmío, in Vision Models for High Dynamic Range and Wide Colour Gamut Imaging, 2020

6.3 The first standard colour spaces

Recapping, a colour sensation can be described with three parameters; given a test colour, we call its *tristimulus* values the amounts of three colours (primaries in some additive colour model) that are needed to match that test colour. If two single, isolated coloured lights have different spectral distributions but the same tristimulus values, then they will be perceived as being of the same colour.

A *colour space* is a method that associates colours with tristimulus values. Therefore, it is described by three primaries and their corresponding colour matching functions. Given their relationship to tristimulus values, colour spaces are three-dimensional: each colour can be represented as a point in a three-dimensional plot.

In 1931, the International Commission on Illumination (or CIE, for its French name) amalgamated Wright and Guild's data [9] and proposed two sets of colour matching functions for a standard observer, known as CIE RGB and CIE XYZ; this standard for colourimetry is still today one of the most used methods for specifying colours in the industry. The CIE RGB colour matching functions are the functions $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ mentioned earlier. The tristimulus values (R, G, B) for a light $E(\lambda)$ are computed from these functions as stated in Eq. (6.1).

For each wavelength λ, one of the three functions is negative. This posed a problem, since the calculators of the time were manually operated and hence errors were quite common in the computation of the tristimulus values [10]. That's why the CIE XYZ colour matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ were also introduced alongside the CIE RGB ones. From the CIE XYZ functions, the (X, Y, Z) tristimulus values for a light source with spectral distribution $E(\lambda)$ can be computed as:

$$X = \int_{380}^{740} \bar{x}(\lambda)E(\lambda)d\lambda \tag{6.3}$$
$$Y = \int_{380}^{740} \bar{y}(\lambda)E(\lambda)d\lambda$$
$$Z = \int_{380}^{740} \bar{z}(\lambda)E(\lambda)d\lambda.$$

The colour matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are obtained as a linear combination of $\bar{r}(\lambda)$, $\bar{g}(\lambda)$, $\bar{b}(\lambda)$ by imposing certain criteria, chiefly among them:

- $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ must always be positive;
- $\bar{y}(\lambda)$ is identical to the standard luminosity function $V(\lambda)$, which is a dimension-less function describing the sensitivity to light as a function of wavelength; therefore, $Y = \int \bar{y}(\lambda)E(\lambda)d\lambda$ would correspond to the luminance of the colour stimulus;
- $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are normalised so that they produce equal tristimulus values $X = Y = Z$ for a white light, i.e. a light with a uniform (flat) spectrum.

Because the CMFs of CIE XYZ are a linear transformation of the CMFs of CIE RGB, this means that we can go from one colour space to the other with a linear, invertible transform:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \mathbf{M} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{6.4}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \mathbf{M}^{-1} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{6.5}$$

where **M** is a 3×3 matrix.

An important point we must stress is the following. It can be shown that for any set of physically realisable primaries there are wavelengths λ for which the colour matching values are negative. Since $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are always positive, this implies that their primaries can never be physically realisable. This is why the primaries for CIE XYZ are called *virtual primaries*.

We now define the values *x*, *y*, *z*:

$$x = \frac{X}{X+Y+Z} \tag{6.6}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z}.$$

It is easy to see that, for lights E_1 and $E_2 = \alpha E_1$, these values are identical: $x_1 = x_2$, $y_1 = y_2$, $z_1 = z_2$. This is why *x*, *y*, *z* are called the *chromaticity coordinates*, because they don't change if the light stimulus only varies its intensity. We will now see that for *x*, *y*, *z* we have the same properties that we mentioned for *r*, *g*, *b* in the previous section.

By construction $x + y + z = 1$, so $z = 1 - x - y$ and all the information of the chromaticity coordinates is contained in the pair (x, y). Therefore, all the possible chromaticities can be represented in a 2D plane, the plane with axes *x* and *y*, and this is called the CIE *xy* chromaticity diagram; see Fig. 6.5.

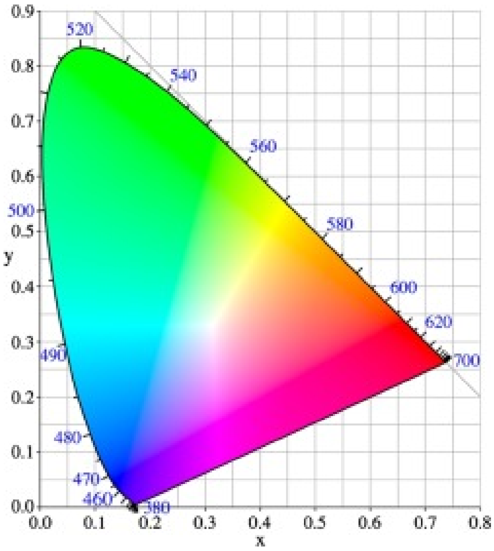

Figure 6.5. CIE *xy* chromaticity diagram

CIE *xy* chromaticity diagram. Figure from [7].

This tongue-shaped region represents all the differents chromaticities that can be perceived by a standard observer; it can be seen as the result of performing this operation: slicing the *XYZ* volume with the plane $X + Y + Z = 1$, then projecting the resulting plane onto the *XY* plane. See Fig. 6.6.

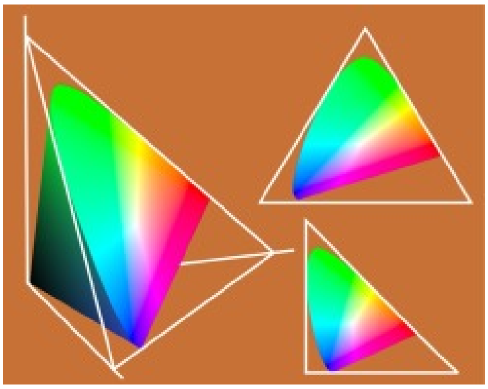

Figure 6.6. *XYZ* volume and *xy* diagram

Left: *XYZ* volume. Top right: after slicing volume with plane *X*+*Y*+*Z*=1. Bottom right: after projecting plane onto *XY* plane.

