

Tutorial: Background and Guidance for Using the ANSI/IES TM-30 Method for Evaluating Light Source Color Rendition

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Abstract

This tutorial article provides a comprehensive overview of the development and use of ANSI/IES TM-30-20, an American National Standard method for evaluating light source color rendition that is published by the Illuminating Engineering Society. Five years since its initial publication, TM-30 is increasingly used by lighting producers, specifiers, and researchers due to its superior accuracy and the expanded scope of provided information compared to predecessor tools for assessing color rendition. Making the most of these improvements requires people who use the method to be more knowledgeable and intentional, and this tutorial consolidates a range of information to assist with best practices. The article, arranged as a series of questions, includes information about the development of the standard, color rendering fundamentals, TM-30 measures and their meaning, TM-30 calculation details, and application of TM-30. The document does not provide instructions for performing TM-30 calculations, which is the purpose of the ANSI/IES TM-30-20 standard, which is freely available.

Keywords

TM-30, Color Rendering, Color Perception, Color Preference, CRI

Learning Outcomes:

After studying this article, it is anticipated that the reader will:

1. understand how TM-30 was developed and how it has evolved over time;
2. have basic conceptual knowledge of color rendition as an important part of lighting quality, including how different aspects of color rendition—such as color fidelity, gamut area, and gamut shape—can be summarized and communicated;
3. be able to describe the components of the core calculation framework of TM-30 and how the system is used to calculate a variety of outputs of the method;
4. know the correct interpretation of values for the 149 numerical output measures and 1 graphic defined in the standard;
5. know what is and is not included in the standardized method and understand how the principles can be applied to a unique or custom situation;
6. feel confident in applying TM-30 to specify the performance characteristics of a light source;
7. understand how TM-30 differs from alternative methods, particularly the CIE General Color Rendering Index, R_a (CRI).

1. Introduction

ANSI/IES TM-30-20 [IES 2020], commonly called TM-30, documents a method for evaluating light source color rendition that was developed by the Illuminating Engineering Society (IES) following American National Standards Institute (ANSI) procedures. The voluntary standard specifies a calculation framework that leads to numerous measures and graphics that can be used together to evaluate and communicate a light source's color rendition properties. It also includes recommendations for using the method to create specification criteria and guidance for reporting calculated data.

Color rendition, or the influence of a light source on the color appearance of objects and surfaces, is an important part of lighting quality that arises from the spectrum of the emitted light, which is reflected by surfaces and processed by the human visual system. Poor color rendition can make the colors of objects look unpleasant or distorted, reducing environmental satisfaction and potentially influencing task performance. Importantly, luminous efficacy—another attribute dependent on a light source's spectrum—is maximized with very poor color rendition. Thus, all light source development must balance color rendition with competing performance characteristics, making accurate and thorough quantification of color rendition critical to optimization of performance and energy use.

Attempts to quantify the color rendition performance of light sources began in the 1930s with the introduction of fluorescent lamps, which had a different spectrum than the incandescent lamps that were then predominant. Following an earlier recommendation called the spectral bands method [CIE 1948], the International Commission on Illumination (CIE) standardized the *Method of Measuring and Specifying Colour Rendering Properties of Lighting Sources*, identified as document 13 in 1965. The method was updated soon after as CIE 13.2 in 1974 and republished without change as CIE 13.3 in 1995 [CIE 1995]. The CIE 13.3 method includes the General Color Rendering Index R_a , colloquially referred to as CRI, and a set of 14 Special Color Rendering Indices, R_i , for which the subscript indicates one of 14 color samples. The method is narrowly focused on color fidelity—simplistic by modern standards—but was sufficient for distinguishing between the limited number of light sources available at the time, and so it was widely used for commercial purposes.

Beginning in the 1970s, researchers from all over the world developed dozens of alternatives that better characterized various aspects of color rendition in ways that were more rooted in human perception, but the conflicting interests of scientific accuracy and commercial expediency thwarted many attempts to reach consensus within the CIE to recommend a new standard method [CIE 1999; Pointer 2004; Sandor and Schanda 2006]. The onset of the solid-state lighting era in the 2000s brought renewed interest in the topic and increased motivation to standardize better methods for evaluating light source color rendition. This situation ultimately led the IES to pursue standardization of a new method for evaluating light source color rendition. The initial development of TM-30, occurring in 2013 and 2014, was a consensus-driven endeavor of the IES Color Committee to synthesize multiple related research efforts and combine existing ideas into a single, cohesive system of objective information recommended for use in specifying and rating color rendition performance. ANSI/IES TM-30-20 is the latest iteration of the standard.

TM-30 is a culmination—but not the end—of decades of work to develop better methods to evaluate light source color rendition. It remedies flaws and limitations of the older CIE 13.3 method (CRI), providing both more accurate and more comprehensive information that better meets the needs of lighting manufacturers, specifiers, researchers, and users in the era of solid-state lighting. TM-30 is now widely used and is the

recommended method of the IES [2018] but efforts continue to educate members of the lighting community on how to make the most of the method. This document consolidates basic information about TM-30, which is arranged as a set of frequently asked questions grouped in six categories: development of the TM-30 standard, color rendering fundamentals, TM-30 measures and their meaning, TM-30 calculation considerations, and application of TM-30.

