



TECHNICAL MEMORANDUM:

IES METHOD FOR EVALUATING LIGHT SOURCE COLOR RENDITION

AN AMERICAN NATIONAL STANDARD



ANSI/IES TM-30-20 ERRATA

If you, as a user of ANSI/IES TM-30-20, believe you have located an error not covered by the following revisions, you should e-mail your information to Pat McGillicuddy, pmcgillicuddy@ies.org or send a letter to Pat McGillicuddy, Manager of Standards Development, IES, 120 Wall St. 17th Floor, New York, NY 10005.

Please confine your comment to specific typographical errors or misstatements of fact in the document's text and/or graphics. Do not attempt revisions of ANSI/IES TM-30-20.

Additions will be posted to this list online as they become available. This errata list was last updated **May 7, 2021**.

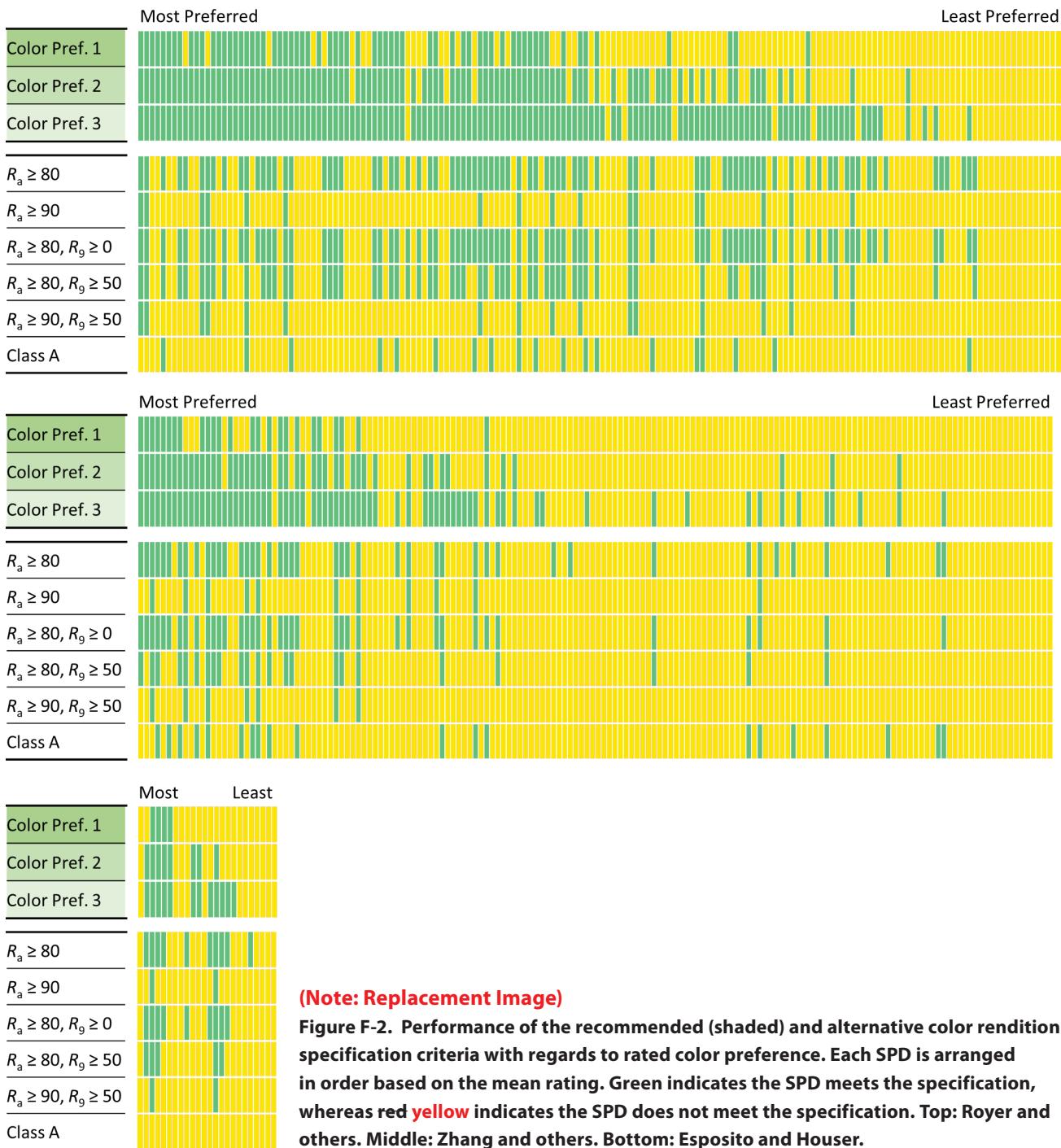
Note: The ANSI/IES TM-30-20 calculation tool files are uploaded to a specific website. The URL is found at the top of the Table of Contents for ANSI/IES TM-30-20. This standard is available in the IES Webstore, www.ies.org/store.

New text is in red. Deletions are shown with strikethrough.

In Section 3.7.1 Calculation of Color Coordinates, the first paragraph:

3.7.1 Calculation of Color Coordinates

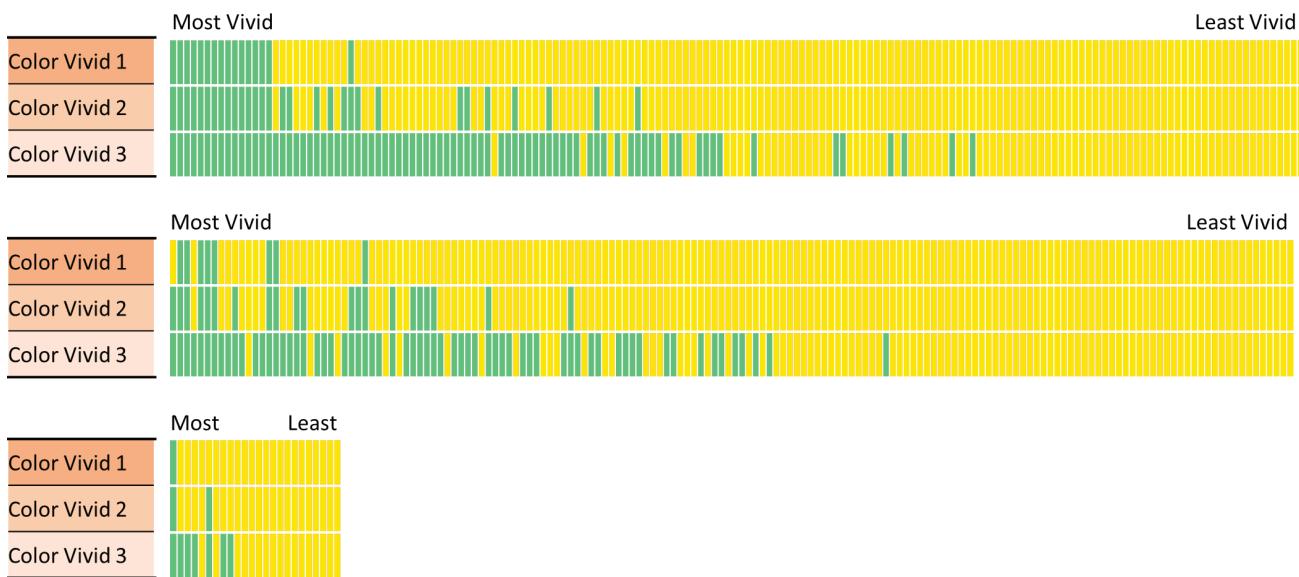
The color coordinates of each CES illuminated by the test source shall be referred to as: $CES_{t,i} = (J_{t,i}', a_{t,i}', b_{t,i}')$, where i is an integer between 1 and 99 representing the CESs. Likewise, the color coordinates of each CES illuminated by the reference illuminant shall be referred to as: $ES_{r,t} = (J_{r,t}', a_{r,t}', b_{r,t}')$ $CES_{r,i} = (J_{r,i}', a_{r,i}', b_{r,i}')$. The subsequently described procedure shall be performed twice for all CESs, 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 all CESs.



In Section F.3.2 Color Vividness:

The Color Vividness specifications were developed using the same three datasets and same procedures as described for the Color Preference specifications. For all three datasets, mean ratings of color vividness were most strongly correlated with $R_{cs,h1}$ and $R_{cs,h16}$ ($r^2 \geq 0.72$). $R_{cs,h1}$ was chosen for its practicality and continuity with the color preference specifications. $R_{cs,h1}$ criteria were augmented with criteria for R_g to improve the fit to collected data and prevent narrow optimizations in the future. **Figure F-3** illustrates the performance of the Color Vividness specifications. Because no specifications have previously been proposed specifically for this design intent, no comparisons are provided.

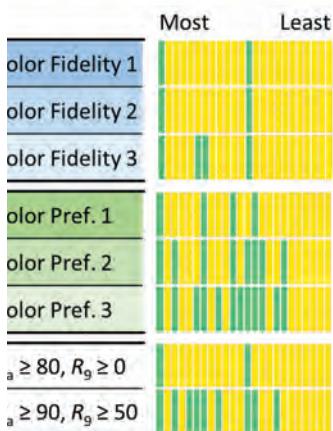
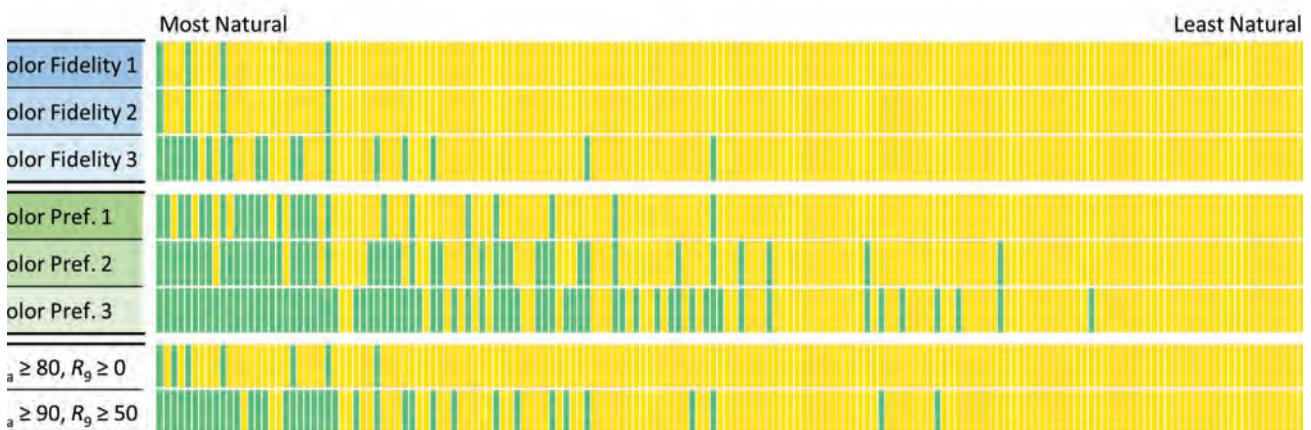
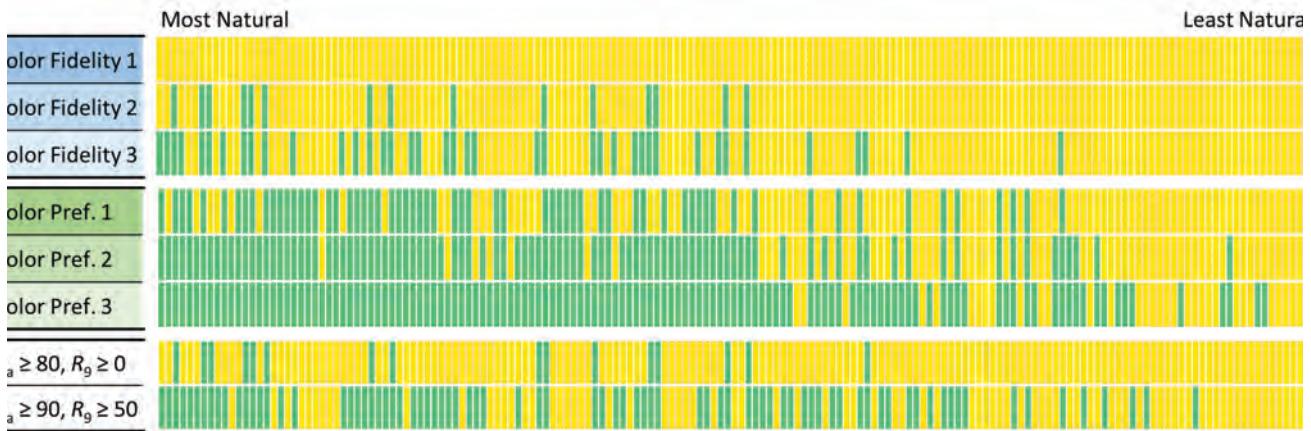
ANSI/IES TM-30-20 ERRATA CONTINUES



(Note: Replacement Image)

Figure F-3. Performance of the recommended specification criteria with regard to rated color preference. Each SPD is arranged in order based on the mean rating. Green indicates the SPD meets the specification, whereas red yellow indicates the SPD does not meet the specification. Top: Royer and others. Middle: Zhang and others. Bottom: Esposito and Houser.

[In Section F.3.3 Color Fidelity]:



(Note: Replacement Image)

Figure F-5. Performance of the recommended (shaded) and alternative color rendition specification criteria with regard to rated color preference. Each SPD is arranged in order based on the mean rating. Green indicates the SPD meets the specification, whereas red yellow indicates the SPD does not meet the specification. Top: Royer and others. Middle: Zhang and others. Bottom: Esposito and Houser.

In Section F.3.6 Performance Compared to Prior Specifications Based on CIE 13.3-1995:

F.3.6 Performance Compared to Prior Specifications Based on CIE 13.3-1995

Figure F-9 illustrates the performance of the Color Preference and Color Fidelity specifications (shown with lines) relative to approximate boundaries for two common specifications based on CIE 13.3-1995: R_a (CRI) ≥ 80 with $R_g \geq$

ANSI/IES TM-30-20 ERRATA CONTINUES

0 (orange) and R_a (CRI) ≥ 90 with $R_9 \geq 50$ (yellow). The latter is shown by color coding the set of theoretical SPDs to translate from R_a and R_9 to the axes of R_f and $R_{cs,h1}$. There is substantial overlap between the criteria using the different color rendition evaluation methods, which was a consideration during the development of the recommended specifications of this document. That is, converting to the new color rendition specifications does not require vast changes in currently available products. It does, however, allow for refinement and differentiation while establishing targets for future development.

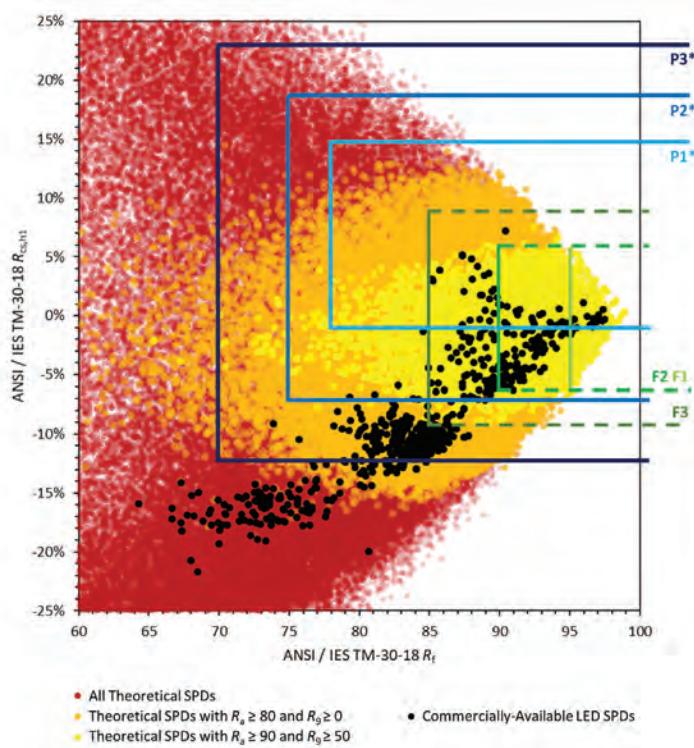


Figure F-9. Comparison of recommended specifications (lines) and commonly used specifications (colored theoretical SPDs).

There are important differences between common past specifications and the recommended specifications of this document. Many theoretical SPDs meeting specifications using the combinations of CIE R_a and R_9 fall outside any of the recommended specifications. Of the theoretical SPDs meeting CIE $R_a \geq 80$ with $R_9 \geq 0$, for example, 9%, 37%, and 69% fail to meet the P3, P2, and P1 specifications, respectively. A substantial portion of this discrepancy is due to misalignment between the previously used measures and the characteristics found to be important for the Color Preference design intent.

However, SPDs meeting CIE $R_a \geq 80$

with $R_9 \geq 0$ have R_f values as low as 41; furthermore, SPDs meeting CIE $R_a \geq 90$ with $R_9 \geq 50$ have R_f values as low as 65. As another illustration, 45% of the SPDs meeting CIE $R_a \geq 90$ with $R_9 \geq 50$ fail to meet the F2 specification, which is conceptually equivalent. The amount is 61% for the commercially available LED set. This is due to the technical limitations of the CIE 13.3-1995 method, specifically the color samples and color space.^{21,30-34,41} It is not due to the scaling factor, which has been adjusted.³³ The new criteria effectively prevent the use of SPDs optimized only for the metric calculation. These examples also illustrate why it is not recommended to simply convert existing specifications to equivalent measures from ANSI/IES TM-30-18.

The new specifications also address products that would otherwise fail to meet common past specifications due to a bias against particular shifts.³³ For example, theoretical SPDs in the P3, P2, and P1 specifications have CIE R_a values as low as 42, 51, 52, and 61, respectively. CIE R_9 values are as low as -173, -118, and -99. The same is true for the F3, F2, and F1 specifications, where the minimum CIE R_a values for the theoretical SPDs are 75, 82, and 91—the gap greatly reduces as average color fidelity is increased. These discrepancies extend to the experimental datasets, where SPDs in the P3, P2, and P1 specifications have CIE R_a values as low as 47, 60, and 68, respectively.

**ANSI/IES TM-30-20
+ERRATA 1**

**TECHNICAL MEMORANDUM:
IES METHOD FOR
EVALUATING LIGHT SOURCE COLOR RENDITION
AN AMERICAN NATIONAL STANDARD**

Publication of this Technical Memorandum
has been approved by IES.
Suggestions for revisions
should be directed to the IES..

**Prepared by the
The IES Color Committee**



Copyright 2018 by the Illuminating Engineering Society.

Approved by the IES Standards Committee, June 25, 2018, as a Transaction of the Illuminating Engineering Society.

Approved as an American National Standard, July 27, 2018.

All of Annex E is new material.

Approved by the IES Standards Committee on April 30, 2019.

Approved as an American National Standard on September 23, 2019.

All of Annex F is new material.

Approved by the IES Standards Committee on April 30, 2019.

Approved as an American National Standard on September 23, 2019.

All rights reserved. No part of this publication may be reproduced in any form, in any electronic retrieval system or otherwise, without prior written permission of the IES.

Published by the Illuminating Engineering Society, 120 Wall Street, New York, New York 10005.

IES Standards and Guides are developed through committee consensus and produced by the IES Office in New York. Careful attention is given to style and accuracy. If any errors are noted in this document, please forward them to the Director of Standards and Research, standards@ies.org or the above address, for verification and correction. The IES welcomes and urges feedback and comments.

Printed in the United States of America.

ISBN# 978-0-87995-379-9

DISCLAIMER

IES publications are developed through the consensus standards development process approved by the American National Standards Institute. This process brings together volunteers representing varied viewpoints and interests to achieve consensus on lighting recommendations. While the IES administers the process and establishes policies and procedures to promote fairness in the development of consensus, it makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

The IES disclaims liability for any injury to persons or property or other damages of any nature whatsoever, whether special, indirect, consequential or compensatory, directly or indirectly resulting from the publication, use of, or reliance on this document.

In issuing and making this document available, the IES is not undertaking to render professional or other services for or on behalf of any person or entity. Nor is the IES undertaking to perform any duty owed by any person or entity to someone else. Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

The IES has no power, nor does it undertake, to police or enforce compliance with the contents of this document. Nor does the IES list, certify, test or inspect products, designs, or installations for compliance with this document. Any certification or statement of compliance with the requirements of this document shall not be attributable to the IES and is solely the responsibility of the certifier or maker of the statement.

AMERICAN NATIONAL STANDARD

Approval of an American National Standard requires verification by ANSI that the requirements for due process, consensus, and other criteria have been met by the standards developer.

Consensus is established when, in the judgment of the ANSI Board of Standards Review, substantial agreement has been reached by directly and materially affected interests. Substantial agreement means much more than a simple majority, but not necessarily unanimity. Consensus requires that all views and objections be considered, and that a concerted effort be made toward their resolution.

The use of American National Standards is completely voluntary; their existence does not in any respect preclude anyone, whether that person has approved the standards or not, from manufacturing, marketing, purchasing, or using products, processes, or procedures not conforming to the standards.

The American National Standards Institute does not develop standards and will in no circumstances give an interpretation to any American National Standard. Moreover, no person shall have the right or authority to issue an interpretation of an American National Standard in the name of the American National Standards Institute. Requests for interpretations should be addressed to the secretariat or sponsor whose name appears on the title page of this standard.

CAUTION NOTICE: This American National Standard may be revised at any time. The procedures of the American National Standards Institute require that action be taken to reaffirm, revise, or withdraw this standard no later than five years from the date of approval. Purchasers of American National Standards may receive current information on all standards by calling or writing the American National Standards Institute.

Prepared by the IES Color Committee:

Wendy Luedtke, Chair

Jason Livingston, Co-Chair

Members

A. David	P. Fini	T. Hensley	L. Whitehead
W. Davis	M. Royer	K. Houser	M. Wood
T. Esposito	M. Wei	H. Ratafia	

Advisory Members

E. Bretschneider*	F. Florentine*	J. Gaines*	N. Miller*
A. Feldman*	J. Fuller*	S. Lavoie*	M. Raz*

Please refer to the IES Bookstore for possible Errata: www.ies.org.

CONTENTS

1.0	Introduction	1
1.1	Calculation Components.....	1
1.2	Calculated Measures.....	2
1.3	Changes from IES TM-30-15	2
2.0	Scope	2
3.0	Core Calculations	2
3.1	Colorimetric Observer	2
3.2	Test Source.....	3
3.3	Reference Illuminant.....	3
3.4	Color Evaluation Samples (CES).....	4
3.5	Range and Interpolation of Data	5
3.6	Calculation of Tristimulus Values	5
3.7	Color Space and Chromatic Adaptation Transformation	5
3.7.1	Calculation of Color Coordinates.....	6
3.8	Color Difference Formula	7
4.0	Calculated Measures	7
4.1	Fidelity Index (R_f)	8
4.2	Sample Color Fidelity ($R_{f,CESi}$).....	9
4.3	Hue-Angle Bins.....	9
4.4	Gamut Index (R_g)	9
4.5	Color Vector Graphic (CVG).....	12
4.6	Local Chroma Shift ($R_{cs,hj}$).....	14
4.7	Local Hue Shift ($R_{hs,hj}$)	16
4.8	Local Color Fidelity ($R_{f,hj}$)	17
5.0	Commentary	18
5.1	Average Values.....	18
5.2	Color Rendition Preference and Other Perceptions	18
5.3	Preferred Chromaticity	18
5.4	Comparison Across CCTs	18
5.5	Energy Efficiency	18
5.6	Color Samples.....	19
5.7	Fluorescence and Whiteness	19

Annex A – Color Evaluation Samples	19
Annex B – Color Specification For Hue-Angle Bin Graphics.....	22
Annex C – Background For Color Vector Graphic	23
Annex D – Color Rendition Report Templates	24
Annex E – Recommendations for Specifying Light Source Color Rendition.....	26
Annex F – Evidence Supporting Recommended Criteria for Specifying Light Source Color Rendition.....	41
 References	 56

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 CIECAM02¹⁷⁻¹⁹ 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 observer²¹ 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,h_j}), 16 hue-specific measures of chroma shift (local chroma shift, R_{cs,h_j}), and 16 hue-specific measures of hue shift (local hue shift, R_{hs,h_j}). 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, $R_{f,CES}$) 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 224:2017²⁷) 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 $Y_{10,t} = 100$.

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:

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

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

$$x_D = \frac{-2.0064 \times 10^9}{T_r^3} + \frac{1.9018 \times 10^6}{T_r^2} + \frac{0.24748 \times 10^3}{T_r} + 0.23704 , \quad (11)$$

and where:

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

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

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

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

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

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

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

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

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 $Y_{10,r} = 100$. The tristimulus values can be calculated as:

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

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

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.