It is worth remarking that the triplet of values formed by chromaticity (x, y) and luminance *Y* perfectly describes a colour, and from (x, y, Y) we can obtain (X, Y, Z).

The upper boundary of the chromaticity diagram is a horseshoe-shaped curve corresponding to monochromatic colours: this curve is called the spectrum locus [10]. The lower boundary is the purple line, and corresponds to mixtures of lights from the extrema of the spectrum.

If monochromatic lights E_1 and E_2 have coordinates (x_1, y_1) and (x_2, y_2) (that will lie on the spectrum locus because the lights are monochromatic), the mixture $E_3 = E_1 + E_2$ will have coordinates (x_3, y_3) located in the segment joining (x_1, y_1) and (x_2, y_2). Therefore, the tongue-shaped region delimited by the spectrum locus and the purple line represents all the possible chromaticities that we can perceive, as mentioned above.

Helmholtz showed that each monochromatic light had a complementary, i.e. the mix of both lights yields white [4]. Monochromatic lights with wavelengths in the range between red and yellow–green have monochromatic complementaries with wavelengths in the range between blue–green and violets. The complementary of green is not a monochromatic light but purple, a mixture of blue and red light from the two ends of the visible spectrum.

Perfect white (i.e. light with a completely uniform power spectrum) has coordinates $x = y = \frac{1}{3}$, so as we mix a monochromatic light with white, its chromaticity coordinates move inwards and the saturation of the colours is reduced. A pure monochromatic light has 100% saturation while white has 0% saturation. But in practice, white lights never have a completely flat spectrum. The CIE has defined a set of standard illuminants: A for incandescent light, B for sunlight, C for average daylight, D for phases of daylight, E is the equal-energy illuminant, while illuminants F represent fluorescent lamps of various compositions [11]. The illuminants in the D series are defined simply by denoting the temperature in Kelvin degrees of the black-body radiator whose power spectrum is closer to that of the illuminant. A black-body radiator is an object that does not reflect light and emits radiation, and the power spectrum of this radiation is uniquely described by the temperature of the object. This is why in photography it is common to express the tonality of an illuminant by its *colour temperature*: a bluish white will have a high colour temperature, whereas a reddish-white will have a lower colour temperature. For instance, CIE illuminant D65 corresponds to the phase of daylight with a power spectrum close to that of a black-body radiator at $6500°$ K, and D60 to $6000°$ K. These two are the common illuminants used in cinema and TV standards.

Another very important consequence of the linearity property stated before is that any system that uses three primaries to represent colours will only be capable of representing the chromaticities lying inside the triangle determined by the chromaticities of the primaries. Furthermore, because of the convex shape of the chromaticity diagram, any such triangle will be fully contained in the diagram, leaving out chromaticity points. Therefore, for any trichromatic system there will always be colours that the system is not capable of representing.

For instance, Fig. 6.7 shows the chromaticity diagram for a display, where the vertices correspond to the chromaticities of the red (mid gray in print version), green (light gray in print version) and blue (dark gray in print version) light-emitting elements of the device. A display with more saturated primaries will have associated a larger triangle in the chromaticity diagram, and therefore will be able to reproduce more colours. In Section 6.6 we will return to the issue of characterising the range of colours achievable by a device, called its colour gamut.

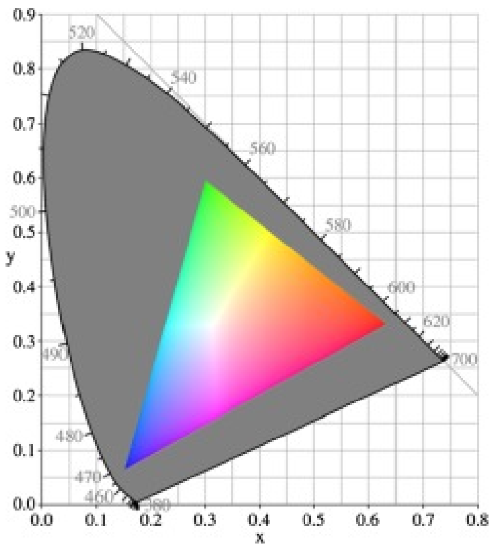

Figure 6.7. Chromaticities of a display

Chromaticities of a display. Image from [12].

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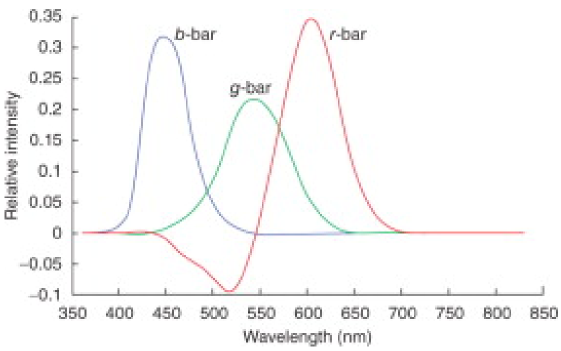
Colour description and communication

J.S. SetchellJr., in Colour Design, 2012

8.12 Derivation of the CIE 1931 standard observer

The experimental basis for determining a person's colour matching functions uses an apparatus that presents the observer with a split field of view. In half the field is presented a mixture of three lights, red, green, and blue, each nearly monochromatic. The intensity of each can be controlled by the observer. In the other half of the field is presented an unknown light. The observer adjusts the intensities of the red, green, and blue lights, called *primaries*, until the mixture matches the unknown. The process is repeated for another unknown, and so on. If the unknowns are themselves nearly monochromatic lights throughout the visible spectrum, a set of curves like Fig. 8.16 results. These curves express the amount of red at 700 nm, green at 546 nm, and blue at 436 nm needed to match light at any given wavelength. It is remarkable that these experiments carried out by W.D. Wright on a handful of subjects in 1930 have formed the basis for the CIE 1931 standard observer, used with considerable success throughout the world for three-quarters of a century!



