ANSI/IES TM-30-18

IES Method for Evaluating Light Source Color Rendition

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The TM-30-18 EXCEL calculation tool files are available for download with the PDF of the TM-30-18 standard at ies.org/store.

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1.0 INTRODUCTION

Accurately quantifying the color rendition characteristics of a light source is a complex problem. Color rendition affects many subjective perceptual attributes of a space, including naturalness, vividness, preference, normalness, and visual clarity. Traditionally, there have been distinct approaches for characterizing color rendition, focusing on concepts such as color fidelity, color discrimination, or color preference, and often relying on a single-number characterization. These approaches vary in their relationship to any given subjective impression. Regardless of approach, there is no one metric or measure that can accurately quantify all subjective perceptions of color rendition or identify the most desirable light source for every application.[1,2] A precise and robust method for comprehensively characterizing color rendition is critical to specifying appropriate light sources and optimizing spectral characteristics of light sources.

This Technical Memorandum describes a method for evaluating light source color rendition that takes an objective and statistical approach, quantifying both overall average properties (color fidelity, gamut area) and hue-specific properties (fidelity, chroma shift, hue shift) of a light source using numerical and graphical techniques. It is important to note that it does not attempt to directly characterize human perceptions, such as color preference, or to provide a single number that captures the combined color rendition qualities of a light source. Using various combinations of the included measures, a user is expected to be able to rely on experience and/or design guidelines to determine what is most appropriate for a specific application. This document focuses only on describing the objective characterization techniques; it does not relate values to a subjective evaluation.

This Technical Memorandum consolidates and synthesizes numerous research efforts that have been ongoing for several years, and was developed by representatives of the manufacturing, specification, and research segments of the lighting industry.

1.1 Calculation Components

This document is a tool comprising a set of measures that are all based on a standardized calculation procedure. The method is based on theoretically comparing the appearance of a set of color samples as rendered by a test light source and a reference illuminant, quantified with a model of human vision. Thus, the method includes three primary components: a system for defining the reference illuminant, specification of the color samples, and implementation of a model of human vision. An overview of each component is provided here.

The method described in this document compares color samples as rendered by a given test source and a reference illuminant at the same correlated color temperature (CCT), with the reference illuminant being Planckian radiation up to and including 4000 K, a proportional blend of Planckian radiation and a CIE daylight (D) series illuminant between 4001 K and 4999 K, or a CIE D series illuminant at or above 5000 K. This familiar reference-based approach is compatible with a typical lighting design process, where color temperature is decided before color rendition is considered. The implications of choosing this system for defining the reference illuminant—based on the 2015 version of this document, IES TM-30-15—have been documented in "What is the Reference? An Examination of Alternatives to the Reference Sources Used in IES TM-30-15."[3] It is important to note that all measures specified in this document rely on the same reference scheme, allowing for a cohesive system.

This method utilizes 99 color evaluation samples (CES)—each represented by a spectral reflectance function—to quantify the difference in color rendition between the test source and reference illuminant. The samples were statistically down-selected from an initial collection of more than 100,000 measured objects, in order to be representative of the world of possible colors.[4-6] A majority of the more than 100,000 spectral reflectance functions considered came from the University of Leeds database,[7] which is itself a meta-base containing objects of various origins: textiles, plastics, skin tones, color systems. The Leeds database also includes the Standard Object Colour Spectra (SOCS) database,[8] which contains printed materials, skin tones, natural objects, paints, and textiles. Additional data included natural objects,[9,10] flowers,[11] skin tones,[12] and paints.[9,13]

Finally, embedded within this method is the most current uniform color space, CAM02-UCS,[14-16] which is based on CIECAM02[17-19] and its native chromatic adaptation transformation. This color space was chosen because of its greater uniformity than CIELAB, and is important for ensuring the uniformity of the CES across color space and at a wide range of CCTs.[5,14,20] The CIE 1964 10° standard colorimetric observer[21] is used for all calculations except in determining CCT, where the definition calls for use of the CIE 1931 2° standard colorimetric observer.[22] This model of human vision helps ensure that color differences are appropriately scaled.

It is possible (and expected) that scientific advances related to any calculation component included in this Technical Memorandum will subsequently lead to updates to the method.

1.2 Calculated Measures

Using a unified calculation system, this Technical Memorandum (TM) provides equations and direction for calculating 50 primary numerical measures and one graphic (color vector graphic). The 50 numerical measures include 1 average color fidelity measure (fidelity index, R_f), 1 gamut area measure (gamut index, R_g), 16 hue-specific fidelity measures (local color fidelity, $R_{f,hj}$), 16 hue-specific measures of chroma shift (local chroma shift, $R_{cs,hj}$), and 16 hue-specific measures of hue shift (local hue shift, $R_{hs,hj}$). Whereas R_f and R_g are global averages, the hue-specific local chroma shift and local hue shift values are important for characterizing *gamut shape*, which is the pattern of hue and chroma shift for different hues. Equations to calculate a sample-specific color fidelity value for each of the 99 CES (sample fidelity, $R_{f,CESi}$) are also provided. This document is accompanied by software to aid in calculation and display of the results.

The measures included within this TM are intended to be used in various combinations—or in isolation—depending on the needs of a given application and design intent. This document does not establish performance thresholds, nor does it provide direction on how to do so, for any of the measures. Some experiments have been completed that relate the measures of this TM to subjective evaluations and propose performance thresholds.[23-26]

1.3 Changes from IES TM-30-15

This document replaces IES TM-30-15. The following technical changes have been made:

- For color samples with no native data outside the range of 400 to 700 nm, the extrapolation method was changed from a logarithm-based extrapolation to a flat extrapolation.
- The range encompassing the blended reference was changed from 4501 – 5499 K to 4001 – 4999 K.
- The scaling factor used in color fidelity calculations was changed from 7.54 to 6.73.

These changes have no material effect on the rank order of light sources for any of the included measures. They make IES R_f (ANSI/IES TM-30-18) and CIE R_f (CIE 224:2017[27]) equivalent measures. CIE 224:2017 is limited only to color fidelity, and its scope does not include measures for color rendition considerations beyond color fidelity.

This revision also provides greater clarity on the derivation of the color vector graphic, and specifies the equations used to calculate local chroma shift and local hue shift.

2.0 SCOPE

This evaluation method is applicable to light sources and lighting systems intended for general illumination of indoor spaces and some outdoor settings, at light levels where photopic vision is dominant. It is best suited to characterize nominally white light sources (i.e., those that fall on or near the Planckian locus). If a light source's chromaticity falls outside of the chromaticity bins defined in ANSI C77.388-2017,[28] then calculations based on this TM should be interpreted with caution.

3.0 CORE CALCULATIONS

3.1 Colorimetric Observer

Tristimulus values for the color evaluation samples shall be determined using the CIE 1964 10° standard colorimetric observer, with color matching functions (CMFs) $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$.[10] The 1 nm-increment table is available in CIE 15:2004, *Colorimetry* – Part 1: CIE Standard Colorimetric Observers.[21] The exception is in determining the CCT of the test source, which by definition requires the use of the CIE 1931 2° standard colorimetric observer.[17,21,22] It should also be noted that, for light source specifications, the CIE 1931 standard colorimetric observer [$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$] is used to calculate chromaticity coordinates (*x*, *y*) and (*u*', *v*'). The 1964 10° CMFs are used for light sources in this document only for the purpose of calculating color rendition measures.

3.2 Test Source

The relative spectral power distribution (SPD) of the light source in question (*test source*) is denoted $S_t(\lambda)$. The necessary wavelength range is described in **Section 3.5.** The tristimulus values of the test source shall be calculated as follows:

$$X_{10,t} = k_t \int_{380}^{780} S_t(\lambda)\bar{x}_{10}(\lambda)d\lambda , \quad (1)$$

$$Y_{10,t} = k_t \int_{380}^{780} S_t(\lambda)\bar{y}_{10}(\lambda)d\lambda , \quad (2)$$

$$Z_{10,t} = k_t \int_{380}^{780} S_t(\lambda)\bar{z}_{10}(\lambda)d\lambda , \quad (3)$$

where:

$$k_t = \frac{100}{\int_{380}^{780} S_t(\lambda)\bar{y}_{10}(\lambda)d\lambda} \quad (4)$$

As shown, during the calculation process normalization occurs so that tristimulus value Y = 100.

3.3 Reference Illuminant

The method used in this Technical Memorandum compares each test source to a reference illuminant of the same correlated color temperature (CCT), with SPD denoted as $S_r(\lambda)$. As noted in **Section 3.0**, CCT shall be calculated using the CIE 1931 2° CMFs. The reference illuminant shall be Planckian radiation, a CIE Daylight (D) Series illuminant, or a combination of the two, depending on the CCT of the test source (T_t). Calculation of both Planckian radiation and the D Series illuminants are covered in CIE 15:2004, *Colorimetry*, 3rd ed.[21] For calculating T_t, the method described in "Practical Use and Calculation of CCT and D_{uv}"[22] shall be used. The necessary wavelength range for the reference illuminant is described in **Section 3.5.**

If $T_t \leq 4000$ K, then the reference illuminant shall be Planckian radiation (subscript P), which can be calculated from:

$$S_{r,P}(\lambda, T_t) = \frac{L_{e,\lambda}(\lambda, T_t)}{L_{e,\lambda}(560 \text{ nm}, T_t)} , \quad (5)$$

where:

$$L_{e,\lambda}(\lambda, T_t) = \lambda^{-5}\left[\exp\left(\frac{1.4388 \times 10^{-2}}{\lambda T_t}\right) - 1\right]^{-1} , \quad (6)$$

If $T_t \geq 5000$ K, then the reference illuminant shall be a phase of the CIE daylight illuminant (subscript D), which can be calculated from:

$$S_{r,D}(\lambda) = S_0(\lambda) + M_1 S_1(\lambda) + M_2 S_2(\lambda) , \quad (7)$$

where $S_0(\lambda)$, $S_1(\lambda)$, and $S_2(\lambda)$, are functions of wavelength and given in Table T.2 of CIE 15:2004, *Colorimetry*, 3rd ed.[21] and where:

$$M_1 = \frac{-1.3515 - 1.7703 x_D + 5.9114 y_D}{0.0241 + 0.2562 x_D - 0.7341 y_D} , \quad (8)$$

$$M_2 = \frac{0.0300 - 31.4424 x_D + 30.0717 y_D}{0.0241 + 0.2562 x_D - 0.7341 y_D} , \quad (9)$$

where if $T_t = T_r \leq 7000$ K, then:

$$x_D = \frac{-4.6070\times10^9}{T_r^3} + \frac{2.9678\times10^6}{T_r^2} + \frac{0.09911\times10^3}{T_r} + 0.244063 , \quad (10)$$

or if $T_t = T_r > 7000$ K, then:

$$x_D = \frac{-2.0064\times10^9}{T_r^3} + \frac{1.9018\times10^6}{T_r^2} + \frac{0.24748\times10^3}{T_r} + 0.23704 , \quad (11)$$

and where:

$$y_D = -3.000 x_D^2 + 2.870 x_D - 0.275 \quad (12)$$

If 4000 K < T_t < 5000 K, then the reference illuminant shall be a proportional mix of Planckian radiation and the CIE Daylight illuminant (subscript M), according to:

$$S_{r,M}(\lambda, T_t) = \frac{5000 - T_t}{1000} S_{r,P} + \left(1 - \frac{5000 - T_t}{1000}\right) S_{r,D} \quad (13)$$

Therefore, the reference $S_r(\lambda, T_t)$ illuminant is given depending on the CCT, T_t, as:

$$S_r(\lambda, T_t) = S_{r,P}(\lambda, T_t);\ T_t \leq 4000 \text{ K} \quad (14)$$

$$S_r(\lambda, T_t) = S_{r,M}(\lambda, T_t);\ 4000 \text{ K} < T_t < 5000 \text{ K} \quad (15)$$

$$S_r(\lambda, T_t) = S_{r,D}(\lambda, T_t);\ T_t \geq 5000 \text{ K} \quad (16)$$

Note that the blended sources shall be normalized so that each has an equal luminous reflectance function (Y). Once the reference illuminant has been calculated, the SPD shall be scaled so that the tristimulus value Y = 100. The tristimulus values can be calculated as:

$$X_{10,r} = k_r \int_{380}^{780} S_r(\lambda)\bar{x}_{10}(\lambda)d\lambda , \quad (17)$$

$$Y_{10,r} = k_r \int_{380}^{780} S_r(\lambda)\bar{y}_{10}(\lambda)d\lambda , \quad (18)$$

$$Z_{10,r} = k_r \int_{380}^{780} S_r(\lambda)\bar{z}_{10}(\lambda)d\lambda , \quad (19)$$

where:

$$k_r = \frac{100}{\int_{380}^{780} S_r(\lambda)\bar{y}_{10}(\lambda)d\lambda} \quad (20)$$

3.4 Color Evaluation Samples (CES)

For this method, the color rendition of a test source and reference illuminant shall be compared using a set of 99 color evaluation samples (CES), the color coordinates of which shall be computed under both conditions. **Figure 1** shows the spectral reflectance function for each CES. Numerical data are available online (refer to top of Table of Contents page for web address). **Annex A** describes the selection procedure used to generate the 99 CES and provides approximate representations for each CES under the 5000-K reference illuminant.