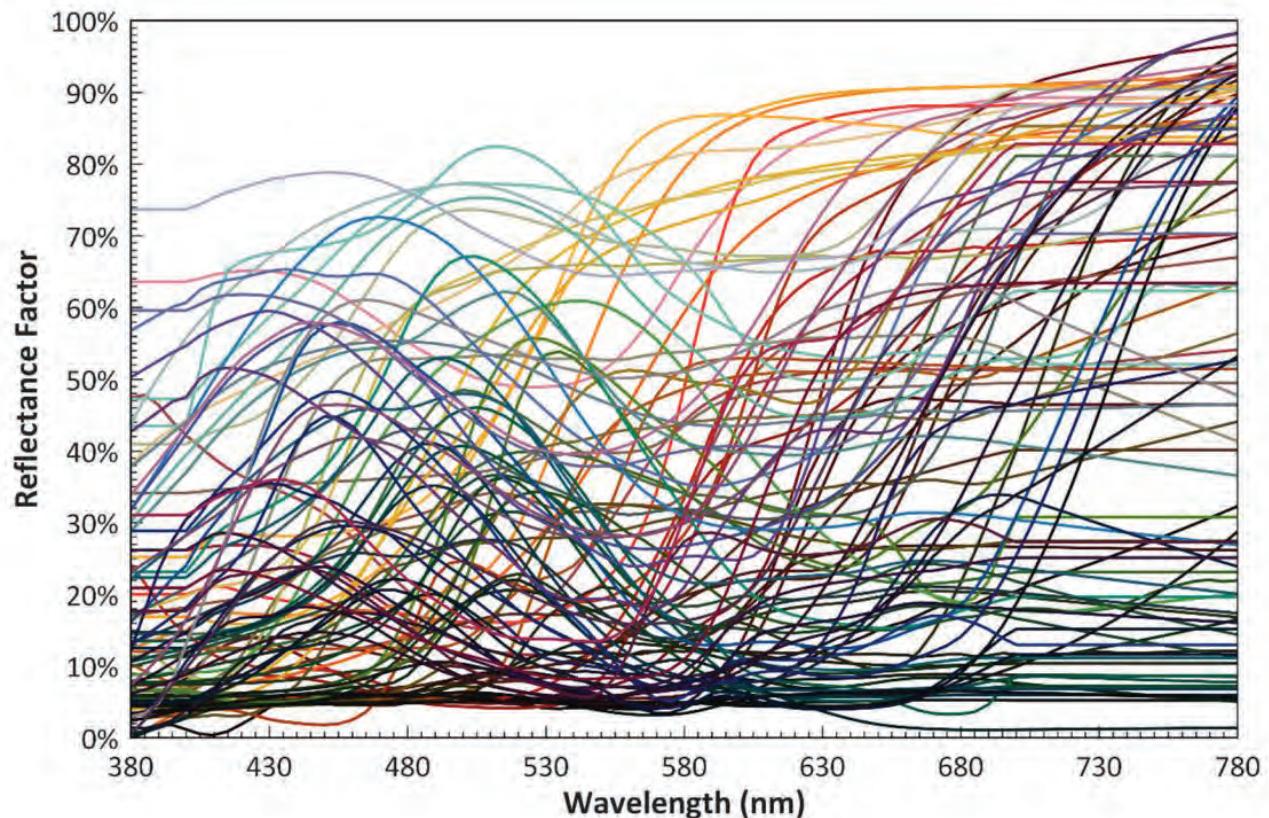


Figure 1. Spectral reflectance functions for the 99 color evaluation samples. The color of the line approximates the color appearance using CIE D₅₀.

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:

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

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

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

where:

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

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

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

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

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

where:

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

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 parameters¹⁸ shall be used:

- Background luminance, $Y_b = 20 \text{ cd/m}^2$
- Surround parameter $F = 1$
- Surround parameter $N_c = 1$
- Surround parameter $c = 0.69$
- Luminance of adapting field, $L_A = 100 \text{ cd/m}^2$
- 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:

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

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 matrix M_{CAT02}^*

*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.

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

where:

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

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

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

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

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

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

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

where:

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

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

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

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

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

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

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

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

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

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

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

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

where the achromatic response (*A*) is:

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

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

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

and where:

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

where the eccentricity (*e*_t) is:

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

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

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

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

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

where:

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

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:

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

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:

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

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:

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

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.

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.

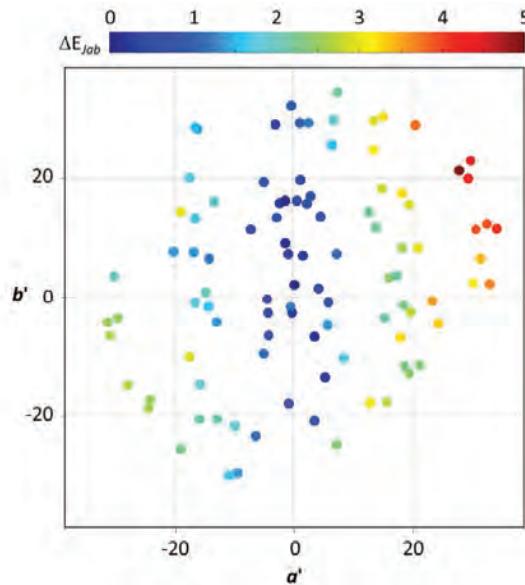


Figure 2. A two-dimensional plot showing the color shift for each color evaluation sample (CES), illuminated by an example test source with an R_f value of 87. The test source produces the most shift (relative to the reference) for saturated red CES.

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

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

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

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

Each $R_{f,CES,i}$ 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 $R_{f,CES,i}$ values.

Because each value corresponds to a specific spectral reflectance function, $R_{f,CES,i}$ values must be carefully considered when applying them to a given object. Individual $R_{f,CES,i}$ 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

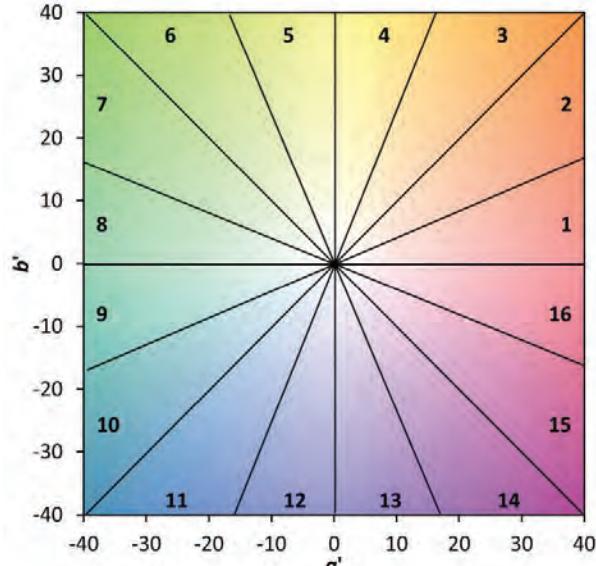


Figure 3. Hue-angle bin numerical designations.

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.

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 as 100 times

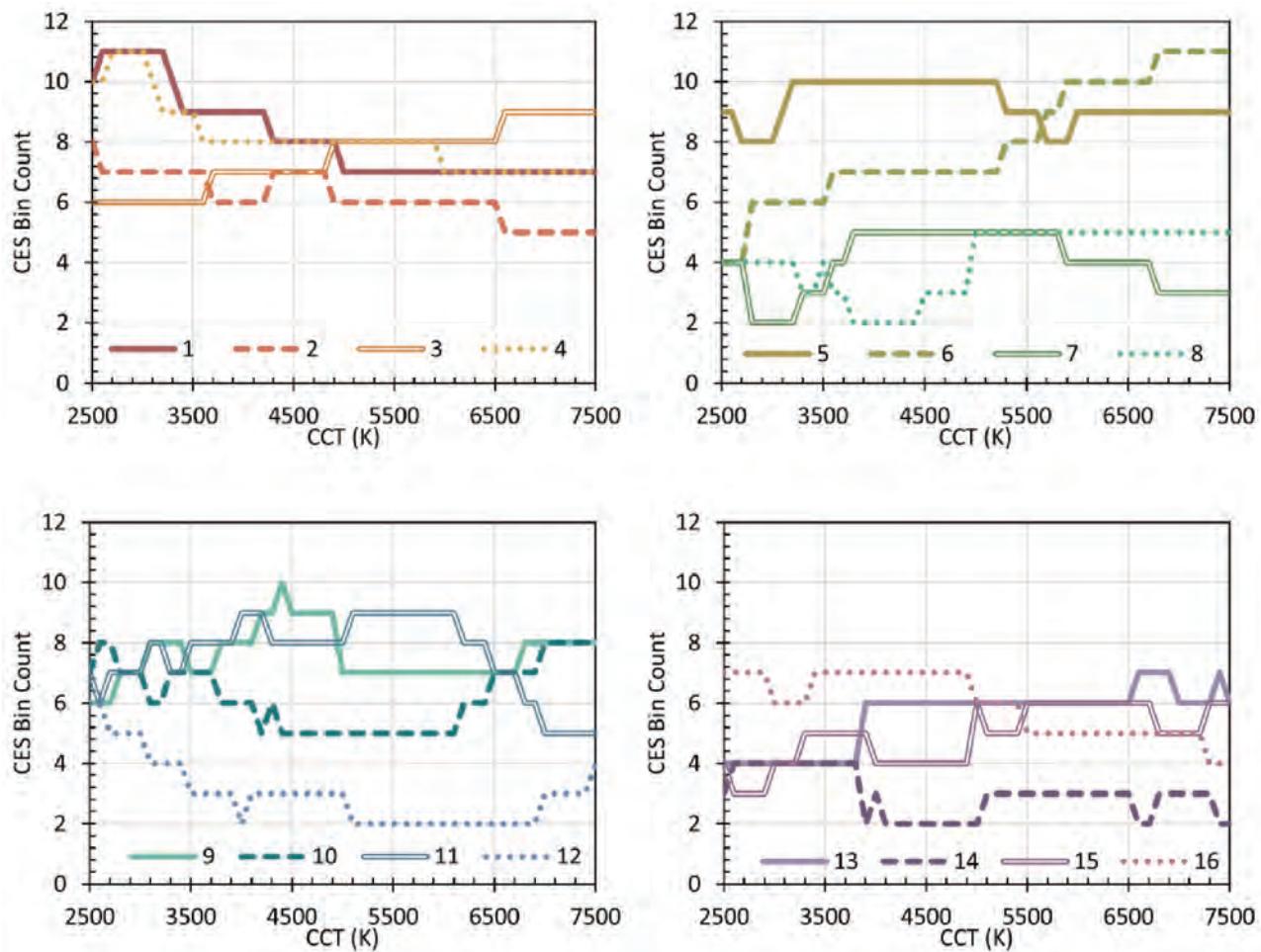


Figure 4. Number of color evaluation samples (CES) per hue-angle bin at different CCTs.

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

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

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.

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

**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.

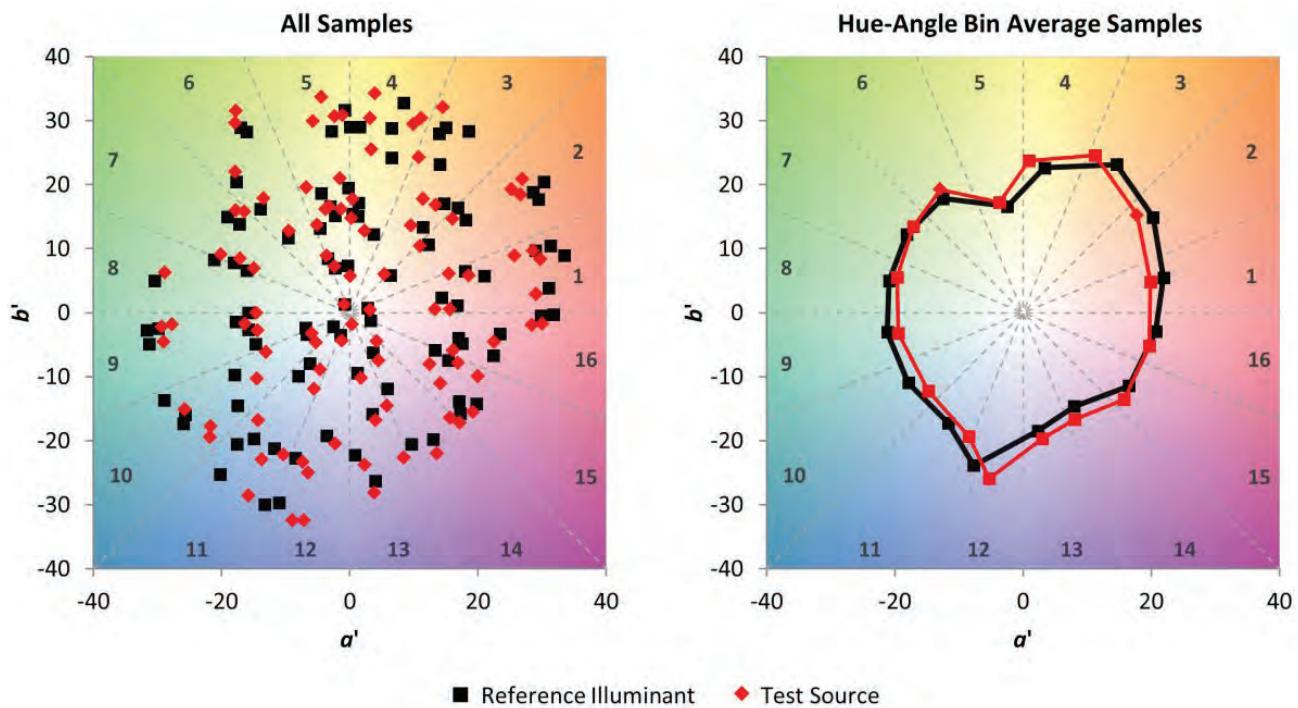


Figure 5. Schematic of R_g calculation. Left: The 99 color evaluation samples are divided among the hue-angle bins in the a' - b' plane of CAM02-UCS. Right: The average coordinates in each hue-angle bin form the vertices of two polygons. Gamut index, R_g , is based on the ratio of the area of the two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

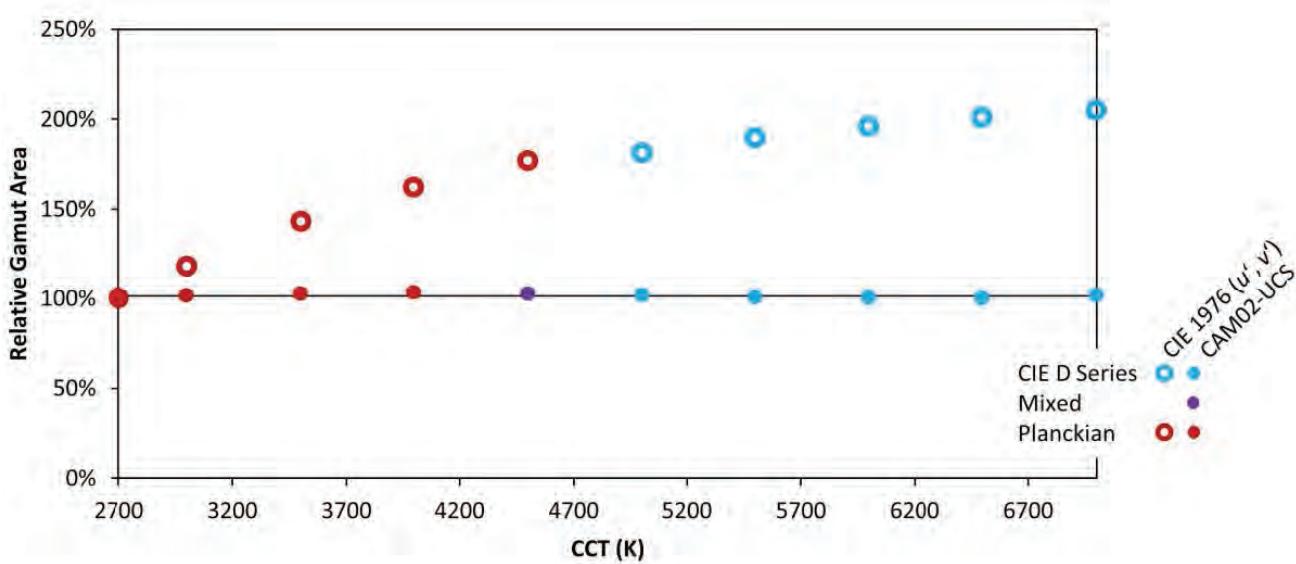


Figure 6. Gamut area for reference illuminants at different CCTs, relative to the gamut area of 2700-K Planckian radiation. The gamut area in CAM02-UCS is calculated according to R_g , whereas the gamut area in CIE 1976 (u' , v') is calculated with the color samples used to calculate CIE R_a .

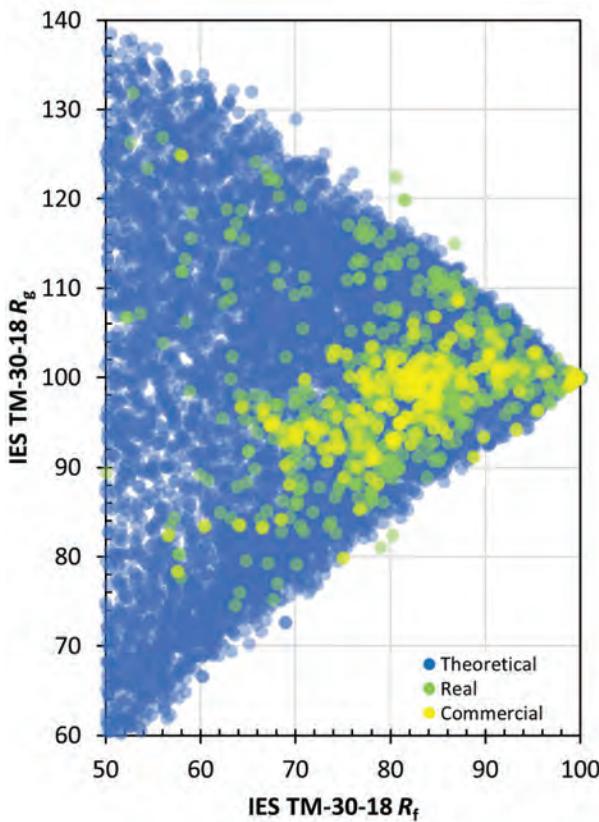


Figure 7. Plot of R_g versus R_f . This includes 212 commercially available light sources, 806 other real light sources (experimental or of unknown origin), and 14,788 theoretical light sources composed of four Gaussian primaries and spanning the range of chromaticities included in ANSI C78.377-2017.

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

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:

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

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

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.

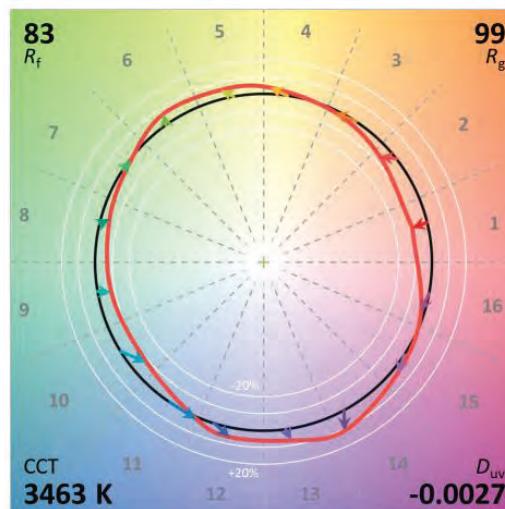
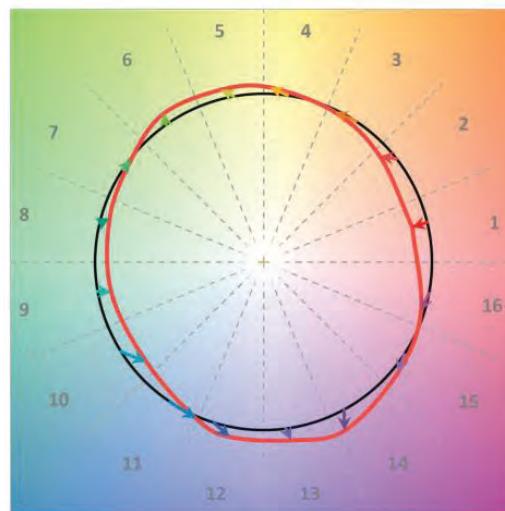


Figure 8. Example of formatting of the color vector graphic. **Top:** minimum required components. **Middle:** minimum recommended representation. **Bottom:** recommended representation with the addition of optional elements.

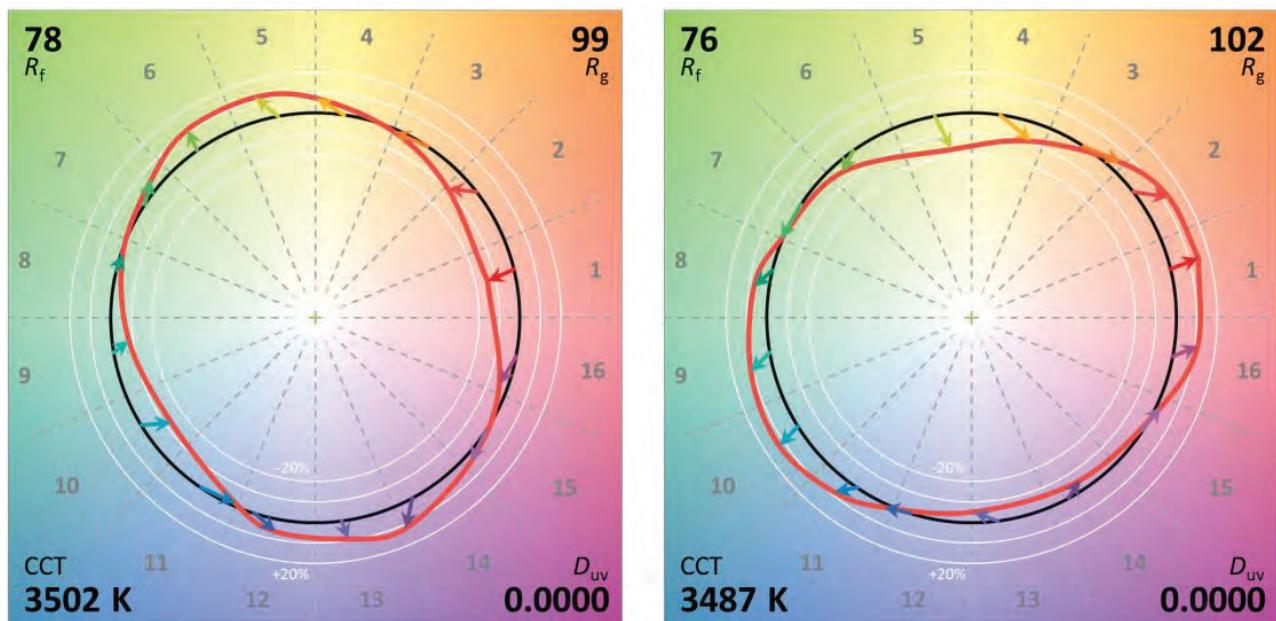


Figure 9. Color Vector Graphics for two SPDs with equivalent R_f and R_g values but substantially different gamut shapes. Such sources may be perceived differently.

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:

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

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

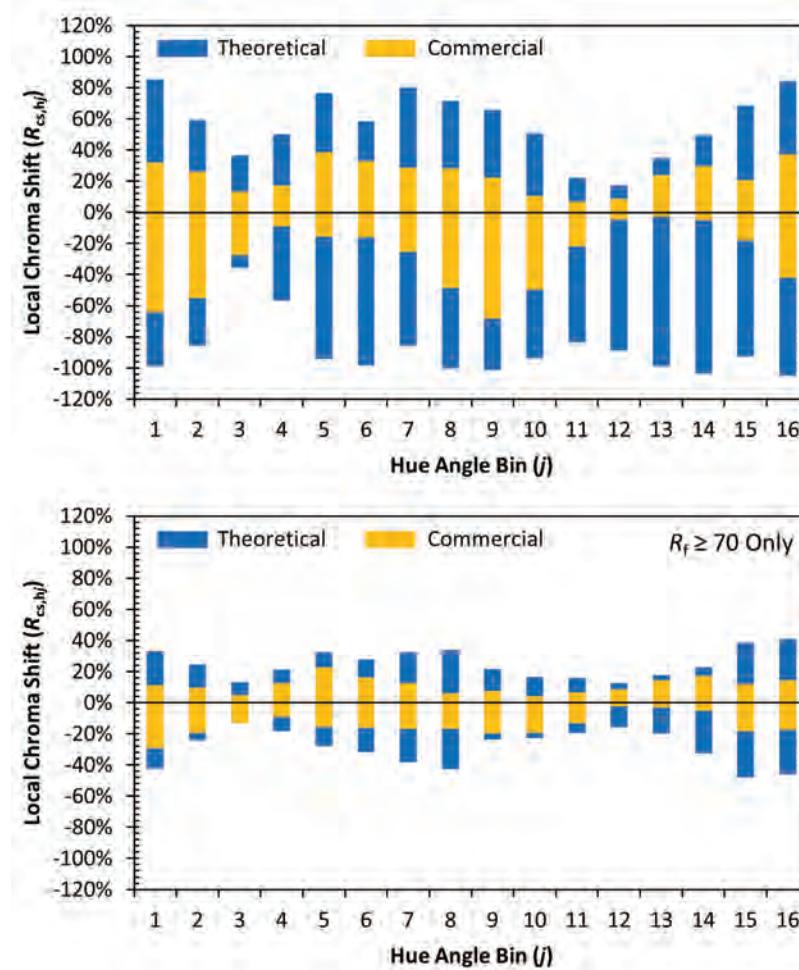


Figure 10. Theoretical range of potential values for local chroma shift, based on 14,788 theoretical SPDs spanning the range of chromaticities specified in ANSI C78.377-2017, and 212 commercially available light sources. Top: all sources. Bottom: only sources with $R_f \geq 70$.

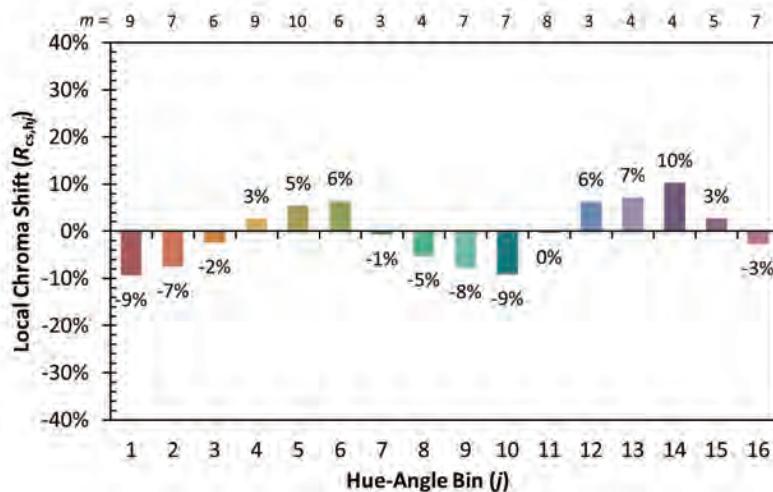


Figure 11. Recommended graphical representation of local chroma shift values to convey gamut shape.

is provided in "Chroma Shift and Gamut Shape: Going Beyond Average Color Fidelity and Gamut Area."³⁶

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

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 $R_{hs,j}$, where j indicates the number of the hue-angle bin:

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

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).

$R_{hs,j}$ 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**.