8.16. Red, green, and blue matching functions.

Notice that a considerable portion of the red curve in the shorter wavelength portion of the spectrum lies below the axis; that is, its values are negative! This feature is an expression of the fact that light of these wavelengths could not be matched by *any* mixture of the primaries. However, when the red primary was shifted to mix with the unknown rather than the other primaries (i.e. 'negative' light), a match could be obtained.

Since it was thought to be inconvenient to deal with colour matching functions containing negative values, a linear transformation was used to convert the *rgb* curves to *x*-bar, *y*-bar, *z*-bar curves having no negative values. This transformation has the form

$$\left(\begin{aligned} \bar{x} &= 2.7688r + 1.7517g + 1.1301b \\ \bar{y} &= 1.0000r + 4.5906g + 0.0601b \\ \bar{z} &= 0.0000r + 0.0565g + 5.5942b \end{aligned} \right\} \quad [8.1]$$

When the *rgb* curves of Fig. 8.16 are multiplied one wavelength value at a time by these coefficients, the *x*-bar, *y*-bar, *z*-bar curves shown in Fig. 8.15 result. These curves are the definition of the 1931 CIE Standard Observer. The XYZ tristimulus values obtained by multiplying *s*-*i* values are a kind of 'red', 'green', and 'blue' description of the colour of the specimen illuminated by the specified light.

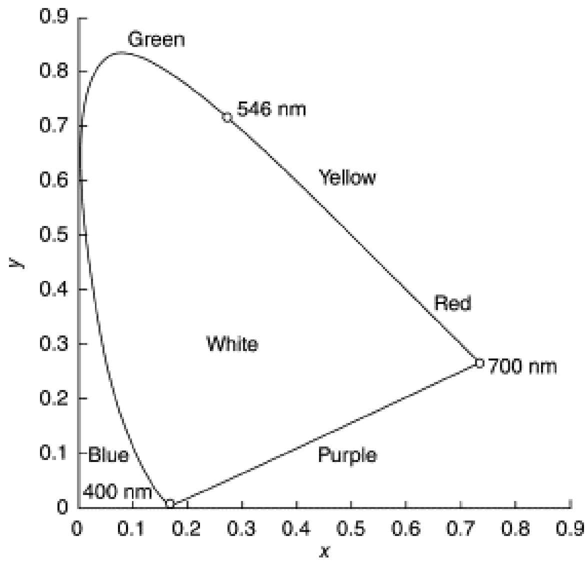
One of the first transformations of XYZ co-ordinates to something else recognized that we tend to separate in our thinking the intensity of light from the 'colour' or, more precisely, the chromatic component of colour, here called *chromaticity*. Chromaticity co-ordinates *x* and *y* are calculated thus:

$$\left(\begin{array}{l} x = \frac{X}{X+Y+Z} \\ y = \frac{Y}{X+Y+Z} \end{array} \right\} \quad [8.2]$$

(Chromaticity co-ordinate z can be calculated in similar fashion, but since $x + y + z = 1$, it is not needed.)

The XYZ co-ordinates have been chosen so that Y represents intensity of the light entering the eye regardless of colour. Therefore *xy*Y is a new triad of numbers specifying a colour, with the intensity all in Y and the chromaticity all in *xy*.

A plot of the horeshoe-shaped locus of pure spectrum colours is shown in Fig. 8.17. Note that the red and blue ends of the spectrum locus are joined by a straight line representing purples, which cannot be made of light at a single wavelength but rather are made by combining red and blue light. Traversing around the spectrum locus and the purple line, we encounter colours varying in a continuous fashion: red, orange, yellow, green, blue, purple, and red again. The Y co-ordinate specifying light intensity is at a right angle to the plane of the spectrum locus, that is, perpendicular to the plane of the figure.



8.17. CIE spectrum locus.

It is easy to see the location of the *rgb* primaries in the *xy* diagram; they are on the spectrum locus in the positions indicated. It might be asked, 'Where are the primaries of the *x*-bar, *y*-bar, *z*-bar system?' The *x*-bar primary is located on the horizontal axis at $x = 1$. The *y*-bar primary is on the vertical axis at $y = 1$. The *z*-bar primary is at the origin, $x = y = 0$. These primaries are all outside the spectrum locus; for this reason, they are *imaginary* rather than real.

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Color Science

Robert M. Boynton, in Encyclopedia of Physical Science and Technology (Third Edition), 2003

II.B Imaginary Primaries

Depending on the choice of primaries, many different sets of color-matching functions are possible, all of which describe the same color-matching behavior. Figure 1 shows experimental data for the primaries 435.8, 546.1, and 700.0 nm. Depicted in Fig. 2 are current estimates of the spectral sensitivities of the three types of cone photoreceptors. These functions, which have been inferred from the data of psychophysical experiments of various kinds, agree reasonably well with direct microspectrophotometric measurements of the absorption spectra of outer segments of human cone photoreceptors containing the photopigments that are the principal determinants of the spectral sensitivity of the cones.

