Application of CIE 13.3-1995 with Associated CRI-based Colour Rendition Properties

November 2020

FOREWORD

About the Global Lighting Association

The Global Lighting Association (GLA) is the voice of the lighting industry on a global basis. GLA shares information on political, scientific, business, social and environmental issues relevant to the lighting industry and advocates the position of the global lighting industry to relevant stakeholders in the international sphere. For more information see www.globallightingassociation.org.

About this document

This publication is identical to the earlier version (December 2018), except for the sign of the hue-angle changes for the test-colour samples (see equation 4 on page 8), which was incorrect in the previous version. In addition, the example output of the Excel calculation tool in Annex A has been replaced by a new one. With these updates, the text is now in agreement with the implementation in version 1.1 (January 2020) of the accompanying Excel calculation tool (GLA calculation tool for CIE 13.3-1995 CRI and Associated CRI-based Colour Rendition Properties).

Summary

On September 18th 2015, the Global Lighting Association (GLA) issued a position statement on Colour Rendering Index in which the need for an additional colour quality measure was indicated. This GLA publication describes the procedure for an accurate calculation of the colour rendering indices (CRI), R_a and R_i, as defined in CIE technical report 13.3-1995 “Method of Measuring and Specifying Colour Rendering Properties of Light Sources” as well as associated CRI-based colour rendition properties that can be used in conjunction with R_a and R_i. These properties, a colour gamut index (G_a), chroma indices (C_i), hue-angle changes (Δh_i), and a colour-shift graphic provide, together with CRI, a more complete description of the colour shifts for the test-colour samples used in CRI. The new CRI-based properties may be useful to explain why object colours can still appear differently when illuminated under light sources with the same CCT and R_a values.

Disclaimer

In addition to the method described in this publication, other methods have been proposed to augment colour fidelity with gamut area, chroma and/or hue metrics, including IES TM-30. The GLA does not prescribe mandatory use of any method. The properties described in this document are provided for evaluation and voluntary usage by members of the lighting industry and other interested parties. This publication can serve as input for a future global colour rendition standard.

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1 Background

The colour rendering index (CRI), as defined in CIE 13.3 (CIE, 1995), is widely adopted and used by the lighting industry, in regulatory documents and in international and regional standards and specifications. The general CRI, R_a, represents an average shift in colour appearance for a set of eight moderately saturated test-colour samples (TCS) under a test light source in comparison to a reference illuminant, having the same correlated colour temperature (CCT) as the test light source. Neither R_a nor the special colour rendering indices, R_i, provide information on the direction of the colour shifts. However, it is well-known that the direction of the colour shifts can also contribute to the appreciation of the perceived object colours.

In 2017, the Commission Internationale de l'Eclairage (CIE) published technical report 224 "CIE 2017 Colour Fidelity Index for accurate scientific use" (CIE, 2017), describing a scientifically more accurate fidelity index, R_f, prepared by CIE technical committee (TC) 1-90. As mentioned in the report, practical applicability of R_f is still under evaluation and the development of a harmonized set of colour quality measures for assessing perception-related effects beyond fidelity has been proposed. The new colour fidelity index, R_f, is not recommended as a replacement of the general colour rendering index, R_a, neither for the purpose of rating and specification of products nor for regulatory or other minimum performance requirements. Consequently, R_a will continue to be used in the lighting industry until the CIE completes this work.

Meanwhile, the major lighting associations, such as the Global Lighting Association (GLA, 2015), LightingEurope (LightingEurope, 2014), and the Middle East Lighting Association (MELA, 2016), expressed in their respective position statements the urgent need for additional specification items that can supplement the well-established R_a.

This document describes the precise procedure for computing the CRI values, R_a and R_i, and, in addition, it provides information on the direction of the colour shifts for all CIE 13.3 TCS (CIE, 1995). An Excel calculation tool is also provided for the users of CRI as the old DOS-based tool, provided by CIE in the past, may no longer run on modern computers. The associated CRI-based colour rendition properties include a colour gamut index (G_a), chroma indices (C_i), and hue-angle changes (Δh_i), which may be useful to explain why object colours can appear differently when illuminated under light sources with the same CCT and R_a value.

2 Calculation procedure for CRI and CRI-based properties

2.1 General

The clauses described in this document are based on Clause 5 in CIE technical report 13.3 (CIE, 1995). Some specific information with regards to the calculation procedures, described in CIE 13.3-1995, is provided in this document to obtain more accurate and reproducible results across different calculation tools.