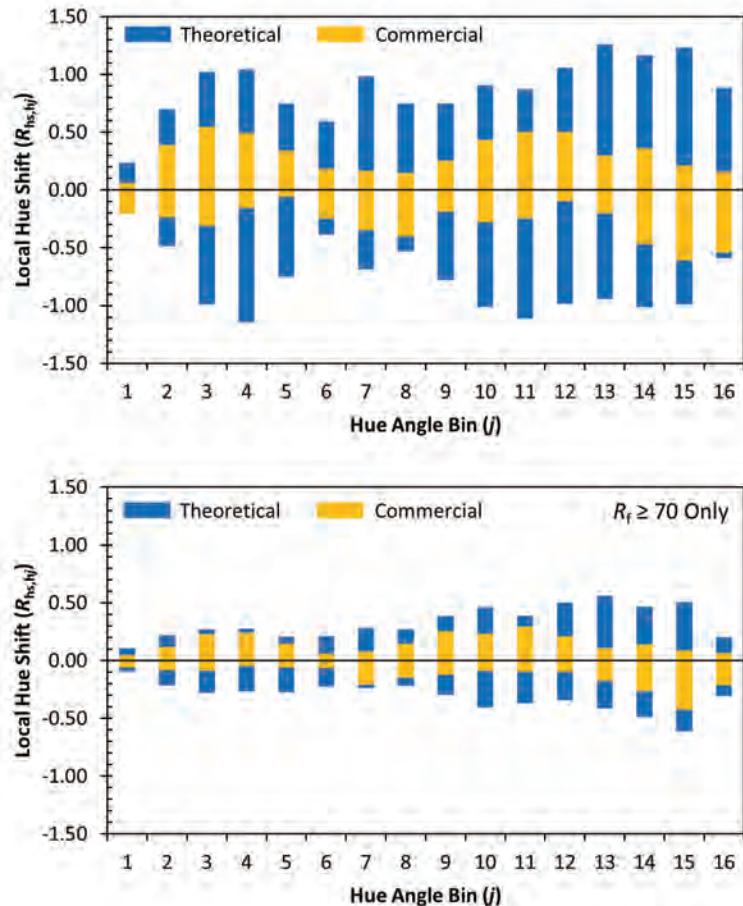


Figure 12. Theoretical range of potential values for local hue shift, based on 14,788 theoretical SPDs spanning the range of chromaticities specified in ANSI C78.377-2017, and 212 commercially available light sources. Top: all sources. Bottom: only sources with $R_f \geq 70$.

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:

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

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

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_g). 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., $R_{f,CESi}$ or CIE R_g) 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

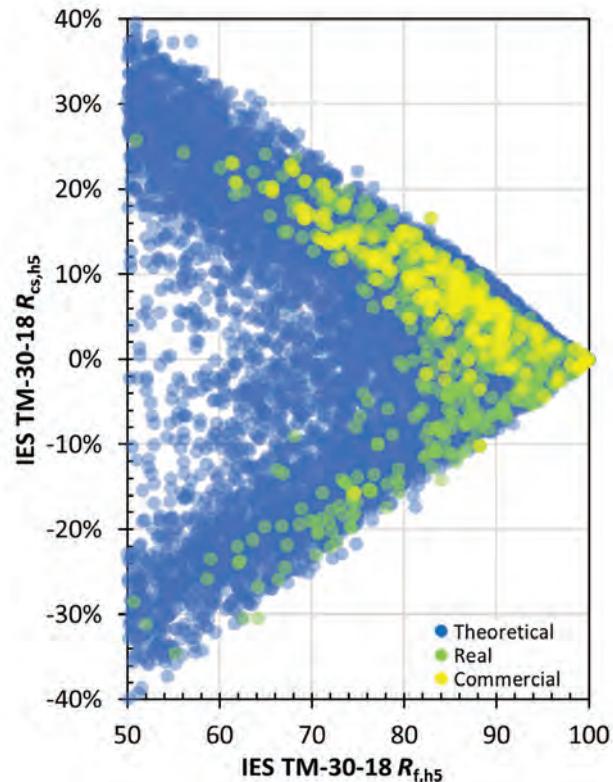
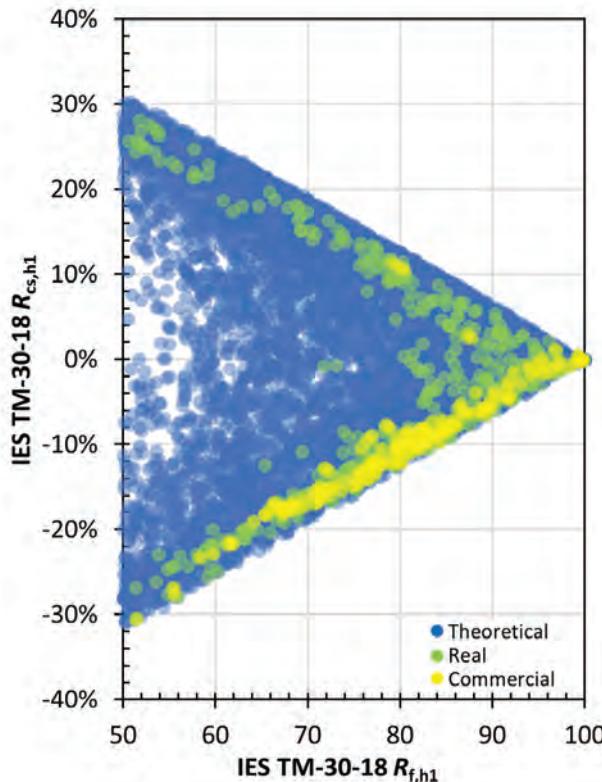


Figure 13. Relationship between Local Chroma Shift and Local Color Fidelity for two example hue-angle bins.
The relationship is less defined for hue-angle bins where hue shift is dominant.

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 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 (www.ies.org/store/). 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 uniformity³ (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 A-1**). Each plot represents a projection of the samples onto the respective plane. These plots demonstrate the uniform distribution and limits of the samples. The boundary reflects the shape of the NCS gamut, which, with the exception of the region where 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 A-2**), 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,

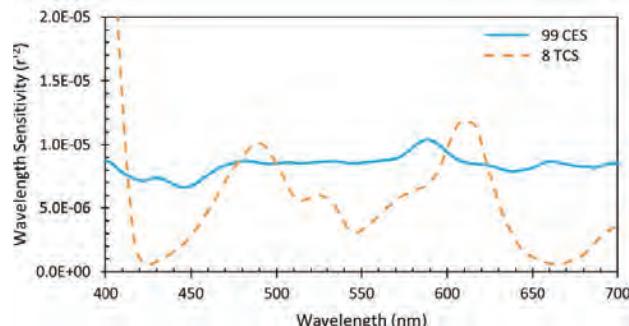


Figure A-2. Spectral sensitivity of the 99 color evaluation samples compared to the 8 test color samples used to calculate CIE R_a .

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 A-3 shows an approximate visual representation of the 99 color evaluation samples.

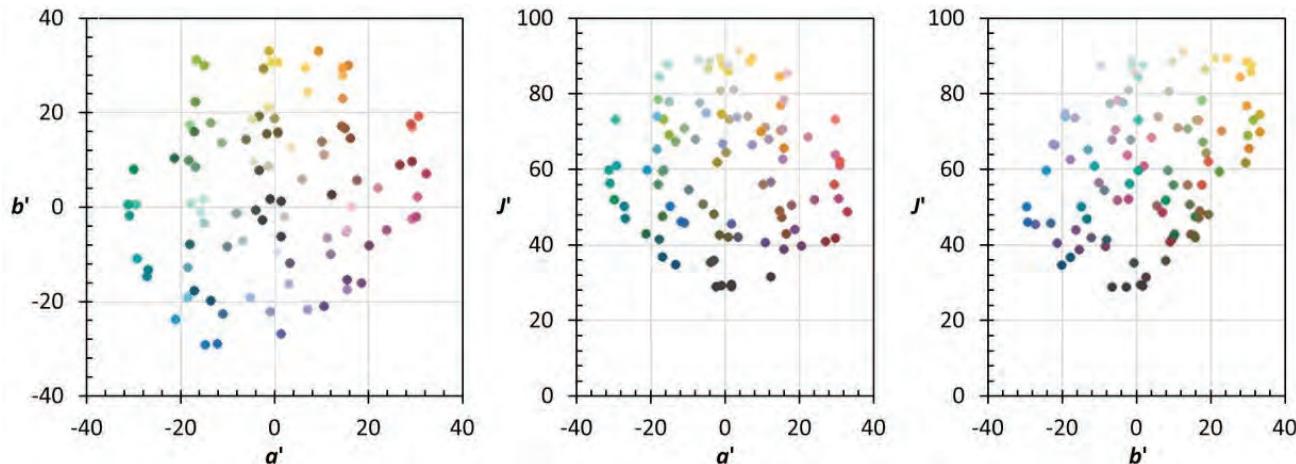


Figure A-1. Plots of the 99 color evaluation samples (CESs) in the CAM02-UCS.

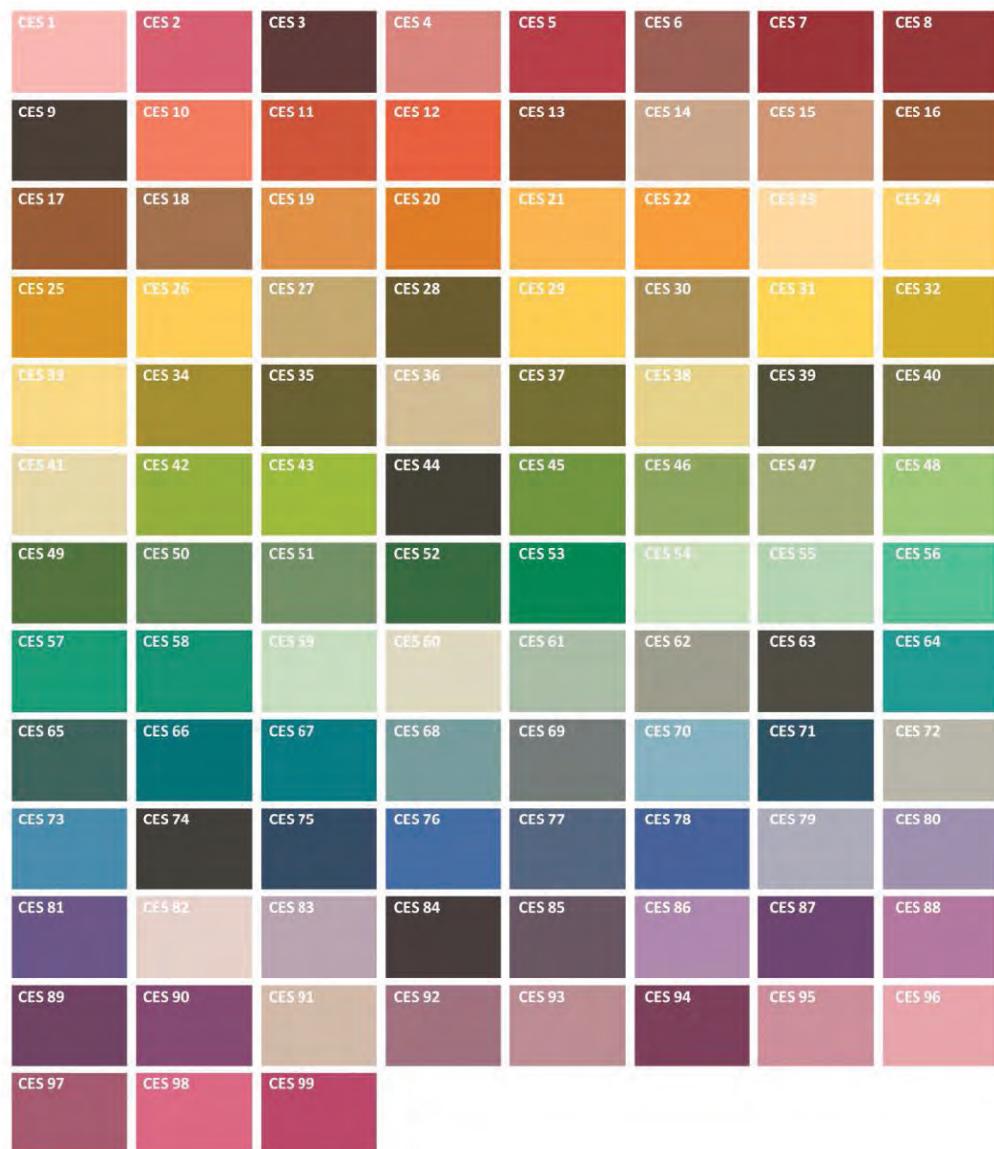


Figure A-3. Approximate colors for the 99 CES, calculated the 5000-K reference illuminant (CIE D₅₀).

Annex B – Color Specification For Hue Angle Bin Graphics

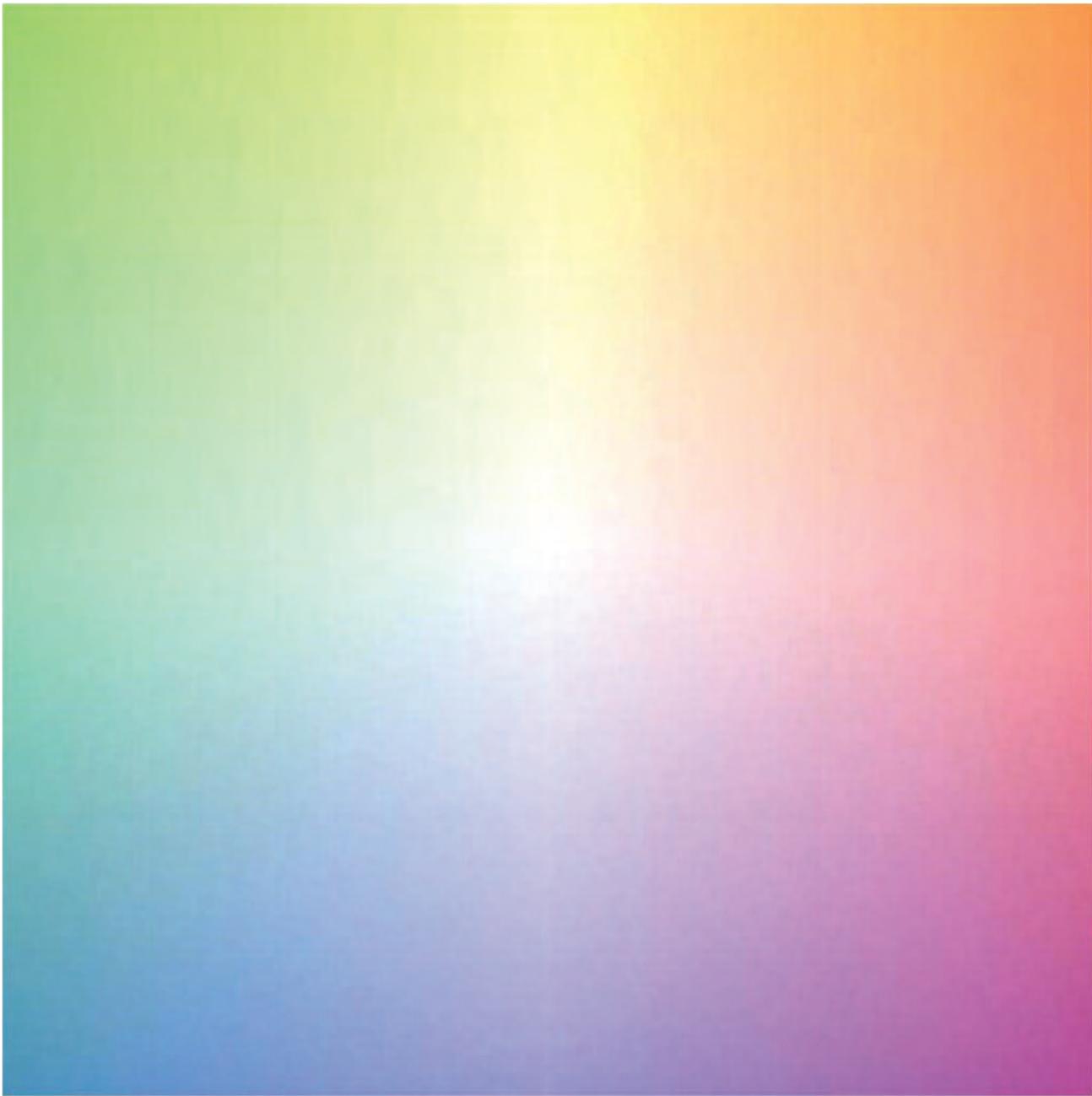
Table B-1. RGB Values for Representing the 16 Hue-Angle Bins in Bar Charts.

	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 B-2. 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-30-20, Technical Memorandum: 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 1/4 page), intermediate (about 1/2 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**.

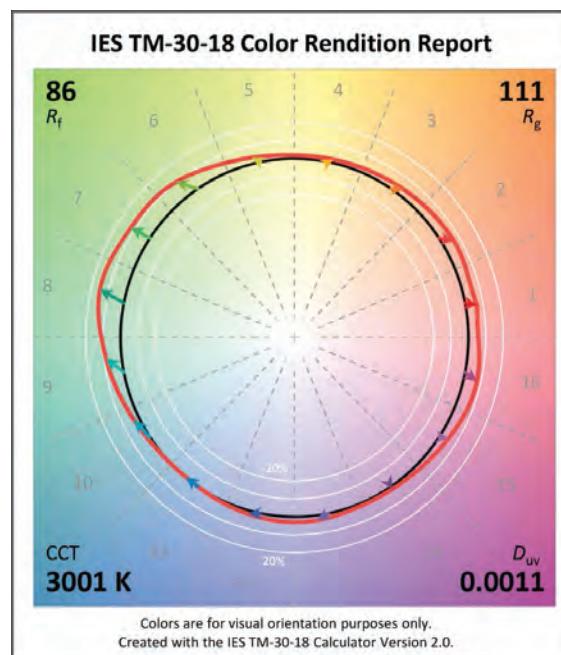


Figure D-1. Example of a simple report.
(Image courtesy of Michael Royer/PNNL)

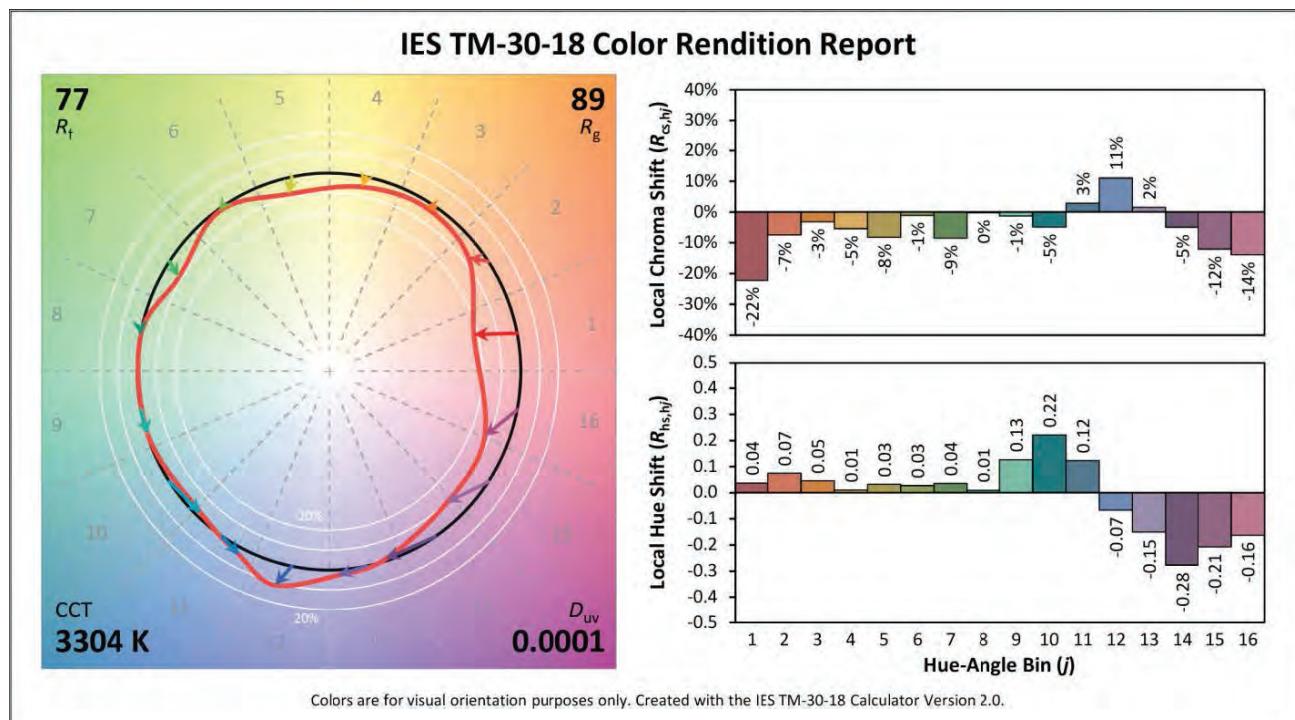
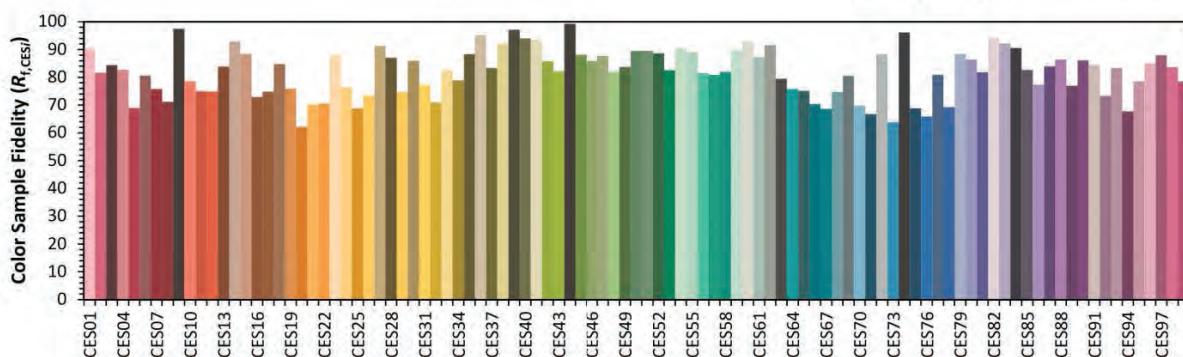
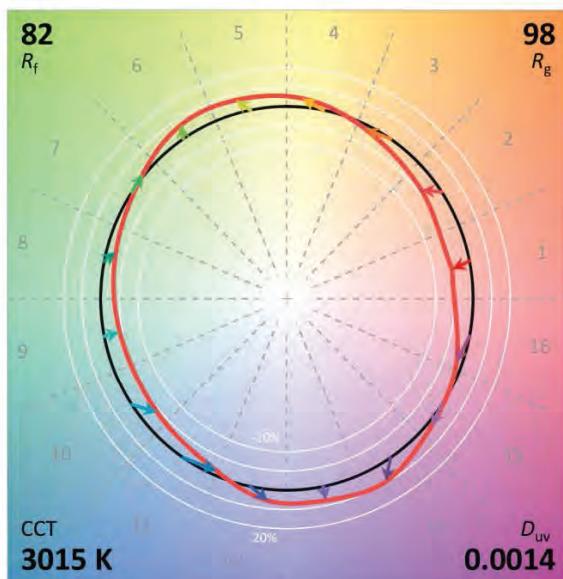
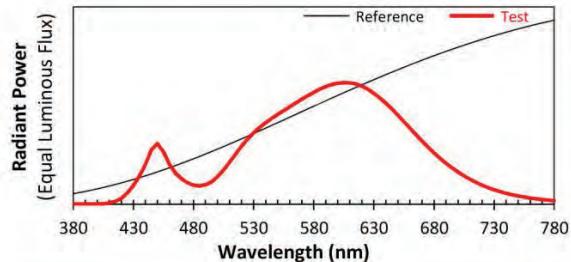


Figure D-2. Example of an intermediate report. (Image courtesy of Michael Royer/PNNL)

IES TM-30-18 Color Rendition Report

Source: Example

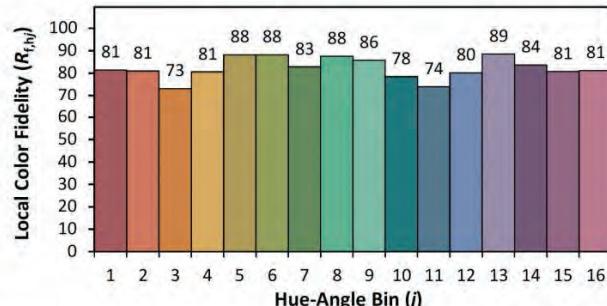
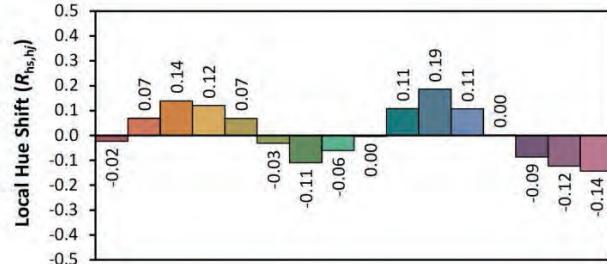
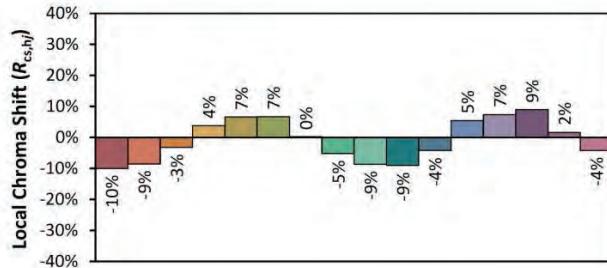
Date: 1/1/2018



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

Manufacturer: Example

Model: Example



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)

Annex E – Recommendations for Specifying Light Source Color Rendition

E.1 Introduction

This Annex provides guidance for applying the measures defined in this Technical Memorandum and documents important considerations for specifying light source color rendition. It includes a table of recommended sets of color rendition specification criteria, subject to simplifying assumptions, that can be selected for use based on the desired outcome and level of compromise with other lighting performance attributes. These recommendations were derived from experimental and analytical work and are made based on the experience and consensus of the IES Color Committee. Additional justification and explanation are provided in **Annex F**. The recommended specification criteria may be adjusted—or completely replaced—at the discretion of the user to better align with intended outcomes; guidance on how this can be accomplished is provided.

