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Colorimetry —

Part 1: CIE standard colorimetric observers

Colorimétrie —

Partie 1: Observateurs CIE de référence pour la colorimétrie

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Foreword

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This document was prepared by the International Commission on Illumination (CIE) in cooperation with Technical Committee ISO/TC 274, *Light and lighting*.

This first edition of ISO/CIE 11664-1 cancels and replaces ISO 11664-1:2007 | CIE S 014-1:2006, of which it constitutes a minor revision, incorporating minor editorial updates.

A list of all parts in the ISO 11664 and ISO/CIE 11664 series can be found on the ISO website.

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Introduction

Colours with different spectral compositions can look alike. An important function of colorimetry is to determine whether a pair of such metameric colour stimuli will look alike. The use of visual colorimeters for this purpose is handicapped by variations in the colour matches made among observers classified as having normal colour vision. Visual colorimetry also tends to be time-consuming. For these reasons, it has long been the practice in colorimetry to make use of sets of colour-matching functions to calculate tristimulus values for colours: equality of tristimulus values for a pair of colours indicates that the colour appearances of the two colours match, when they are viewed in the same conditions by an observer for whom the colour-matching functions apply. The use of standard sets of colour-matching functions makes the comparison of tristimulus values obtained at different times and locations possible.

Colorimetry —

Part 1: CIE standard colorimetric observers

1 Scope

This document specifies colour-matching functions for use in colorimetry. Two sets of colour-matching functions are specified.

a) Colour-matching functions for the CIE 1931 standard colorimetric observer.

This set of colour-matching functions is representative of the colour-matching properties of observers with normal colour vision for visual field sizes of angular subtense from about 1° to about 4°, for vision at photopic levels of adaptation.

b) Colour-matching functions for the CIE 1964 standard colorimetric observer.

This set of colour-matching functions is representative of the colour-matching properties of observers with normal colour vision for visual field sizes of angular subtense greater than about 4°, for vision at sufficiently high photopic levels and with spectral power distributions such that no participation of the rod receptors of the retina is to be expected.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

CIE S 017:—,[1)] *ILV: International Lighting Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in CIE S 017 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
colour stimulus function
$\varphi_\lambda(\lambda)$
function describing the spectral distribution of the colour stimulus

Note 1 to entry: The colour stimulus function is generated by the spectral distribution of a radiometric quantity, such as radiance or radiant flux.

Note 2 to entry: For object colours the colour stimulus function, $\varphi_\lambda(\lambda)$, is equal to the product of the relative spectral distribution, $S(\lambda)$, and either the spectral reflectance, $\rho(\lambda)$, or the spectral radiance factor, $\beta(\lambda)$, or the spectral transmittance, $\tau(\lambda)$, depending on the application.

1) Under preparation. Stage at the time of publication: CIE DIS 017:2016.

[SOURCE: CIE S 017:—, entry 17-23-003, modified — The definition has been completely revised and the notes to entry have been added.]

3.2
metameric colour stimuli, pl
metamers, pl
spectrally different colour stimuli that have the same tristimulus values in a specified colorimetric system

Note 1 to entry: The corresponding property is called “metamerism”.

[SOURCE: CIE S 017:—, entry 17-23-008]

3.3
monochromatic stimulus
spectral stimulus
stimulus consisting of monochromatic radiation

[SOURCE: CIE S 017:—, entry 17-23-011]

3.4
equi-energy spectrum
equal energy spectrum
spectrum of radiation whose spectral distribution of a radiometric quantity as a function of wavelength is constant throughout the visible region

Note 1 to entry: The radiation of the equi-energy spectrum is sometimes regarded as an illuminant, in which case it is denoted by the symbol E.

[SOURCE: CIE S 017:—, entry 17-23-023, modified — “$(\varphi_\lambda(\lambda) = \text{constant})$” at the end of the definition omitted.]

3.5
additive mixture
<colour stimuli> stimulation that combines on the retina the actions of various colour stimuli in such a manner that they cannot be perceived individually

[SOURCE: CIE S 017:—, entry 17-23-030]

3.6
colour matching
action of making a colour stimulus appear the same in colour as a given colour stimulus

[SOURCE: CIE S 017:—, entry 17-23-031]

3.7
trichromatic system
system for specifying colour stimuli in terms of tristimulus values, based on matching colours by additive mixture of three suitably chosen reference colour stimuli

[SOURCE: CIE S 017:—, entry 17-23-036]

3.8
reference colour stimuli, pl
three colour stimuli on which a trichromatic system is based

Note 1 to entry: These stimuli are either real colour stimuli or theoretical stimuli which are defined by linear combinations of real colour stimuli.