2.1.1 Input wavelength range and spectral sampling interval for test source

The Excel calculation tool is designed for the input spectral range from 360 nm to 830 nm at any intervals from 1 nm to 5 nm (default is 1 nm). The input spectral power distribution (SPD) of the test light source does not have to fill this entire range, but it should have:

1) a sufficiently large wavelength range covering at least 380 nm to 780 nm, conforming to the recommended practice in CIE 15:2004 (CIE, 2004); and
2) a sufficiently fine spectral sampling interval (between 1 nm and 5 nm) recommended for accurate colour calculations (CIE, 2004).

In the calculation tool, as per CIE recommendation (CIE, 2004), to avoid interpolation artefacts for spiked spectra (spectra with narrow band emission peaks), the input SPD are not interpolated, but instead all TCS spectral radiance factors will be interpolated to the sampling intervals of the input SPD. The CIE 1931, 2-degree, colour-matching functions (CMFs) published in Table 1 of ISO 11664-1:2007(E)/CIE S 014-1/E:2006 (ISO/CIE, 2007) are used in the calculation tool. Values between the 1 nm intervals will be calculated with linear interpolation (according to clause 5.4 in CIE 13.3-1995).

2.1.2 Reference illuminant

The same procedure is employed as described in 5.2 in CIE technical report 13.3 (CIE, 1995). The relative spectral power distribution for the blackbody radiator is calculated according to Appendix E in CIE15:2004 and for daylight according to 3.1 (Other illuminants D, Item b) in the same document. The reference illuminant in the Excel tool is calculated for the full wavelength range 360 nm to 830 nm, with 1 nm increments.

2.1.3 Correlated colour temperature T_{cp} and distance to the Planckian locus D_{uv}

The calculation tool outputs values of correlated colour temperature (T_{cp}) as well as distance to the Planckian locus, D_{uv}, of the test light source. These two values, also visualized in a graphical format in the Excel tool (see Annex A for an example), provide full information of chromaticity of a light source in an intuitive manner.

NOTE The distance to Planckian locus D_{uv} is defined as the closest distance of the chromaticity coordinates of a light source to the Planckian locus on the (u', 2/3 v') chromaticity diagram (CIE 1960 chromaticity diagram), the value of which is positive if the chromaticity coordinates of the light source are above the Planckian locus and negative if the chromaticity coordinates of the light source are below the Planckian locus.

The CCT of the test light source is determined according to 9.5 in CIE 15:2004 (CIE, 2004) and has been implemented in the Excel tool according to the combined triangular-parabolic method with a 0.25% CT-step table described by Ohno (Ohno, 2014). This method is accurate to within 1 K for a CCT range of 1 000 K to 20 000 K and within a distance to the Planckian locus (D_{uv}) from ±0.03.

NOTE Although the concept of CCT is defined for $|D_{uv}| < 0.05$ and the D_{uv} calculation is accurate to within 1 K up to $|D_{uv}| < 0.03$, a smaller range ($-0.02 \le D_{uv} \le 0.01$) is used in the graphical presentation in the tool as a practical limit for white-light sources.

2.1.4 Test-colour samples

All 14 test-colour samples (TCS) as described in 5.4 (and Clause 8, Tables 1 & 2) in CIE 13.3 (CIE, 1995) are included in the calculation tool, covering the whole visual wavelength range (360 nm to 830 nm). Linear interpolation has been applied to the spectral radiance factors provided with 5 nm increments in Tables 1 and 2 in CIE 13.3 (CIE, 1995) to store the spectral radiance factors of the 14 TCS in the Excel tool with 1 nm intervals.

NOTE One additional, optional, TCS (#15), East Asian skin tone as tabulated in JIS 8726-1990 (JIS, 1990), is included in the calculation tool. If desired, this TCS can be replaced in the tool with another user defined TCS with spectral radiance factors covering the whole visual wavelength range (360 nm – 830 nm) and with 1 nm increments.

2.2 Determination of CIE 1964 uniform space coordinates

The same procedures as specified in 5.5, 5.6, 5.7, and 5.8 in CIE 13.3 (CIE 1995) are used in the calculation tool. These provide the CIE 1964 uniform space coordinates ($U^*_{k,i}, V^*_{k,i}$) and ($U^*_{r,i}, V^*_{r,i}$) for all individual test-colour samples (i) of the reference illuminant (r) and the light source to be tested (k).

2.3 Colour rendering indices R_i and R_a

The colour rendering indices R_i and R_a are calculated following formulae provided in clauses 6.2 and 6.3 in CIE 13.3 (CIE, 1995).