(NOTE: Red superscripts indicate references found at the end of Annex E.)

E.2 Quantifying Light Source Color Rendition

Color rendition is a complex phenomenon. A given light source can have a range of effects on the color appearance of an object, changing its hue, chroma, and/or lightness compared to another light source, typically defined as a *reference illuminant*.¹ These changes are not the same for all objects; rather, they vary for objects throughout the range of possible colors. In some cases, any observable change may be unacceptable, but in other cases, certain changes from the reference illuminant may be desirable.

The ANSI/IES TM-30-18 method uses a common calculation framework—including the 99 spectrally neutral color evaluation samples, color space (CAM02-UCS), and blended reference illuminant scheme—based on modern color science^{2,3} to determine a wide range of measures that quantify different objective aspects of color rendition, including average color fidelity⁴ and

Table E-1. Summary of Measures and Graphics included in ANSI/IES TM-30-18.

Measure		What it Characterizes*	Interpretation	Possible Values	Typical Values
Fidelity Index	R_f	Average similarity for all colors	Values closer to 100 indicate greater similarity to the reference	0 to 100	70 to 100
Gamut Index	R_g	Approximation of the average change in chroma for color	Values above 100 increase in chroma; values below 100 decrease in chroma	0 to 150	80 to 120
Color Vector Graphic	CVG	Visual representation of hue and chroma changes for all colors (i.e., <i>gamut shape</i>)	Radial arrows for chroma shift, tangential arrows for hue shift	NA	NA
Local Chroma Shift	$R_{cs,hj}$	Average relative change in chroma for colors within 1 of 16 hue angle bins (j)	Values above 0% for increased chroma, values below 0% for decreased chroma	Approx. -100% to 100% (varies by hue)	Approx. -20% to 20% (varies by hue)
Local Hue Shift	$R_{hs,hj}$	Average change in hue angle (in radians) for colors within 1 of 16 hue angle bins (j)	Positive values for counterclockwise shift (e.g., red to orange), negative values for clockwise shift	Approx. -1 to 1 (varies by hue)	Approx. -0.2 to 0.2 (varies by hue)
Local Color Fidelity	$R_{f,hj}$	Average similarity for color within 1 of 16 hue angle bins (j)	Values closer to 100 indicate greater similarity to the reference	0 to 100	60 to 100
Sample Color Fidelity	$R_{f,cesi}$	Average similarity for a specific color sample (i)	Values closer to 100 indicate greater similarity to the reference	0 to 100	60 to 100

* Relative to reference illuminant.

gamut area,⁵ as well as 16 values each for hue-specific chroma shift,⁶ hue shift, and color fidelity. These are briefly summarized in **Table E-1**. Rather than weighting various color shifts or attempting to derive a single metric that quantifies preferred color rendition—or any other subjective quality—TM-30-18 provides a system of measures and graphics that can be used in combination to specify appropriate color rendition across many different lighting applications, at the discretion of the lighting specifier, or to develop new lighting products. Unlike single-number, higher-is-better metrics, applying TM-30-18 relies on the user’s understanding the lighting requirements, which can help identify which measures and the values of those measures that should be used for specification of color rendition.

E.3 Establishing Specification Criteria for Light Source Color Rendition

E.3.1 Basic Considerations. Color rendition specification criteria define the acceptable or desirable range of values for one or more color rendition measures or metrics. There are many factors that influence what measures are included in specification criteria. A key element of setting color rendition criteria is deciding on the desired outcome, here called the *intent*. Different intents may include promotion of:

- **Subjective qualities**, such as acceptability, naturalness, vividness, preference, or other aspects of aesthetics
- **Objective qualities**, such as color fidelity, gamut area, or any other specific measure in ANSI/IES TM-30-18
- **Task performance**, such as color discrimination, color matching, or object detection via color contrast

Each intent requires consideration of different combinations of color rendition attributes, which are quantified with different measures. ANSI/IES TM-30-18 facilitates this process, allowing for a variety of intents to be considered. There are also tradeoffs related to the *priority* of color rendition—and the specific design intent—within the overall scope of lighting characteristics. These include:

- **Minimum qualification versus highest quality:** Color rendition criteria can be used to create minimum standards (i.e., a floor) as a counter to a

performance aspect that is inherently in opposition, such as luminous efficacy. In other cases, color rendition criteria can be used to promote desirable lighting quality, ensuring the most appropriate color rendition performance for the intended outcome.

- **Flexibility versus prescription:** More-lenient criteria may allow a greater variety of products, enabling a diversity of capabilities but perhaps requiring more individual discretion. In contrast, more-stringent criteria can be more predictable in delivering the intended outcome but may limit innovation or the ability to deliver appropriate performance in another area, such as luminous efficacy.

The priority level helps to determine the values that are set as minimum or maximum for a given measure. It influences the balance between inadvertently allowing inappropriate products and inadvertently disallowing appropriate products. In general, priority level is related to the likelihood that a design intent is achieved. It can also influence the availability and cost of products that meet the specification criteria, particularly if the tradeoff leans toward a higher priority level—although this is fluid as new products are developed.

Another basic consideration when establishing color rendition specification criteria is simplicity versus complexity.⁷ Using a single measure can be easier for users to understand and remember, but a more complex multi-measure approach can be more transparent and/or informative in some cases, allowing a better match with the intent.

E.3.2 Application-Specific Considerations. Beyond the basic considerations of intent and priority level, there are many application-specific factors that should be considered when establishing color rendition specification criteria for a specific use case. Indeed, application has been shown to influence what color rendition attributes are desirable.⁸ Application-specific factors can affect both the type of measures included and the threshold values that are set, refining what might otherwise have been determined based on intent and priority level alone. These factors include:

- 1. **Objects being illuminated:** If one or more specific objects of known hue are being illuminated, it is more appropriate to use a hue-specific local measure

($R_{cs,hj}$, $R_{hs,hj}$, or $R_{f,hj}$) than an average measure (R^f or R_g). The specific local measure can be determined based on the intent. Even if the environment is filled with many colors (i.e., a polychromatic environment), the nature of the objects can lead to changes in the most appropriate color shifts. Vibrant environments might call for color rendition that enhances chroma. In contrast, the presence of objects for which color is an essential element of the identity may dictate a need for limited hue shifts. Research has shown that certain hues, particularly red, are more particularly influential in color psychology.⁹

2. Illuminance level: Color perception changes with luminance. One known characteristic, the Hunt effect,^{10,11} is that perception of colorfulness decreases as luminance decreases. In practical terms, colors look duller as lighting is dimmed. In contrast to this known behavior, existing measures of color rendition—including ANSI/IES TM-30-18—assume equal illuminance of the test source and reference illuminant. Many experiments have shown that increasing chroma (which is related to colorfulness) relative to the reference illuminant, particularly for red hues, improves subjective evaluations of preference and naturalness when the illuminance is typical of architectural interiors (approximately 200 to 700 lux). Recent research has shown that this effect is related to the illuminance,^{12,13} which suggests adjusting target color rendition criteria based on illuminance level if the aesthetics of the space is the primary design consideration. A gradient of criteria is not practical, but varying color rendition for light levels outside the range of 200 to 700 lux may be appropriate.

3. Need for hue stability: Because color shifts smoothly vary around the hue circle, chroma shifts are accompanied by hue shifts in nearby hue-angle bins.^{6,14} Thus, if preserving hue is an important consideration, large increases in chroma should be avoided. Hue shifts can be assessed by examining local hue shift values ($R_{hs,hj}$).

4. Tolerance for uncertainty: Measures of color rendition rely on standardized sets of color samples to represent colors in architectural environments. Depending on the characteristics of the light source SPD, the appearance predicted by color rendition

measures can vary relative to the actual appearance of colors in an architectural space. Some SPDs render similar, or metameric, colors in similar ways (less uncertainty), while others can render such colors in very different ways (more uncertainty). A measure was recently proposed by a group of researchers to capture this aspect of color rendition, the metamerism uncertainty index (R_t).¹⁴ It is based on the same calculation framework as ANSI/IES TM-30-18, but it is not currently part of the ANSI/IES method. This characteristic is very important in certain situations, such as where color matching or metamerism are important, but may be less important in situations where the precise appearance of individual colors is not a consideration.

5. Viewing population age: As the human eye ages, lens transmission decreases, and the lens selectively absorbs more short-wavelength radiation (i.e., “blue light”).¹⁵⁻¹⁷ There is currently insufficient research on the effect of the aging eye on color perception to establish age-adjustment factors for color rendition specification criteria. However, those developing color rendition criteria for spaces whose occupants are elderly or “aging in place” should be aware of age-induced changes in the visual system.

6. Viewing population culture: Cultural preferences related to subjective aspects of color rendition have been examined to a limited extent, with mixed results.¹⁸⁻²¹ The most comprehensive of these studies found that cross-cultural geographic variability did not exceed the within-culture variability.

7. Viewing conditions: Methods for evaluating light source color rendition, such as ANSI/IES TM-30-18, rely on underlying assumptions embedded in the color appearance models used in the calculation framework. One of the most important considerations is chromatic adaptation, or the ability of the human visual system to maintain white balance. Color rendition measures assume the viewer has adapted to the chromaticity of the light being emitted. In cases where a single space is illuminated with multiple chromaticities, complete chromatic adaptation may not be possible, and the color appearance of objects may not match what is predicted by color appearance models. This can introduce uncertainty to color rendition

specification criteria. No research has been conducted to address this issue.

8. Practitioner's discretion: Lighting design is art and science, and the opinion and experience of the lighting practitioner is an important part of the decision-making process. Experience can help practitioners bridge the gap between science and application.

There are also many lighting design factors that are independent of color rendition. These include but are not limited to: chromaticity, correlated color temperature (CCT), circadian and other photobiological effects, glare, flicker, whiteness rendition, luminous intensity distribution, distribution of light within a space, physical luminaire aesthetics, and luminaire profile. As used

here, *independent* means that these factors can be changed without any influence on color rendition; said another way, there is no tradeoff between color rendition and these factors. As such, these factors were not considered in the determination of the criteria presented in this Annex.

E.4 Recommended Color Rendition Specification Criteria

Table E-2 provides a set of recommended color rendition specification criteria based on ANSI/IES TM-30-18 that were developed using empirical data and consensus-based decision making. They are intended to guide lighting practitioners and others who implement such criteria. They represent current best practices for the identified intents, but adjustments may be warranted to better align the criteria with their specific end use, given

Table E-2. Recommended Specification Criteria.

		Design Intent (The desired effect of color rendition on the illuminated environment)		
		Preference (P)	Vividness (V)	Fidelity (F)
Priority Level (The balance between allowing for tradeoffs and increasing the likelihood of meeting the design intent)	1	P1 $R_f \geq 78$ $R_g \geq 95$ $-1\% \leq R_{cs,h1} \leq 15\%$	V1 $R_g \geq 118$ $R_{cs,h1} \geq 15\%$	F1 $R_f \geq 95$
	2	P2 $R_f \geq 75$ $R_g \geq 92$ $-7\% \leq R_{cs,h1} \leq 19\%$	V2 $R_g \geq 110$ $R_{cs,h1} \geq 6\%$	F2 $R_f \geq 90$ $R_{f,h1} \geq 90$
	3	P3 $R_f \geq 70$ $R_g \geq 89$ $-12\% \leq R_{cs,h1} \leq 23\%$	V3 $R_g \geq 100$ $R_{cs,h1} \geq 0\%$	F3 $R_f \geq 85$ $R_{f,h1} \geq 85$

Table note: All criteria assume a polychromatic environment with average horizontal illuminance between 200 and 700 lux and uniform chromaticity.

the many factors that can influence color rendition specification criteria. In practice, these specification criteria form qualification boundaries, but they do not guarantee an outcome—neither appropriateness of qualified products or inappropriateness of not-qualified products.

The recommended criteria of **Table E-2** feature three design intents and three priority levels. The design intents—Color Preference (P), Color Vividness (V), and Color Fidelity (F)—were chosen based on the ability to establish recommended criteria and anticipated relevance to lighting specification. Each intent is described further in **Section E.4.3**. Additional design intents could be added in the future. The three priority levels (1, 2, 3, with Level 1 considered highest) relate to the stringency of the criteria: higher levels increase the likelihood of achieving the design intent, whereas lower levels offer increased flexibility to account for other

considerations. All priority levels are nested, so that qualifying for a higher level ensures qualification for all lower levels.

Important: The recommendations are subject to two key assumptions, which address some of the application-specific factors listed in **Section E.2**: 1) average illuminance is approximately 200 to 700 lux (19 to 65 fc); and 2) the environment is polychromatic—that is, rendition of all colors is a consideration, not just certain ones.

Important: The design intents are distinct, but the qualification ranges are not mutually exclusive. It is possible to meet one of the three levels for each design intent, although it is not possible to meet Priority Level 1 for all three design intents. The regions of overlap between the specification ranges are shown in **Figure E-1** and described further in **Annex F**.

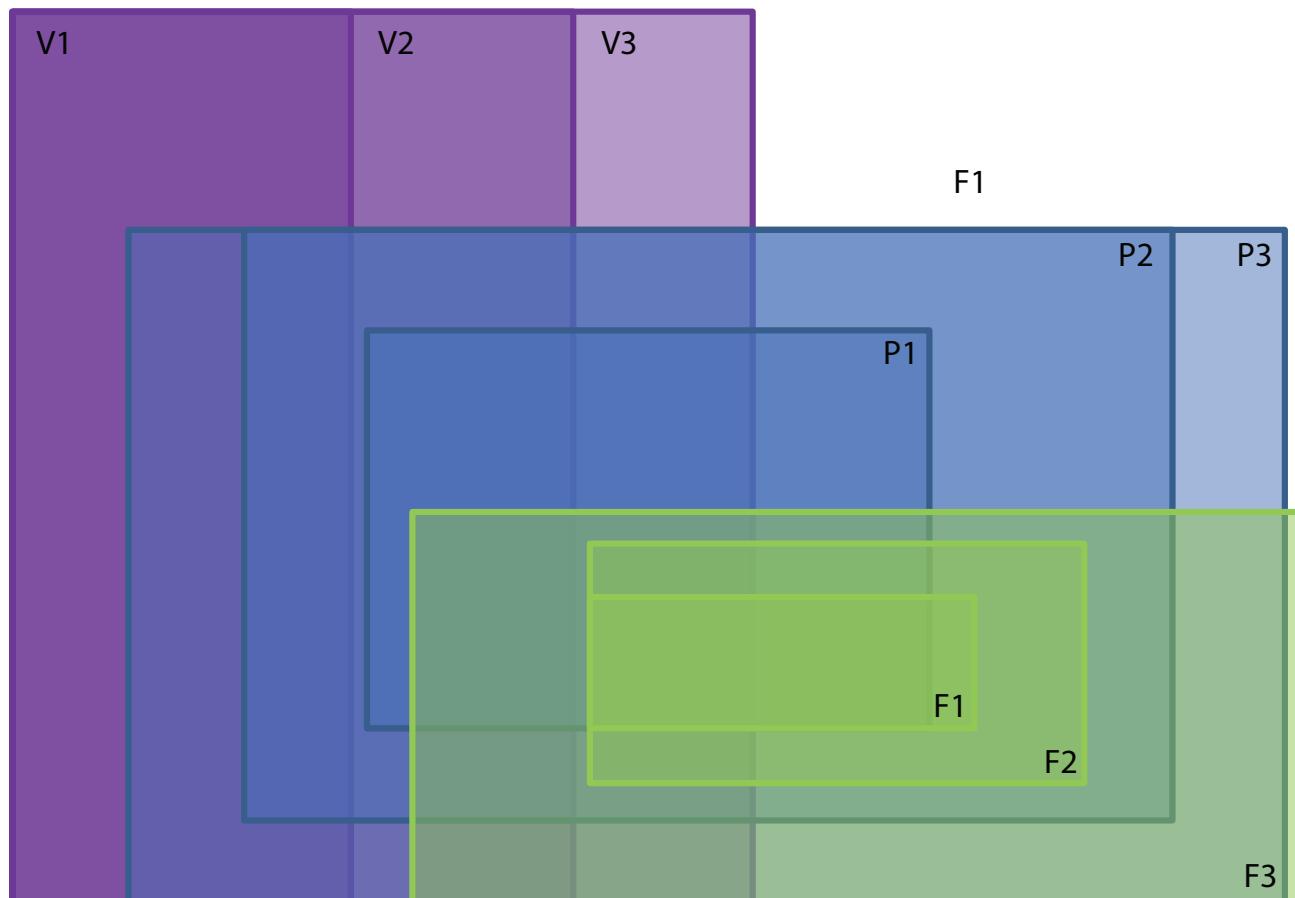


Figure E-1. Illustration of overlap between specifications. Overlapping areas represent a possible combination. The areas are not to scale.

If color rendition needs are complex or specialized, i.e., falling outside the intents and assumptions of **Table E-2**, full consideration of all factors influencing choice of color rendition specification criteria (see **Section E.3**) is warranted, resulting in the development of a customized solution. Some situations that may not meet these assumptions include roadway lighting (low illuminance levels), single-material architectural facades (not polychromatic), dimly lit interior architectural environments (low illuminance levels), and some storage spaces (color rendition not a priority).

If color rendition is of low priority relative to other design considerations, such that meeting any of the basic design intents identified in **Table E-2** is not important, alternatives with more lenient criteria may be appropriate. Benchmarking is one method that may be appropriate in certain situations where color rendition is of low priority. For example, approximation of $R_a \geq 70$ for LED products is $R_f \geq 70$, $R_g \geq 90$, and $R_{cs,h1} \geq -18\%$. This is explained further in **Annex F**.

Important: Simply converting existing minimum values used with CIE R_a to the same values for R_f is not recommended. There are considerable differences between the CIE General Color Rendering Index (R_a ; colloquially, CRI)²² and R_f , despite both being measures of average color fidelity.²⁻⁴ Furthermore, the design intent behind existing specifications based on CIE R_a is generally unclear, and has not been supported by empirical data.^{20,23-35} This is demonstrated further in **Annex F**

E.4.1 Nomenclature. Each set of specification values in **Table E-2** is assigned an abbreviation based on the first letter of the design intent (P, V, or F) and the priority level (1, 2, or 3). For example, the color preference specification with the highest priority level is given the code P1. These codes are suggested for use where concise communication is needed, either within a specification or in relation to the performance of a lighting product.

E.4.2 Transitions. It is acknowledged that some existing specifications rely on the combination of R_a and R_g from CIE 13.3-1995. The transition to new specifications can be a challenge because

products that meet existing specifications may not meet new specifications. To address this practical consideration, a phased approach is recommended, with dual paths to qualification for a limited time while the market transitions.³⁶

E.4.3 Tolerances. The recommended values are minimum and maximum specifications, not design targets. Therefore, tolerances are not specified. Where measurement and manufacturing tolerances are relevant, users should establish appropriate targets at their own discretion.

E.4.4 Description of the Three Design Intents. This section describes the function, meaning, and limitations of the three design intents. (For additional explanation of how the specific values were derived, see **Annex F**.)

E.4.4.1 Color Preference. This design intent captures subjective evaluations of preference, pleasantness, naturalness, acceptability, and related qualities. These sets of criteria utilize three ANSI/IES TM-30-18 measures: $R_{cs,h1}$, R_f , and R_g . With increasing priority level, the recommended lower limit of $R_{cs,h1}$ increases from -12% to -7% to -1%, reducing the desaturation of reds. The upper limit also decreases, limiting oversaturation of reds. The use of $R_{cs,h1}$ as a central component for this design intent aligns with experimental and experiential evidence about the importance of red.

The R_f values for the Color Preference intent are lower than for the Color Fidelity intent, at 70, 74, and 78 for the three priority levels. This is a response to the fact that increases in red chroma lead to lower color fidelity. Lower average color fidelity values allow for higher theoretical maximum energy efficiency but also allow for lower metameristic uncertainty—though neither is a guaranteed outcome of these sets of specification criteria, as there is substantial variability among SPDs meeting the criteria. The criteria for this design intent encompass a larger area within the range of possible color rendition characteristics than the other two design intents.

The Color Preference criteria do not ensure hue stability, and considerable hue shift can occur if red chroma is substantially increased—especially if gamut area is not increased simultaneously. Rather, they prioritize red chroma enhancement relative to the reference illuminant. Increasing red chroma relative to the reference illuminant (at equal illuminance, by definition) helps counteract the Hunt Effect, making reds appear more similar to their perceived appearance under a reference illuminant at high illuminance levels.

Majorities of currently available white phosphor-converted LED, fluorescent, and ceramic metal halide products that are intended for interior use fall into the P3 specification. Some products are available in the P2 and P1 specifications. Both standard and neodymium incandescent lamps typically fall in the P1 specification, providing a reasonable demonstration of the range of color rendition characteristics for P1 products.

Color Preference may be the dominant color rendition design intent in retail, office, hospitality, and residential lighting applications. As with all design intents, this is at the discretion of the lighting specifier, in consultation with other members of the design team.

E.4.4.2 Color Fidelity. This design intent captures the objective quantification of color fidelity. Average color fidelity measures, such as ANSI/IES TM-30-18 R_f (or CIE R_a), quantify the average color shift in comparison to a reference illuminant; in the ANSI/IES TM-30-18 method, this is always a broadband illuminant. High levels of color fidelity minimize all types of color shifts relative to the appearance under a reference illuminant, which may be important for object identification.

Because measures of average color fidelity, such as R_f , do not indicate color fidelity of any particular hue region or color evaluation sample, a minimum $R_{f,h1}$ (equal to the specified R_f criterion) is also specified for Priority Levels 2 and 3. This is the conceptual equivalent of supplementing CIE R_a with R_9 . It is not specified for Priority Level 1,

because the range of $R_{f,h1}$ is already reasonably constrained by the very high R_f criterion. Due to the cohesive underlying system of ANSI/IES TM-30-18, $R_{f,h1} \geq 85$ is approximately equivalent to $-9\% \leq R_{cs,h1} \leq 9\%$, and $R_{f,h1} \geq 90$ is approximately equivalent to $-6\% \leq R_{cs,h1} \leq 6\%$. It would be reasonable to employ these $R_{cs,h1}$ criteria in lieu of an $R_{f,h1}$ criterion.

While high color fidelity implies only small differences from the reference condition, it also reduces metamerism uncertainty. Increasing color fidelity increases the need for a broad distribution of spectral power, avoiding peaks and valleys that can interact with the reflectance characteristics of specific objects. High color fidelity improves the predictability of the color appearance of objects that are not included in the 99 standardized color evaluation samples.

The Color Fidelity intent, treating all color shifts equally, contrasts with the Color Preference intent, which prioritizes preservation of colorfulness over preservation of hue. However, there is strong overlap between the two. It is possible to simultaneously achieve Priority Level 1 for both intents.

Majorities of currently available white phosphor-converted LED and fluorescent lighting fall outside of the Color Fidelity specifications, but products in all three priority levels do exist. A standard incandescent or tungsten-halogen lamp meets the F1 specification, whereas a neodymium incandescent lamp would typically meet the F3 specification. The neodymium incandescent lamp has lower color fidelity because it intentionally shifts colors relative to the reference illuminant in order to increase color preference.

Color fidelity may be the most important design intent in manufacturing, medical, color matching, or color reproduction applications. As with all design intents, this is at the discretion of the lighting specifier, in consultation with other members of the design team.

E.4.4.3 Color Vividness. This design intent captures subjective evaluations of color vividness, which may alternatively be referred to as *vibrancy* or *saturation*. $R_{cs,h1}$ is a key criterion for this design intent. It is augmented with R_g to prevent focused optimizations for a specific hue. The Color Vividness specifications have no upper limits on $R_{cs,h1}$ or R_g . Very large increases in vividness may not be viewed as natural or preferred and should be reserved for specific applications where these considerations are not important. Strong increases in $R_{cs,h1}$ and/or R_g induce hue shifts and reduce color fidelity.

There is some overlap between the performance characteristics of the Color Preference and Color Vividness design intents, although Priority Level 1 cannot be achieved simultaneously for both. In short, color preference is maximized at an intermediate, above-average level of color vividness, where colors are neither dull nor too vivid. This design intent focuses only on increasing color vividness, and targets above-average performance. It is possible to simultaneously achieve any level of Color Preference and Color Fidelity at Priority Level 3 for Color Vividness (e.g., P1, V3, F1). Likewise, it is possible to achieve V2, F3, and P1. These are important regions of overlap but do not necessarily represent performance that is suitable for all situations, given tradeoffs with other lighting characteristics. Some other possible combinations are illustrated with examples in **Section E.5**.

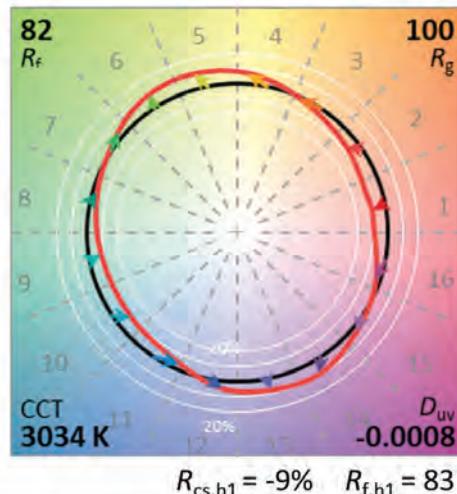
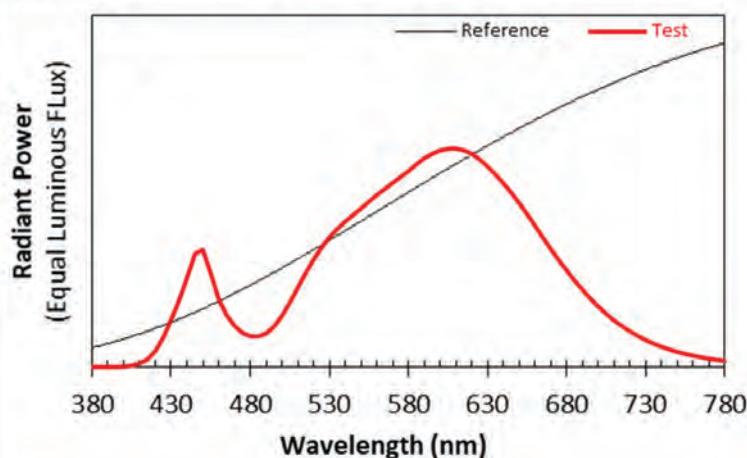
Majorities of currently available white phosphor-converted LED and fluorescent lighting fall outside of the Color Vividness specifications, although some products achieving up to V2 exist. At present, the V1 specification is most readily achieved using color-mixed LEDs. Color vividness may be the dominant color rendition design intent in some entertainment, display, or retail applications. As with all design intents, this is at the discretion of the lighting specifier, in consultation with other members of the design team.