Note 2 to entry: In the CIE standard colorimetric systems, the reference colour stimuli are represented by the symbols [R], [G], [B]; [X], [Y], [Z]; $[\mathrm{R}_{10}]$, $[\mathrm{G}_{10}]$, $[\mathrm{B}_{10}]$ or $[\mathrm{X}_{10}]$, $[\mathrm{Y}_{10}]$, $[Z_{10}]$.

[SOURCE: CIE S 017:—, entry 17-23-037, modified — “set of three" has been changed to “three" and the "and" has been changed to "or" in Note 2 to entry.]

3.9
tristimulus values, pl
<of a colour stimulus> amounts of the reference colour stimuli, in a given trichromatic system, required to match the colour of the stimulus considered

Note 1 to entry: In the CIE standard colorimetric systems, the tristimulus values are represented, for example, by the symbols R, G, B; X, Y, Z; R_{10}, G_{10}, B_{10} or X_{10}, Y_{10}, Z_{10}.

[SOURCE: CIE S 017:—, entry 17-23-038, modified — “amount of the three reference" has been changed to "amounts of the reference".]

3.10
colour-matching functions, pl
<of a trichromatic system> tristimulus values of monochromatic stimuli of equal radiant flux

[SOURCE: CIE S 017:—, entry 17-23-039, modified — Notes to entry omitted.]

3.11
CIE 1931 standard colorimetric system
X, *Y*, *Z*
system for determining the tristimulus values of any spectral power distribution using the set of reference colour stimuli [X], [Y], [Z], and the three CIE colour-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ adopted by the CIE in 1931

Note 1 to entry: $\bar{y}(\lambda)$ is identical to $V(\lambda)$ and hence the tristimulus values Y are proportional to values of luminance.

Note 2 to entry: The CIE 1931 standard colorimetric system is applicable to centrally viewed fields of angular subtense between about 1° and about 4° (0,017 rad and 0,07 rad).

Note 3 to entry: The CIE 1931 standard colorimetric system can be derived from the CIE 1931 RGB colorimetric system using a transformation based on a set of three linear equations. The CIE 1931 RGB system is based on three real monochromatic reference stimuli.

Note 4 to entry: See also CIE 15, *Colorimetry*.

[SOURCE: CIE S 017:—, entry 17-23-045]

3.12
CIE 1964 standard colorimetric system
X_{10}, Y_{10}, Z_{10}
system for determining the tristimulus values of any spectral power distribution using the set of reference colour stimuli [X_{10}], [Y_{10}], [Z_{10}], and the three CIE colour-matching functions $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ adopted by the CIE in 1964

Note 1 to entry: The CIE 1964 standard colorimetric system is applicable to centrally viewed fields of angular subtense greater than about 4° (0,07 rad).

Note 2 to entry: When the CIE 1964 standard colorimetric system is used, all symbols that represent colorimetric measures are distinguished by use of the subscript 10.

Note 3 to entry: See also CIE 15, *Colorimetry*.

[SOURCE: CIE S 017:—, entry 17-23-046]

3.13
CIE colour-matching functions, pl
functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ in the CIE 1931 standard colorimetric system or $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ in the CIE 1964 standard colorimetric system

[SOURCE: CIE S 017:—, entry 17-23-047]

3.14
CIE 1931 standard colorimetric observer
ideal observer whose colour-matching properties correspond to the CIE colour-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ adopted by the CIE in 1931

[SOURCE: CIE S 017:—, entry 17-23-049]

3.15
CIE 1964 standard colorimetric observer
ideal observer whose colour-matching properties correspond to the CIE colour-matching functions $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ adopted by the CIE in 1964

[SOURCE: CIE S 017:—, entry 17-23-050, modified — Note 1 to entry omitted.]

3.16
chromaticity coordinates, pl
coordinates expressing the quotients of each of a set of three tristimulus values to their sum

Note 1 to entry: As the sum of the three chromaticity coordinates is equal to 1, two of them are sufficient to define a chromaticity.

Note 2 to entry: In the CIE standard colorimetric systems, the chromaticity coordinates are represented by the symbols x, y, z or x_{10}, y_{10}, z_{10}.

Note 3 to entry: The chromaticity coordinates are a quantity of unit one.

[SOURCE: CIE S 017:—, entry 17-23-053, modified — “ratios” has been changed to “quotients”.]