2.4 CRI-based colour rendition properties

Associated CRI-based colour rendition properties, to more completely describe changes in colour appearance of the TCS, are introduced in this document to supplement R_i and R_a; they are: a colour gamut index (G_a), chroma indices (C_i) and hue-angle changes (Δh_i). These properties are calculated from the CIE 1964 uniform space coordinates (see 2.2).

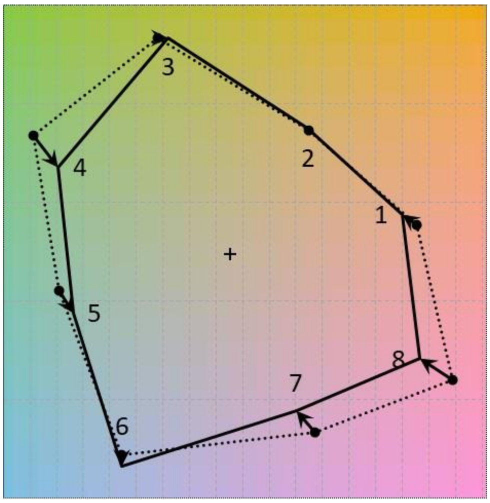
NOTE The CIE 1964 uniform colour space is obsolete and known to be less uniform than the more recent colour spaces (e.g., CIELAB and CIECAM02), but it is intentionally used in this document, and in the calculation tool, for the CRI-based colour rendition properties to retain the characteristics of the CRI.

2.4.1 Colour gamut index G_a

The colour gamut for the reference illuminant (G_r) and the test source (G_k) formed by the first eight TCS on the U^*–V^* plane of the CIE 1964 uniform colour space (see Figure 1) is calculated by using the formula:

$$G_x = \Big[\big(U^*_{x,1} \times V^*_{x,2}\big) - \big(U^*_{x,2} \times V^*_{x,1}\big) + \big(U^*_{x,2} \times V^*_{x,3}\big) - \big(U^*_{x,3} \times V^*_{x,2}\big) + \big(U^*_{x,3} \times V^*_{x,4}\big) - \big(U^*_{x,4} \times V^*_{x,3}\big) + \big(U^*_{x,4} \times V^*_{x,5}\big) - \big(U^*_{x,5} \times V^*_{x,4}\big) + \big(U^*_{x,5} \times V^*_{x,6}\big) - \big(U^*_{x,6} \times V^*_{x,5}\big) + \big(U^*_{x,6} \times V^*_{x,7}\big) - \big(U^*_{x,7} \times V^*_{x,6}\big) + \big(U^*_{x,7} \times V^*_{x,8}\big) - \big(U^*_{x,8} \times V^*_{x,7}\big) + \big(U^*_{x,8} \times V^*_{x,1}\big) - \big(U^*_{x,1} \times V^*_{x,8}\big)\Big]/2 \quad (1)$$

In equation 1, $x = \mathrm{k}$ for the light source to be tested and $x = \mathrm{r}$ for the reference illuminant.



NOTE The numbers in the figure represent the TCS#, the dotted line connects the U^*, V^* coordinates for the reference illuminant and the solid line for the test light source, where the arrows indicate the direction of the colour shifts (from the coordinates for the reference illuminant to the coordinates for the test source).

Figure 1 — Example of colour gamut formed by the eight TCS for a test source (solid line) and the corresponding reference illuminant (dotted line).

The colour gamut index G_a is derived from the colour gamut values of the reference illuminant G_r and of the light source to be tested G_k according to the following formula:

$$G_\mathrm{a} = 100 \cdot \frac{G_\mathrm{k}}{G_{\mathrm{r},}} \quad (2)$$

The colour gamut index value is normally rounded to the nearest integer.

NOTE JIS Z 8726 (JIS, 1990) includes a colour gamut area ratio in the informative annex, designated by the symbol G_a, which is identical to the one described in this document.

2.4.2 Chroma indices, C_i

For all test-colour samples (i), the chroma indices C_i are calculated from the CIE 1964 uniform space coordinates (see 2.2) by using the following formula:

$$C_i = 100 \cdot \frac{C_{k,i}}{C_{r,i}} = 100 \cdot \frac{\sqrt{\left(U^*_{k,i}\right)^2 + \left(V^*_{k,i}\right)^2}}{\sqrt{\left(U^*_{r,i}\right)^2 + \left(V^*_{r,i}\right)^2}} \tag{3}$$

Chroma index C_i shows the direction of colour shift for each TCS. A C_i value of less than 100 indicates a reduced chroma, and a C_i value greater than 100 represents an increased chroma compared to the reference illuminant. Chroma index C_9 can be referred to as the *red chroma index*, because TCS #9 represents strong red. Similarly, C_{10} represents the *yellow chroma index*, C_{11} the *green chroma index* and C_{12} the *blue chroma index*.