3.5 Range and Interpolation of Data

Calculations shall be performed over a range of 380 to 780 nm, which corresponds to the range of each CES. If the available test source SPD has a range greater than 380 to 780 nm, values less than 380 nm or greater than 780 nm shall be dropped from the calculation. If the available test source SPD has a range less than 380 to 780 nm, but not less than 400 to 700 nm, missing values shall be replaced by zeros. The minimum range shall be 400 to 700 nm. The spectral reflectance functions are provided in 1-nm increments (see **Annex A**), which is the preferred increment for all calculations. An increment not greater than 5 nm is needed to achieve reasonable accuracy;[29] greater increments shall not be used.

Interpolation may be required so that the increments of the test source SPD, reference illuminant SPD, CES spectral reflectance functions, and color matching functions (CMF) match. In this case, the CES spectral reflectance functions and/or CMFs should be interpolated to the increment of the test source. Linear interpolation shall be used. The SPD of the test source shall never be interpolated or extrapolated.

3.6 Calculation of Tristimulus Values

Tristimulus values for each of the 99 CES (theoretically) illuminated by the test source shall be calculated as follows:

$$X_{10,t,i} = k_t \int_{380}^{780} S_t(\lambda) R_i(\lambda) \bar{x}_{10}(\lambda) d\lambda \,, \quad (21)$$

$$Y_{10,t,i} = k_t \int_{380}^{780} S_t(\lambda) R_i(\lambda) \bar{y}_{10}(\lambda) d\lambda \,, \quad (22)$$

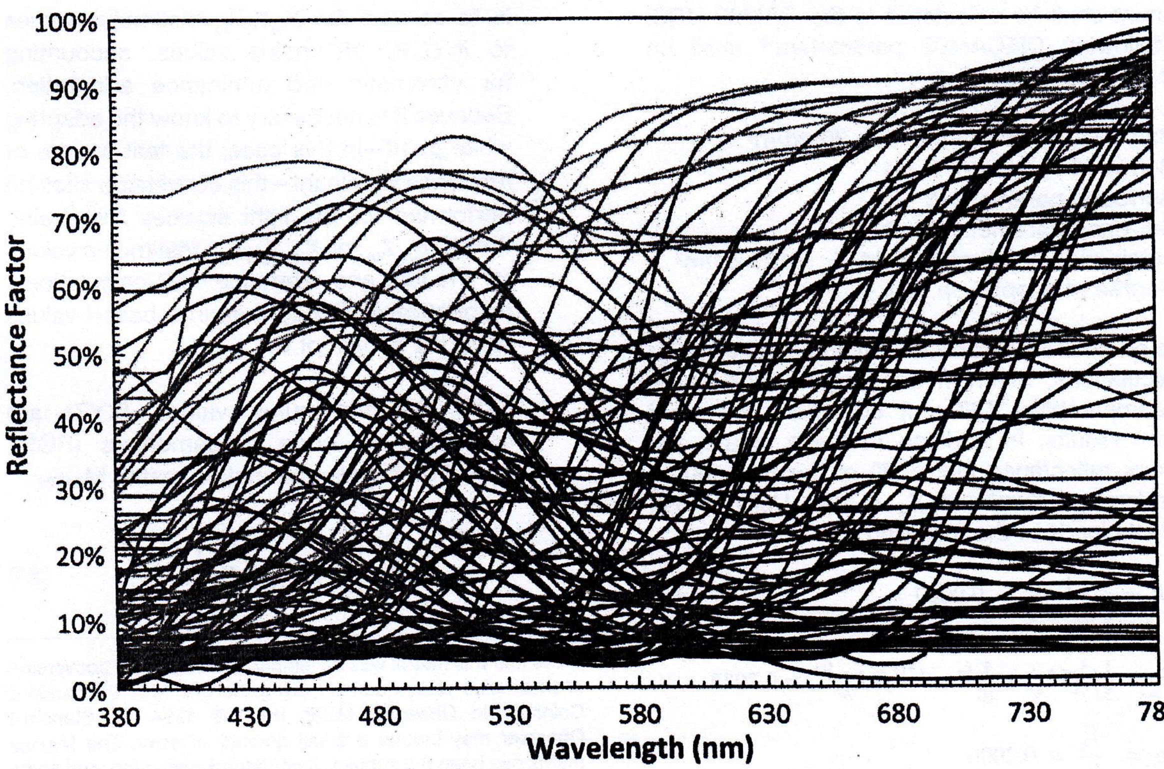


Figure 1. Spectral reflectance functions for the 99 color evaluation samples. The color of the line approximates the color appearance using CIE D_{50}.

$$Z_{10,t,i} = k_t \int_{380}^{780} S_t(\lambda) R_i(\lambda) \bar{z}_{10}(\lambda) d\lambda, \quad \textbf{(23)}$$

where:

$$k_t = \frac{100}{\int_{380}^{780} S_t(\lambda) \bar{y}_{10}(\lambda) d\lambda} \quad \textbf{(24)}$$

Likewise, tristimulus values for each of the 99 CES (theoretically) illuminated by the reference illuminant shall be calculated as follows:

$$X_{10,r,i} = k_r \int_{380}^{780} S_r(\lambda) R_i(\lambda) \bar{x}_{10}(\lambda) d\lambda, \quad \textbf{(25)}$$

$$Y_{10,r,i} = k_r \int_{380}^{780} S_r(\lambda) R_i(\lambda) \bar{y}_{10}(\lambda) d\lambda, \quad \textbf{(26)}$$

$$Z_{10,r,i} = k_r \int_{380}^{780} S_r(\lambda) R_i(\lambda) \bar{z}_{10}(\lambda) d\lambda, \quad \textbf{(27)}$$

where:

$$k_r = \frac{100}{\int_{380}^{780} S_r(\lambda) \bar{y}_{10}(\lambda) d\lambda} \quad \textbf{(28)}$$

3.7 Color Space and Chromatic Adaptation Transformation

Color coordinates of each CES (theoretically) illuminated by the test source and reference illuminant shall be calculated in the CAM02-UCS. The following CIECAM02 parameters[18] shall be used:

- Background luminance, Y_b = 20 cd/m²
- Surround parameter F = 1
- Surround parameter N_c = 1
- Surround parameter c = 0.69
- Luminance of adapting field, L_A = 100 cd/m²
- Degree of adaptation, D = 1

These parameters establish common conditions for all calculations, which in turn ensure consistency and comparability. Different conditions will yield different results. In addition to these inputs, the luminous reflectance factor (Y) of the test source and reference illuminant Y_w = 100. Using these constants leads to the following:

- $k = \dfrac{1}{5L_A + 1} = 0.0020$
- $F_L = \frac{1}{5}k^4(5L_A) + \frac{1}{10}(1-k^4)^2(5L_A)^{1/3} = 0.7937$
- $n = \dfrac{Y_b}{Y_w} = 0.2000$
- $N_{bb} = N_{cb} = 0.725n^{-0.2} = 1.0003$
- $z = 1.48 + \sqrt{n} = 1.9272$

It is important to note that CIECAM02 includes a chromatic adaptation transformation, which is thus embedded within the CAM02-UCS. No further manipulation of the color coordinates is necessary.

3.7.1 Calculation of Color Coordinates. The color coordinates of each CES illuminated by the test source shall be referred to as: $CES_{t,i} = (J'_{t,i},\ a'_{t,i},\ b'_{t,i})$, where i is an integer between 1 and 99 representing the CES. Likewise, the color coordinates of each CES illuminated by the reference illuminant shall be referred to as: $CES_{r,i} = (J'_{r,i},\ a'_{r,i},\ b'_{r,i})$. The subsequently described procedure shall be performed twice for all CES, once using the test source and once using the reference illuminant. In each respective calculation, the light source is also the adapting condition. It is important to note that subscripts t, r, and i are omitted from the equations shown below, which are generalized for both the test source and reference illuminant, and for each CES.

The first stage in the calculation process is to convert the $X_{10}Y_{10}Z_{10}$ tristimulus values to $R_a'G_a'B_a'$ tristimulus values, accounting for chromatic and luminance adaptation. Because it is necessary to know the adapting white point—in this case, the test source or reference illuminant—this conversion shall be performed for the light sources first (using the $X_{10,t}Y_{10,t}Z_{10,t}$ or $X_{10,r}Y_{10,r}Z_{10,r}$ tristimulus values for the test and reference CES calculations, respectively). The light-source-based values carry the subscript w.

First, the tristimulus values (XYZ) are converted to cone fundamentals (RGB), based on the transformation matric M_{CAT02}*.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X_{10} \\ Y_{10} \\ Z_{10} \end{bmatrix}, \quad \textbf{(29)}$$

*Note that this matrix was developed to be used for conversion of tristimulus values derived using the CIE 1931 2° Standard Colorimetric Observer. Using the CIE 1964 10° Standard Observer may induce a small amount of error. The M_{CAT02} matrix has been the subject of continued evaluation, and some slight adjustments have been proposed. The official matrix from "A Colour Appearance Model for Colour Management Systems"[17] has been used here.

where:

$$M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix} \quad \textbf{(30)}$$

Applying a chromatic adaptation transformation, the corresponding color using the illuminant is then (with $D = 1$ and $Y_w = 100$, following normalization):

$$R_C = \left(\frac{100}{R_w}\right) R \quad \textbf{(31)}$$

$$G_C = \left(\frac{100}{G_w}\right) G \quad \textbf{(32)}$$

$$B_C = \left(\frac{100}{B_w}\right) B \quad \textbf{(33)}$$

The cone responses are then converted to the $X_{10}Y_{10}Z_{10}$ color space and back:

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} \begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = M_{HPE}\, M_{CAT02}^{-1} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix}, \quad \textbf{(34)}$$

where:

$$M_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix} \quad \textbf{(35)}$$

The luminance level adaptation factor is then applied, so that the adapted cone responses are:

$$R'_a = \frac{400\left(F_L R'/100\right)^{0.42}}{27.13 + \left(F_L R'/100\right)^{0.42}} + 0.1, \quad \textbf{(36)}$$

$$G'_a = \frac{400\left(F_L G'/100\right)^{0.42}}{27.13 + \left(F_L G'/100\right)^{0.42}} + 0.1, \quad \textbf{(37)}$$

$$B'_a = \frac{400\left(F_L B'/100\right)^{0.42}}{27.13 + \left(F_L B'/100\right)^{0.42}} + 0.1 \quad \textbf{(38)}$$

Next, two CIECAM02 correlates for red-green (a) and yellow-blue (b) opponent channels can be determined as:

$$a = R'_a - \frac{12}{11}G'_a + \frac{1}{11}B'_a \quad \textbf{(39)}$$

$$b = \frac{1}{9}\left(R'_a + G'_a - 2B'_a\right) \quad \textbf{(40)}$$

Three relevant CIECAM02 appearance correlates—lightness (J), chroma (C), and colorfulness (M)—can be calculated as:

$$J = 100\left(\frac{A}{A_w}\right)^{cz}, \quad \textbf{(41)}$$

$$C = t^{0.9} \times \sqrt{\frac{1}{100}J} \times (1.64 - 0.29^{n})^{0.73}, \quad \textbf{(42)}$$

$$M = C \times F_L^{0.25}, \quad \textbf{(43)}$$

where the achromatic response (A) is:

$$A = \left(2R'_a + G'_a + \frac{1}{20}B'_a - 0.305\right) \times N_{bb}, \quad \textbf{(44)}$$

and where here the hue-angle in degrees (h) is found by converting the rectangular coordinates (a, b) into polar coordinates:

$$h = \angle(a, b), \quad \textbf{(45)}$$

and where:

$$t = \frac{\frac{50000}{13} \times N_{cb} \times N_c \times e_t \sqrt{a^2 + b^2}}{R'_a + G'_a + \frac{21}{20}B'_a}, \quad \textbf{(46)}$$

where the eccentricity (e_t) is:

$$e_t = \frac{1}{4}\left(\cos\left(\frac{\pi}{180}h + 2\right) + 3.8\right) \quad \textbf{(47)}$$

Finally, the CIECAM02 appearance correlates can be converted to coordinates in the CAM02-UCS color space:

$$J' = \frac{(1 + 100 \times 0.007) \times J}{1 + 0.007J}, \quad \textbf{(48)}$$

$$a' = M' \times \cos\left(\frac{h\pi}{180}\right), \quad \textbf{(49)}$$

$$b' = M' \times \sin\left(\frac{h\pi}{180}\right), \quad \textbf{(50)}$$

where:

$$M' = \left(\frac{1}{0.0228}\right)\ln(1 + 0.0228M) \quad \textbf{(51)}$$

3.8 Color Difference Formula

In determining the difference between each CES (subscript i) under the test source (subscript t) and reference illuminant (subscript r), the Euclidean distance in the $J'a'b'$ color space—which is the canonical color difference formula in the CAM02-UCS—shall be calculated:

$$\Delta E_{Jab,i} = \sqrt{\left(J'_{t,i} - J'_{r,i}\right)^2 + \left(a'_{t,i} - a'_{r,i}\right)^2 + \left(b'_{t,i} - b'_{r,i}\right)^2} \quad \textbf{(52)}$$

4.0 CALCULATED MEASURES

The color coordinates of the CES under the test light source and reference illuminant can be compared in many different ways. Six types of numerical measures and one graphic are specified in this document, and shall be calculated according to the provided formulas. These measures were chosen based on historical precedence and known applicability to architectural lighting. Other, non-standardized measures can be calculated for research purposes, with potential for inclusion in future revisions of this Technical Memorandum; however, such measures should not be identified as part of this TM's method.