3.17
spectral chromaticity coordinates, pl
$r(\lambda), g(\lambda), b(\lambda); x(\lambda), y(\lambda), z(\lambda); r_{10}(\lambda), g_{10}(\lambda), b_{10}(\lambda); x_{10}(\lambda), y_{10}(\lambda), z_{10}(\lambda)$
chromaticity coordinates of monochromatic stimuli

[SOURCE: CIE S 017:—, entry 17-23-055]

3.18
spectral luminous efficiency
$V(\lambda)$, <for photopic vision>; $V'(\lambda)$, <for scotopic vision>; $V_{mes;m}(\lambda)$, <for mesopic vision>; $V_{10}(\lambda)$, <for the CIE 10° photopic photometric observer>; $V_{M}(\lambda)$, <for the CIE 1988 modified 2° spectral luminous efficiency function for photopic vision>
<for a specified photometric condition> quotient of the radiant flux at wavelength λ_m and that at wavelength λ, such that both produce equally intense luminous sensations for a specified photometric condition and λ_m is chosen so that the maximum value of this quotient is equal to 1

[SOURCE: CIE S 017:—, entry 17-21-035, modified — Notes to entry omitted.]

3.19
perfect reflecting diffuser
ideal isotropic diffuser with a reflectance equal to unity

4 Specifications

4.1 Colour-matching functions

The colour-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ of the CIE 1931 standard colorimetric observer are defined by the values given in Table 1, and those $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ of the CIE 1964 standard colorimetric observer are defined by the values given in Table 2. The values are given at 1 nm wavelength intervals from 360 nm to 830 nm. If values are required at closer wavelength intervals than 1 nm, they should be derived by linear interpolation.

4.2 Spectral chromaticity coordinates

Tables 1 and 2 also give values for the spectral chromaticity coordinates, $x(\lambda)$, $y(\lambda)$, $z(\lambda)$; $x_{10}(\lambda)$, $y_{10}(\lambda)$, $z_{10}(\lambda)$; these have been derived from the appropriate colour-matching functions by forming the ratios according to Formulae (1) to (6):

$$x(\lambda) = \frac{\bar{x}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)} \quad (1)$$

$$y(\lambda) = \frac{\bar{y}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)} \quad (2)$$

$$z(\lambda) = \frac{\bar{z}(\lambda)}{\bar{x}(\lambda)+\bar{y}(\lambda)+\bar{z}(\lambda)} \quad (3)$$

and

$$x_{10}(\lambda) = \frac{\bar{x}_{10}(\lambda)}{\bar{x}_{10}(\lambda)+\bar{y}_{10}(\lambda)+\bar{z}_{10}(\lambda)} \quad (4)$$

$$y_{10}(\lambda) = \frac{\bar{y}_{10}(\lambda)}{\bar{x}_{10}(\lambda)+\bar{y}_{10}(\lambda)+\bar{z}_{10}(\lambda)} \quad (5)$$

$$z_{10}(\lambda) = \frac{\bar{z}_{10}(\lambda)}{\bar{x}_{10}(\lambda)+\bar{y}_{10}(\lambda)+\bar{z}_{10}(\lambda)} \quad (6)$$

NOTE All wavelengths are for standard air.

5 Derivation of the colour-matching functions for the CIE 1931 standard colorimetric observer

5.1 Experimental basis

The CIE 1931 colour-matching functions, $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$, were derived from experimental work carried out by Wright[1][2] and Guild[3] in which a total of 17 observers matched the monochromatic stimuli of the spectrum, over the range of about 400 nm to 700 nm, with additive mixtures of red, green and blue lights, using observing fields of 2° angular subtense.

5.2 Transformation procedures

The experimental results were converted into those that would have been obtained if the matching had been carried out using, as reference colour stimuli, monochromatic radiations of wavelengths 700 nm for the red [R], 546,1 nm for the green [G] and 435,8 nm for the blue [B], measured in units such that equal quantities of [R], [G] and [B] were required to match the equi-energy spectrum.

The results for the 17 observers were averaged and then slightly adjusted so that by adding together suitable proportions of the [R], [G], [B] colour-matching functions $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ it was possible to obtain a function identical to that of the CIE spectral luminous efficiency, $V(\lambda)$; the proportions used were in the ratios of 1,000 0 to 4,590 7 to 0,060 1, and these were then the relative luminances of unit quantities of [R], [G] and [B]. The CIE 1931 colour-matching functions were then determined by Formulae (7) to (9):

$$\bar{x}(\lambda) = \left[0{,}49\,\bar{r}(\lambda) + 0{,}31\,\bar{g}(\lambda) + 0{,}20\,\bar{b}(\lambda)\right] n \tag{7}$$

$$\bar{y}(\lambda) = \left[0{,}176\,97\,\bar{r}(\lambda) + 0{,}812\,40\,\bar{g}(\lambda) + 0{,}010\,63\,\bar{b}(\lambda)\right] n \tag{8}$$

$$\bar{z}(\lambda) = \left[0{,}00\,\bar{r}(\lambda) + 0{,}01\,\bar{g}(\lambda) + 0{,}99\,\bar{b}(\lambda)\right] n \tag{9}$$

where

n is a normalizing constant given by Formula (10).