The chroma indices are normally rounded to the nearest integer values.

2.4.3 Hue-angle changes, Δh_i

For all test-colour samples (i), the hue-angle changes Δh_i are calculated from the CIE 1964 uniform space coordinates (see 2.2) by using the following formula:

$$\Delta h_i = \arctan\left(\frac{V^*_{k,i}}{U^*_{k,i}}\right) - \arctan\left(\frac{V^*_{r,i}}{U^*_{r,i}}\right) \tag{4}$$

NOTE This equation differs from the previous version (December 2018) in which for each test-colour sample (i) the hue-angle for the test source was subtracted from the hue-angle for the reference illuminant.

The hue-angle changes are expressed in degrees (°) and are normally rounded to the nearest integer values.

3 Colour-shift graphic

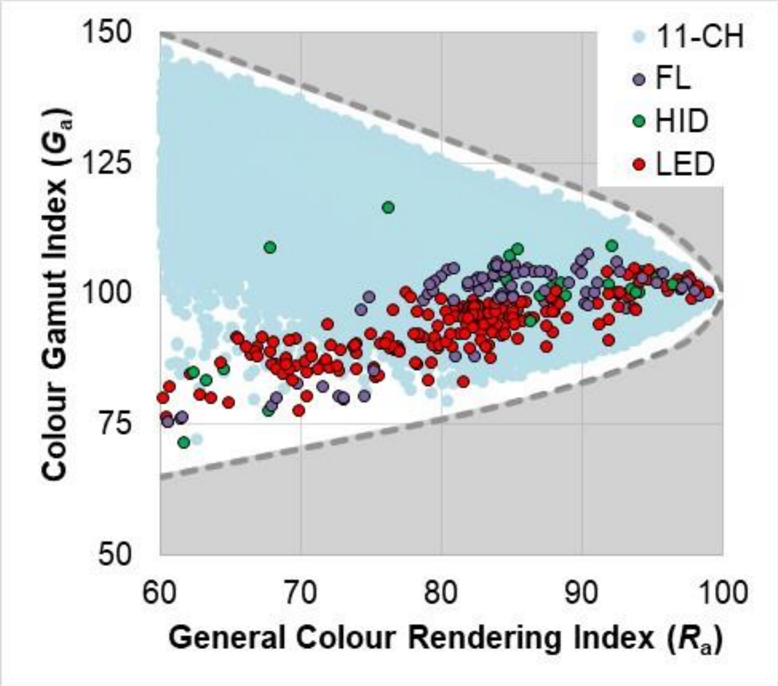
The colour coordinates for the first eight TCS derived in clause 2.2 for the reference illuminant ($U^*_{r,i}, V^*_{r,i}$) and for the test light source ($U^*_{k,i}, V^*_{k,i}$) are plotted in the U^*–V^* plane of the CIE 1964 uniform colour space (see Figure 1). The resulting colour-shift graphic provides a rough indication for the individual colour shifts, represented by arrows. For visual comparison purposes, the axes (U^* and V^*) are rescaled by the calculation tool such that the coordinates for all TCS (eight for both the test light source and the reference illuminant) just fit within the square area of the U^*–V^* plane. An example of a colour-shift graphic is provided in Figure 1 as well as in Annex A.

NOTE The numbers in the colour-shift graphic (Figure 1) represent the TCS#, the dotted line connects the coordinates for the reference illuminant and the solid line for the test light source, where the arrows indicate the direction of the colour shifts. The dashed gridlines have the same unit size for the two axes (U^* on the horizontal axis, V^* on the vertical axis), which shows possible scale differences for the axes, and the + indicates the origin (coordinates 0,0) of the graph.

4 Two-dimensional R_a–G_a graphic

As described in the introduction, R_a represents an average colour fidelity for eight moderately saturated TCS under a test light source in comparison to a reference illuminant, without indicating the direction of the colour shifts. The colour gamut index G_a provides an indication on whether the colour gamut of the test source is enlarged (G_a > 100) or reduced (G_a < 100) compared to the gamut for the reference illuminant. If colour fidelity is very high (R_a is close to 100), variations in colour gamut are limited. With increasing differences from the reference illuminant (thus with decreasing R_a values), the possible variation in G_a values increases. This is illustrated in Figure 2 in which R_a–G_a combinations are included, based on slightly more than 100 000 SPDs.