E.5 Performance of Select Spectral Power Distributions

The performance of SPDs representative of currently available products is shown in the following series of graphics. It should be noted that identified product categories are not homogeneous in terms of color rendition; these are examples only and should not be used for any other purpose. Categorization according to the recommended color rendition specification criteria is shown in the upper-right corner, using the defined nomenclature (see **Section E.4.1**). A dash is used to indicate that none of the priority levels are met for the specific design intent.

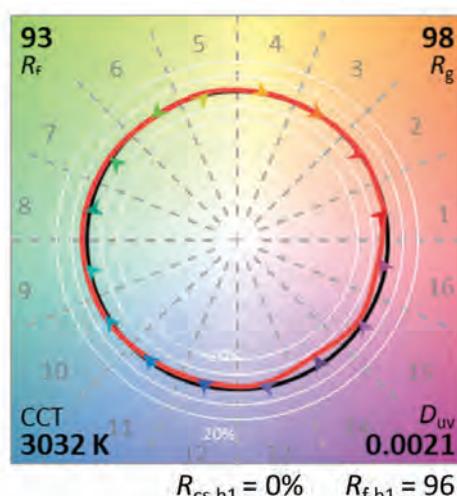
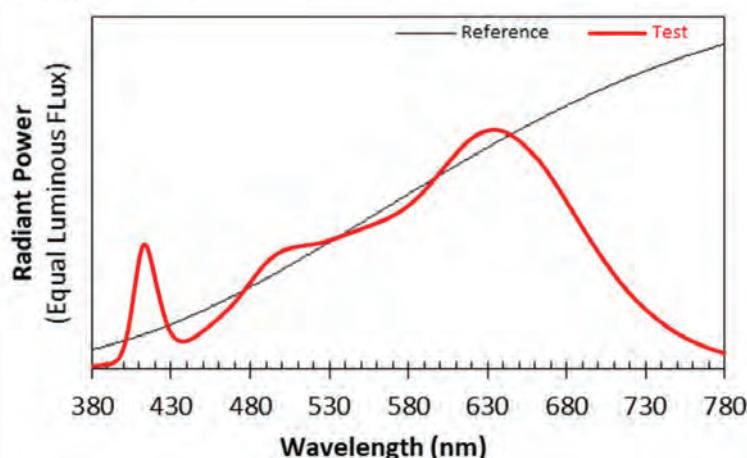
Phosphor-Converted White LED 1

P3 | V- | F-



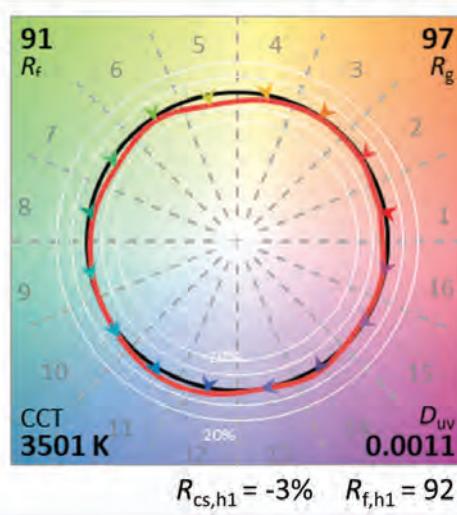
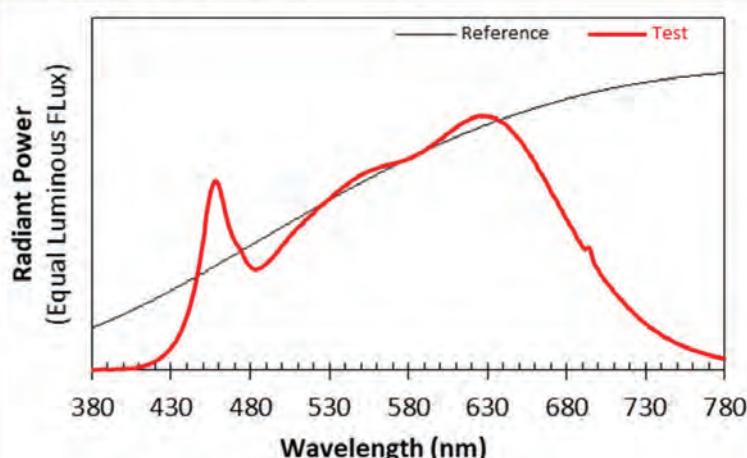
Phosphor-Converted White LED 2

P1 | V- | F2



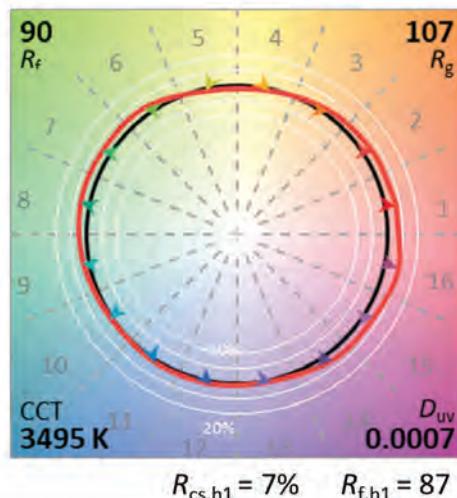
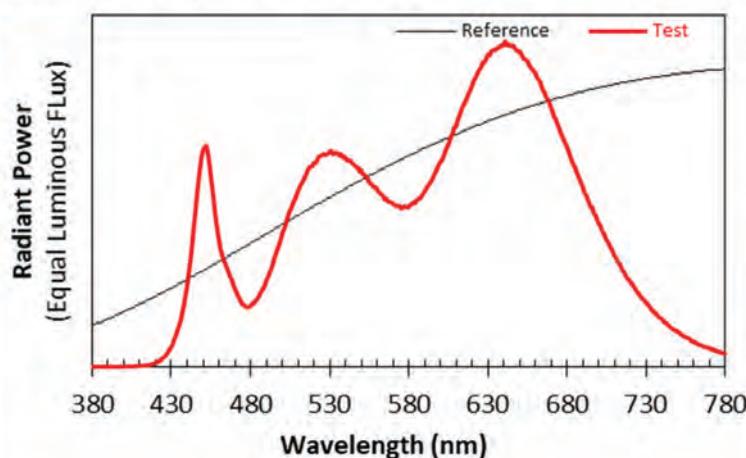
Phosphor-Converted White LED 3

P2 | V- | F2



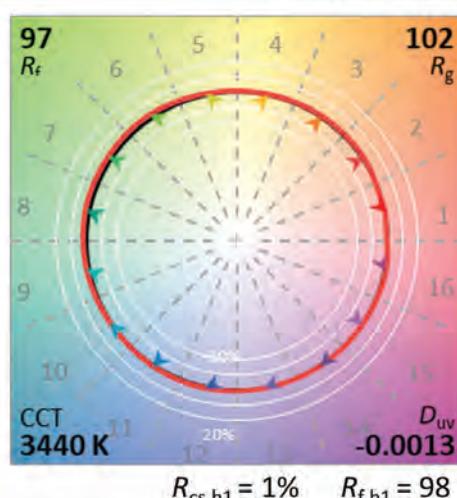
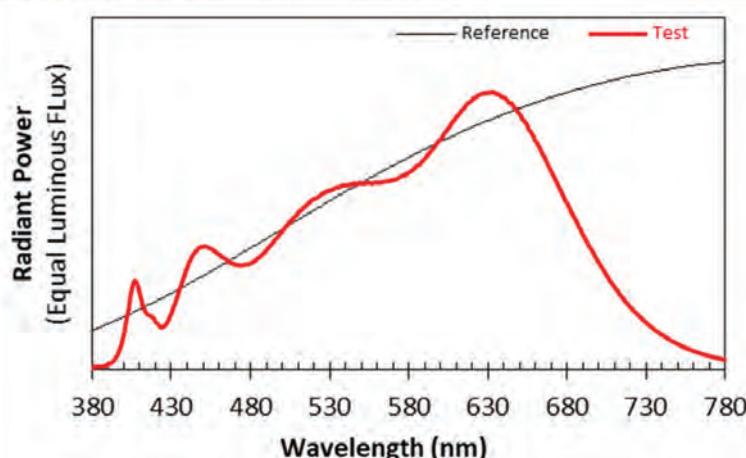
Phosphor-Converted White LED 4

P1 | V3 | F2



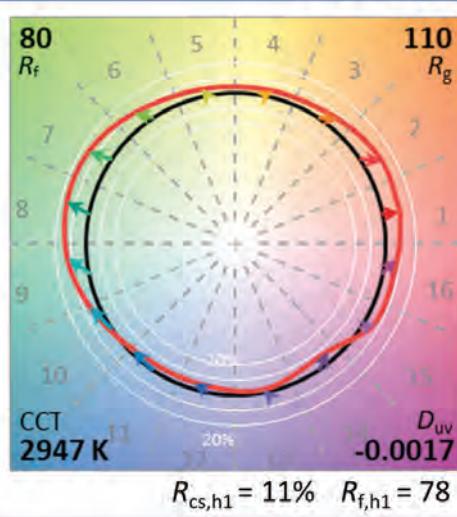
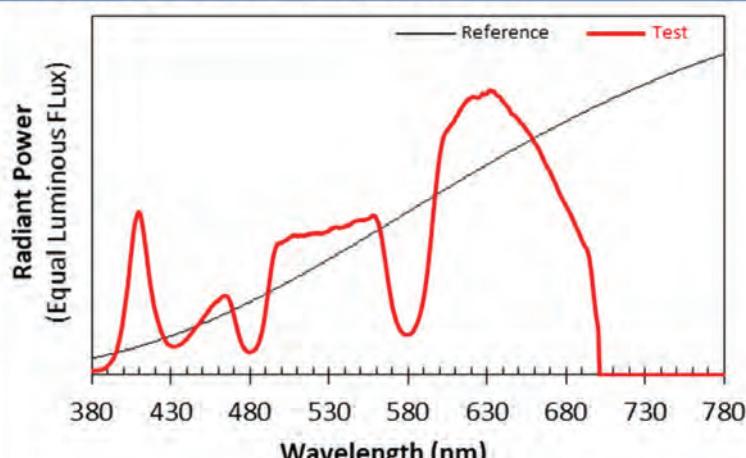
Phosphor-Converted White LED 5

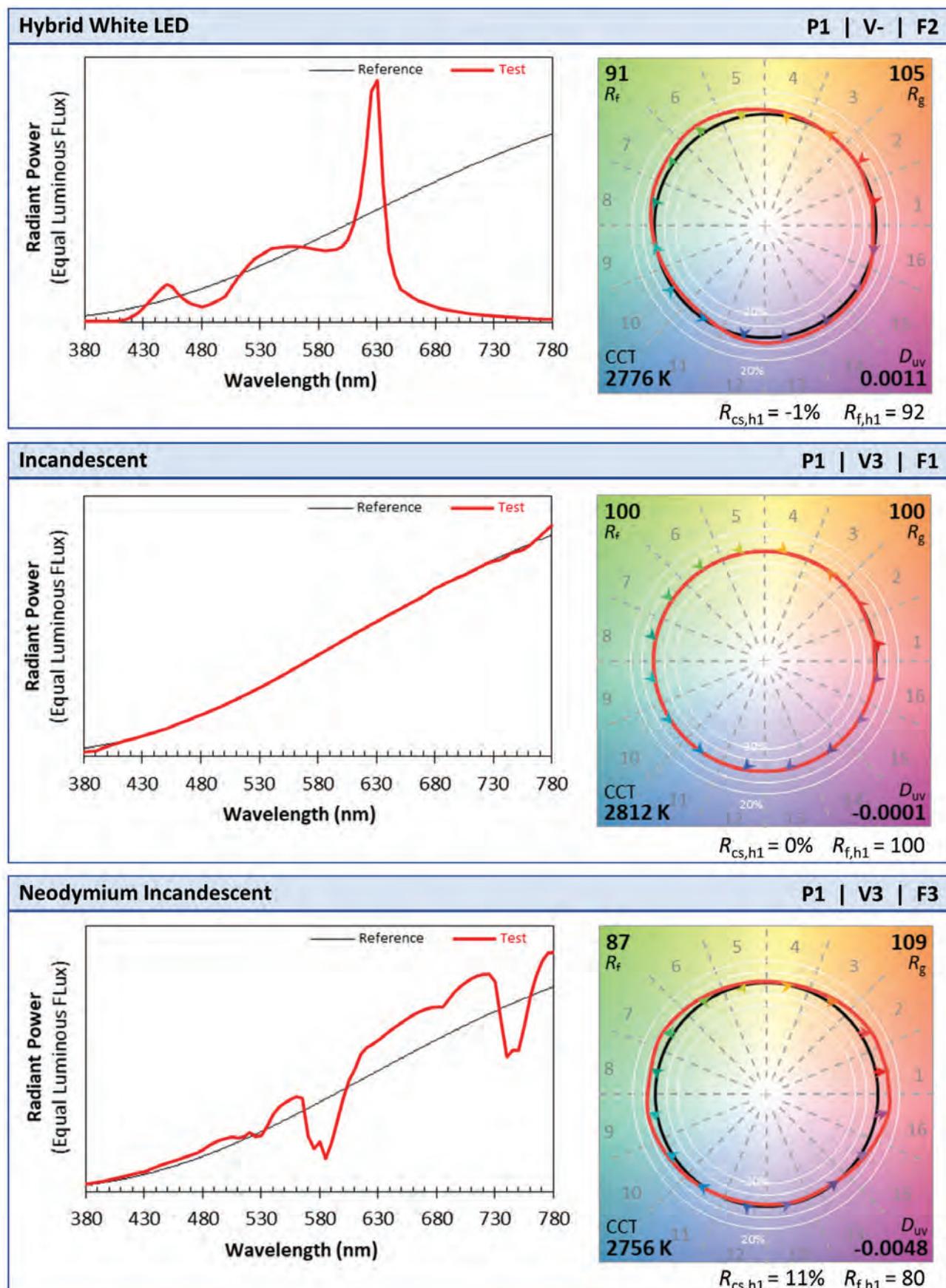
P1 | V3 | F1



Phosphor-Converted White LED 6

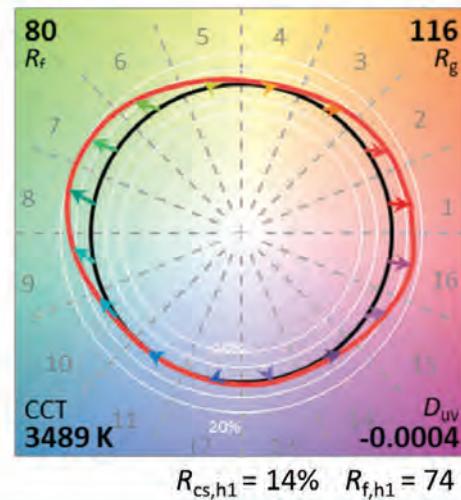
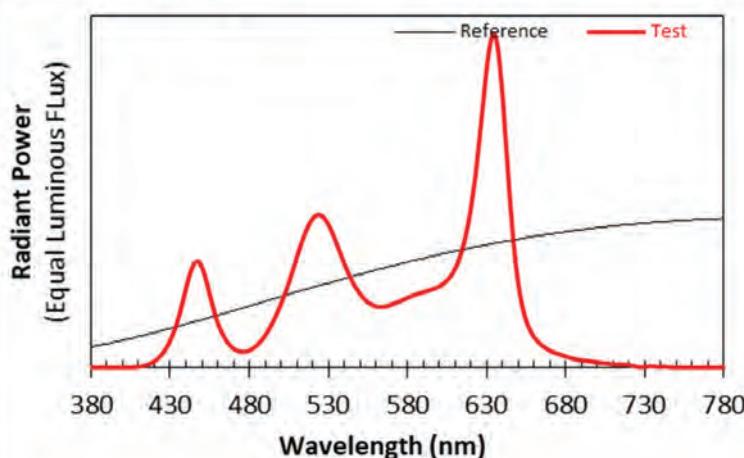
P1 | V2 | F-





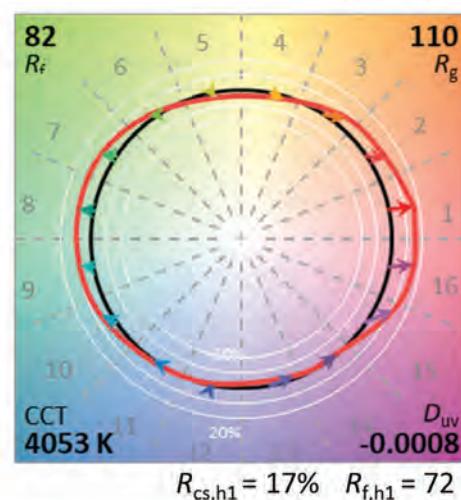
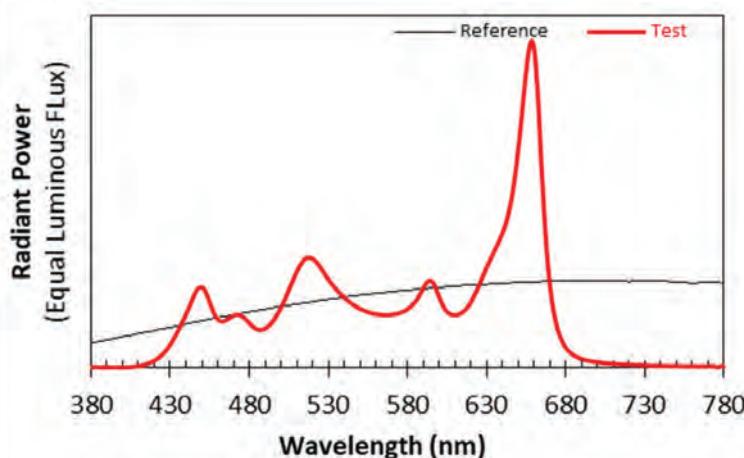
Color Mixed LED 1

P1 | V2 | F-



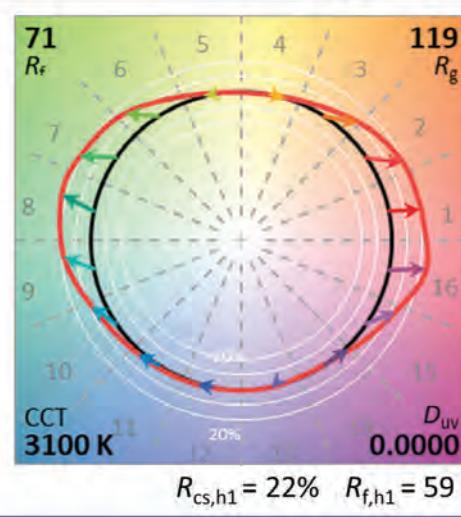
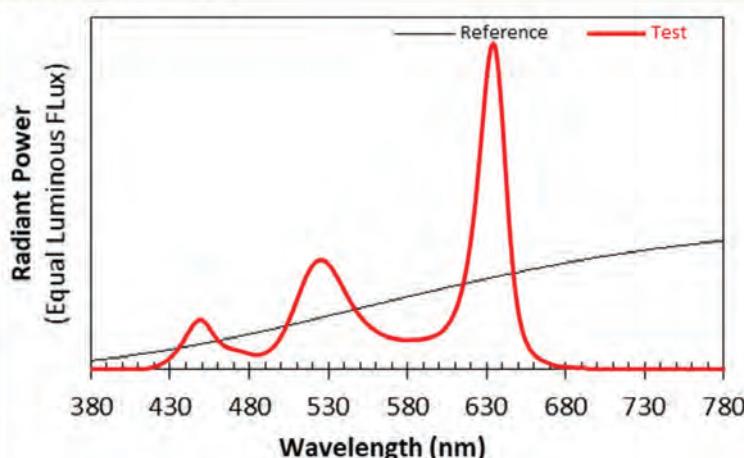
Color Mixed LED 2

P2 | V2 | F-



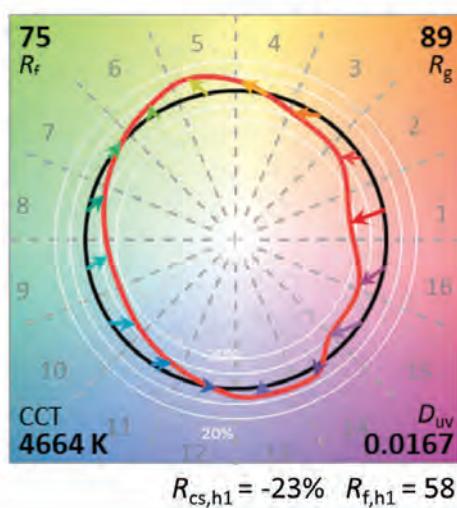
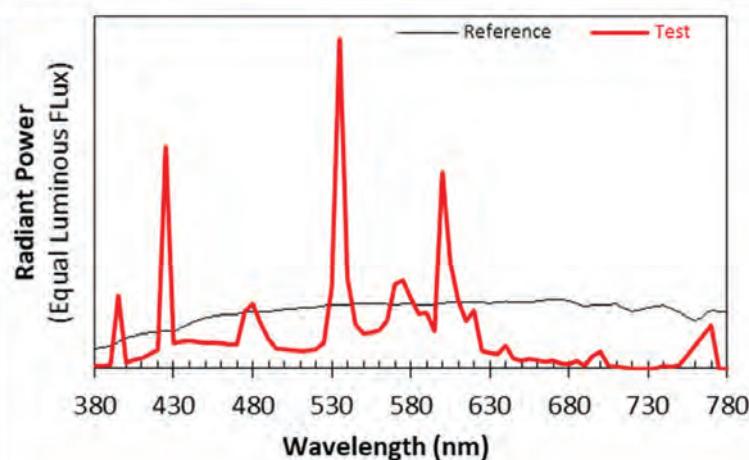
Color Mixed LED 3

P3 | V1 | F-



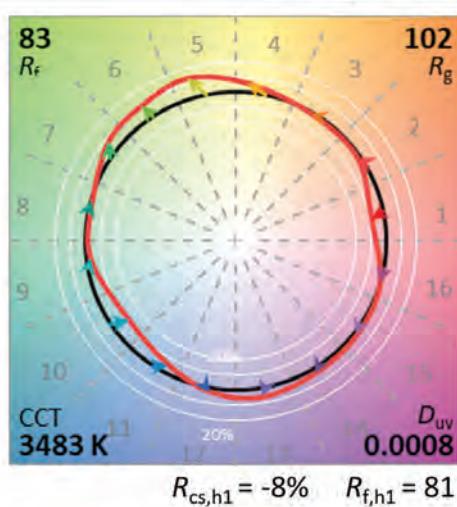
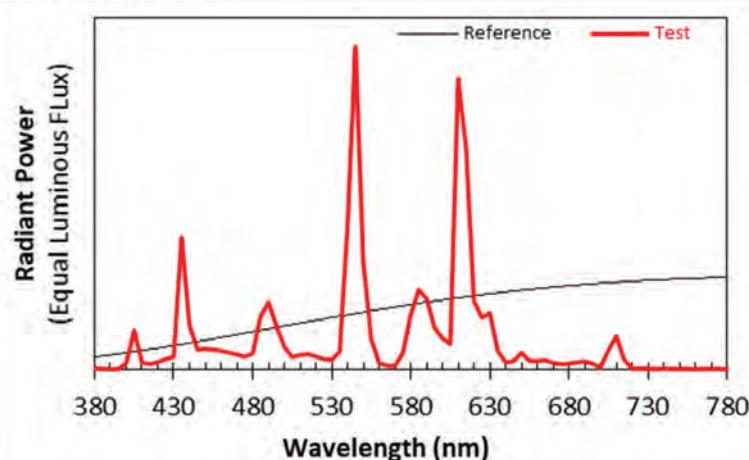
741 Fluorescent

P- | V- | F-



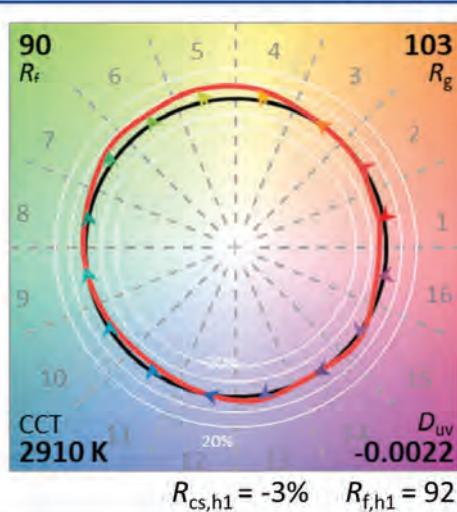
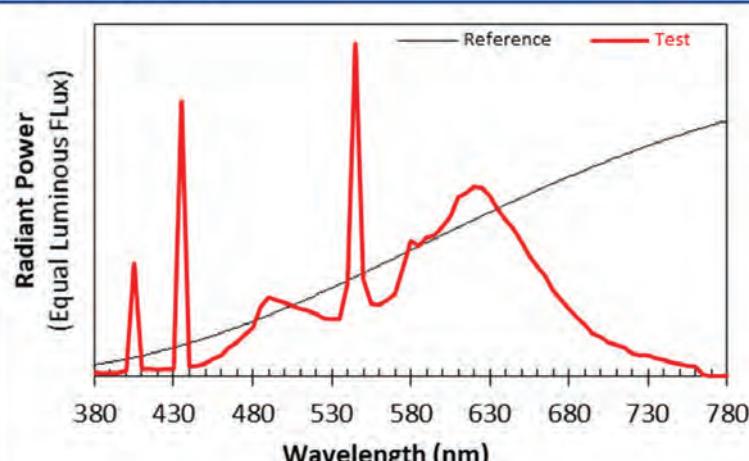
835 Fluorescent