It is not necessary to use or calculate all of the measures specified in this document, but it is recommended that measures beyond the fidelity index (R_f) and gamut index (R_g) be considered.

4.1 Fidelity Index (R_f)

R_f, this document's measure for average color fidelity, is calculated by determining the difference between the CAM02-UCS coordinates of each CES ($\Delta E_{Jab,i}$) under the test source and reference illuminant, then determining the arithmetic mean of those color differences. The mean shall be scaled by a factor of 6.73 and subtracted from 100:

$$R'_f = 100 - 6.73\left[\frac{1}{99}\sum_{i=1}^{99}\left(\Delta E_{Jab,i}\right)\right] \quad \textbf{(53)}$$

Finally, the scale shall be adjusted so that the minimum R_f value is 0, to avoid producing negative numbers. Rescaling to the final R_f value shall be accomplished using:

$$R_f = 10\ln\left[\exp\left(R'_f/10\right) + 1\right] \quad \textbf{(54)}$$

As described in this document, R_f is an accurate measure of average color fidelity—the similarity of colors rendered by the test source and reference illuminant. It addresses many of the well-documented limitations[4,19,24,30-33] of the familiar CIE General Color Rendering Index R_a (CRI).[34] R_f as defined in this TM is identical to the R_f documented in CIE 224:2017.[27] R_f has a range of 0 to 100, with higher numbers indicating more similarity to the reference. It does not attempt to characterize average *perceived* color fidelity in polychromatic environments, nor any other effects related to color memory. It is also not a measure of human color preference or perception of naturalness. Thus, maximizing R_f does not necessarily correspond to increased desirability or utility, or any other perceptual attribute. Two light sources with the same R_f value (other than 100) will not necessarily lead to the same color appearance for objects in the space they illuminate, even if they have the same chromaticity. By itself, R_f is most informative when the value approaches 100 because then all color shifts versus the reference illuminant are by definition minimal. At lower R_f values, additional measures are needed to understand how colors are being shifted.

The scaling factor (k) for R_f was determined such that the mean R_f value for a library of 187 commercially available light sources with $R_a \geq 60$ was equal to the mean CIE R_a value for the same light sources.[27] However, R_f and CIE R_a are different,[4,5,32] and light sources may have higher or lower R_f values than CIE R_a values. Different light sources that each have a CIE R_a value of 80 can have R_f values that differ by more than 30 points. In particular, light sources that increase red chroma tend to have higher R_f values than CIE R_a values.[32] Further, light sources previously optimized to maximize CIE R_a or achieve a certain threshold value, such as 80, may have lower R_f values due to the characteristics of the broader set of color samples.[4,5,32,35] It is possible to render the eight color samples used to calculate CIE R_a with greater fidelity than the 99 CES, but the reverse has not been demonstrated. **Figure 2** illustrates the color shift for an example light source distributed over the CAM02-UCS.

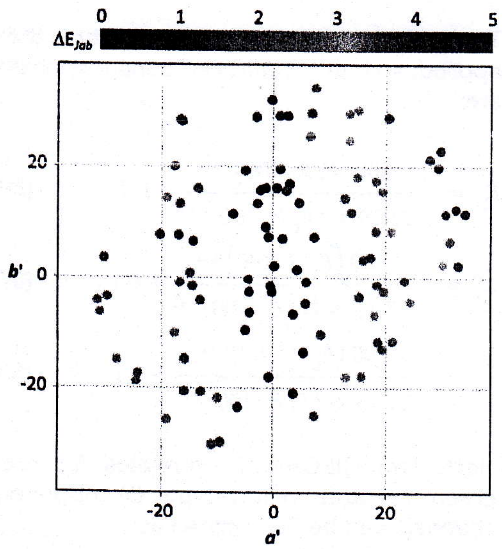


Figure 2. A two-dimensional plot showing the color shift for each color evaluation sample (CES), illuminated by an example test source with an R_f value of 87. The test source produces the most shift (relative to the reference) for saturated red CES.

Due to the systematic differences between R_f and CIE R_a, existing performance thresholds (e.g., CIE $R_a \geq 80$) cannot simply be transferred to the R_f measure without affecting the qualifying sources. Manufacturers, specifiers, and other stakeholders should establish new performance thresholds for R_f, to which historical precedent, current experiences, and research with human participants should contribute. Consideration of additional criteria beyond R_f is also recommended.

4.2 Sample Color Fidelity ($R_{f,CESi}$)

A fidelity value for each of the 99 CES may be calculated using the same scaling protocol as for R_f. The equations are:

$$R'_{f,CESi} = 100 - 6.73 \times \Delta E_{Jab,i} \quad \textbf{(55)}$$

$$R_{f,CESi} = 10\ln\left[\exp\left(R'_{fces,i}/10\right) + 1\right] \quad \textbf{(56)}$$

Each $R_{f,CESi}$ value has a range of 0 to 100. Because of the logarithmic transformation that is applied to fidelity measures in this document, R_f does not exactly equal the mean of the 99 $R_{f,CESi}$ values.

Because each value corresponds to a specific spectral reflectance function, $R_{f,CESi}$ values must be carefully considered when applying them to a given object. Individual $R_{f,CESi}$ values may be imperfect at predicting the fidelity of similar colors, due to metamerism. However, they may help to identify light sources with greater disparity in rendition of similar-colored objects when considered collectively.

Of particular interest may be CES 15 and CES 18, which are the two samples representing human skin tones. These two samples were specifically selected from the broader collection of skin spectral reflectance functions such that the mean of the color fidelity values for the two samples is correlated well with the mean of the color fidelity values for all of the skin samples included in the color sample database.

4.3 Hue-Angle Bins

To calculate the remaining specified measures, the 99 CES are divided in 16 groups. The boundaries are established by dividing the a'-b' plane of CAM02-UCS into 16 sections following a radial pattern, with each encompassing 22.5°. These hue-angle bins are shown in **Figure 3.** The positive horizontal axis (a'-axis) is assigned as 0°, with angles and hue-angle bin numerical labels (j) increasing in the counterclockwise direction.

A CES is assigned to a bin based on its (a', b') coordinates under the reference illuminant. Thus, the corresponding hue-angle bin for each sample varies with the CCT of the reference illuminant and needs to be determined as part of the calculation procedure by comparing the hue angle (h, **Eq. 3.7.17**) of the sample as rendered by the reference illuminant to the hue-angle bin boundaries shown in **Figure 3.** At any given CCT, the number of samples (m) in a given bin may range from as little as 2 to as many as 11 (see **Figure 4**). This unequal distribution occurs in part because the color volume is not spherical, and as a result of the procedure used to select the 99 CES.[36] Because object hues vary with CCT in CAM02-UCS, the number of CES per hue-angle bin varies with CCT.

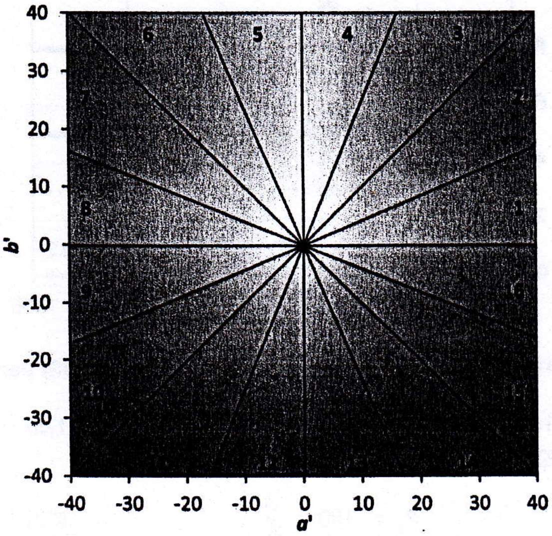


Figure 3. Hue-angle bin numerical designations.

Within each hue-angle bin, the arithmetic mean of the a' and b' coordinates for each CES is calculated for both the test source and reference illuminant conditions, ($J'_{test,j}$, $a'_{test,j}$, $b'_{test,j}$) and ($J'_{ref,j}$, $a'_{ref,j}$, $b'_{ref,j}$) respectively. The resulting set of 16 coordinate pairs is the basis for several calculated measures. The advantage of this approach, as opposed to using a small number of individual color samples, is described in "Chroma Shift and Gamut Shape: Going Beyond Average Color Fidelity and Gamut Area."[36]

4.4 Gamut Index (R_g)

R_g is a measure of the area spanned by the average (a', b') coordinates of the CES in each hue-angle bin, ($a'_{test,j}$, $b'_{test,j}$) and ($a'_{ref,j}$, $b'_{ref,j}$). The J' coordinate is discarded, so that the ($a'_{test,j}$, $b'_{test,j}$) and ($a'_{ref,j}$, $b'_{ref,j}$) coordinates each form a polygon. R_g is calculated

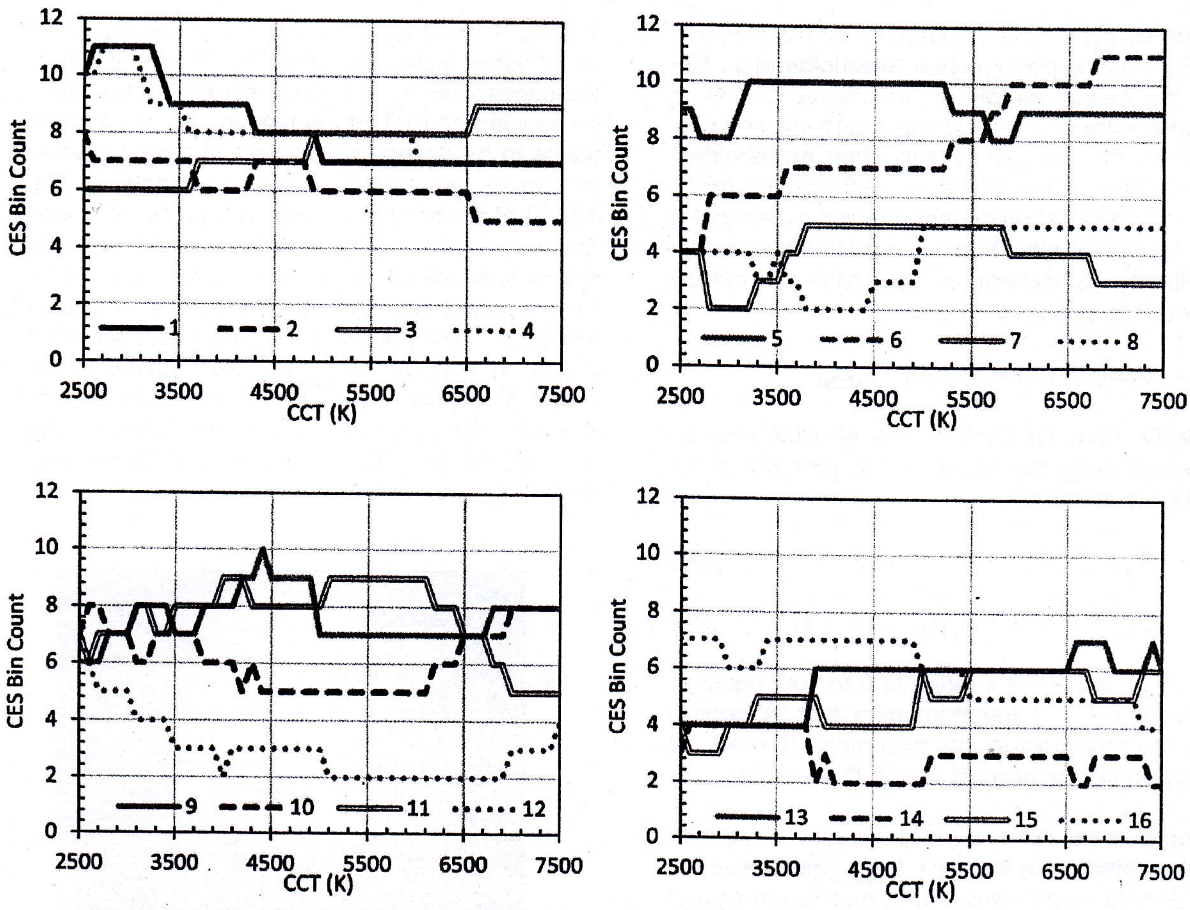


Figure 4. Number of color evaluation samples (CES) per hue-angle bin at different CCTs.