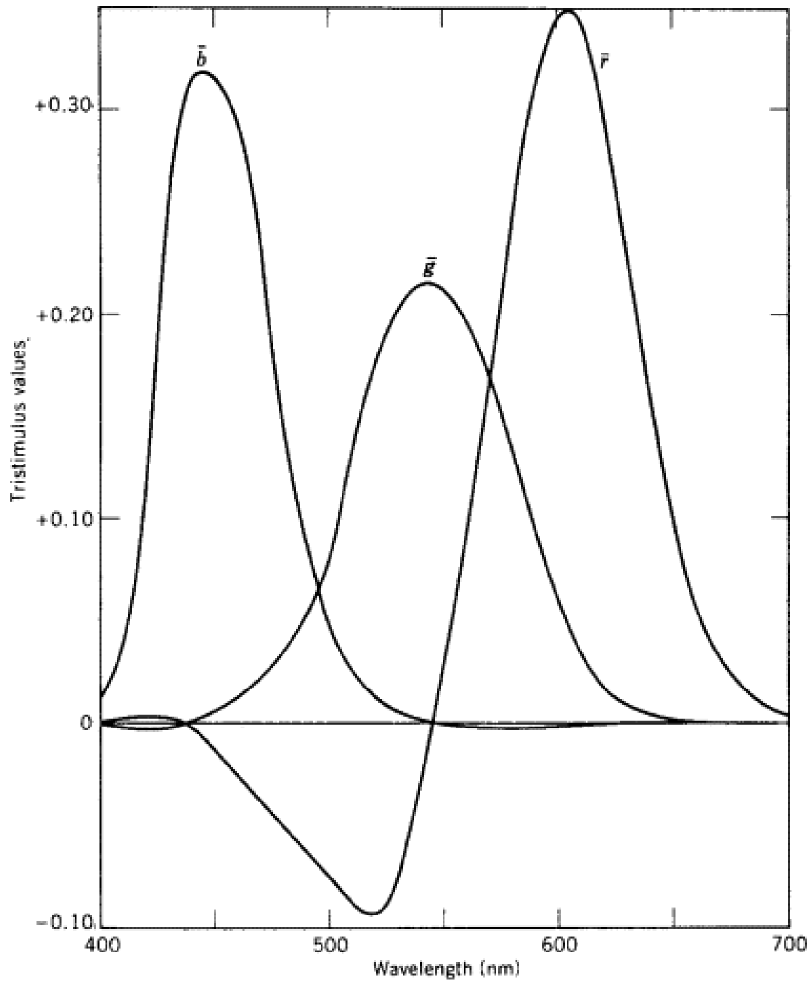

FIGURE 1. Experimental color-matching data for primaries at 435.8, 546.1, and 700.0 nm. [From Billmeyer, F. W., Jr., and Saltzmann, M. (1981). “Principles of Color Technology,” 2nd ed. Copyright © 1981 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.]

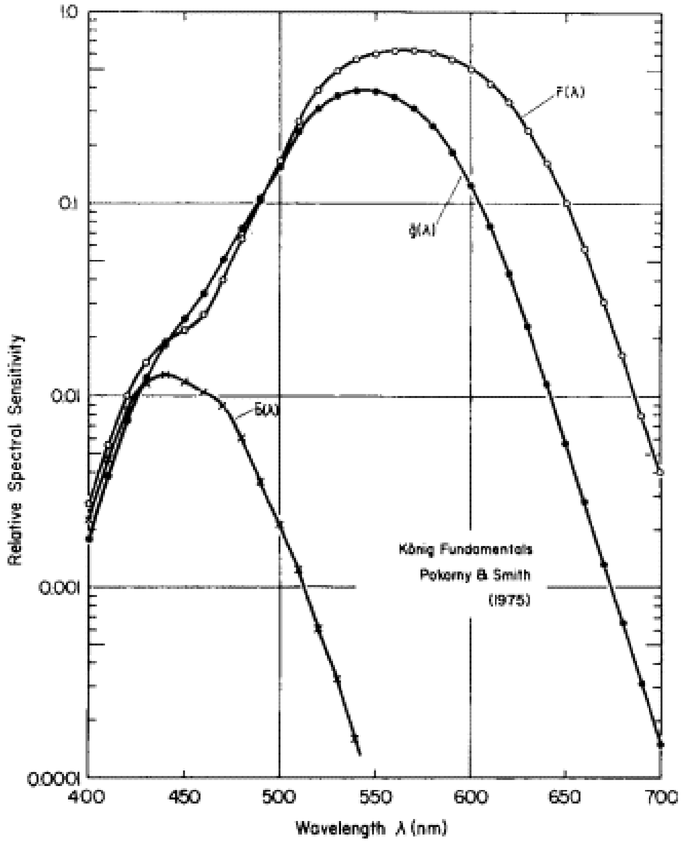

FIGURE 2. Estimates of human cone action spectra (König fundamentals) derived by V. Smith and J. Pokorny. [From Wyszecki, G., and Stiles, W. S. (1982). “Color Science: Concepts and Methods, Quantitative Data and Formulate,” 2nd ed. Copyright © 1982 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.]

The cone spectral sensitivities may be regarded as color-matching functions based on primaries that are said to be imaginary in the sense that, although calculations of color matches based on them are possible, they are not physically realizable. To exist physically, each such primary would uniquely excite only one type of cone, whereas real primaries always excite at least two types.

Another set of all-positive color-matching functions, based on a different set of imaginary primaries, is given in Fig. 3. This set, which makes very similar predictions about color matches as the cone sensitivity curves, was adopted as a standard by the International Commission on Illumination (CIE) in 1931.