P3 | V- | F-



930 Fluorescent

P2 | V- | F2



REFERENCES FOR ANNEX E

1. Royer MP. What is the reference? An examination of alternatives to the reference sources used in IES TM-30-15. *Leukos*. 2016;13:71-89. DOI: 10.1080/15502724.2016.1255146.
2. Smet K, David A, Whitehead L. Why color space uniformity and sample set spectral uniformity are essential for color rendering measures. *Leukos*. 2015;12:39-50. DOI: 10.1080/15502724.2015.1091356.
3. David A, Fini PT, Houser KW, Ohno Y, Royer MP, Smet KA, Wei M, Whitehead L. Development of the IES method for evaluating the color rendition of light sources. *Opt Express*. 2015;23:15888-15906. DOI: 10.1364/OE.23.015888.
4. Royer M. Comparing measures of average color fidelity. *Leukos*. 2017;14:69-85. DOI: 10.1080/15502724.2017.1389283.
5. Royer M. Comparing measures of gamut area. *Leukos*. 2018; Online Before Print. DOI: 10.1080/15502724.2018.1500485. DOI: 10.1080/15502724.2018.1500485.
6. Royer M, Houser K, David A. Chroma shift and gamut shape: Going beyond average color fidelity and gamut area. *Leukos* 2018; 14: 149-165. DOI: 10.1080/15502724.2017.1372203.
7. Van der Burgt P, van Kemenade J. About color rendition of light sources: The balance between simplicity and accuracy. *Color Research & Application* 2010; 35: 85-93. DOI: 10.1002/col.20546.
8. Lin Y, Wei M, Smet K, Tsukitani A, Bodrogi P, Khanh T. Colour preference varies with lighting application. *Lighting Res Technol*. 2015;49:316-328. DOI: 10.1177/1477153515611458.
9. Elliot AJ and Maier MA. Color psychology: effects of perceiving color on psychological functioning in humans. *Annu Rev Psychol*. 2014;65:95-120. DOI: 10.1146/annurev-psych-010213-115035.
10. Fairchild MD. *Color Appearance Models*. 3 ed. Chichester, United Kingdom: Wiley; 2013.
11. Hunt R. Light and dark adaptation and the perception of color. *J Opt Soc Am*. 1952;42:190-199.
12. Wei M, Bao W, Huang H. Consideration of light level in specifying light source color rendition. *Leukos*. 2018; Online Before Print. DOI: 10.1080/15502724.2018.1448992.
13. Kawashima Y, Ohno Y, Oh S. Vision experiment on verification of Hunt Effect for lighting. In: 11th Biennial Joint CIE/USNC and CNC/CIE Techn Conf. Gaithersburg, Maryland; 2017.
14. David A, Esposito T, Houser K, Royer M, Smet K, Whitehead L. A vector field color rendition model for characterizing color shifts and metameric mismatch. *Leukos*. 2019; Online before print. DOI: 10.1080/15502724.2018.1554369.
15. Pokorny J, Smith VC, Lutze M. Aging of the human lens. *Applied Optics*. 1987;26:1437-1440. DOI: 10.1364/AO.26.001437.
16. Weale RA. Age and the transmittance of the human crystalline lens. *J Physiology*. 1988;395:577-587. DOI: doi:10.1113/jphysiol.1988.sp016935.
17. Turner PL, Mainster MA. Circadian photoreception: Ageing and the eye's important role in systemic health. *Br J Ophthalmol*. 2008;92:1439-44. DOI: 10.1136/bjo.2008.141747.
18. Smet K, Hanselaer P. Impact of cross-regional differences on color rendition evaluation of white light sources. *Opt Express*. 2015;23:30216-26. DOI: 10.1364/OE.23.030216.
19. Smet K, Lin Y, Nagy BV, Nemeth Z, Duque-Chica GL, Quintero JM, Chen HS, Luo RM, Safi M, Hanselaer P. Cross-cultural variation of memory colors of familiar objects. *Opt Express*. 2014;22:32308-28. DOI: 10.1364/OE.22.032308.
20. Tang X and Teunissen C. The appreciation of LED-based white light sources by Dutch and Chinese people in three application areas. *Lighting Res Technol*. 2018; Online Before Print. DOI: 10.1177/1477153517754130. DOI: 10.1177/1477153517754130.
21. Liu A, Tuzikas A, Zukauskas A, Vaicekauskas R, Vitta P, Shur M. Cultural preferences to color quality of illumination of different artwork objects revealed by a color rendition engine. *IEEE Photonics J*. 2013;5:6801010. DOI: 10.1109/jphot.2013.2276742.

22. International Commission on Illumination: CIE 13.3-1995 Method of measuring and specifying colour rendering properties of light sources, 3rd ed. Vienna: CIE; 1995.
23. Royer M. Analysis of color rendition specification criteria. In: SPIE Photonics West Opto: Light-Emitting Devices, Materials, and Applications. San Francisco: SPIE; 2019:55.
24. Royer M, Wilkerson A, Wei M, Safranak S. Experimental validation of color rendition specification criteria based on ANSI/IES TM-30-18. *Lighting Res Technol.* 2019; Submitted for publication.
25. Royer M, Wilkerson A, Wei M. Human perceptions of color rendition at different chromaticities. *Lighting Res Technol.* 2017; Online before print. DOI: 10.1177/1477153517725974. DOI: 10.1177/1477153517725974.
26. Royer MP, Wilkerson A, Wei M, Houser K, Davis R. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. *Lighting Res Technol.* 2016;49:966-91. DOI: 10.1177/1477153516663615.
27. Ohno Y, Fein G and Miller C. Vision Experiment on chroma saturation for color quality preference. In: 28th Session CIE, Manchester, UK, 2015 Jun 28 - Jul 4. Vienna: International Commission on Illumination; 2015:2124.
28. Davis W, Ohno Y. Color quality scale. *Opt Engineer.* 2010;49:033602. DOI: 10.1117/1.3360335.
29. Esposito T, Houser K. Models of colour quality over a wide range of spectral power distributions. *Lighting Res Technol.* 2018; Online Before Print. DOI: 10.1177/1477153518765953. DOI: 10.1177/1477153518765953.
30. Zhang F, Xu H, Feng H. Toward a unified model for predicting color quality of light sources. *Applied Optics.* 2017;56:8186-8195. DOI: 10.1364/AO.56.008186.
31. Wei M, Houser KW. Systematic changes in gamut size affect color preference. *Leukos.* 2017;13:23-32. DOI: 10.1080/15502724.2016.1192402.
32. Wei M, Houser K, David A, Krames M. Effect of gamut shape on color preference. *Proc CIE 2016 Lighting Quality and Energy Efficiency*, Melbourne, Australia. Vienna: International Commission on Illumination; 2016:32-41.
33. Wei M, Houser K, David A, Krames M. Colour gamut size and shape influence colour preference. *Lighting Res Technol.* 2016; Online before print. DOI: 10.1177/1477153516651472. DOI: 10.1177/1477153516651472.
34. Teunissen C, van der Heijden F, Poort SHM, de Beer E. Characterising user preference for white LED light sources with CIE colour rendering index combined with a relative gamut area index. *Lighting Res Technol.* 2016;49:461-480. DOI: 10.1177/1477153515624484.
35. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Correlation between color quality metric predictions and visual appreciation of light sources. *Opt Express.* 2011;19:8151-8166. DOI: 10.1364/OE.19.008151.
36. Illuminating Engineering Society. PS-11-18, IES Position Statement on TM-30-18, IES Method for Evaluating Light Source Color Rendition. New York: IES; 2018.

Annex F – Evidence Supporting Recommended Criteria for Specifying Light Source Color Rendition

F.1 Introduction

This Annex provides additional background and evidence to support the recommendations for specifying light source color rendition provided in **Annex E**. It examines the types of data that help consensus-based decision making and summarizes historical color rendition specification criteria. It describes the data sources and procedures that were used to establish the values in **Table E-2** of **Annex E**, then provides data on the performance of these specifications using datasets of theoretical and commercially available light source spectral power distributions (SPDs). The tradeoff between energy efficiency and color rendition is briefly discussed to help users of the recommended specification criteria make informed decisions. (NOTE: Blue superscripts indicate references found at the end of Annex F.)

F.2 Background

Empirical evidence can bolster the validity of any consensus-based process. For color rendition specification criteria, empirical evidence helps to identify the objective measures that are most correlated with specific design intents, and the threshold values that differentiate the priority levels. Empirical evidence for color rendition specification criteria can be derived from several different processes, including benchmarking, experimentation, and design experience. All three were involved in the development of the recommendations in **Annex E**.

Benchmarking describes a process of translating specification criteria from one measure (or set of measures) to another using an existing set of qualified products. That is, new qualifying ranges for a new measure (or set of measures) can be established based on the properties of products that qualified according to a previous system. Because this method is simply a translation from one set of specification criteria to another, benchmarking relies heavily on the assumption that the existing specification criteria are effective at qualifying appropriate light sources

and disqualifying those that are not. Benchmarking can be quick and straightforward but has a limited ability to account for future changes in product performance. At least one published work has translated a specification based on R_a to TM-30 values: The U.S. Department of Defense's *Unified Facilities Criteria 4-510-01 Design: Military Medical Facilities*.¹

Empirical evidence can be gained from human factors experimentation, where responses from human participants are collected for varying color rendition conditions. Human factors color rendition experiments are typically psychophysical experiments that attempt to determine a causal link between light source colorimetric characteristics and repeatable visual sensations. They frequently involve participants providing subjective evaluations for naturalness, vividness, preference, or acceptability. Experiments present the opportunity to investigate novel light sources but rely on the assumption that the effects of color rendition in the controlled environment are applicable to other situations. Many human factors experiments have investigated the performance of TM-30 measures.²⁻¹⁷

Finally, empirical evidence from lighting specification experience can be an important complement to benchmarking and experimentation. It can inform the consensus process in areas where experimentation has not been completed or benchmarking is insufficient.

F.2.1 Existing Color Rendition Specification Criteria.

The history of institutional color rendition specification criteria is not well-documented, but perhaps begins with several utility energy efficiency programs in the 1990s, where CIE General Color Rendering Index R_a (colloquially, *CRI*) ≥ 80 was a common criterion.¹⁸ These programs were predecessors to ENERGY STAR™, which adopted CIE $R_a \geq 80$ in 2001 as part of CFLs version 2.0.¹⁹ The CIE $R_a \geq 80$ criterion was not based on experimental evidence, but rather on a combination of the capabilities of fluorescent lamps, manufacturing tolerances, and common practices. Eventually, CIE $R_a \geq 80$ became a de facto standard for architectural interiors where color rendition is an important consideration and was instrumental in

the development of LED technology. It became known as a delineator between acceptable and unacceptable (or liked and disliked) lighting, even though no experiments ever supported that idea—and many contradicted it.^{3,4,6-9,11,20-24} Still, with a limited selection of lamps to choose from, CIE R_a and its associated criteria performed well enough to last for many years.

There has been some movement away from CIE $R_a \geq 80$ since 2010. With only one standardized method for evaluating color rendition prior to the adoption of IES TM-30-15, the options to improve the specified level of color quality amounted to increasing the CIE R_a requirement or supplementing it with a requirement for the Special Color Rendering Index CIE R_9 —a recognition of the specific importance of reds. California Title 20 has increased the threshold to CIE $R_a \geq 82$ (with CIE R_i minimum requirements for test color samples 1 to 8 of 72).²⁵ The WELL Building Standard v2 allows qualification with CIE $R_a \geq 90$.²⁶ Specifications augmenting CIE $R_a \geq 80$ with a CIE R_9 requirement include ENERGY STAR^{27,28} (CIE $R_9 \geq 0$) and WELL Building Standard v2 (CIE $R_9 \geq 50$). The most stringent color rendition criteria based on CIE R_a and R_9 may be California Title 24 JA8,²⁹ with requirements of $R_a \geq 90$ and $R_9 \geq 50$. Efforts to increase CIE R_a and R_9 thresholds in California elicited concerns that the values are too restrictive, induce energy inefficiency, and are not inherently more correlated with lighting preferences than existing criteria.

As of 2018, IES Recommended Practice documents included recommendations for minimum R_a values of 70, 80, 85 or 90, depending on the specific intent, with no recommendations for R_9 .

Due to the well-documented limitations of both CIE R_a and R_9 ,^{21,30-34} concerning both technical accuracy and completeness, it has been recommended that existing specifications and recommended practices based on these measures be reevaluated and updated to reflect current science, as embodied in ANSI/IES TM-30-18.³⁵ New criteria based on TM-30 are already being used as an alternative (or preferred) path to qualification

in some specifications, including *UFC 4-510-01: Design Military Medical Facilities*,¹ the Well Building Standard v2,²⁶ and the DesignLights Consortium SSL Technical Requirements v5.³⁶ The latter two include tiers that roughly align with the Color Preference design intent defined in **Annex E**. All three allow at least a partial alternative path to qualification using CIE R_a and R_9 , smoothing the transition to the new method.

F.3 Development of Recommended Color Rendition Specification Criteria

F.3.1 Color Preference. The primary data source for Color Preference specification criteria was the results of five experiments^{4,6-9} conducted by three organizations. These were grouped as three datasets: Zhang and others, Royer and others, and Esposito and Houser.³⁷ The independent experiments shared a common goal of evaluating subjective responses to light source color rendition, including color preference, using a large quantity and wide variety of color rendition conditions. Two of the three datasets included varied chromaticity—and accounted for chromatic adaptation. The nominal horizontal illuminance levels for the five individual experiments were 250, 270, 330, 450, and 650 lux. Between them, the experiments presented a variety of objects arranged in a polychromatic scene, using different display types (booths and full rooms), different luminaires (with different spectral components), and different subject pools (including age, gender, and culture).

In total, 354 color rendition conditions were evaluated (see **Figure F-1**). R_f was between 63 and 98, R_g was between 79 and 124, and $R_{cs,h1}$ was between -31% and 33%. CCTs were between 2681 K and 6574 K, and D_{uv} values were between -0.0143 and 0.0051. The experiments involved 137 participants (70 female, 67 male) between 19 and 70 years of age. In total, the participants made 7,278 recorded judgements of color preference using a Likert scale. Other attributes studied included naturalness or normalness, and vividness or saturation. Royer and others also included acceptability in two of the three experiments.

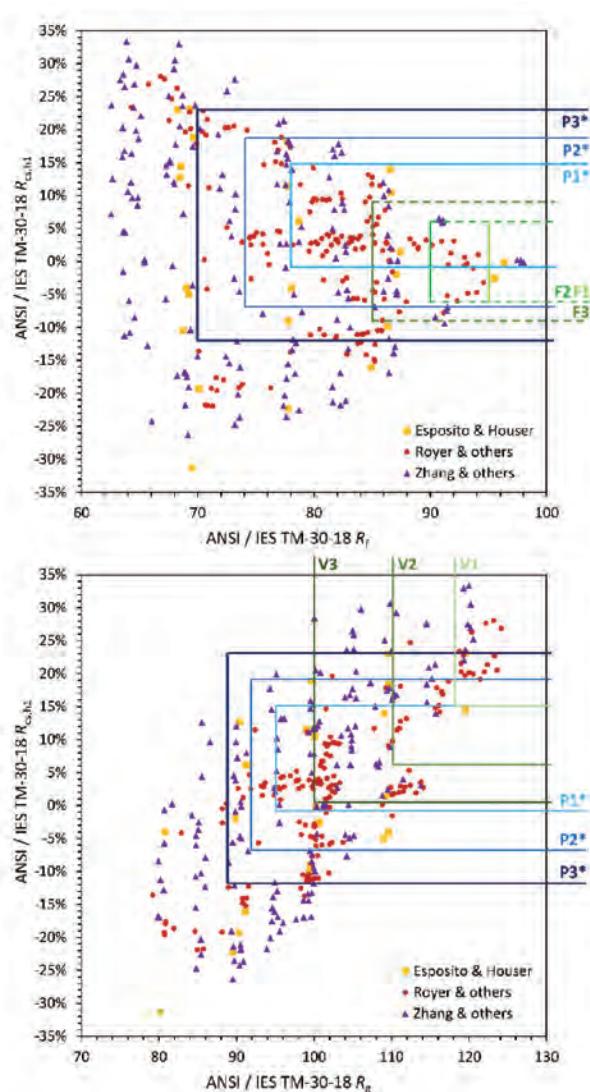


Figure F-1. Color rendition characteristics (R_f , R_g , $R_{cs,h1}$) of the 354 experimental SPDs from the three datasets that were used as primary sources for developing the recommended color rendition specification criteria. The broad coverage of possible characteristics makes these datasets useful for establishing color rendition specification criteria.

A combination of R_f , R_g , and/or red chroma shift (either $R_{cs,h1}$ or $R_{cs,h16}$, which as measures for adjacent hue-angle bins are closely correlated) provided the best-fit regression model for color preference in all cases. Despite differences in coefficients and structure of the regression models, the consistency of the included measures established R_f , R_g , and $R_{cs,h1}$ as key factors for specifying color preference.

Only Royer and others explicitly suggested specification criteria. To evaluate the performance of those criteria and examine possible alternatives, the SPDs from each of the three datasets were arranged in rank order. Each prospective set of color rendition specification criteria was visually evaluated by color coding the pass (green) and fail (yellow) outcomes (see **Figure F-2**). An ideal specification would result in homogeneous blocks of green and yellow, but in reality the variance associated with the experimental samples means that some intermixing is to be expected.³⁷ The overall ratio of green to yellow between the datasets is not an indicator of performance; rather, it results from differences in the types of SPDs shown. For example, the Zhang and others dataset featured substantially more SPDs.

As is evident, criteria based on R_a alone or on R_a and R_g are not effective for predicting color preference. With criteria that are too relaxed, SPDs throughout the rank order qualify, and with more-restrictive criteria, many of the most-preferred SPDs do not qualify. This situation is not remedied by adding another metric, Gamut Area Index (GAI), as proposed as part of the Class A specification.³⁸⁻⁴⁰ The inherent non-uniformity underlying the CIE 13.3-1995 method means multi-measures systems derived from it do not have the same orthogonality as ANSI/IES TM-30-18 measures,^{32,33,41} reducing the effectiveness of any derived specifications. GAI also is dependent on CCT,^{41,42} but the experimental results were not.

To augment the visual analysis and explore improvements, optimizations were performed by assigning positive and negative scores based on position in the rank order relative to a practical dividing line. Both unweighted (e.g., -1 or 1) and weighted (based on position from the dividing line) were considered. Minimum and maximum R_f , R_g , and $R_{cs,h1}$ values were allowed to vary, with the goal of maximizing the sum of the assigned values for SPDs that met the combined criteria. (Passing SPDs above the dividing line contributed positively, whereas passing SPDs below the dividing line contributed negatively.)

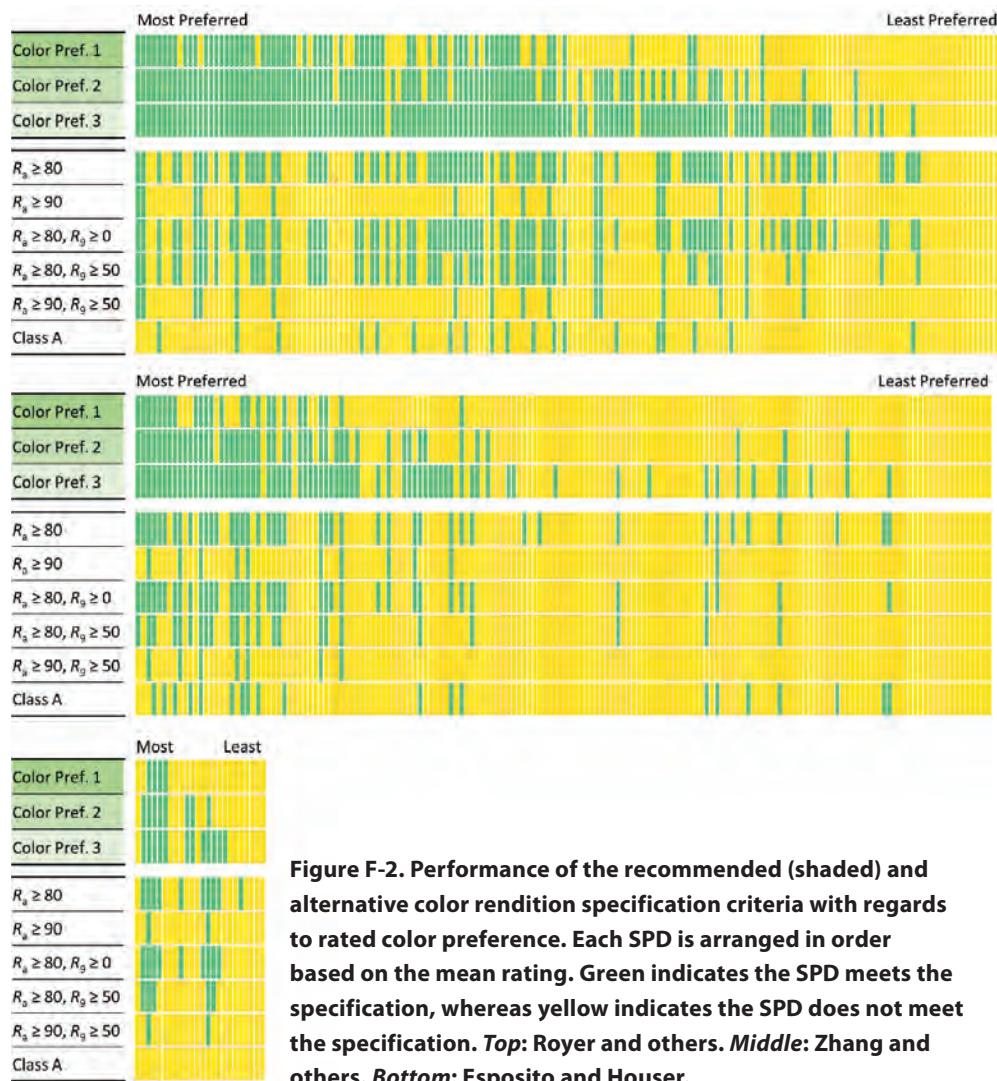


Figure F-2. Performance of the recommended (shaded) and alternative color rendition specification criteria with regards to rated color preference. Each SPD is arranged in order based on the mean rating. Green indicates the SPD meets the specification, whereas yellow indicates the SPD does not meet the specification. Top: Royer and others. Middle: Zhang and others. Bottom: Esposito and Houser.

The visual and numerical optimizations required the use of datasets with many SPDs covering a range of possibilities, which resulted in the selection of the three datasets over other experiments in this field that were considered.^{3,4,6-10,12-15,20,22,24,40,43-86} Without sufficient coverage of the three-dimensional space with axes of R_f , R_g , and $R_{cs,h1}$, it is not possible to establish specifications. Many prior studies were limited by light source capabilities and were more focused on establishing best-fit models and/or single-number metrics of color preference.

The final specification criteria (see **Table E-2**, in **Annex E**) were established by considering the visual and numerical optimization results for all three datasets. Practical considerations, such as

symmetry and equal increments across priority levels, also influenced the recommendations. As shown in **Figure F-2**, there is some variation in the performance of the specification criteria across the three datasets, but the agreement was enough to support generalization under the assumptions listed with **Table E-2**. That is, the specification criteria are not limited to specific cultures, genders, ages, or applications. Nonetheless, these factors should be understood by the user.

Color Preference Priority Level 3 (P3) was benchmarked to qualify a vast majority of SPDs meeting criteria of CIE $R_a \geq 80$ with $R_g \geq 0$. Accordingly, **Figure F-2** shows similar performance for these two specifications. From a

set of approximately 165,000 theoretical SPDs,^{87*} 91% of SPDs that met $R_a \geq 80$ with $R_g \geq 0$ also met the P3 specification. Likewise, about 98% of products that met $R_a \geq 80$ with $R_g \geq 0$ in a set of 668 commercially available SPDs also met the P3 specification. In contrast, the P3 specification allows qualification of a considerable range of SPDs that do not meet the $R_a \geq 80$ with $R_g \geq 0$ specification; 39% of the theoretical SPDs that met the P3 specification did not meet the $R_a \geq 80$ with $R_g \geq 0$ specification. Ninety-six percent of such SPDs within the theoretical set had $R_{cs,h1} \geq 0\%$, exceeding the red chroma criterion for the P1 specification.

The recommended specification criteria are also supported in principle by a wider range of research. The use of $R_{cs,h1}$ as a central component for this design intent aligns with evidence of the importance of reds in subjective evaluations of color rendition,^{3,4,6-9,11,20,22,40} and in color psychology in general.⁸⁸ It also aligns with research indicating a broader correlation between chroma (saturation) and color preference,^{4,6-9,20,21,23,24,43,46,57,61,68,73-76,89-92} with many prior studies conducted prior to the availability of a specific measure of red chroma or a definition of gamut shape. The recommended Color Preference specification criteria prioritize red chroma enhancement relative to the reference illuminant, which is believed to counter changes in color perception that reduce colorfulness as luminance decreases (the Hunt Effect).^{10,93,94} Increasing red chroma relative to the reference illuminant (at equal illuminance, by definition) helps reds appear more like they would under the reference illuminant at high illuminance levels. New research has indicated that light level can influence the preferred level of chroma enhancement^{10,70}; this is a key reason why the recommended specification are limited to a defined illuminance range.

SPDs with characteristics meeting the Color Preference criteria also tend to be rated as more natural for all three datasets, with linear regressions having coefficients of determination (r^2) of 0.69 (Zhang and others), 0.66 (Royer and others), and 0.35 (Esposito and Houser). For the two datasets with the highest correlation, naturalness ratings were maximized at slightly lower ratings of vividness than color preference ratings. For the one dataset that included a question about acceptability (Royer and others), preference and acceptability were highly linearly correlated ($r^2 = 0.85$). The three priority levels correspond to acceptability rates of approximately 65%, 80%, and 90%, although there is variation within each priority level.³⁷

Covering a large area of color rendition space, it is possible for an SPD to be classified as P3 or P2 and meet any level of Color Vividness or Color Fidelity. SPDs in the P1 category can achieve all other designations except for V1.