The SPDs were created by an 11-channel (11-CH) light source by randomly assigning (8-bit) drive values to the individual channels. Also, R_a–G_a combinations of commercially available fluorescent (FL), high intensity discharge (HID) and light emitting diode (LED) light sources have been included in Figure 2. The following characteristics were used to include the R_a–G_a combinations of the light sources: 1 500 < T_{cp}(K) < 20 000, $R_a \geq 60$, and $-0{,}02 \leq D_{uv} \leq 0{,}01$.



Key:

11-CH: 100 000 randomly assigned SPDs with an 11-channel light box
FL: fluorescent type light sources
HID: high intensity discharge type light sources
LED: light-emitting diode type light sources

NOTE The dashed contour line is just an indication and encloses all calculated SPDs. The number of SPDs is limited, so the line anticipates a somewhat broader range of R_a-G_a combinations. It is included to show that the range of possible G_a values increase with decreasing R_a values.

Figure 2 — Illustration of possible R_a-G_a combinations.

5 Use of CRI-based colour rendition properties

The colour gamut index G_a described in section 2.4.1 and calculated with the Excel calculation tool is for use with R_a. The range of possible G_a values increase with decreasing R_a value, allowing for more differentiation between light sources at lower R_a values. Any judgement on the suitability of G_a values, or the combination of R_a and G_a values, should be made based on experiences in each application.

Similar to R_a, the special colour rendition indices for the individual TCS R_i also do not carry information on the direction of colour shifts. The chroma indices C_i do provide information on the increase or decrease in chroma for the individual TCS and can supplement R_i values. Since chroma indices are calculated using the same colour space as used for R_i, it is likely that when chroma is reduced, both C_i and R_i are less than 100 and when chroma is increased, C_i becomes larger than 100 while, by definition, R_i will be less than 100. The Δh_i values indicate if the colour shifts for the individual TCS are mainly caused by chroma changes or (also) by hue-angles changes.

R_a and R_9 are used as minimum performance requirements of lighting products. The minimum requirement on R_9 is intended to exclude light sources with insufficient red rendering, but at the same time it excludes light sources with an increased chroma for the strong red TCS (#9). When an increase in red chroma is allowed or desired, C_9 may be used instead of R_9, where the minimum of C_9 can be chosen independent of R_a. Similarly, when an increase in yellow, green, or blue chroma is allowed or desired, C_{10}, C_{11}, or C_{12} may be used instead of R_{10}, R_{11}, R_{12}, respectively. This way, the minimum performance requirements can be made more specific without significantly narrowing the design freedom of lighting products.

References

CIE 1995. CIE 13.3-1995. *Method of Measuring and Specifying Colour Rendering Properties of Light Sources*. Vienna, Austria: CIE.

CIE 2004. CIE 15:2004. *Colorimetry, 3rd ed.* Vienna, Austria: CIE.

CIE 2017. CIE 224:2017. *CIE 2017 Colour Fidelity Index for accurate scientific use*. Vienna, Austria: CIE.

ISO/CIE 2007. ISO 11664-1:2007(E)/CIE S 014-1/E:2006*. Colorimetry — Part 1: CIE Standard Colorimetric Observers*. Vienna, Austria: CIE.

GLA 2015. *Global Lighting Association's Position Statement on Colour Rendering Index*, 18 September 2015.

JIS 1990. Japanese Industrial Standard. JIS Z 8726-1990. *Method of Specifying Colour Rendering Properties of Light Sources*. Translated and Published by Japanese Standards Association, Printed in Japan.

LightingEurope 2014. *LightingEurope Position Paper on Color Quality*. 6 October 2014.

MELA 2016. *The Middle East Lighting Association (MELA) Position Statement on Colour Quality*. 4th February 2016.

OHNO, Y. 2014. Practical Use and Calculation of CCT and Duv. *LEUKOS*, 10(1), 47-55.

Annex A
Example output of the Excel tool with the CRI-based properties

Output of GLA Calculation Tool for CIE 13.3 CRI and Associated CRI-based Colour Rendition Properties

Test Source:	Example (CIE 224) LED spectrum	
Notes:	From CIE 2017 Colour Fidelity Index Calculator 5 nm - V.3 (2017-07-15).xlsx	
Date / Time:	**Tuesday, 10 November 2020**	**15:00:19**

Correlated Colour Temperature (T_{cp}) in K	3288	CIE1931 chromaticity coordinate, x	0.4174
Distance to Blackbody Locus (D_{uv})	-0.0003	CIE1931 chromaticity coordinate, y	0.3957
General Colour Rendering Index (R_a)	**80**	CIE1976 chromaticity coordinate, u'	0.2415
Red Rendering Index (R_9)	**12**	CIE1976 chromaticity coordinate, v'	0.5151
Colour Gamut Index (G_a)	**93**		
Red Chroma Index (C_9)	**85**