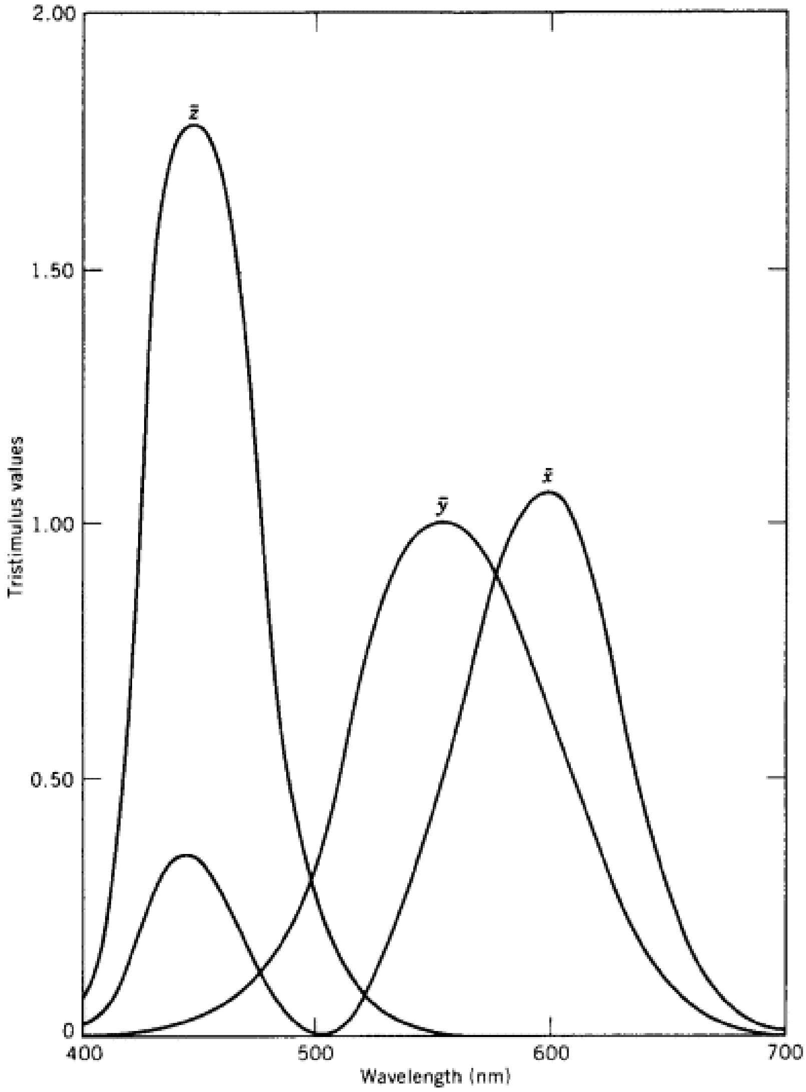

FIGURE 3. Tristimulus values of the equal-energy spectrum of the 1931 CIE system of colorimetry. [From Billmeyer, F. W., Jr., and Saltzmann, M. (1981). "Principles of Color Technology," 2nd ed. Copyright © 1981 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.]

By simulating any of these sets of sensitivity functions in three optically filtered photocells, it is possible to remove the human observer from the system of color measurement (colorimetry) and develop a purely physical (though necessarily very limited) description of color, one that can be implemented in automated colorimeters.

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Principles of colour perception

Asim Kumar Roy Choudhury, in Principles of Colour and Appearance Measurement, 2014

4.6 CIE 10° standard observer functions

2° area of viewing was used for assessment of the 1931 standard colour matching function. Jacobson (1948) showed that the CIE $\bar{z}(\lambda)$ function gives less weight to short waves near violet. Less violet sensitivity for a small area of viewing may be due to the presence of yellow pigment in the central portion of the retina. As most commercial visual judgements employ a larger area of viewing, CIE proposed 10° Standard Observer in 1960 based on matching data for a matching field of 10°

angular subtenses ignoring the central area because of its difference in appearance from the rest of the field.

Stiles-Burch 10° data (Wyszecki and Stiles, 1982), together with those obtained by Speranskaya (MacDonald, 1987), formed the basis for the CIE 1964 supplementary standard observer functions. The CIE standard observer functions are shown in Table 4.3. The $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, $\overline{z}(\lambda)$ functions of 2° and 10° Standard Observers are compared in Fig. 4.3b. The differences are not very high and the changes caused by using 10° Observer instead of the 1931 2° Observer are small.

Table 4.3. CIE 2° (1931)° and 10° (1964) standard observer functions

Wavelength	**2° standard observer functions**			**10° standard observer functions**		
(nm)	$\overline{x}(\lambda)$	$\overline{y}(\lambda)$	$\overline{z}(\lambda)$	$\overline{x}(\lambda)$	$\overline{y}(\lambda)$	$\overline{z}(\lambda)$
380	0.0014	0	0.0065	0.0002	0	0.0007
390	0.0042	0.0001	0.0201	0.0024	0.0003	0.0105
400	0.0143	0.0004	0.0679	0.0191	0.002	0.086
410	0.0435	0.0012	0.2074	0.0847	0.0088	0.3894
420	0.1344	0.004	0.6456	0.2045	0.0214	0.9725
430	0.2839	0.0116	1.3856	0.3147	0.0387	1.5535
440	0.3483	0.023	1.7471	0.3837	0.0621	1.9673
450	0.3362	0.038	1.7721	0.3707	0.0895	1.9948
460	0.2908	0.06	1.6692	0.3023	0.1282	1.7454
470	0.1954	0.091	1.2876	0.1956	0.1852	1.3176
480	0.0956	0.139	0.8132	0.0805	0.2536	0.7721
490	0.032	0.208	0.4652	0.0162	0.3391	0.4153
500	0.0049	0.323	0.272	0.0038	0.4608	0.2185
510	0.0093	0.503	0.1582	0.0375	0.6067	0.112
520	0.0633	0.71	0.0782	0.1177	0.7618	0.0607
530	0.1655	0.862	0.0422	0.2365	0.8752	0.0305
540	0.2904	0.954	0.0203	0.3768	0.962	0.0137
550	0.4334	0.995	0.0087	0.5298	0.9918	0.004
560	0.5945	0.995	0.0039	0.7052	0.9973	0
570	0.7621	0.952	0.0021	0.8787	0.9556	0
580	0.9163	0.87	0.0017	1.0142	0.8689	0
590	1.0263	0.757	0.0011	1.1185	0.7774	0
600	1.0622	0.631	0.0008	1.124	0.6583	0
610	1.0026	0.503	0.0003	1.0305	0.528	0
620	0.8544	0.381	0.0002	0.8563	0.3981	0
630	0.6424	0.265	0	0.6475	0.2835	0
640	0.4479	0.175	0	0.4316	0.1798	0

Wavelength	2° standard observer functions			10° standard observer functions		
(nm)	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$	$\bar{x}(\lambda)$	$\bar{y}(\lambda)$	$\bar{z}(\lambda)$
650	0.2835	0.107	0	0.2683	0.1076	0
660	*0.1649*	*0.061*	*0*	0.1526	0.0603	0
670	0.0874	0.032	0	0.0813	0.0318	0
680	0.0468	0.017	0	0.0409	0.0159	0
690	0.0227	0.0082	0	0.0199	0.0077	0
700	0.0114	0.0041	0	0.0096	0.0037	0
710	0.0058	0.0021	0	0.0046	0.0018	0
720	0.0029	0.001	0	0.0022	0.0008	0
730	0.0014	0.005	0	0.001	0.0004	0
740	0.0007	0.0003	0	0.0005	0.0002	0
750	0.0003	0.001	0	0.0003	0.0001	0
760	0.0002	0.001	0	0.0001	0	0
770	0.0001	0	0	0.0001	0	0
780	0	0	0	0	0	0