F.3.2 Color Vividness. The Color Vividness specifications were developed using the same three datasets and same procedures as described for the Color Preference specifications. For all three datasets, mean ratings of color vividness were most strongly correlated with $R_{cs,h1}$ and $R_{cs,h16}$ ($r^2 \geq 0.72$). $R_{cs,h1}$ was chosen for its practicality and continuity with the color preference specifications. $R_{cs,h1}$ criteria were augmented with criteria for R_g to improve the fit to collected data and prevent narrow optimizations in the future. **Figure F-3** illustrates the performance of the Color Vividness specifications. Because no specifications have previously been proposed specifically for this design intent, no comparisons are provided.

Although vividness may be a less prominent design intent, other subjective qualities are related to color vividness. For all three datasets, there is a quadratic relationship between ratings of color preference and ratings of color vividness (see **Figure F-4**). This indicates that color vividness is preferred up to a certain level, at which point object appearances become oversaturated and/or hue shifts become too substantial. The Color Vividness specification criteria focus only on the vividness aspect, and thus do not

*This set features 150,000 theoretical SPDs with 3, 4, 5, 6, or 7 Gaussian components—representing a typical LED emission spectrum—with peak wavelengths between 400 and 700 nm and full-width-half-maximum values between 1 and 100 nm. CCTs are between 2700 K and 6500 K, with D_{uv} values between -0.018 and 0.006. The remainder of SPDs are also theoretical compositions of multiple components creating white light.

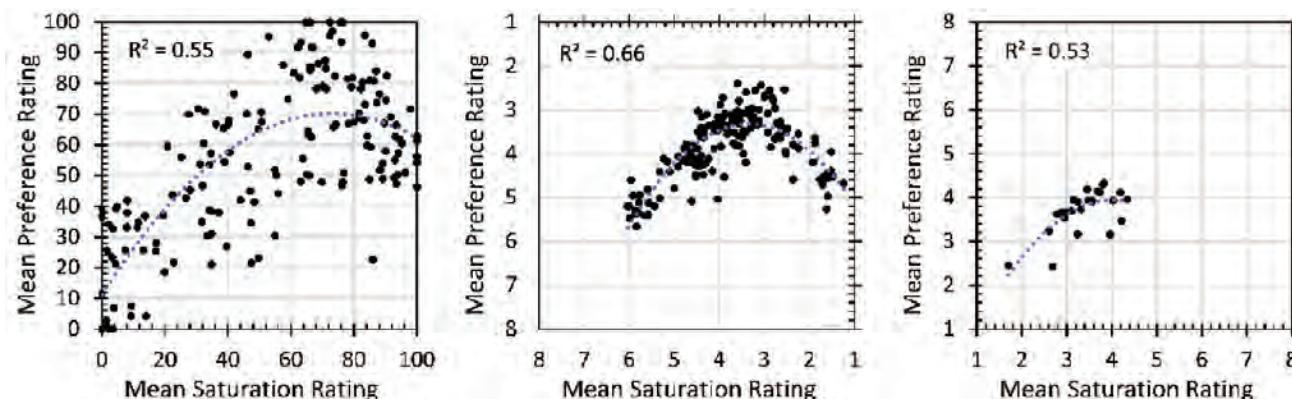
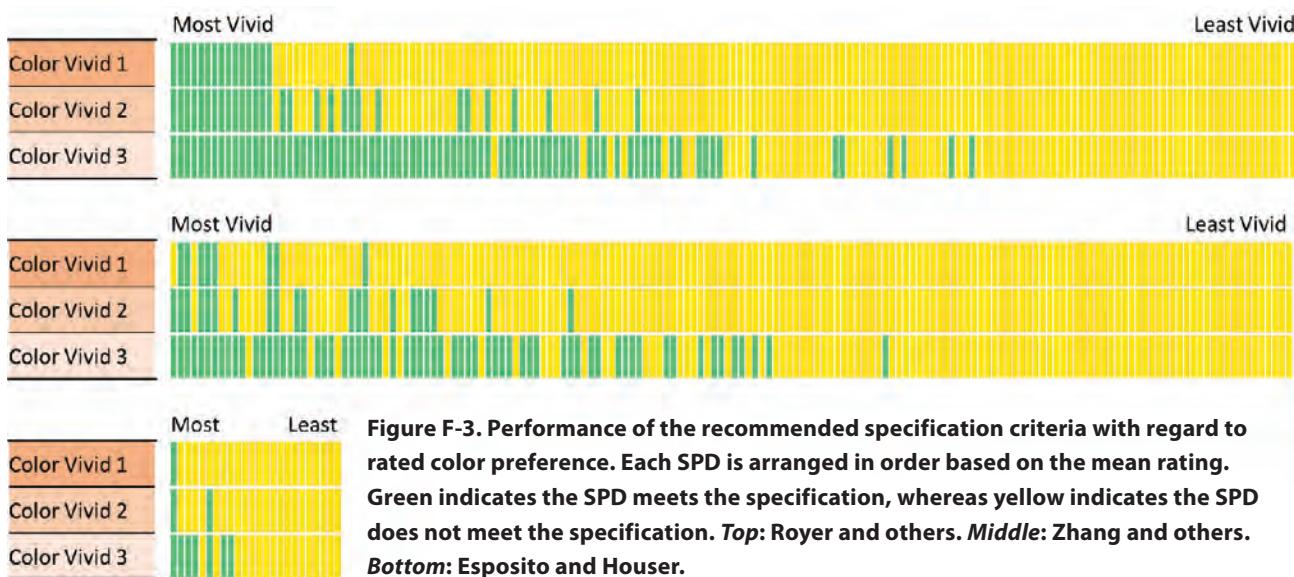


Figure F-4. Mean preference rating vs. mean saturation rating for each SPD in the three datasets. Left: Zhang and others. Middle: Royer and others. Right: Esposito and Houser.

limit oversaturation. The V3 specification begins at an approximately neutral rating between dull and vivid, and overlaps with specifications for Color Preference and Color Fidelity. The V3 thresholds are set at the neutral points for R_g (100) and $R_{cs,h1}$ (0%). In contrast, The V1 specification is effectively exclusive of the P1 and F1-F3 specifications. SPDs classified as V2 can achieve any Color Preference level and a maximum of F3. SPDs classified as V3 may or may not meet any of the other specifications.

F.3.3 Color Fidelity. Average color fidelity has historically been the characteristic used to understand and communicate light source color rendition. It was historically characterized by the CIE General Color Rendering Index, R_a (CRI).¹⁸ ANSI/IES

TM-30-18 and CIE 224:2017⁹⁵ provide an updated, scientifically accurate measure of color fidelity, addressing the many known inaccuracies of CIE R_a .^{32,33,96} ANSI/IES TM-30-18 also includes 16 local color fidelity measures ($R_{f,hj}$) to address the rendition of specific hues without relying on individual color samples that can be specifically targeted in spectral optimization.

Development of the Color Fidelity specifications relied more on experience and intuition than the Color Preference or Color Vividness specifications did. Color fidelity is most useful and meaningful when the values are high. As color fidelity is reduced, the range of gamut area and possible gamut shape orientations increases, such that SPDs

with the same R_f value can result in increasingly different object color appearances. SPDs with R_f values of 85 and equal R_g values have been shown to induce substantially different color shifts.⁷ The lowest recommended Color Fidelity specification (F3) is $R_f \geq 85$, which is higher than many existing specifications for CIE R_a that are ostensibly more about acceptability than color fidelity. In specific circumstances, there is no R_f value other than 100 that can ensure no difference in color appearance compared to the reference illuminant; however, the F1 specification was deemed high enough to achieve this under practical architectural lighting circumstances.

In acknowledgement of the particular importance of red to color psychology and the precedent of including red color fidelity in specifications, the F3 and F2 tiers include limits for $R_{f,h1}$ that are equal to the respective limits for R_f . That is, the color fidelity for reds cannot be worse than the average color fidelity for all hues. The R_f criterion for F1 provides sufficient limitation on all hues that an $R_{f,h1}$ criterion was not needed. From the set of approximately 165,000 theoretical SPDs, the minimum $R_{f,hj}$ value (across all hue-angle bins) for an SPD meeting the F1 specification was 87, and the minimum $R_{f,h1}$ value was 95. For all hue angle bins, the 10th percentile was 93 or greater.

The Color Fidelity specifications contrast with the Color Preference specifications, but there is strong overlap between the two sets. SPDs within any of the Color Fidelity specifications that have $R_{cs,h1} \geq -1\%$ fall into P1—those with $R_{cs,h1} \geq 0$ also fall into V3. SPDs within any of the color fidelity specifications that have $R_{cs,h1} < -1\%$ fall in either P2 or P3. All SPDs meeting the F2 or F1 specifications will at least meet the P2 specification but cannot meet the V2 or V1 specifications. SPDs with the F3 designation may be in any Color Preference level but cannot achieve V1. The Color Fidelity specifications are more restrictive than the Color Preference or Color Vividness specifications; that is, they cover a much smaller region of the $R_f-R_{cs,h1}$ space (see **Figure F-1**, in **Section F.3.1**).

As opposed to color preference and vividness, color fidelity is an objective aspect of color rendition. It was not studied as a dependent measure in the five experiments used to determine the Color Preference and Color Vividness specifications. However, a number of psychophysical studies have been completed that have supported the improvements of R_f over CIE R_a ,^{2,5,16,97} particularly the use of CAM02-UCS color space—which is the most readily testable attribute.

Color fidelity has long been viewed as related to color naturalness, but none of the three datasets discussed in this Annex (among others) supports that relationship. The coefficients of determination (r^2) for R_f versus rated naturalness were 0.56 (Zhang and others), 0.43 (Royer and others), and 0.30 (Esposito and Houser). The level of correlation depends on the specific SPDs included.³³ **Figure F-5** illustrates the fit of the Color Preference and Color Fidelity specifications to rated naturalness or normalness data for the three datasets. A major difference is the restrictiveness of the two design intents: The Color Preference specifications qualify substantially more SPDs within each set. The Color Fidelity specifications tend to qualify only highly-rated SPDs, but also disqualify many of the highest-rated SPDs.

An alternative to objective color fidelity is “perceived color fidelity,” which is intended to relate to color naturalness (or color preference) by variably weighting color shifts to form a subjective, single-number metric. ANSI/IES TM-30-18 does not include subjective metrics, instead providing enough objective data to facilitate effective multi-measure specifications.

F.3.4 Performance of Existing Products. Figures

F-6 ($R_{cs,h1}-R_f$) and **F-7** ($R_{cs,h1}-R_g$) illustrate the range of performance for a set of 668 commercially available LED products sold for architectural lighting compared to the theoretical range of possible combinations. The nine recommended specifications are also shown—the Color Preference specifications are split across both figures. The existing products fall into only a small

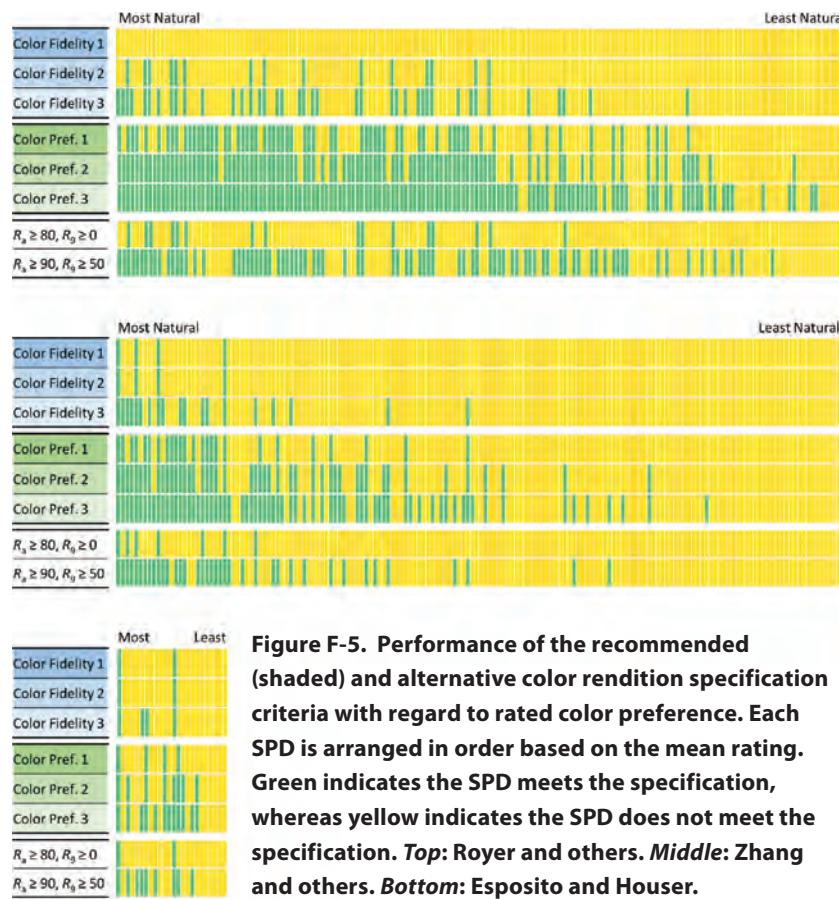


Figure F-5. Performance of the recommended (shaded) and alternative color rendition specification criteria with regard to rated color preference. Each SPD is arranged in order based on the mean rating. Green indicates the SPD meets the specification, whereas yellow indicates the SPD does not meet the specification. Top: Royer and others. Middle: Zhang and others. Bottom: Esposito and Houser.

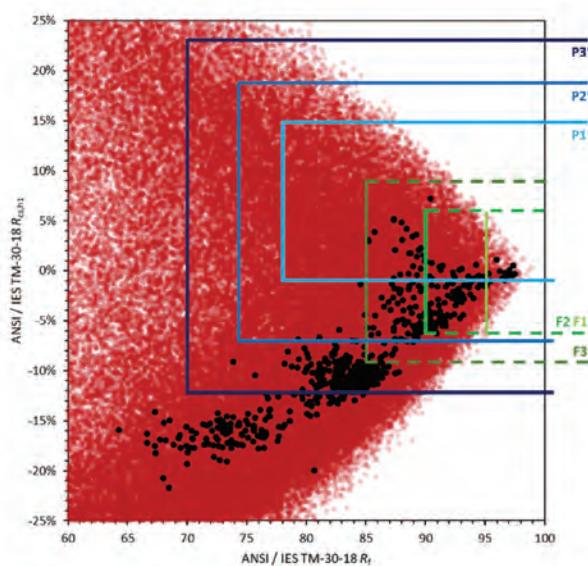


Figure F-6. Performance of 668 commercially-available LED SPDs compared to the range of possible R_f and $R_{cs,h1}$ values, as demonstrated by a set of approximately 165,000 theoretical SPDs.

* The Color Preference Criteria include a third measure, R_g , shown in Figure F-7.

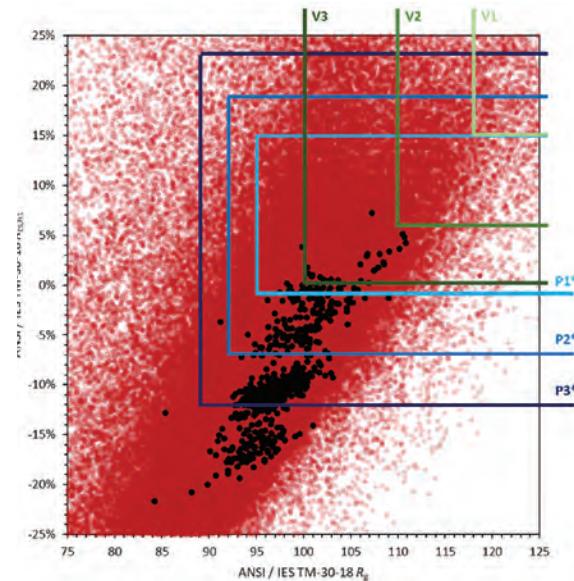


Figure F-7. Performance of 668 commercially-available LED SPDs compared to the range of possible R_f and $R_{cs,h1}$ values, as demonstrated by a set of approximately 165,000 theoretical SPDs.

* The Color Preference Criteria include a third measure, R_g , shown in Figure F-6.

region compared to the overall possibilities, due to a combination of energy efficiency tradeoffs (see **Section F.3.5**) and prior color rendition specifications (see **Section F.3.6**). In particular, a majority of current products—featuring a blue-pump phosphor-converted white architecture—have R_f values around 82 and $R_{cs,h1}$ values around -11%.³⁷ It is anticipated that the recommended color rendition specifications will allow greater product differentiation and will incentivize novel product development. The commercial product with the highest $R_{cs,h1}$ value was engineered based on color preference research using TM-30.

The commercially available LED products fall into all three recommended Color Preference specifications and all three Color Fidelity specifications. None of the products meets the V2 or V1 specification, although such conditions are easily achieved with color-mixed LED systems, such as those used to generate the experimental datasets (see **Figure F-1**, in **Section F.3.1**).

Section E.5 in **Annex E** provides additional examples of the specification levels met by current products, including non-LED products.

F.3.5 Energy Efficiency Tradeoffs. Color rendition is generally considered to be a tradeoff against energy efficiency, as quantified with luminous efficacy of radiation (LER)—which only accounts for spectral efficiency, ignoring electrical efficiency. This is because the highest LER, 683 lm/W_{optical}, occurs with monochromatic light having a wavelength of 555 nm. Any specifications for color rendition necessarily reduce this maximum. Many studies have examined this tradeoff in the past, and the relationship has been reexamined using measures from TM-30.^{96,98}

For all three design intents, increasing the priority level (e.g., from 2 to 1), reduces the maximum possible LER. The pole of maximum LER for nominally white light sources occurs with low color fidelity and low red chroma, as illustrated in **Figure F-8**. The color-coded regions of LER are not exclusive; rather, they overlap. However, higher LER is more likely

to be achieved in certain regions of R_f - $R_{cs,h1}$ space, and high LER cannot be achieved in others. This tradeoff should be considered when choosing from the recommended specification criteria priority levels. What is important is that SPDs with LER equal to or greater than that of currently available products for architectural lighting (approximately 300 to 340 lm/W_{optical}) exist in the regions for all nine recommended specifications.

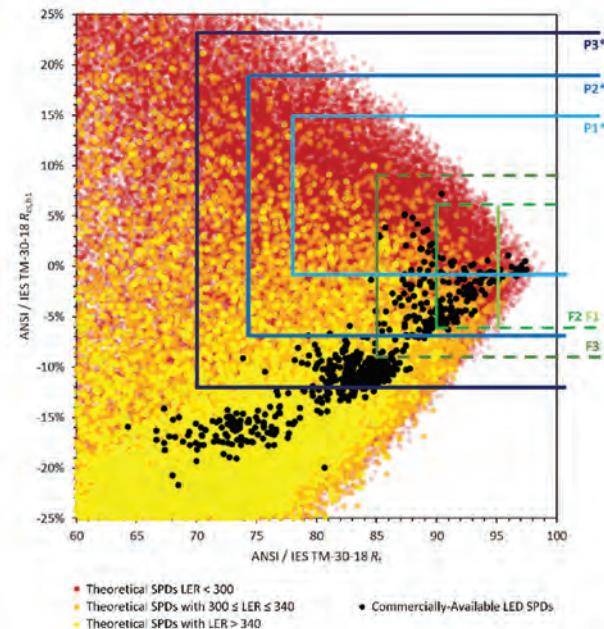


Figure F-8. Recommended specifications (lines) shown against luminous efficacy of radiation (LER) of the theoretical SPDs.

F.3.6 Performance Compared to Prior Specifications Based on CIE 13.3-1995. **Figure F-9** illustrates the performance of the Color Preference and Color Fidelity specifications (shown with lines) relative to approximate boundaries for two common specifications based on CIE 13.3-1995: R_a (CRI) ≥ 80 with $R_9 \geq 0$ (orange) and R_a (CRI) ≥ 90 with $R_9 \geq 50$ (yellow). The latter is shown by color coding the set of theoretical SPDs to translate from R_a and R_9 to the axes of R_f and $R_{cs,h1}$. There is substantial overlap between the criteria using the different color rendition evaluation methods, which was a consideration during the development of the recommended specifications of this document. That is, converting to the new

color rendition specifications does not require vast changes in currently available products. It does, however, allow for refinement and differentiation while establishing targets for future development.

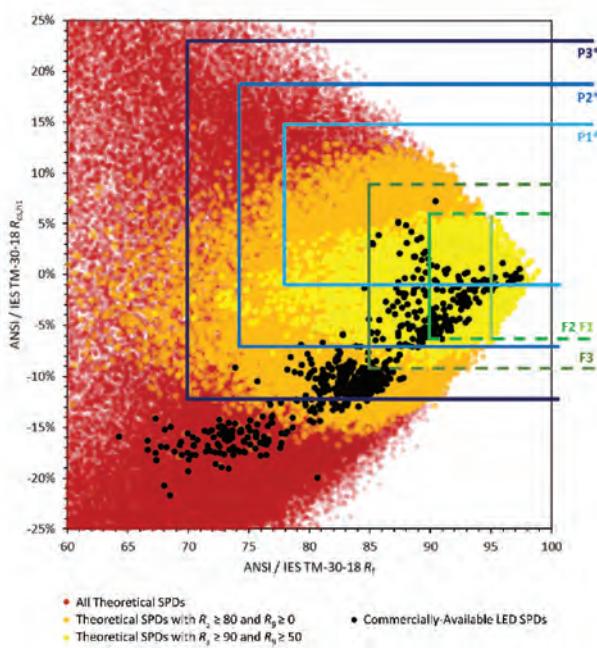


Figure F-9. Comparison of recommended specifications (lines) and commonly used specifications (colored theoretical SPDs).

There are important differences between common past specifications and the recommended specifications of this document. Many theoretical SPDs meeting specifications using the combinations of CIE R_a and R_9 fall outside any of the recommended specifications. Of the theoretical SPDs meeting CIE $R_a \geq 80$ with $R_9 \geq 0$, for example, 9%, 37%, and 69% fail to meet the P3, P2, and P1 specifications, respectively. A substantial portion of this discrepancy is due to misalignment between the previously used measures and the characteristics found to be important for the Color Preference design intent. However, SPDs meeting CIE $R_a \geq 80$ with $R_9 \geq 0$ have R_f values as low as 41; furthermore, SPDs meeting CIE $R_a \geq 90$ with $R_9 \geq 50$ have R_f values as low as 65. As another illustration, 45% of the SPDs meeting CIE $R_a \geq 90$ with $R_9 \geq 50$ fail to meet the F2 specification, which is conceptually equivalent. The amount is 61% for the commercially available LED set. This is due to the technical limitations of the CIE

13.3-1995 method, specifically the color samples and color space.^{21,30-34,41} It is not due to the scaling factor, which has been adjusted.³³ The new criteria effectively prevent the use of SPDs optimized only for the metric calculation. These examples also illustrate why it is not recommended to simply convert existing specifications to equivalent measures from ANSI/IES TM-30-18.

The new specifications also address products that would otherwise fail to meet common past specifications due to a bias against particular shifts.³³ For example, theoretical SPDs in the P3, P2, and P1 specifications have CIE R_a values as low as 42, 52, and 61, respectively. CIE R_9 values are as low as -173, -118, and -99. The same is true for the F3, F2, and F1 specifications, where the minimum CIE R_a values for the theoretical SPDs are 75, 82, and 91—the gap greatly reduces as average color fidelity is increased. These discrepancies extend to the experimental datasets, where SPDs in the P3, P2, and P1 specifications have CIE R_a values as low as 47, 60, and 68, respectively.

Finally, to qualify the same products using specifications based on CIE R_a and complementary measures (i.e., using the same color samples)^{24,38,40,78} requires substantially reducing the CIE R_a threshold, which would also allow products rated as providing less preferred or less natural color rendition to qualify. In other words, the non-uniformity of CIE R_a in response to color shift in different hue regions^{32,33} cannot be overcome by augmenting it with additional measures to craft effective specifications for color preference or color fidelity. This approach is not recommended.

F.3.7 Benchmarking to Prior Specifications Based on CIE 13.3-1995. In some cases where color rendition is a relatively low priority, converting old specifications (typically based on measures from CIE 13.3-1995) to new specifications based on ANSI/IES TM-30-18 using a benchmarking approach is possible. As previously stated, benchmarking to a specification of $R_a \geq 80$ with $R_9 > 0$ contributed to the P3 specification. Because benchmarking has strong limitations based on the set of SPDs used, it

is not a substitution for more carefully considered revisions of color rendition specifications for situations where color quality is important. When benchmarking is performed, the recommended minimum included specification parameters are R_f , R_g , and $R_{cs,h1}$, with potential inclusion of $R_{f,h1}$.

To illustrate this process, a collection of 886 SPDs for commercially available products of varying technologies was assembled. Of those products, 817 met $R_a \geq 70$. The minimum ANSI/IES TM-30-18 parameters for those 817 SPDs were $R_f = 64$, $R_g = 75$, and $R_{cs,h1} = -23\%$. If the collection of SPDs was limited to the 668 LED products, the corresponding minimum values for the 641 SPDs with $R_a \geq 70$ was $R_f = 67$, $R_g = 85$, and $R_{cs,h1} = -20\%$. The collections of SPDs should represent the products that are intended to be covered by the new specification.

Outliers are an additional consideration, and the decision can be made to remove a certain percentage of the values. For the latter example with 641 LED products having $R_a \geq 70$, removing the bottom 1% of products for each parameter would result in a new specification (rounding down) of $R_f \geq 71$, $R_g \geq 91$, and $R_{cs,h1} \geq -18\%$. For clarity, this could be further smoothed to $R_f \geq 70$, $R_g \geq 90$, and $R_{cs,h1} \geq -18\%$.

