



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

December 2018

## Summary

On September 18<sup>th</sup> 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 ( $\Delta h_i$ ), 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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## **About the Global Lighting Association**

*The Global Lighting Association (GLA) is a grouping of peak national and regional lighting associations representing over 5,000 lighting manufacturers and US\$75 billion annual sales. The GLA is the voice of the lighting industry on a global basis. Its primary mission is to share information, within the limits of national and EU competition law, on political, scientific, business, social and environmental issues of relevance to the lighting industry and to develop, implement and publish the position of the global lighting industry to relevant stakeholders in the international sphere. See: <http://www.globallightingassociation.org/>*

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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 ( $\Delta h_i$ ), 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  $\pm 0.03$ .

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 ( $-0.02 \leq D_{uv} \leq 0.01$ ) 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 ( $\Delta h_i$ ). These properties are calculated from the CIE 1964 uniform space coordinates (see 2.2).

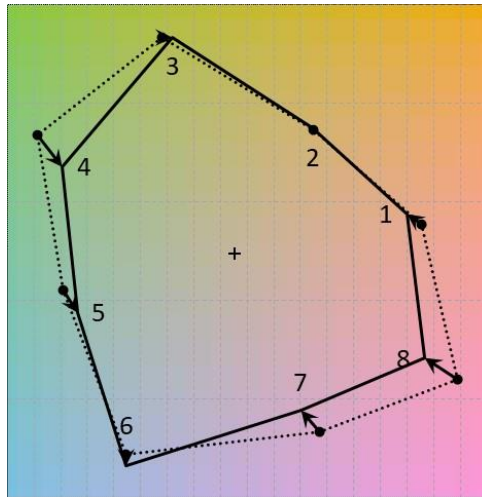
NOTE The CIE 1964 uniform colour space is obsolete and known to be less uniform than the more recent colour spaces (e.g., CIELAB and CIECAM02), but it is intentionally used in this document, and in the calculation tool, for the CRI-based colour rendition properties to retain the characteristics of the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

$$G_x = [(U_{x,1}^* \times V_{x,2}^*) - (U_{x,2}^* \times V_{x,1}^*) + (U_{x,2}^* \times V_{x,3}^*) - (U_{x,3}^* \times V_{x,2}^*) + (U_{x,3}^* \times V_{x,4}^*) - (U_{x,4}^* \times V_{x,3}^*) + (U_{x,4}^* \times V_{x,5}^*) - (U_{x,5}^* \times V_{x,4}^*) + (U_{x,5}^* \times V_{x,6}^*) - (U_{x,6}^* \times V_{x,5}^*) + (U_{x,6}^* \times V_{x,7}^*) - (U_{x,7}^* \times V_{x,6}^*) + (U_{x,7}^* \times V_{x,8}^*) - (U_{x,8}^* \times V_{x,7}^*) + (U_{x,8}^* \times V_{x,1}^*) - (U_{x,1}^* \times V_{x,8}^*)]/2 \quad (1)$$

In equation 1,  $x = k$  for the light source to be tested and  $x = r$  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:

$$G_a = 100 \cdot \frac{G_k}{G_r} \quad (2)$$

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:

$$C_i = 100 \cdot \frac{C_{k,i}}{C_{r,i}} = 100 \cdot \frac{\sqrt{(U_{k,i}^*)^2 + (V_{k,i}^*)^2}}{\sqrt{(U_{r,i}^*)^2 + (V_{r,i}^*)^2}} \quad (3)$$

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, $\Delta h_i$

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

$$\Delta h_i = \arctan\left(\frac{V_{r,i}^*}{U_{r,i}^*}\right) - \arctan\left(\frac{V_{k,i}^*}{U_{k,i}^*}\right) \quad (4)$$

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

## 3 Colour-shift graphic

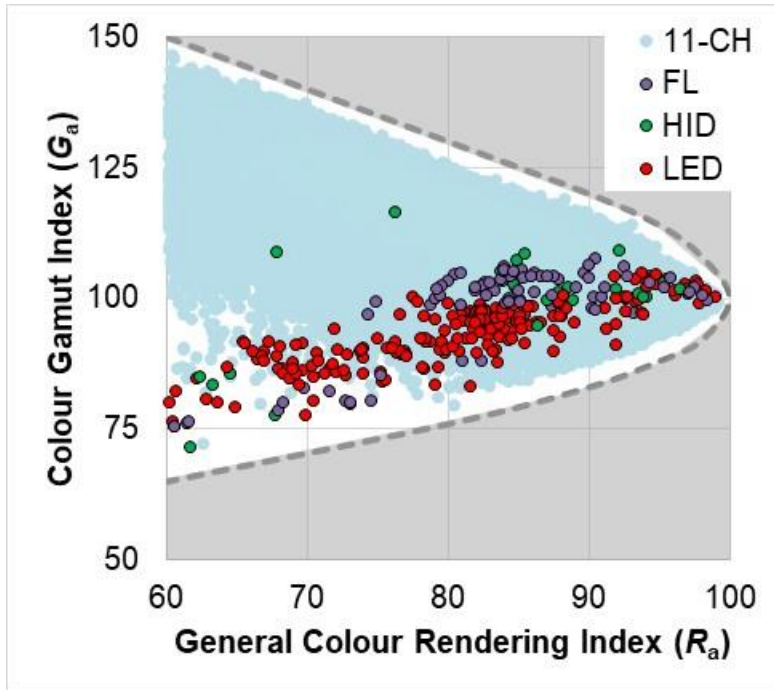
The colour coordinates for the first eight TCS derived in clause 2.2 for the reference illuminant ( $U_{r,i}^*, V_{r,i}^*$ ) and for the test light source ( $U_{k,i}^*, V_{k,i}^*$ ) are plotted in the  $U^*-V^*$  plane of the CIE 1964 uniform colour space (see Figure 1). The resulting colour-shift graphic 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  $\Delta h_i$  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.



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## Annex A

### Example output of the Excel tool with the CRI-based properties