$$n = \frac{V(\lambda)}{0{,}176\,97\,\bar{r}(\lambda) + 0{,}812\,40\,\bar{g}(\lambda) + 0{,}010\,63\,\bar{b}(\lambda)} \tag{10}$$

n is a constant, not a function of wavelength, because the coefficients 0,176 97, 0,812 40, and 0,010 63 are in the same ratios to one another as the ratio of 1,000 0 to 4,590 7 to 0,060 1; n is equal to Formula (11).

$$\frac{1{,}000\,0 + 4{,}590\,7 + 0{,}060\,1}{0{,}176\,97 + 0{,}812\,40 + 0{,}010\,63} = 5{,}650\,8 \tag{11}$$

The values of $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ given in Table 1 from 360 nm to 400 nm and from 700 nm to 830 nm are extrapolations.

5.3 Transformation properties

The transformation given in Formulae (7) to (9) was chosen to achieve the following objectives:

1) The $\bar{y}(\lambda)$ function is identical to the $V(\lambda)$ function.

2) The values of $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are all positive for all wavelengths of the spectrum (unlike $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$, one of which is negative at most wavelengths because of the need to desaturate spectral stimuli when matching them with red, green and blue reference stimuli).

3) The values of $\bar{z}(\lambda)$ are zero for wavelengths longer than 650 nm.

4) The values of $\bar{x}(\lambda)$ are nearly zero at wavelengths around 505 nm.

5) The values of $\bar{x}(\lambda)$ and $\bar{y}(\lambda)$ are small at the short-wavelength end of the spectrum.

6) The equi-energy spectrum is specified by equal amounts of X, Y and Z.

Because the $\bar{y}(\lambda)$ function is identical to the $V(\lambda)$ function, the Y tristimulus value is proportional to luminance.

5.4 Comparison with earlier data

The values of $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ given in Table 1 for the spectral range of 380 nm to 780 nm at 5 nm intervals, when rounded to four decimal places, agree closely with those originally published in 1931. There are only three minor differences: at λ = 775 nm the new value of $\bar{x}(\lambda)$ is 0,000 1 instead of 0,000 0; at λ = 555 nm, $\bar{y}(\lambda)$ = 1,000 0 instead of 1,000 2 and at λ = 740 nm, $\bar{y}(\lambda)$ = 0,000 2 instead of 0,000 3. These changes are considered insignificant in most colorimetric computations.

When the relative luminances of unit quantities of [R], [G] and [B] are deduced from the data of Table 1, the values obtained are 1,000 0 to 4,588 8 to 0,060 3 instead of 1,000 0 to 4,590 7 to 0,060 1, the relative radiances being 71,893 8 to 1,374 7 to 1,000 0 instead of 72,096 2 to 1,379 1 to 1,000 0. These changes are also considered insignificant in practice.

The values given in CIE 15 at 5 nm intervals agree exactly with those given in Table 1.

6 Derivation of the colour-matching functions for the CIE 1964 standard colorimetric observer

6.1 Experimental basis

The CIE 1964 colour-matching functions $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ were derived from experimental work carried out by Stiles and Burch[4] and by Speranskaya[5] in which a total of 67 observers matched monochromatic stimuli of the spectrum from approximately 390 nm to 830 nm with additive mixtures of red, green, and blue lights, using observing fields of 10° angular subtense (but ignoring the central 4° or so).

6.2 Transformation procedures

The experimental results were converted into those that would have been obtained if the matching had been carried out using, as reference colour stimuli, monochromatic radiations of wavenumbers 15 500 cm^{-1} for the red $[R_{10}]$, 19 000 cm^{-1} for the green $[G_{10}]$ and 22 500 cm^{-1} for the blue $[B_{10}]$, corresponding approximately to wavelengths 645,2 nm, 526,3 nm and 444,4 nm, respectively. The units used for the quantities of $[R_{10}]$, $[G_{10}]$ and $[B_{10}]$ were such that equal amounts were required to match the equi-energy spectrum. A weighted average of the results for the 67 observers was used to provide a set of colour-matching functions $\bar{r}_{10}(\nu), \bar{g}_{10}(\nu), \bar{b}_{10}(\nu)$. The CIE 1964 colour-matching functions were then derived using Formulae (12) to (14):

$$\bar{x}_{10}(\nu) = 0{,}341\,080\,\bar{r}_{10}(\nu) + 0{,}189\,145\,\bar{g}_{10}(\nu) + 0{,}387\,529\,\bar{b}_{10}(\nu) \tag{12}$$

$$\bar{y}_{10}(\nu) = 0{,}139\,058\,\bar{r}_{10}(\nu) + 0{,}837\,460\,\bar{g}_{10}(\nu) + 0{,}073\,316\,\bar{b}_{10}(\nu) \tag{13}$$