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International standards for colour

T.M. Goodman, in Colour Design (Second Edition), 2012

18.4 Future trends

Colourimetry has three key objectives: colour specification, colour difference evaluation and the prediction of colour appearance. The fact that the CIE 1931 and 1964 standard colourimetric observers are still in general use today demonstrates that the tristimulus values calculated using these functions provide a reasonably accurate description of a colour stimulus across an extremely wide range of applications. This practical utility, and the huge upheaval in colour measurement and specification that would result from any change to the basis of colour specification, means that there would be strong resistance from industry (and elsewhere) to any proposed change in these functions. Thus the CIE 1931 and 1964 standard colourimetric observers, and the associated X, Y, Z (or X_{10}, Y_{10}, Z_{10}) tristimulus values, are likely to continue to underpin all areas of colourimetry for the foreseeable future. Similarly, the systems that have been developed and standardised for colour specification, colour difference evaluation and colour appearance modelling, described earlier in this chapter, have proved successful in a wide range of applications and are therefore likely to continue to be used in product design and specification, quality control and legislative requirements for many years to come.

This does not mean, however, that research into colour vision, colour-matching functions, more uniform colour spaces, improved systems for colour appearance, and improved measurement instrumentation and calibration standards will not (or indeed should not) continue. On the contrary, it is still the case that human observers are able to see differences between coloured samples that are at the limit of, or even exceed, what can be reliably achieved by instrumental measurement and the use of colour difference formulae, and that colour appearance models give only a limited representation of the actual visual impression. Thus colourimetry continues to be an area of extremely active research, much of which is being coordinated through the auspices of the CIE, including:

- Standardised response curves based on the physiological properties of the eye (i.e. on the spectral response of the long-, middle- and short-wavelength sensitive cone receptors in the retina and the selective absorption properties of the lens, macular pigment, etc. in the eye). This may ultimately lead to a new 'fundamental' chromaticity diagram based on these cone responses, and to the ability to make measurements in a way that allows for variations between individuals (colour blindness being an extreme example) or for changes in visual characteristics as we age (e.g. 'yellowing of the lens').
- Standardised daylight sources that provide a close representation of the standard daylight illuminants, possibly coupled with a redefinition of the daylight illuminants themselves. This is important not just for visual colour matching in viewing booths, but also for instrumental measurements of fluorescent materials.
- Improved colour difference formulae that correlate more closely with human visual colour discrimination, particularly for small colour differences, nondaylight illuminants or comparisons between images (as opposed to object colours).
- Improved colour appearance models, incorporating spatial (and possibly also temporal) aspects of visual perception. This would enable better evaluation of the appearance of complex visual stimuli, such as images displayed on a television, and provide the basis for image quality metrics.
- Models for total appearance that include not just colour, but also other factors that influence the appearance of three dimensional objects in particular, such as haze, gloss and texture (Pointer, 2003).

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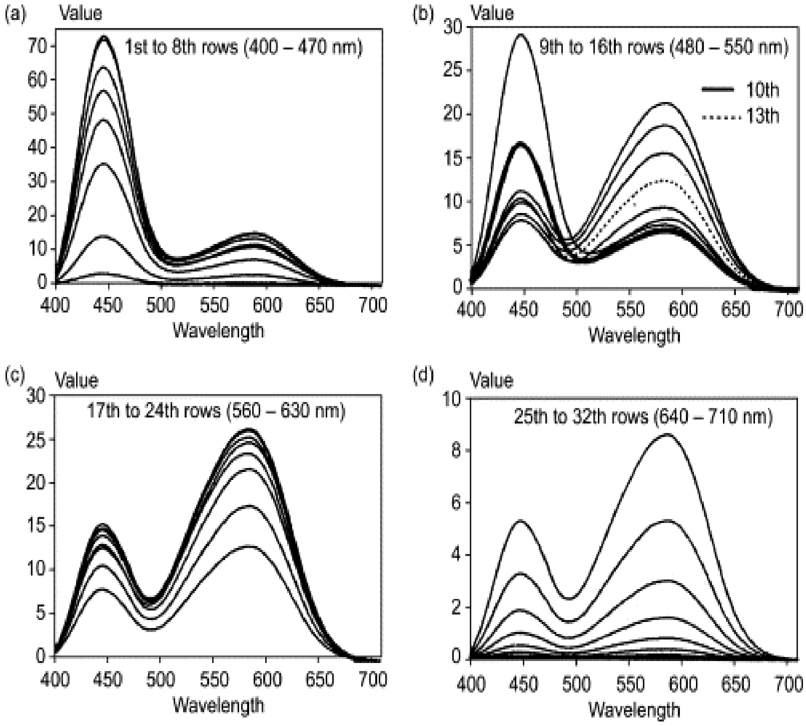
Metamerism and shade sorting

A.K. Roy Choudhury, in Principles of Colour and Appearance Measurement, 2015

5.11.2 Computation of Matrix R

The Matrix R (32 × 32 matrix) was derived from the 1964 colour matching functions A ($\bar{x}_\lambda, \bar{y}_\lambda, \bar{z}_\lambda$, 32 × 3 matrix) using Equation [5.19]. The 32 rows (in groups of eight) of the Matrix R are plotted in Figs 5.6a–d. Each row or column represents every 10th nm wavelength between 400 and 710 nm. All the rows have two maxima – one at 450 nm (first peak), another at 590 nm (second peak). From the first row till 6th, values increase at each wavelength. At sixth row (top-most curve in Fig. 5.6a), the value reaches to a maximum of 74.3 at 450 nm and 15.7 at 590 nm. Then the values decrease for the subsequent rows and reach lowest values of 11.92 at 450 nm for 13th row and 6.84 at 590 nm for 10th row (Fig. 5.6b). The values again increase and reach maximum values of 15.7 and 27.01 for successive peaks at the 20th row (topmost curve in Fig. 5.6c). The values then decrease again for successive rows at all wavelengths and reach near unity at the 32nd row (lowest curve in Fig. 5.6d). As the matrix is symmetric, column values also change in a similar way. The colour matching functions used for deriving Matrix R were not weighted with SPD of any illuminant. Therefore, the fundamentals and the residuals obtained using the Matrix R may be considered to be equivalent to those under equi-energy spectrum.