as 100 times the ratio of the area of the two polygons (A_t and A_r, respectively):

$$R_g = 100 \times \frac{A_t}{A_r} \quad \textbf{(57)}$$

A schematic of R_g calculations is provided in **Figure 5.** An R_g value of 100 indicates that, on average, the test source does not increase or decrease chroma† compared to the reference illuminant. It does not, however, indicate that all colors will have equal chroma under the test source and reference illuminant. An R_g value greater than 100 indicates an overall average increase in chroma compared to the test illuminant, whereas an R_g value less than 100 indicates an overall average decrease in chroma. R_g does not describe the colors for which increases or decreases in chroma occur; two sources with the same R_g value may render colors differently.

†In this document, *chroma* is used to refer to the radial dimension of color space. Officially, the radial dimension of CAM02-UCS is a modified version of the CIECAM02 correlate for colorfulness. With fixed viewing conditions, chroma (C) and colorfulness (M) have a direct linear relationship. The term *chroma* was chosen for use in this document because its meaning was expected to be clearer for a broader audience.

Because R_g utilizes CAM02-UCS, the areas of the reference illuminants are nearly constant over the applicable range of CCT, as shown in **Figure 6.** There are some small differences in gamut shape as the reference changes with CCT.[3]

R_f and R_g—the two global average measures described herein, capturing color fidelity and gamut area, respectively—quantify characteristics that are separate dimensions of color rendition.[1] An increase or decrease in gamut area necessitates a reduction in color fidelity; the two values cannot be simultaneously maximized. The R_g value does not have an overall maximum, but the possible range increases as R_f decreases, as shown in **Figure 7.** For instance, if one wants to maintain a value of R_f above 80, the value of R_g is approximately bound to the range of 80 to 120. Maximizing (or minimizing) R_g does not necessarily correspond to increased desirability. Two light sources with the same R_f *and* R_g value—or any analogous measures of average color fidelity and gamut area—will not necessarily lead to the same color appearance in the space they illuminate, because neither distinguishes between hues.[24]

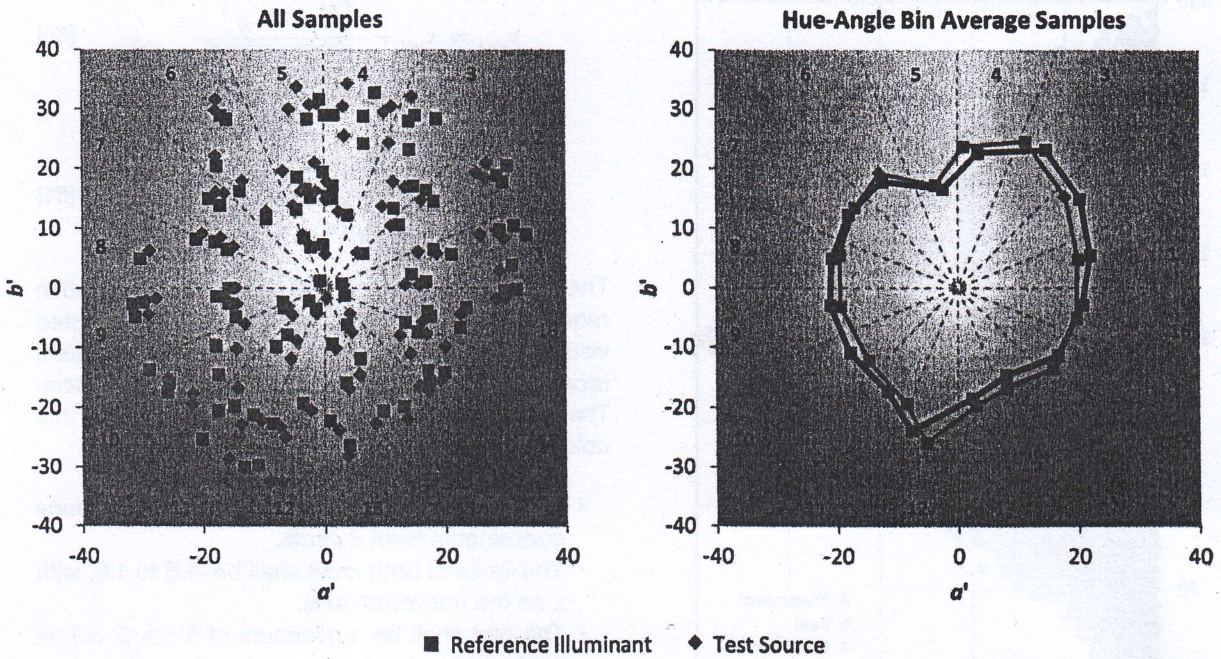


Figure 5. Schematic of R_g calculation. Left: The 99 color evaluation samples are divided among the hue-angle bins in the a'-b' plane of CAM02-UCS. Right: The average coordinates in each hue-angle bin form the vertices of two polygons. Gamut index, R_g, is based on the ratio of the area of the two polygons.

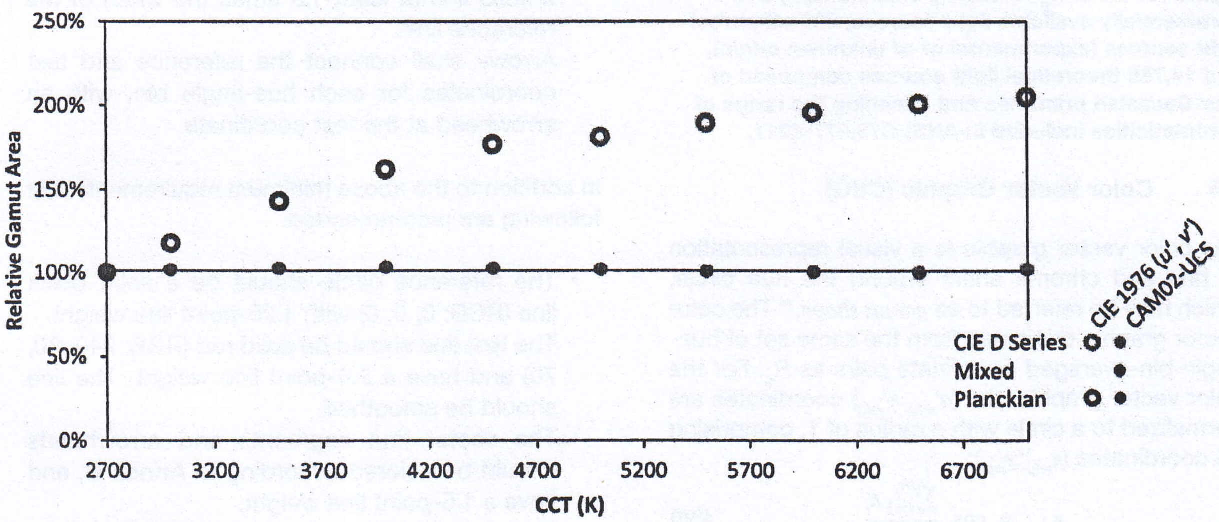


Figure 6. Gamut area for reference illuminants at different CCTs, relative to the gamut area of 2700K Planckian radiation. The gamut area in CAM02-UCS is calculated according to R_g, whereas the gamut area in CIE 1976 (u', v') is calculated with the color samples used to calculated CIE R_a.

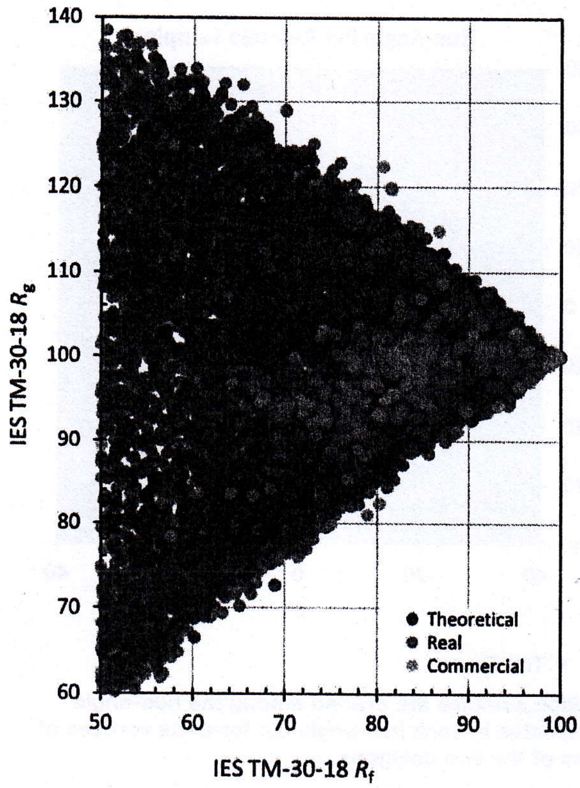


Figure 7. Plot of R_g versus R_f. This includes 212 commercially available light sources, 806 other real light sources (experimental or of unknown origin), and 14,788 theoretical light sources composed of four Gaussian primaries and spanning the range of chromaticities included in ANSI C78.377-2017.

4.5 Color Vector Graphic (CVG)

The color vector graphic is a visual representation of hue and chroma shifts around the hue circle, which may be referred to as *gamut shape*.[36] The color vector graphic originates from the same set of hue-angle-bin-averaged coordinate pairs as R_g. For the color vector graphic, the $(a'_{ref,j}, b'_{ref,j})$ coordinates are normalized to a circle with a radius of 1, comprising 16 coordinates $(x_{ref,j}, y_{ref,j})$:

$$x_{ref,j} = \cos\frac{\sum_{i=1}^{m_j} h_i}{m_j}, \quad (58)$$

$$y_{ref,j} = \sin\frac{\sum_{i=1}^{m_j} h_i}{m_j}, \quad (59)$$

where h_i is the hue angle of the m (a'_{ref}, b'_{ref}) coordinates in a given hue-angle bin (j).

The color difference between the average coordinates in each hue-angle bin is then transferred to the respective position along the reference circle, with the vector endpoints forming the vertices of a polygon representing the test source. The specific equations to determine each of the 16 vector endpoints are:

$$x_{test,j} = x_{ref,j} + \frac{\left(a'_{test,j} - a'_{ref,j}\right)}{\sqrt{\left(a'_{test,j} + b'_{ref,j}\right)^2}} \quad (60)$$

$$y_{test,j} = y_{ref,j} + \frac{\left(b'_{test,j} - b'_{ref,j}\right)}{\sqrt{\left(a'_{test,j} + b'_{ref,j}\right)^2}} \quad (61)$$

The CVG is a visual tool, and complete specification requires consideration for the non-calculated visual aspects—especially to ensure a consistent representation that is easily interpreted by users. The following are required, acknowledging that color reproduction is not always possible:

- The plot shall be scaled so that the reference coordinates form a circle.
- The limits of both axes shall be -1.5 to 1.5, with x as the horizontal axis.
- The plot shall be a minimum of 5 cm (2 in.) on each side.
- The reference coordinates shall be connected with a solid-line circle.
- The test coordinates shall be connected with a solid line at least 1.5 times the width of the reference line.
- Arrows shall connect the reference and test coordinates for each hue-angle bin, with an arrowhead at the test coordinate.