REFERENCES FOR ANNEX F

1. U.S. Department of Defense. UFC 4-510-01, Design: Military Medical Facilities with Change 2. Washington, DC: Dept Defense; 2017;442.
2. Xu W, Wei M, Smet K, Lin Y. The prediction of perceived colour differences by colour fidelity metrics. *Lighting Res Technol*. 2016; 2016;49(7):805-17. DOI: 10.1177/1477153516653650.
3. Wei M, Houser K, David A, Krames M. Colour gamut size and shape influence colour preference. *Lighting Res Technol*. 2016;49(8):992-1014. DOI: 10.1177/1477153516651472.
4. Royer M, Wilkerson A, Wei M, Safranak S. Experimental validation of color rendition specification criteria based on ANSI/IES TM-30-18. *Lighting Res Technol*. 2019; Submitted for publication.
5. Wei M, Royer M, Huang H-P. Perceived colour fidelity under LEDs with similar R_f but different R_a . *Lighting Res Technol*. 2019 Jan 31. DOI: 10.1177/1477153519825997.
6. Royer M, Wilkerson A and Wei M. Human Perceptions of Color Rendition at Different Chromaticities. *Lighting Res Technol*. 2016;49:966-91. DOI: 10.1177/1477153517725974.
7. Royer MP, Wilkerson A, Wei M, Houser K, Davis R. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. *Lighting Res Technol*. 2016;49:966-991. DOI: 10.1177/1477153516663615.
8. Esposito T, Houser K. Models of colour quality over a wide range of spectral power distributions. *Lighting Res Technol*. 2018;51(3):331-52. DOI: 10.1177/1477153518765953.
9. Zhang F, Xu H, Feng H. Toward a unified model for predicting color quality of light sources. *Applied Optics*. 2017;56:8186-95. DOI: 10.1364/AO.56.008186.
10. Wei M, Bao W, Huang H. Consideration of Light Level in Specifying Light Source Color Rendition. *Leukos*. 2018; Online Before Print. DOI: 10.1080/15502724.2018.1448992.
11. Wei M, Houser K, David A, Krames M. Effect of gamut shape on color preference. *CIE 2016 Lighting Quality and Energy Efficiency*. Melbourne, Australia. Vienna: CIE; 2016:32-41.
12. Khanh T, Bodrogi P. Colour preference, naturalness, vividness and colour quality metrics, Part 3: Experiments with makeup products and analysis of the complete warm white dataset. *Lighting Res Technol*. 2018;50:218-36.
13. Khanh T, Bodrogi P, Vinh Q, Guo X, Anh T. Colour preference, naturalness, vividness and colour quality metrics, part 4: experiments with still life arrangements at different correlated colour temperatures. *Lighting Res Technol*. 2018;50:862-79.

14. Khanh T, Bodrogi P, Vinh Q, Stojanovic D. Colour preference, naturalness, vividness and colour quality metrics, Part 2: Experiments in a viewing booth and analysis of the combined dataset. *Lighting Res Technol.* 2017;49:714-26.
15. Khanh T, Bodrogi P, Vinh Q, Stojanovic D. Colour preference, naturalness, vividness and colour quality metrics, Part 1: Experiments in a room. *Lighting Res Technol.* 2017;49:697-713.
16. Jost S, Cauwerts C and Avouac P. CIE 2017 color fidelity index R_f: a better index to predict perceived color difference? *J Optical Soc America A.* 2018;35:B202-13. DOI: 10.1364/JOSAA.35.00B202.
17. Wang Y, Wei M. Preference among light sources with different Duv but similar colour rendition: A pilot study. *Lighting Res Technol.* 2017;50(7):1013-23. DOI: 10.1177/1477153517712552.
18. International Commission on Illumination (CIE). CIE 13.3:1995, Method of measuring and specifying colour rendering properties of light sources. Vienna: CIE; 1995.
19. U.S. Department of Energy. ENERGY STAR Program Requirements for Compact Fluorescent Lamps (CFLs) – Partner Commitments, V2.0. Washington, DC: Dept Energy.
20. Ohno Y, Fein G, Miller C. Vision Experiment on chroma saturation for color quality preference. In: 28th CIE Session, Manchester, UK. 2015 Jun 28 - Jul 4. Vienna: CIE; 2015:2124
21. Davis W ,Ohno Y. Color quality scale. *Optical Engineering.* 2010;49:033602. DOI: 10.1117/1.3360335.
22. Wei M, Houser KW. Systematic changes in gamut size affect color preference. *Leukos.* 2017;13:23-32. DOI: 10.1080/15502724.2016.1192402.
23. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Correlation between color quality metric predictions and visual appreciation of light sources. *Opt Express.* 2011;19:8151-66. DOI: 10.1364/OE.19.008151.
24. Teunissen C, van der Heijden F, Poort SHM, de Beer E. Characterising user preference for white LED light sources with CIE colour rendering index combined with a relative gamut area index. *Lighting Res & Technol.* 2016;49:461-80. DOI: 10.1177/1477153515624484.
25. State of California. California Code of Regulations Title 20, Public Utilities and Energy. Sacramento: Calif Energy Commission; 2018.
26. International WELL Building Institute. WELL Building Standard v2 pilot; 2019. Online: <https://v2.wellcertified.com/v/en/overview>. (Accessed 2019 May 16).
27. U.S. Department of Energy. ENERGY STAR Luminaires Specification v2.1. Washington, DC: Dept Energy.
28. U.S. Department of Energy. ENERGY STAR Lamps Specification v2.1. Washington, DC: Dept Energy.
29. State of California. Building Energy Standard Title 24, Part 6, Appendix JA8, Qualification Requirements for High Efficacy Light Sources. Sacramento: Calif Energy Commission; 2016..
30. Houser K, Mossman M, Smet K, Whitehead L. Tutorial: Color rendering and its applications in lighting. *Leukos.* 2016;12:7-26. DOI: 10.1080/15502724.2014.989802.
31. van Trigt C. Color rendering, a reassessment. *Color Res Applic.* 1999;24:197-206. DOI: 10.1002/(SICI)1520-6378(199906)24:3<197::AID-COL6>3.0.CO;2-S.
32. Smet K, David A, Whitehead L. Why color space uniformity and sample set spectral uniformity are essential for color rendering measures. *Leukos* 2015;12:39-50. DOI: 10.1080/15502724.2015.1091356.
33. Royer M. Comparing measures of average color fidelity. *Leukos* 2017;14:69-85. DOI: 10.1080/15502724.2017.1389283.
34. International Commission on Illumination (CIE). CIE 177:2007, Colour Rendering of White LED Light Sources. Vienna: CIE; 2007.
35. P Illuminating Engineering Society. PS-11-18, IES Position on TM-30-18, IES Method for Evaluating Light Source Color Rendition. New York: IES; 2018.

36. DesignLights Consortium. Solid-State Lighting (SSL) Technical Requirements v5.0. Medford, Mass.: DLC; 2019.
37. Royer M. Analysis of color rendition specification criteria. In: SPIE Photonics West Opto: Light-Emitting Devices, Materials, and Applications. San Francisco: SPIE; 2019:55.
38. Rea MS. A practical and predictive two-metric system for characterizing the color rendering properties of light sources used for architectural applications. Proc SPIE. 2010; 7652:765206-7. DOI: 10.1117/12.868799.
39. Freyssinier JP, Rea M. The Class A color designation for light sources. In: DOE Solid-State Lighting R&D Workshop, Long Beach, CA, 2013 Jan 29-31.
40. Rea MS, Freyssinier JP. Color rendering: Beyond pride and prejudice. Color Res Applic. 2010;35:401-409. DOI: 10.1002/col.20562.
41. Royer M. Comparing measures of gamut area. Leukos. 2018;15(1):29-53. DOI: 10.1080/15502724.2018.1500485.
42. Houser KW, Wei M, David A, Krames MR, Shen XS. Review of measures for light-source color rendition and considerations for a two-measure system for characterizing color rendition. Opt Express. 2013;21:10393-411. DOI: 10.1364/OE.21.010393.
43. Sanders C. Color preferences for natural objects. Illumin Engineering. 1959;47:452-6.
44. Sanders C. Assessment of color rendition under an illuminant using color tolerances for natural objects. J Illumin Engineering Soc. 1959:640-6.
45. Aston SM, Belichambers HE. Illumination, colour rendering and visual clarity. Lighting Res Technol. 1969;1:259-61. DOI: 10.1177/14771535690010040401.
46. Jerome CW. Flattery vs Color Rendition. J Illumin Engineering Soc. 1972;1:208-11. DOI: 10.1080/00994480.1972.10732210.
47. Thornton WA. A validation of the color-preference index. J Illumin Engineering Soc. 1974;4:48-52. DOI: 10.1080/00994480.1974.10732288.
48. Rea MS, Robertson AR, Petrusic WM. Colour rendering of skin under fluorescent lamp illumination. Color Res Applic. 1990;15:80-92. DOI: 10.1002/col.5080150206.
49. Veitch JA, Whitehead LA, Mossman M, Pilditch TD. Chromaticity-matched but spectrally different light source effects on simple and complex color judgments. Color Res Applic. 2014;39:263-74. DOI: 10.1002/col.21811.
50. Veitch JA, Tiller DK, Pasini I, Arsenault CD, Jaekel RR, Svec JM. The effects of fluorescent lighting filters on skin appearance and visual performance. J Illumin Engineering Soc. 2002;31:40-60.
51. Quellman EM, Boyce PR. The light source color preferences of people of different skin tones. J Illumin Engineering Soc. 2002;31:109-18. DOI: 10.1080/00994480.2002.10748376.
52. Narendran N, Deng L. Color rendering properties of LED light sources. In: Proc SPIE 4776, Solid State Lighting II. San Francisco: SPIE; 2002.
53. Schanda J, Sandor N. Colour rendering, past – present – future. Intl Lighting Colour Conf. Cape Town, South Africa, 2003:76-85.
54. Schanda J, Madar G. Light source quality assessment. In: Proc CIE 26th Session, Beijing, China; 2007. Vienna: CIE; 2007.
55. Rea MS, Freyssinier-Nova JP. Color rendering: A tale of two metrics. Color Res Applic. 2008;33:192-202. DOI: 10.1002/col.20399.
56. Jost-Boissard S, Avouac P, Fontoynont M. Assessing the colour quality of LED sources: Naturalness, attractiveness, colourfulness and colour difference. Lighting Res Technol. 2014;47:769-94. DOI: 10.1177/1477153514555882.
57. (Not used).
58. Jost-Boissard S, Fontoynont M, Blanc-Gonnet J. Perceived lighting quality of LED sources for the presentation of fruit and vegetables. J Modern Optics. 2009;56:1420-32. DOI: 10.1080/09500340903056550.

59. Szabó F, Csuji P, Schanda J. Color preference under different illuminants—New approach of light source colour quality. In: Light Lighting Conf Special Emphasis LEDs Solid State Lighting. Budapest, Hungary, 2009 May 27-29. Vienna: CIE; 2009:PWDAS-43.
60. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Memory colours and colour quality evaluation of conventional and solid-state lamps. *Opt Express*. 2010;18:26229-44. DOI: 10.1364/OE.18.026229.
61. Liu A, Tuzikas A, Zukauskas A, Vaicekauskas R, Vitta P, Shur M. Cultural preferences to color quality of illumination of different artwork objects revealed by a color rendition engine. *IEEE Photonics J*. 2013;5:6801010. DOI: 10.1109/jphot.2013.2276742.
62. Zukauskas A, Vaicekauskas R, Vitta P, Tuzikas A, Petrusis A, Shur M. Color rendition engine. *Opt Express*. 2012;20:5356-67. DOI: 10.1364/OE.20.005356.
63. Imai Y, Kotani T, Fuchida T. A study of color rendering properties based on color preference in adaptation to LED lighting: CIE 2012 Lighting Quality & Energy Efficiency, Hangzhou, China. Vienna: CIE 2012:369-74.
64. Spaulding JM. Evaluation of Desirability Assessment Techniques for Tunable Solid State Lighting Applications. In: Proc Human Factors Ergonomics Soc Annual Meeting, 2012 Oct 22-26:643-7.
65. Smet KAG, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Optimization of colour quality of LED lighting with reference to memory colours. *Lighting Res Technol*. 2012;44:7-15. DOI: 10.1177/1477153511432250.
66. Baniya RR, Dangol R, Bhusal P, Wilm A, Baur E, Puolakka M, Halonen L. User-acceptance studies for simplified light-emitting diode spectra. *Lighting Res Technol*. 2015;47:177-91. DOI: 10.1177/1477153513515264.
67. Dangol R, Islam MS, Hyvarinen M, Bhushal P, Puolakka M, Halonen L. User acceptance studies for LED office lighting: Preference, naturalness and colourfulness. *Lighting Res Technol*. 2015;47:36-53. DOI: 10.1177/1477153513514424.
68. Islam MS, Dangol R, Hyvarinen M, Bhusal P, Puolakka M, Halonen L. User preferences for LED lighting in terms of light spectrum. *Lighting Res Technol*. 2013;45:641-65. DOI: 10.1177/1477153513475913.
69. Dangol R, Islam M, Hyvarinen M, Bhusal P, Puolakka M, Halonen L. Subjective preferences and colour quality metrics of LED light sources. *Lighting Res Technol*. 2013;45:666-88. DOI: 10.1177/1477153512471520.
70. Kawashima Y, Ohno Y, Oh S. Vision experiment on verification of Hunt Effect for lighting. In: 11th Biennial Joint CIE/USNC and CNC/CIE Techn Conf. Gaithersburg, Maryland; 2017.
71. Imai Y, Kotani T, Fuchida T. A study of color rendering properties based on color preference of objects in adaptation to LED lighting. In: CIE Centenary Conf, Towards a New Century of Light; 2013:62-7.
72. Tsukitani A. Optimization of colour quality for landscape lighting based on feeling of contrast index. In: CIE Centenary Conf, Towards a New Century of Light; 2013:68-71.
73. Szabo F, Keri R, Schanda J, Csuji P, Mihalyko-Orban E. A study of preferred colour rendering of light sources: Home lighting. *Lighting Res Technol*. 2014;46:103-25. DOI: 10.1177/1477153514555536.
74. Lin Y, Wei M, Smet K, Tsukitani A, Bodrogi P, Khanh T. Colour preference varies with lighting application. *Lighting Res Technol*. 2015;49:316-28. DOI: 10.1177/1477153515611458.
75. Wei M, Houser KW, Allen GR, Beers WW. Color preference under LEDs with diminished yellow emission. *Leukos*. 2014;10:119-31. DOI: 10.1080/15502724.2013.865212.
76. Wei M, Houser K, David A, Krames M. Perceptual responses to LED illumination with colour rendering indices of 85 and 97. *Lighting Res Technol*. 2014;47:810-27. DOI: 10.1177/1477153514548089.
77. Smet K, Hanselaer P. Impact of cross-regional differences on color rendition evaluation of white light sources. *Opt Express*. 2015;23:30216-26. DOI: 10.1364/OE.23.030216.

78. Tang X, Teunissen C. The appreciation of LED-based white light sources by Dutch and Chinese people in three application areas. *Lighting Res Technol.* 2018;51(3):353-72. DOI: 10.1177/1477153517754130.
79. Khanh T, Bodrogi P, Vinh Q, Stojanovic D. Colour preference, naturalness, vividness and colour quality metrics, Part 1: Experiments in a room. *Lighting Res Technol.* 2016;49(6):697-713. DOI: doi:10.1177/1477153516643359.
80. Khanh T, Bodrogi P. Colour preference, naturalness, vividness and colour quality metrics, Part 3: Experiments with makeup products and analysis of the complete warm white dataset. *Lighting Res Technol.* 2016;50(2):218-36. DOI: doi:10.1177/1477153516669558.
81. Khanh T, Bodrogi P, Vinh Q, Stojanovic D. Colour preference, naturalness, vividness and colour quality metrics, Part 2: Experiments in a viewing booth and analysis of the combined dataset. *Lighting Res Technol.* 2016;49(6):714-726. DOI: doi:10.1177/1477153516643570.
82. Bodrogi P, Brückner S, Khanh TQ, Winkler H. Visual assessment of light source color quality. *Color Res Applic.* 2013;38:4-13. DOI: 10.1002/col.20726.
83. Khanh T, Bodrogi P, Guo X, Anh P. Towards a user preference model for interior lighting. Part 2: Experimental results and modeling. *Lighting Res Technol.* 2018 Dec 13:1477153518816474.
84. Khanh T, Bodrogi P, Guo X, Anh P. Towards a user preference model for interior lighting Part 1: Concept of the user preference model and experimental method. *Lighting Res Technol.* 2018 Dec 13: 1477153518816469.
85. Liu Q, Huang Z, Pointer MR, Luo MR, Xiao K, Westland S. Evaluating colour preference of lighting with an empty light booth. *Lighting Res Technol.* 2017;50(8):1249-56. DOI: 10.1177/1477153517727330.
86. Huang Z, Liu Q, Westland S, Pointer MR, Luo MR, Xiao K. Light dominates colour preference when correlated colour temperature differs. *Lighting Res Technol.* 2017;50(7):995-1012. DOI: 1477153517713542.
87. Royer M. Spectral power distributions. DOI: 10.6084/m9.figshare.7704566.v1. Online: https://figshare.com/articles/Spectral_power_distributions/7704566. (Accessed 2019 May 17).
88. Elliot AJ, Maier MA. Color psychology: Effects of perceiving color on psychological functioning in humans. *Annu Rev Psychol.* 2014;65:95-120. DOI: 10.1146/annurev-psych-010213-115035.
89. Judd DB. Flattery index for artificial illuminants. *IES Trans.* 1967:593-8.
90. Jerome CW. The flattery index. *J Illumin Engineering Soc.* 1973;2:351-4. DOI: 10.1080/00994480.1973.10747727.
91. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Optimization of colour quality of LED lighting with reference to memory colours. *Lighting Res Technol.* 2012;44:7-15. DOI: 10.1177/1477153511432250.
92. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Colour appearance rating of familiar real objects. *Color Res Applic.* 2011;36:192-200. DOI: 10.1002/col.20620.
93. Hunt R. Light and dark adaptation and the perception of color. *J Opt Soc Am.* 1952;42:190-9.
94. Fairchild MD. *Color Appearance Models*, 3rd ed. Chichester, UK: Wiley; 2013.
95. International Commission on Illumination (CIE). CIE 224:2017, CIE 2017 Colour Fidelity Index for accurate scientific use. Vienna: CIE; 2017.
96. David A, Fini PT, Houser KW, Ohno Y, Royer MP, Smet KA, Wei M, Whitehead L. Development of the IES method for evaluating the color rendition of light sources. *Opt Express.* 2015;23:15888-906. DOI: 10.1364/OE.23.015888.
97. Gu H, Luo M, Liu X. Testing different colour rendering metrics using colour difference data. *Lighting Res Technol.* 2017;49:539-60. DOI: 10.1177/1477153516653649.
98. Zhang F, Xu H, Wang Z. Optimizing spectral compositions of multichannel LED light sources by IES color fidelity index and luminous efficacy of radiation. *Applied Optics.* 2017;56:1962-71. DOI: 10.1364/AO.56.001962.

REFERENCES

1. Houser KW, Wei M, David A, Krames MR, Shen XS. Review of measures for light-source color rendition and considerations for a two-measure system for characterizing color rendition. *Opt Express*. 2013;21:10393-411.
2. Smet K, Ryckaert WR, Pointer MR, Deconinck G, Hanselaer P. Correlation between color quality metric predictions and visual appreciation of light sources. *Opt Express*. 2011;19:8151-66.
3. Royer MP. What is the Reference? An examination of alternatives to the reference sources used in IES TM-30-15. *Leukos*. 2016;13:71-89.
4. David A, Fini PT, Houser KW, et al. Development of the IES method for evaluating the color rendition of light sources. *Opt Express*. 2015;23:15888-906.
5. Smet K, David A and Whitehead L. Why color space uniformity and sample set spectral uniformity are essential for color rendering measures. *Leukos*. 2015;12:39-50.
6. Royer M, Wei M. The role of presented objects in deriving color preference criteria from psychophysical Studies. *Leukos*. 2017;13:143-57.
7. Li CJ, Luo MR, Pointer MR and Green P. Comparison of real colour gamuts using a newreflectance database. *Color Res & Appl*. 2014;39:442-51.
8. International Organization for Standardization. Graphic Technology - Standard Object Colour Spectra Database for Colour Reproduction Evaluation (SOCS). Geneva: The Organization; 2003.
9. Vrhel M, Gershon R, Iwan L. Measurement and analysis of object reflectance spectra. *Color Res & Appl*. 1994;19:4-9.
10. Finland UoE. Spectral Database. <http://www.uef.fi/spectral/spectra-database>.
11. Arnold S, Faruq S, Savolainen V, McOwan P, Fred LC. The floral reflectance database - A web portal for analysis of flower colour. *PLoS One*. 2013;5:e14287.
12. Marszalec E, Martinkauppi B, Soriano M, Petikainen M. A physics-based face database for color research. *J Electronic Imaging*. 2000; 9: 32-8.
13. Kovacs-Vajna Z. Rs2color database. <http://www.ing.unibs.it/~zkovacs/color/rs2color/rs2colorE.html> 2013.
14. Luo MR, Cui G, Li C. Uniform colour spaces based on CIECAM02 colour appearance model. *Color Res & Appl*. 2006;31:320-30.
15. Hunt R, Pointer M. Measuring Color, 4th ed. Chichester, United Kingdom: Wiley; 2011.
16. Luo MR. The quality of light sources. *Coloration Technol*. 2011;75-87.
17. International Commision on Illumination. A Colour Appearance Model for Colour Management Systems: CIECAM02. Vienna: The Organization; 2004. (CIE 159:2004).
18. Fairchild MD. Color Appearance Models. 3rd ed. Chichester, United Kingdom: Wiley; 2013.
19. Smet K, Schanda J, Whitehead L, Luo RM. CRI2012: A proposal for updating the CIE colour rendering index. *Ltg Res & Technol*. 2013;45:689-709.
20. Xu W, Wei M, Smet K, Lin Y. The prediction of perceived colour differences by colour fidelity metrics. *Ltg Res & Technol*. 2017;49(7):805-817.

21. International Commision on Illumination. Colorimetry, 3rd ed. Vienna: The Organization; 2004. (CIE 15:2004).
22. Ohno Y. Practical use and calculation of CCT and Duv. *Leukos*. 2013;10:47-55.
23. Royer M, Wilkerson A, Wei M. Human Perceptions of Color Rendition at Different Chromaticities. *Ltg Res & Technol*. 2017; Online before print. DOI: 10.1177/1477153517725974.
24. Royer M, Wilkerson A, Wei M, Houser K, Davis R. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. *Ltg Res & Technol*. 2016; 49(8):966-99.
25. Esposito T. Modeling color rendition and color discrimination with average fidelity, average gamut, and gamut shape. *Architectural Engineering*. University Park, PA: Penn State University; 2016.
26. Zhang F, Xu H, Feng H. Toward a unified model for predicting color quality of light sources. *Applied Optics*. 2017;56:8186-95.
27. International Commision on Illumination. CIE 2017 Colour Fidelity Index for Accurate Scientific Use. Vienna: The Organization; 2017. (CIE 224:2017).
28. National Electrical Manufacturers Association. American National Standard for Electric Lamps—Specifications for the Chromaticity of Solid State Lighting Products. Rosslyn, Virginia: The Organization; 2017:48. (ANSI/NEMA C78.377-2017).
29. Sandor N, Ondro T, Schanda J. Spectral interpolation errors. *Color Res Appl*. 2005;30:348-53.
30. Davis W, Ohno Y. Color quality scale. *Optical Engineering*. 2010;49:033602.
31. Houser K, Mossman M, Smet K, Whitehead L. Tutorial: Color Rendering and Its Applications in Lighting. *Leukos*. 2016;12:7-26.
32. Royer M. Comparing Measures of Average Color Fidelity. *Leukos*. 2017;14(2):69-85.
33. Van Trigt C. Color rendering, a reassessment. *Color Res & Appl*. 1999;24:197-206.
34. International Commission on Illumination. Method of Measuring and Specifying Colour Rendering Properties of Light Sources, 3rd ed. Vienna: The Organization; 1995:16. (CIE 13.3).
35. David A. Color fidelity of light sources evaluated over large sets of reflectance samples. *Leukos*. 2013;10:59-75.
36. Royer M, Houser K, David A. Chroma shift and gamut shape: Going beyond average color fidelity and gamut area. *Leukos*. 2018;14(3):149-165.
37. Dikel EE, Burns GJ, Veitch JA, Mancini S, Newsham GR. Preferred chromaticity of color-tunable LED lighting. *Leukos*. 2013;10:101-15.
38. Rea MS, Freyssinier JP. White lighting. *Color Res & Appl*. 2013;38:82-92.
39. Smet K, Deconinck G, Hanselaer P. Chromaticity of unique white in illumination mode. *Opt Express*. 2015;23:12488-95.

40. Smet K, Deconinck G, Hanselaer P. Chromaticity of unique white in object mode. *Opt Express*. 2014; 22: 25830-41.
41. Ohno Y, Oh S. Vision experiment II on white light chromaticity for lighting. *CIE x042:2016*. 2016:175-84.
42. Ohno Y, Fein M. Vision experiment on acceptable and preferred white light chromaticity for lighting. *Proceedings: CIE 2014, Lighting Quality and Energy Efficiency*. Kuala Lumpur, Malaysia; 2014.
43. Houser K, Wei M, David A, Krames M. Whiteness perception under LED illumination. *Leukos*. 2014;10:165-80.
44. International Commision on Illumination. Recommended Practice for Tabulating Spectral Data for Use in Colour Computations. Vienna: The Organization; 2005. (CIE 167:2005).
45. Natural Colour System. Online: <http://ncscolour.com/about-us/how-the-ncs-system-works/>



Lighting Science Standards

Fundamentals, Metrics and Calculations

Lighting Practice Standards

Design, Engineering, and Specifications

Lighting Applications Standards

Design Criteria and Illumination Recommendations

Lighting Measurements and Testing Procedure Standards

Industry Standardization

Roadway and Parking Facility Lighting Standards

Criteria and Illumination Recommendations

Order# ANSI/IES TM-30-20+E1

ISBN# 978-0-87995-379-9

www.ies.org