5.6. Matrix R based on 1964 colour matching functions.

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Color and Multispectral Image Representation and Display

H.J. Trussell, in The Essential Guide to Image Processing, 2009

8.5.3.2 Property 2 (Transformation of Primaries)

If a different set of primary sources, **Q**, are used in the color-matching experiment, a different set of color-matching functions, **B**, are obtained. The relation between the two color-matching matrices is given by

$$\mathbf{B}^T = \left(\mathbf{A}^T\mathbf{Q}\right)^{-1}\mathbf{A}^T. \tag{8.19}$$

The more common interpretation of the matrix $\mathbf{A}^T\mathbf{Q}$ is obtained by a direct examination. The *j*th column of **Q**, denoted $\mathbf{q}_j$, is the spectral distribution of the *j*th primary of the new set. The element $[\mathbf{A}^T\mathbf{Q}]_{i,j}$ is the amount of the primary $\mathbf{p}_i$ required to match primary $\mathbf{q}_j$. It is noted that the above form of the change of primaries is restricted to those that can be adequately represented under the assumed sampling discussed previously. In the case that one of the new primaries is a Dirac delta function located between sample frequencies, the transformation $\mathbf{A}^T\mathbf{Q}$ must be found by interpolation. The CIE RGB color-matching functions are defined by the monochromatic lines at 700 nm, 546.1 nm, and 435.8 nm, shown in Fig. 8.7. The negative portions of these functions are particularly important since it implies that all color-matching functions associated with realizable primaries have negative portions.

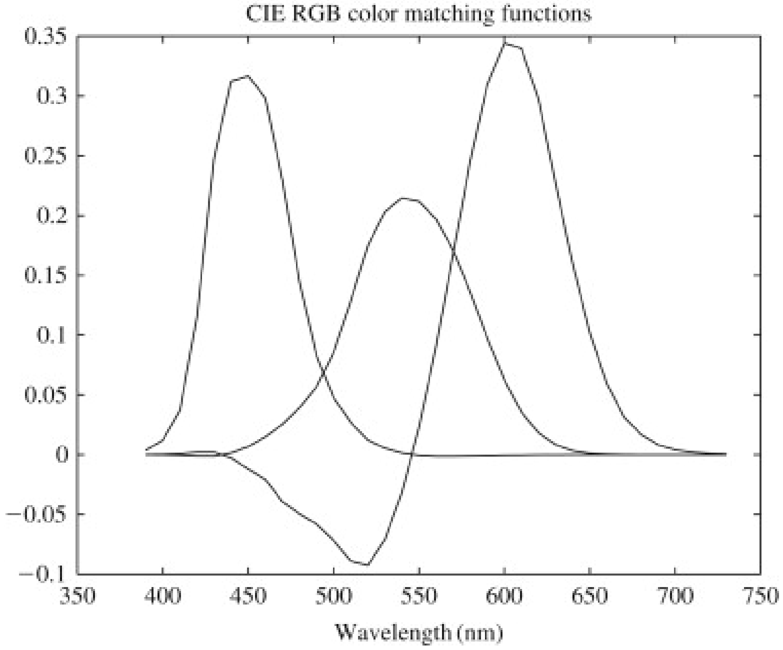

FIGURE 8.7. CIE XYZ color-matching functions.

One of the uses of this property is in determining the filters for color television cameras. The color-matching functions associated with the primaries used in a television monitor are the ideal filters. The tristimulus values obtained by such filters would directly give the values to drive the color guns. The NTSC standard [*R*, *G*, *B*] are related to these color-matching functions. For coding purposes and efficient use of bandwidth, the RGB values are transformed to YIQ values, where Y is the CIE Y (luminance) and, I and Q carry the hue and saturation information. The transformation is a 3×3 matrix multiplication [3] (see Property 3).

Unfortunately, since the TV primaries are realizable, the color-matching functions which correspond to them are not. This means that the filters which are used in TV cameras are only an approximation to the ideal filters. These filters are usually obtained by simply clipping the part of the ideal filter which falls below zero. This introduces an error which cannot be corrected by any postprocessing.

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URL: https://www.sciencedirect.com/science/article/pii/B9780123744579000081

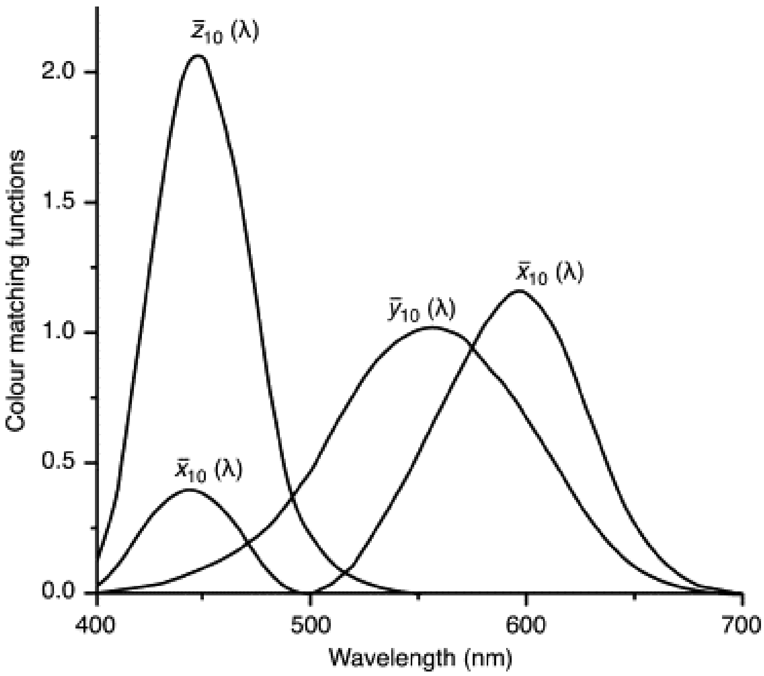
Colour measurement of food: principles and practice