In addition to the above minimum requirements, the following are recommended:

- The reference circle should be a solid black line (RGB: 0, 0, 0) with 1.25-point line weight.
- The test line should be solid red (RGB: 240, 80, 70) and have a 2.0-point line weight. The line should be smoothed.
- The vector line segments and arrowheads should be colored according to **Annex B**, and have a 1.5-point line weight.
- The hue-angle bin boundaries should be identified with dashed gray lines (RGB: 166, 166, 166) with 0.75-point line weight. Each line is recommended to have a length of 0.73 and to begin a distance of 0.02 from the origin.
- The hue-angle bins should be labelled in a circular pattern at the end of the boundary lines. The font size should be a minimum of 8-point.
- The background should be that provided in **Annex C.** A digital file is also available (refer to top of Table of Contents page for web address to download).

The following optional items may also be added:

- Circles with radius 0.8, 0.9, 1.1, and 1.2. The circles should be solid white lines with 0.5-point line weight.
- R_f (upper left), R_g (upper right), CCT (lower left), and D_{uv} (lower right) values.

Figure 8 provides an example of the minimum required representation, a minimum recommended representation, and an optional representation.

The color vector graphic can be interpreted as follows: where the line demarcating the test source extends outside the line demarcating the reference illuminant, chroma is increased on average; where the line demarcating the test source is inside the line demarcating the reference illuminant, chroma is decreased on average; hue shifts occur where a component of the vector is tangential to the reference circle. By conveying gamut shape, the color vector graphic is useful in further clarifying the global average values, indicating where chroma is increased or decreased and which colors undergo a hue shift.[36] This is important because two sources with essentially equal R_f and R_g values, such as those shown in **Figure 9**, may be perceived differently.

Like the values of R_f and R_g, the color vector graphic is statistical, in that it is obtained by averaging over 16 subsets of the CES. Though predictive, the color vector graphic cannot explicitly represent the hue or chroma shift of any specific object. The color vector graphic does not illustrate the variation in shifts that can occur within any hue-angle bin. This variation occurs because the vectors are averages over the full range of chroma and a small range of hue angle.

4.6 Local Chroma Shift ($R_{cs,hj}$)

The purely radial shift in the vectors of the color vector graphic is quantified in a series of 16 measures referred to as local chroma shift, with each value corresponding to one of the hue-angle bins.

Local chroma shift values are denoted $R_{cs,hj}$, where j indicates the number of the hue-angle bin:

$$R_{cs,hj} = \frac{\left(a'_{test,j} - a'_{ref,j}\right)}{\sqrt{\left({a'_{ref,j}}^2 + {b'_{ref,j}}^2\right)}} \cos\theta_j + \frac{\left(b'_{test,j} - b'_{ref,j}\right)}{\sqrt{\left({a'_{ref,j}}^2 + {b'_{ref,j}}^2\right)}} \sin\theta_j, \quad (62)$$

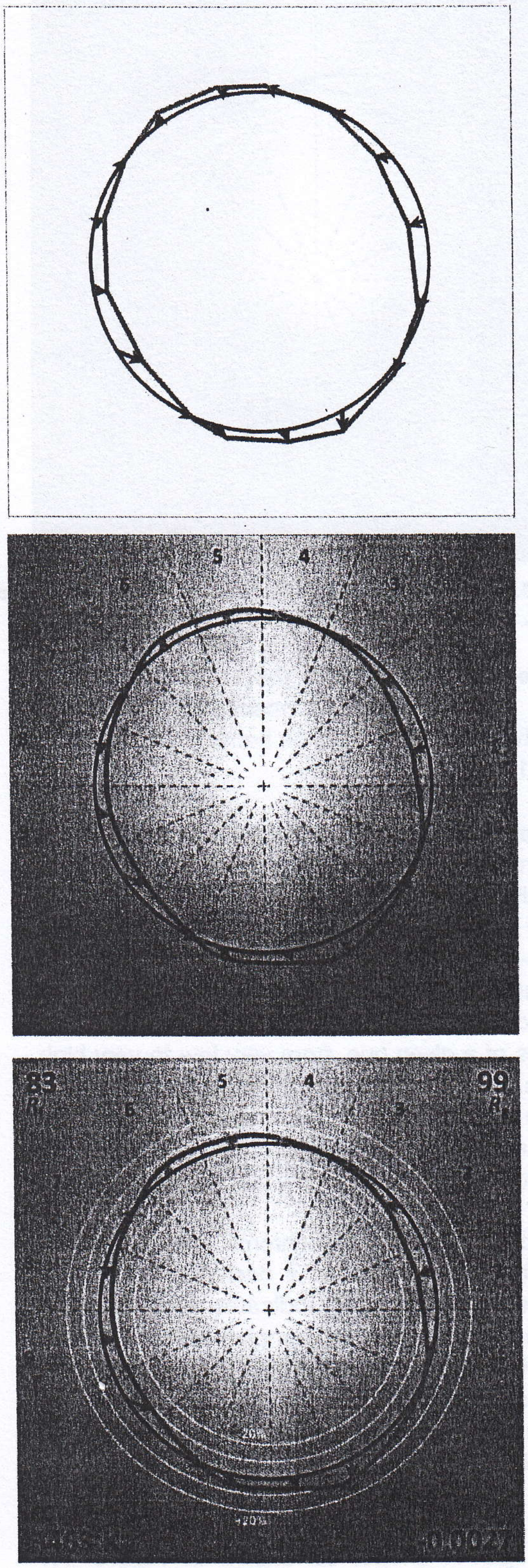


Figure 8. Example of formatting of the color vector graphic. Top: minimum required components. Middle: minimum recommended representation. Bottom: recommended representation with the addition of optional elements.

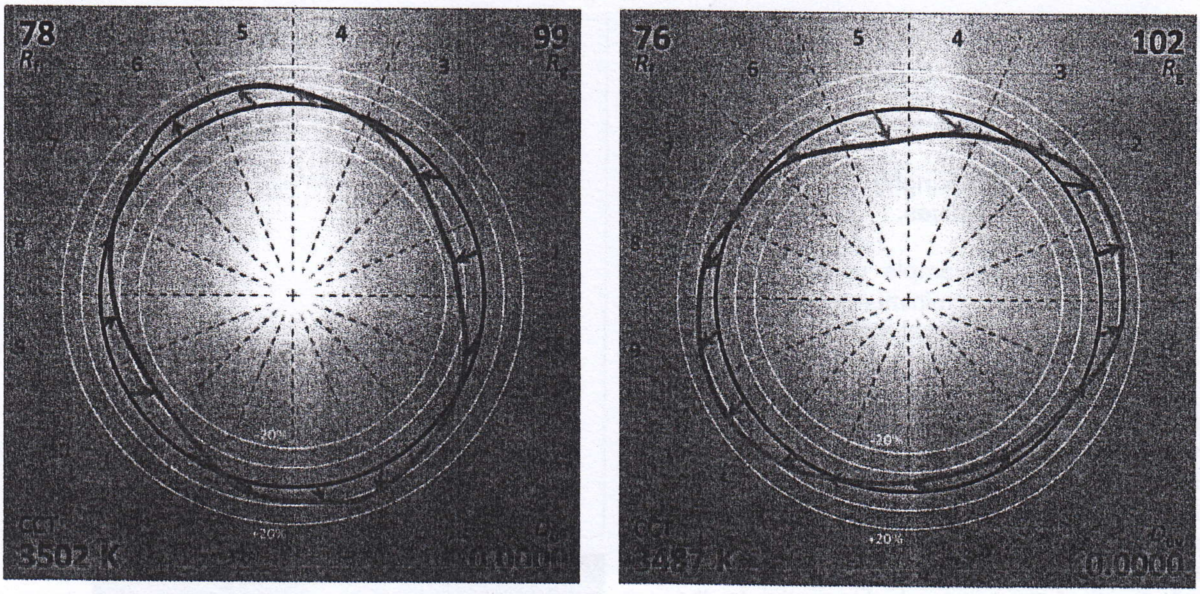


Figure 9. Color Vector Graphics for two SPDs with equivalent R_f and R_g values but substantially different gamut shapes. Such sources may be perceived differently.

where θ_j is the angle of the vector bisecting each hue-angle bin, as measured from the positive *a*' axis (the division between hue-angle bins 1 and 16).

$R_{cs,hj}$ values represent a *relative* average chroma shift and shall be represented as a percentage. Since the *absolute* chroma shift of a color sample roughly scales with the absolute chroma value (that is, high-chroma samples undergo a larger shift),[6,32,35] the relative shift is a well-defined quantity that can be used to estimate the effect of the SPD on all samples of a given hue, from very low to very high chroma. Local chroma shift values represent the chroma shift for the averaged a' and b' coordinates within a hue-angle bin. Individual shifts for the included CES, or for a specific real object, may vary.

For each of the 16 local chroma shift measures, a negative value indicates a decrease in chroma, whereas a positive value indicates an increase in chroma for the averaged samples within the hue-angle bin. Information about both lightness and hue changes is discarded. The range of possible local chroma shift values varies with hue-angle bin, as shown in **Figure 10**.

The 16 values may be presented as a group to convey gamut shape, as shown in **Figure 11. Annex B** provides recommended colors for the bars. More information is provided in "Chroma Shift and Gamut Shape: Going Beyond Average Color Fidelity and Gamut Area."[36]

4.7 Local Hue Shift ($R_{hs,hj}$)

The purely tangential shift in the vectors of the color vector graphic is quantified in a series of 16 measures referred to as local hue shift, with each value corresponding to one of the hue-angle bins. Local hue shift values are denoted $R_{hs,hj}$, where j indicates the number of the hue-angle bin:

$$R_{hs,hj} = -\frac{\left(a'_{test,j} - a'_{ref,j}\right)}{\sqrt{\left(a'^{2}_{ref,j} + b'^{2}_{ref,j}\right)}} \sin\theta_j + \frac{\left(b'_{test,j} - b'_{ref,j}\right)}{\sqrt{\left(a'^{2}_{ref,j} + b'^{2}_{ref,j}\right)}} \cos\theta_j\,, \qquad (63)$$

where θ_j is the angle of the vector bisecting each hue-angle bin, as measured from the positive *a*' axis (the division between hue-angle bins 1 and 16).

$R_{hs,hj}$ values represent the hue shift for the averaged a' and b' coordinates within a hue-angle bin. Individual shifts for the included CES, or for a specific real object, may vary.

For each of the 16 local hue shift measures, a negative value indicates a clockwise shift (e.g., orange toward red, blue toward green, green toward yellow). A positive value indicates a counterclockwise shift. Information about both lightness and chroma changes is discarded. The range of possible local hue shift values varies with hue-angle bin, as shown in **Figure 12**.

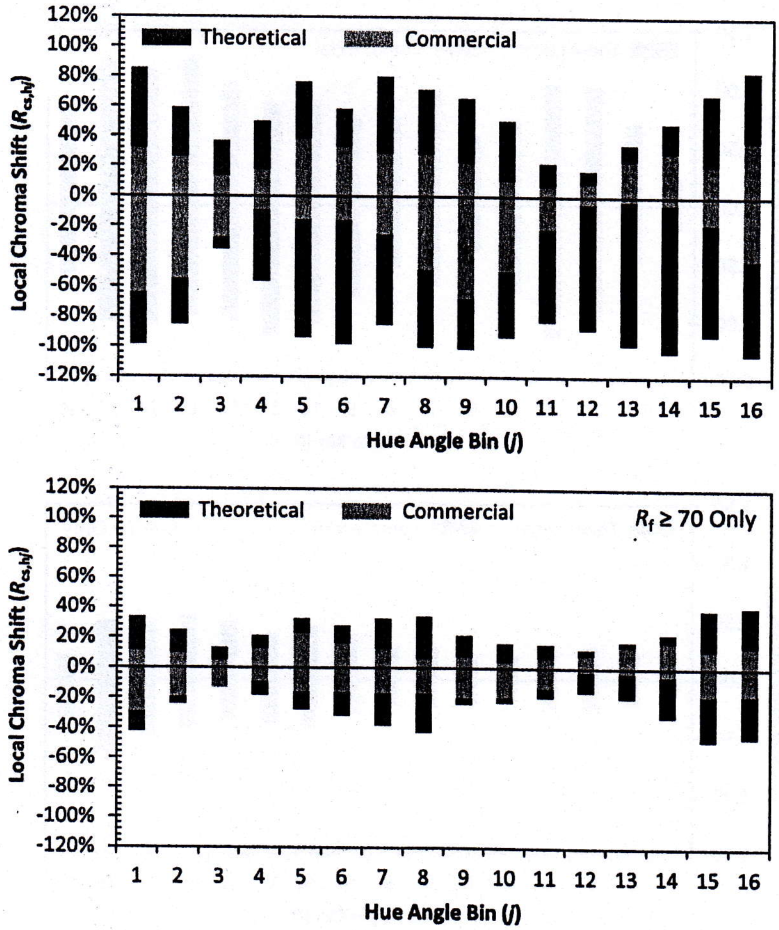


Figure 10. Theoretical range of potential values for local chroma shift, based on 14,788 theoretical SPDs spanning the range of chromaticities specified in ANSI C78.377-2017, and 212 commercially available light sources. Top: all sources. Bottom: only sources with $R_f \geq 70$.

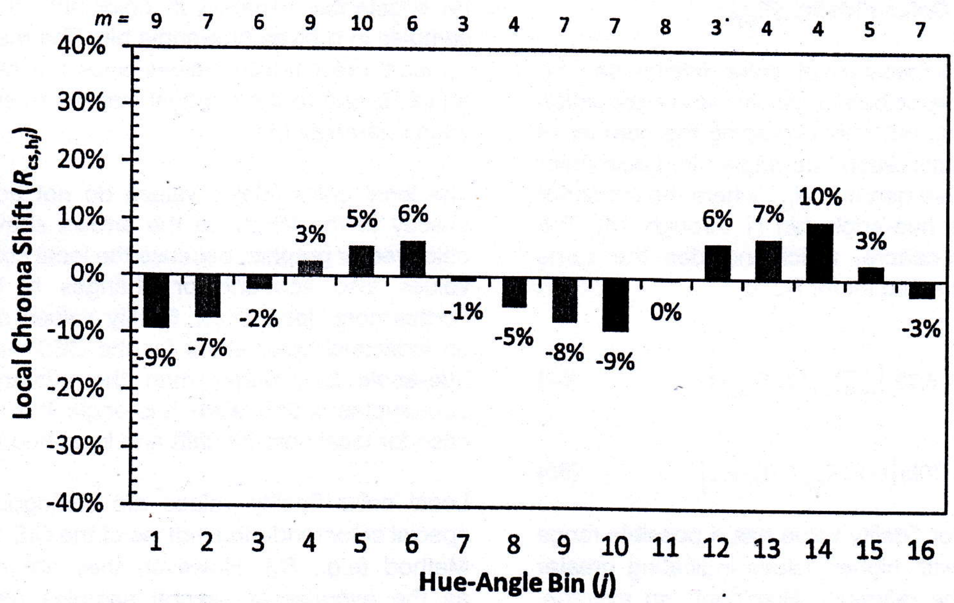


Figure 11. Recommended graphical representation of local chroma shift values to convey gamut shape.

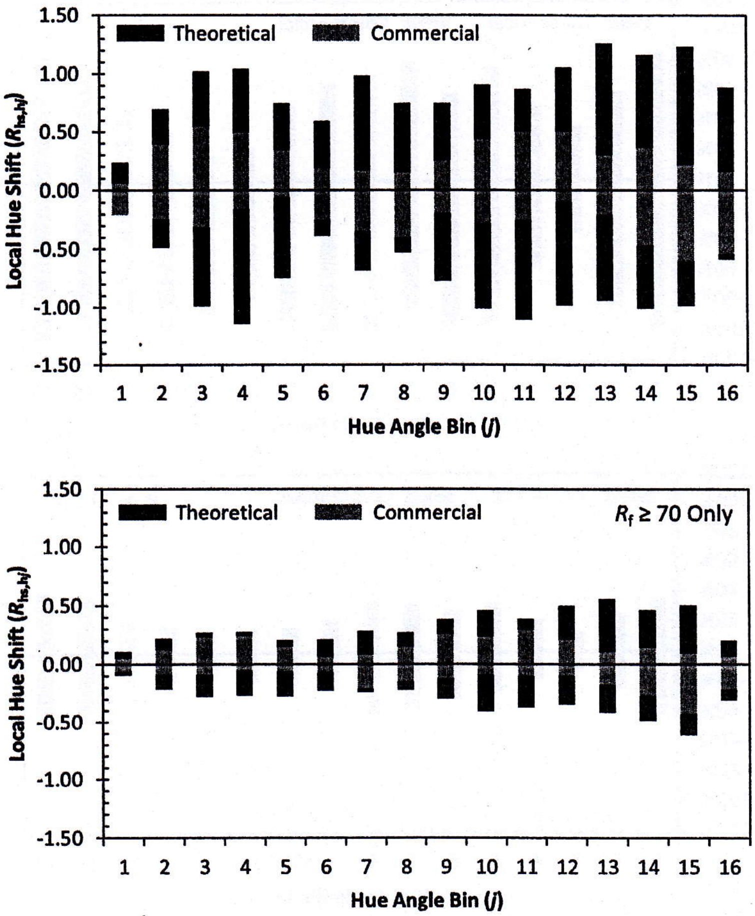


Figure 12. Theoretical range of potential values for local hue shift, based on 14,788 theoretical SPDs spanning the range of chromaticities specified in ANSI C78.377-2017, and 212 commercially available light sources. Top: all sources. Bottom: only sources with $R_f \geq 70$.

4.8 Local Color Fidelity ($R_{f,hj}$)

A hue-specific measure of color fidelity can be determined for each hue-angle bin using an equation analogous to R_f, but only averaging the number of samples (m) within each hue-angle bin. Local color fidelity values are denoted $R_{f,hj}$, where the subscript j indicates the hue-angle bin (1 through 16). The calculation procedure, which includes the same re-scaling procedure as for R_f, is:

$$R'_{f,hj} = 100 - 6.73 \left[\frac{1}{m}\sum_{i=1}^{m}\left(\Delta E_{Jab,i}\right)\right], \quad \textbf{(64)}$$

$$R_{f,hj} = 10\ln\left[\exp\left(R'_{f,hj}/10\right) + 1\right] \quad \textbf{(65)}$$

Each local color fidelity value has a possible range of 0 to 100, with higher values indicating greater similarity to the reference illuminant, on average, for the samples within the hue-angle bin. There can be substantial variation in color shift among the samples in a given hue-angle bin. The mean of the 16 local color fidelity values does not necessarily equal R_f, due to the unequal number of samples in each hue-angle bin.

The local color fidelity values do not correspond exactly to the length of the arrows shown in the color vector graphic, because the local color fidelity values also account for changes in lightness. Furthermore, local color fidelity values are based on individual color shifts for the CES within each hue-angle bin, rather than the averaged color coordinates within each hue-angle bin (as is the case for local chroma shift and local hue shift).

Local color fidelity values are analogous to the special color rendering indices of the CIE Test Color Method (e.g., R_9). However, they are computed as the average of several samples rather than one specific sample, and so are more likely to be predictive of the magnitude of color shift for an unknown real object of a similar hue than any one specific color sample (e.g., $R_{f,CES i}$ or CIE R_i) within the hue-angle bin.

The same local color fidelity value can be achieved with increases or decreases in the corresponding local chroma shift value (see **Figure 13**), or similarly with various directions of local hue shift. While local color fidelity may help in identifying the magnitude of differences—and thus, perceptibility—the values are not informative for understanding or predicting how colored objects will appear, because shifts of a given magnitude may be in any direction.

5.0 COMMENTARY

5.1 Average Values

The method described in this Technical Memorandum includes two measures, R_f and R_g, that average color differences across all color evaluation samples. As with all color rendition evaluation systems that take this approach, the measures do not convey performance with respect to any specific color sample or any particular color region, such as blues or reds. If a specific color region is of interest, the relevant local chroma shift, local hue shift value, or local color fidelity should be consulted, as described in **Sections 4.6, 4.7** and **4.8**, respectively. The color vector graphic (**Section 4.5**), which displays similar information visually, can also be consulted. It should be noted, however, that the local values also average color differences over subsets of the CES. If a specific color is of concern for a specific application, then measures for the most closely matched CES could be evaluated; however, a better solution is to perform an analogous calculation using the spectral reflectance function of the object of interest, rather than one of the CES. None of the measures included in this TM can predict metameric mismatches for real objects.

5.2 Color Rendition Preference and other Perceptions

This Technical Memorandum does not provide a single number intended to characterize color preference, nor does it attempt to identify particular combinations of the included measures that are perceived as natural, normal, saturated, accepted, or preferred. The numerical measures and graphics specified herein are intended to be combined in various ways to meet the needs of different design

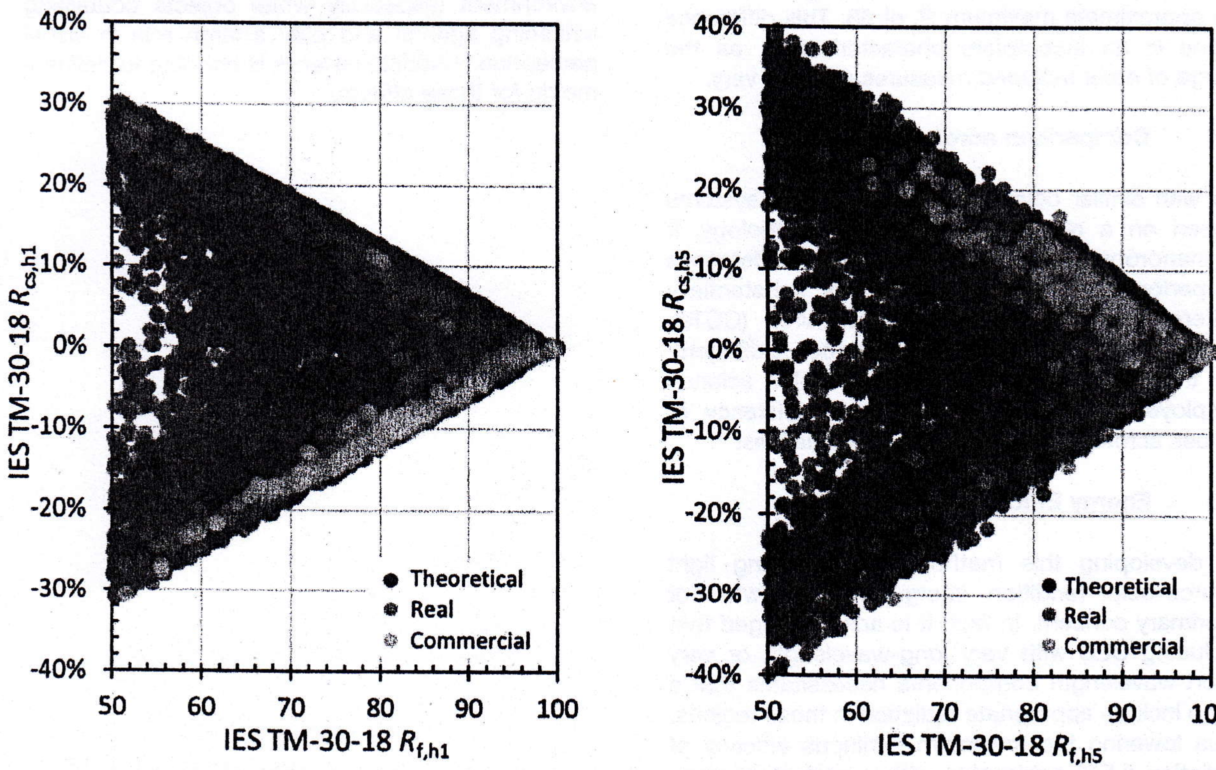


Figure 13. Relationship between Local Chroma Shift and Local Color Fidelity for two example hue-angle bins. The relationship is less defined for hue-angle bins where hue shift is dominant.

and engineering goals, within different architectural lighting contexts. This flexibility contributes to the value of the method. Recent research has shown that various combinations of the measures included in ANSI/IES TM-30-18 could be used in combination to provide excellent predictions of participants' responses to questions about the naturalness, normalness, saturation, vividness, preference, and acceptability of various illuminated scenes.[23-26] Such combinations should be considered context dependent, potentially changing based on the viewer, type of space, objects in the space, chromaticity of the light, illuminance, and design intent. More research is necessary to explore all of these variables.

5.3 Preferred Chromaticity

The optimal chromaticity of light sources is attracting significant attention, and preliminary results suggest that sources far off the Planckian locus can be desirable.[37-42] The approach described in this TM allows for evaluation of such sources, but no consideration is given to preferred chromaticity or perceptions of neutral white—this TM strictly comprises objective characterizations of color differences.

As with CIE R_a, sources off the Planckian locus cannot achieve an R_f value of 100. For example, a source with a CCT of 2700 K and a D_{uv} of -0.01 has an approximate maximum R_f of 98. This difference alone is an incomplete characterization, as the range of other included measures will also vary.