D.B Macdougall, in Colour Measurement, 2010

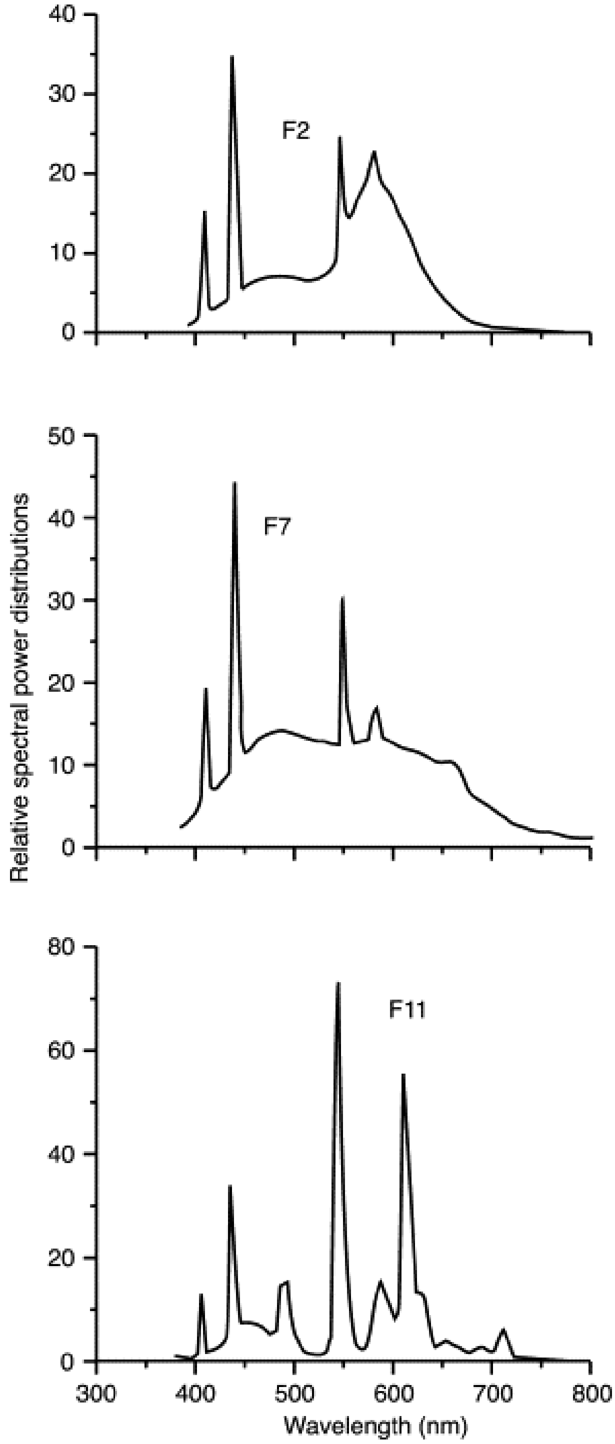
13.6 Colour description: the CIE system

The CIE system of colour measurement (ASTM 2000; CIE 1986) transforms the reflection or transmission spectrum of the object into three-dimensional colour space using the spectral power distribution of the illuminant and the colour-matching functions of the standard observers (CIE 1986). The mathematical procedures are given in any standard text on colour, for example Wright (1980), Judd and Wyszecki (1975), Hunt (2001) and Berns (2000). The system is based on the trichromatic principle but, instead of using 'real' red, green and blue primaries with their necessity for negative matching, it uses 'imaginary' positive primaries X, Y, and Z. Primary Y, known as luminous reflectance or transmittance, contains the entire lightness stimulus. Every colour can be located uniquely in the 1931 CIE colour space by *Y* and its chromaticity coordinates $x = X/(X + Y + Z)$ and $y = Y/(X + Y + Z)$, provided the illuminant and the observer are defined.

The original illuminant representative of daylight was defined by the CIE as source C, but is now superseded by D65, i.e., an illuminant which includes an ultraviolet component and has a colour temperature of 6500°K. The colour temperatures of lamps and daylight range from approximately 3000°K for tungsten filament lamps and 4000°K for warm white fluorescent to 5500°K for sunlight and 6500°K for average overcast daylight to approximately 20000°K for totally sunless blue sky. Because the original 2° colour-matching functions apply strictly only to small objects, i.e., equivalent to a 15 mm diameter circle viewed at a distance of 45 cm, the CIE has added a 10° observer (Fig. 13.2) where the object diameter is increased to 75 mm. Currently, the trend in colour measurement is to use D65 and the 10° observer except for very small objects. The 1986 CIE recommended procedures for colorimetry are included in the ASTM Standards (2000) and also in Hunt (2001) along with the weighting factors for several practical illuminants (Rigg 1987). These include representative fluorescent lamps, of which F2 is a typical lamp at 4230° K but with a low colour-rendering index (R_a) of 64 (Fig. 13.3). The colour-rendering index R_a is a measure of the efficiency of a lamp at a given colour temperature to render the true appearance of Munsell colours. The broadband lamp F7 has the same colour temperature (6500°K) and chromaticity co-ordinates as D65 and, because of its flatter spectrum, it has a high R_a of 90. The triband lamp F11 (4000° K) also has a moderately high R_a of 80, but its main advantage is its much improved efficiency in energy utilisation.



13.2. Colour matching functions of the CIE 10° standard observer.



13.3. Relative spectral power distributions of preferred CIE representative fluorescent lamps.

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Appendix 4: Color images

Mark S. Nixon, Alberto S. Aguado, in Feature Extraction & Image Processing for Computer Vision (Third Edition), 2012

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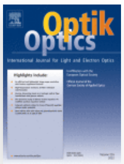

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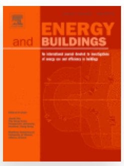

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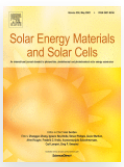

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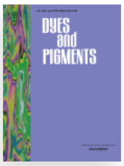

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