5.4 Comparison across CCTs

As with similar color rendition evaluation systems based on a reference-illuminant methodology, it is inappropriate to assess rank order differences in performance for test sources of substantially different correlated color temperatures (CCTs), because the reference for those sources is different. At the same time, the updated color science employed in this TM allows for consistency of values across a wide range of chromaticities.

5.5 Energy Efficiency

In developing this method for evaluating light source color rendition, energy efficiency was not a primary concern. In fact, it is acknowledged that including CES with very long-wavelength or very short-wavelength components necessitates that a lamp include appropriate radiation in those regions, thus lowering the maximum luminous efficacy of radiation (LER) achievable with a perfect or near-perfect R_f value, compared to that possible with a more limited sample set.[4] Ultimately, it is the responsibility of manufacturers to optimize products based on a variety of criteria, including color quality, luminous efficacy, energy efficiency, cost, luminous intensity distribution, and appearance.

5.6 Color Samples

The complete set of more than 100,000 object colors, from which the CES were chosen, was considered to represent all possible colors, but the selection procedure did not attempt to account for the undoubtedly uneven distribution of colors and object types within interior environments. For example, textiles were not given increased prominence in the final test color sample set compared to flowers. This decision was made because there is insufficient data to accurately characterize the prevalence of object types or object colors within interior environments. Furthermore, the method is intended to be independent of application; specifiers need to use knowledge of the application context to most effectively utilize the tools provided in this TM.

5.7 Fluorescence and Whiteness

The CES used in this TM's methodology include only non-fluorescent samples. However, some fluorescent objects are commonplace in the built environment (especially white objects containing whitening agents) and play a large role in visual perception.[43] Additional work is ongoing to define a metric for these effects.

ANNEX A – COLOR EVALUATION SAMPLES

The reflectance function for each CES, in 1-nm increments, is provided as a download to accompany this document (refer to top of Table of Contents page for web address). It should be noted that 33 of the 99 of the color evaluation samples (CES) were extrapolated from an original measured range of 400 to 700 nm.[4] A flat extrapolation was performed to extend the data to a range of 380 to 780 nm. These samples are denoted with an asterisk. The extrapolation does not greatly affect the results, as the color matching functions (CMFs) used to calculate color coordinates give very little weight to wavelengths outside the 400- to 700-nm range. Additionally, six samples were smoothed to eliminate measurement noise. These samples are denoted with a superscript *s*.

These CES match those used to calculate CIE R_f, having been interpolated to 1-nm increments using the Sprague interpolation method,[44] as recommended in CIE 224:2017.[27] As originally generated for IES TM-30-15, the samples used an alternative extrapolation method. The change in extrapolation method has an effect of between -0.02 and +0.04 points on R_f scores.[32]

A.1 Selection Procedure

During the development of IES TM-30-15, the CES were mathematically down-selected from a set of approximately 105,000 spectral reflectance functions, which were held by the authors to represent the range of all possible colors of real objects. The complete selection procedure is described in "Development of the IES Method for Evaluating Light Source Color Rendition."[4]

The mathematical down-selection procedure consisted of these steps:

1. The samples under consideration were restricted to the volume encompassed by the gamut of the Natural Colour System®© (NCS).[45] This gamut boundary was selected because it approximates the limits for which color error formulas have been tested, and precludes selection of samples from regions with few samples. In addition, the reduced color gamut was considered to better represent typical objects found in most interior rooms than the full gamut of the original 105,000 samples. The reduced-gamut set included approximately 65,000 spectral reflectance functions.

2. A set of 4,880 samples with desirable properties was selected within the NCS gamut. These properties were three-dimensional color space uniformity[3] (the distribution of the samples' chromaticities is approximately uniform in CAM02-UCS) and spectral uniformity[5,19] (the spectral features of the reflectance functions are uniformly distributed across wavelength, so that no specific wavelengths are unduly penalized or favored by the calculations). This yields a set that generates effective predictions for color rendition, but is fairly large.

3. In order to generate a more practically sized sample set, a new set of only 99 CES was chosen from the original set of 65,000 samples, such that they had very similar values for R_f, R_g, gamut shape parameters, and spectral flatness compared to the same values for the set of 4,880 samples.

The resulting 99 CES are relatively uniform across color space (see **Figure A1**). Each plot represents a projection of the samples onto the respective plane. These plots demonstrate the uniform distribution

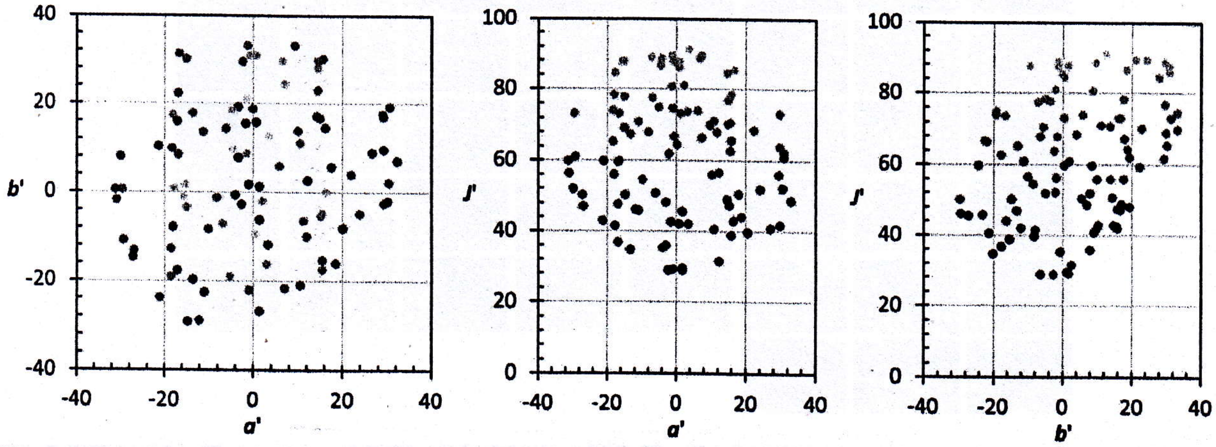


Figure A1. Plots of the 99 color evaluation samples (CESs) in the CAM02-UCS.

and limits of the samples. The boundary reflects the shape of the NCS gamut, which, with the exception of the region were *J'* is less than 20, closely resembles the shape of the color solid held to represent all possible colors. This solid is not spherical. The colors of the points approximate the colors of the samples illuminated by Planckian radiation of 5000 K.

When combined, the CES show little preference for any wavelength (see **Figure A2**), mimicking the properties of the 4,880 sample set, as intended. The set of 99 CES is of reasonable size for use in practical calculations, but is also very well correlated to the larger set of 4,880 samples, so that using only 99 samples does not significantly compromise accuracy. Explicitly, computer modeling showed that 95 percent of 5,000 real and modelled SPDs were within 1.2 points of the mean R_f and R_g values, and other considerations showed similar agreement.[4]

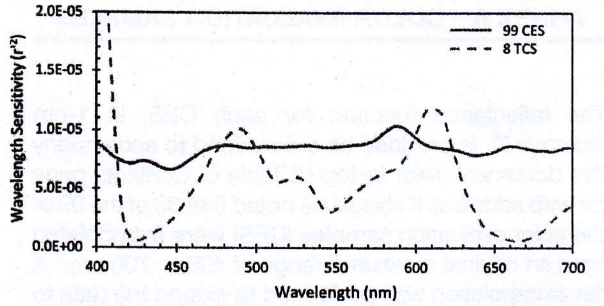


Figure A2. Spectral sensitivity of the 99 color evaluation samples compared to the 8 test color samples used to calculate CIE R_a.

Figure A3 shows an approximate visual representation of the 99 color evaluation samples.

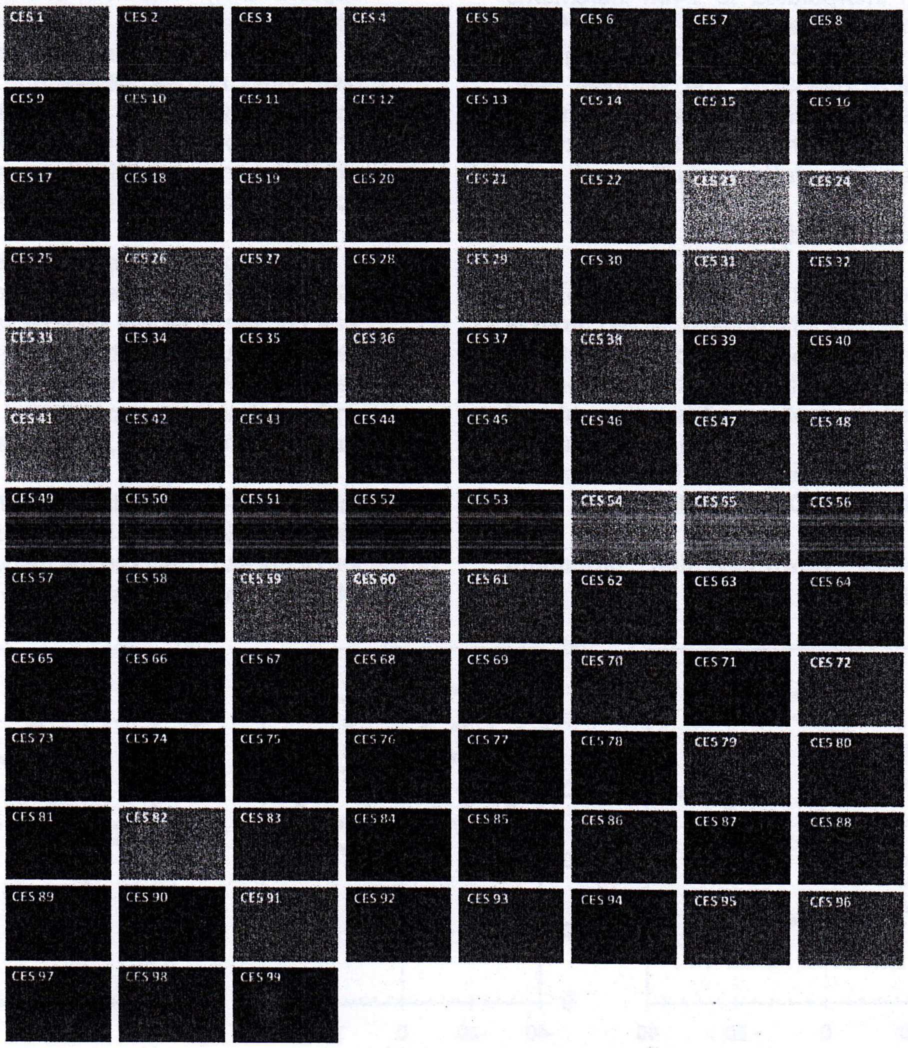


Figure A3. Approximate colors for the 99 CES, calculated the 5000-K reference illuminant (CIE D_{50}).

ANNEX B – COLOR SPECIFICATION FOR HUE-ANGLE BIN GRAPHICS

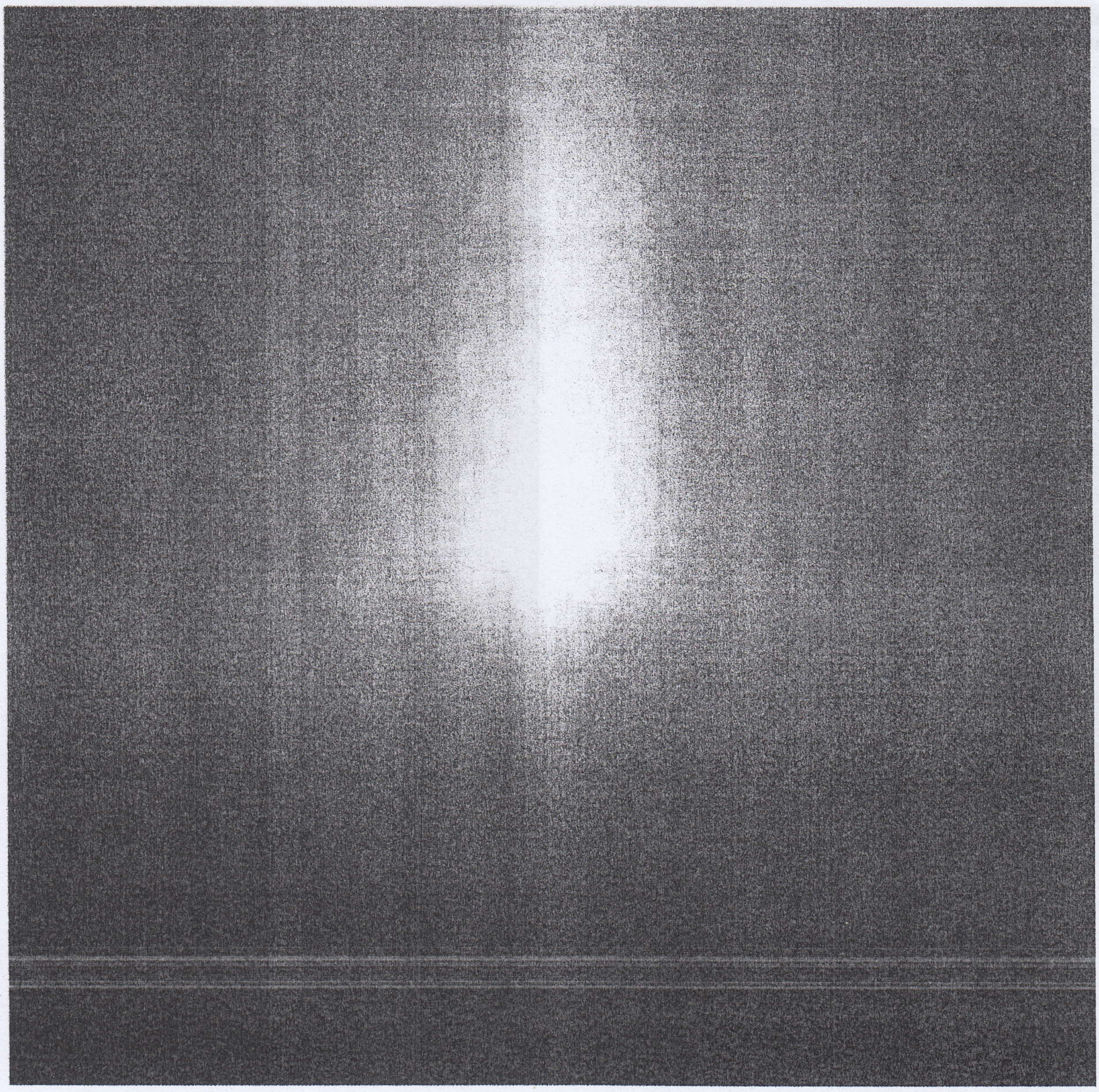
Table B1. RGB Values for Representing the 16 Hue-Angle Bins in Bar Charts.

	R	G	B
1	163	92	96
2	204	118	94
3	204	129	69
4	216	172	98
5	172	153	89
6	145	158	93
7	102	139	94
8	97	178	144
9	123	186	166
10	41	122	126
11	85	120	141
12	112	138	178
13	152	140	170
14	115	88	119
15	143	102	130
16	186	122	142

Table B2. RGB Values for Representing the 16 Hue-Angle Bin Vectors in the Color Vector Graphic.

	R	G	B
1	230	40	40
2	231	75	75
3	251	129	46
4	255	181	41
5	203	202	70
6	126	185	76
7	65	192	109
8	0	156	124
9	22	188	176
10	0	164	191
11	0	133	195
12	59	98	170
13	69	104	174
14	106	78	133
15	157	105	161
16	167	79	129

ANNEX C – BACKGROUND FOR COLOR VECTOR GRAPHIC



ANNEX D – COLOR RENDITION REPORT TEMPLATES

This Annex is not part of ANSI/IES TM-30-18, IES Method for Evaluating Light Source Color Rendition. *It is provided for informational purposes only.*

To facilitate easy comparison of products, three templates for reporting data that has been produced in accordance with IES TM-30-18 are provided here. The templates include simple (about ¼ page), intermediate (about ½ page), and full (full page) layouts, each containing subsequently more information. These templates provide information without explanation and are intended for an educated audience (e.g., lighting specifiers and manufacturers).

These recommended templates are included as printable output in the latest version of the IES TM-30-18 Calculator tools. They are also intended to guide implementation of TM-30-18 reporting by custom software. While small differences in implementation are inevitable, the general arrangement of data and formatting be maintained to the extent practicable. The color vector graphic includes optional elements that may be included or omitted (see **Section 4.5**). Because the information does not appear elsewhere in these templates the values for R_f, R_g, CCT, and D_{uv} should always be embedded, as shown in **Figures D-1** through **D-3.**

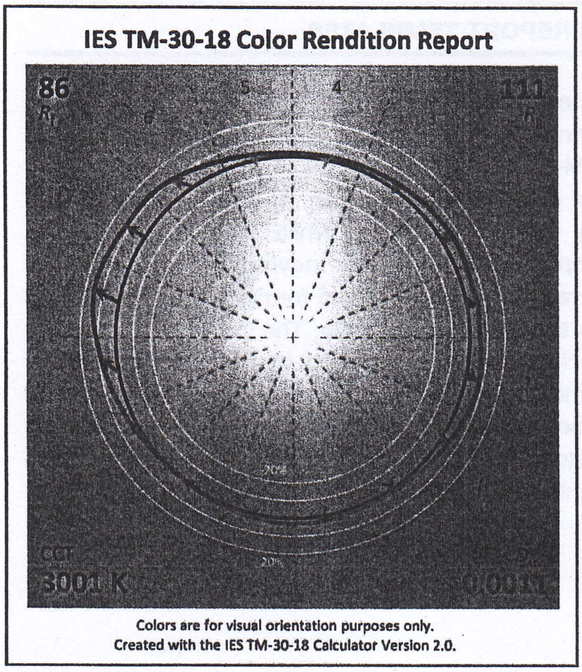


Figure D-1. Example of a simple report.
(Image courtesy of Michael Royer/PNNL)

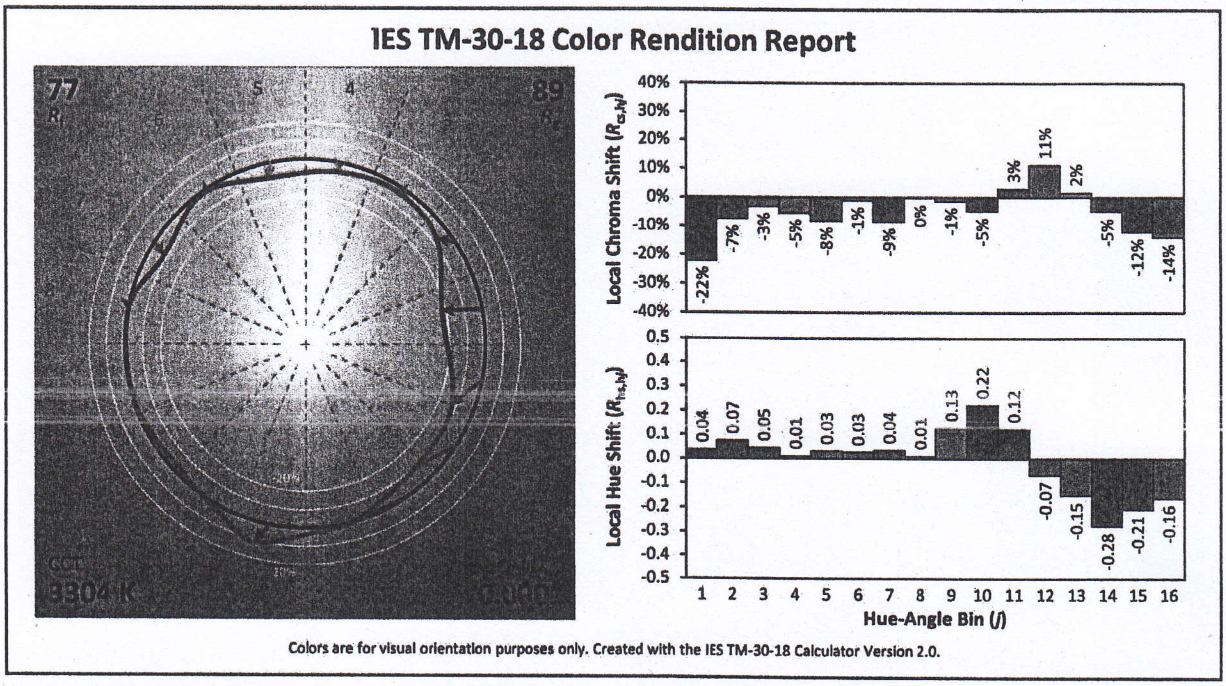


Figure D-2. Example of an intermediate report. (Image courtesy of Michael Royer/PNNL)

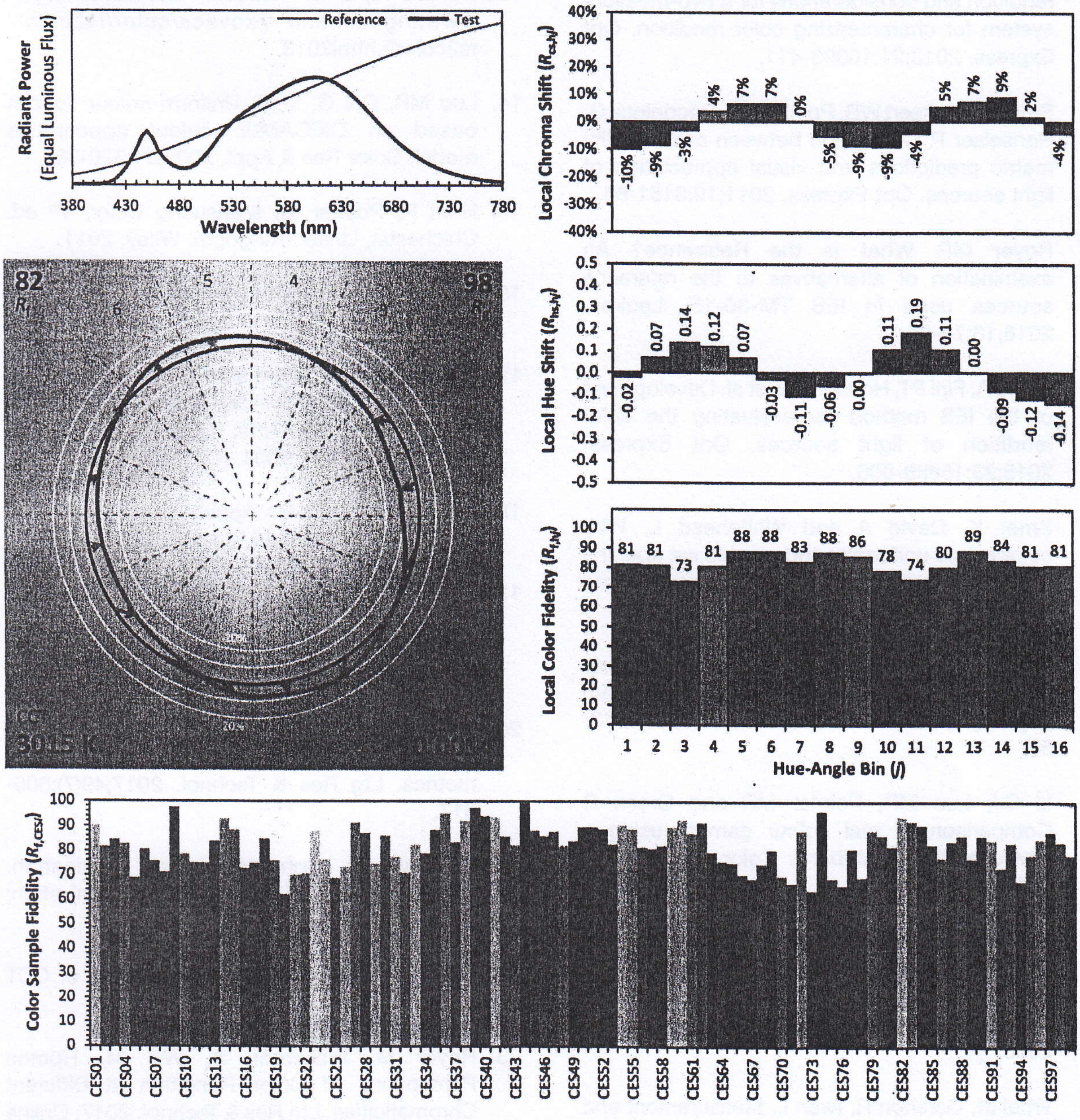
IES TM-30-18 Color Rendition Report

Source: Example

Date: 1/1/2018

Manufacturer: Example

Model: Example



Notes: This is a recommended method for displaying IES TM-30-18 information.

x	**0.4379**
y	**0.4080**
u'	**0.2495**
v'	**0.5231**

CIE 13.3-1995 (CRI)	
R_a	80
R_9	18

Colors are for visual orientation purposes only. Created with the IES TM-30-18 Calculator Version 2.0.

Figure D-3. Example of a full report. (Image courtesy of Michael Royer/PNNL)

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