2. Development of the TM-30 Standard

This section provides background information on the development of TM-30: who, what, how, when, and why.

2.1 What is TM-30?

ANSI/IES TM-30-20 is a voluntary standard document—part of the IES technical memorandum (TM) series—that describes the IES recommended method for evaluating light source color rendition (see Section 3.1 for more background on color rendition). The document specifies:

1. A core calculation framework—which consists of a model of color perception, a representative set of surface colors (defined as spectral reflectance functions), and defined reference conditions—that is used to determine color shifts (the difference between the test and reference conditions) given the input of a light source’s spectral power distribution (SPD), defined as the relative amount of energy a light source emits at each wavelength.
2. Ways to summarize the color shifts with outputs consisting of numerical measures and graphics that complement one another and provide a comprehensive prediction of how the light source will influence the color appearance of objects in an architectural environment.
3. Recommendations for how to present the calculated information.
4. Recommendations for how to use the numerical measures to establish color rendition specification criteria that help ensure that the calculated color rendition performance is appropriate for achieving a desired effect and meeting the needs of occupants.

2.2 When was TM-30 developed?

The development of TM-30 began in 2013 and the first version of the standard, IES TM-30-15, was published in 2015. An update was published in 2018 to harmonize the document with CIE 224:2017 [CIE 2017], which adopted the TM-30 calculation framework with minor modifications but only addressed part of the output. The 2018 update, during which TM-30 became an American National Standard, included three mostly inconsequential technical changes [Royer 2017b; IES 2020] while providing additional detail on many of the measures and graphics specified in the document. ANSI/IES TM-30-18 also added Annex D, covering recommended layouts for specification material. Annex E and Annex F, establishing methods and recommendations for TM-30-based specification criteria, were added in 2019. The document was republished as ANSI/IES TM-30-20 in 2020, with no changes to the technical content. Refer to Section 6.1 for additional discussion of the differences between the versions. A timeline of the development process is provided in Figure 1.

2.3 Who developed TM-30?

IES TM-30-15 was drafted by the Color Metrics Task Group of the IES Color Committee, with the underlying details the result of decades of work by dozens of lighting researchers. The Task Group was comprised of seven voting members with backgrounds in lighting research, production, or specification. The full IES Color

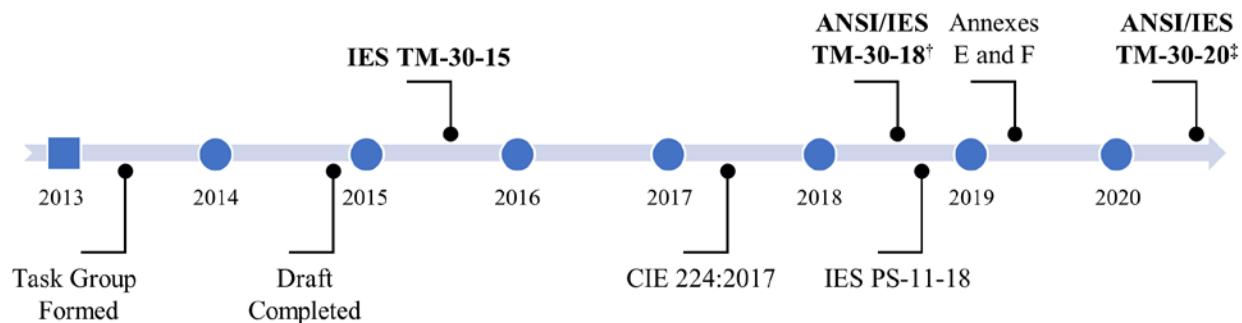


Figure 1. Timeline of the development of TM-30. [†]Modified to align core calculation framework with CIE 224:2017. [‡]No technical changes (republication with IES online lighting library).

Committee has handled all revisions and additions to the document directly. The IES Color Committee follows ANSI guidelines that define the balance of interest groups (e.g., producers, researchers, users, government) and geographic considerations, as well as procedures for balloting and developing consensus documents.

2.4 Why was TM-30 developed?

The incumbent color rendering metric that has been widely used in the lighting industry, CRI, has existed for more than 50 years. Although it served a vital purpose, its limitations have been widely recognized by researchers, specifiers, and even the CIE [CIE 1995; van Trigt 1999; CIE 2007; Davis and Ohno 2009; Davis and Ohno 2010; de Beer et al. 2015; David et al. 2015; Houser et al. 2016; CIE 2017]. By 2013, dozens of new metrics for evaluating light source color rendition had been developed, but none was adopted by the CIE—despite decades of committees focused on replacing CRI. A key divide, dating to at least the 1990s and perhaps the 1980s, was the competing desires of scientific accuracy and commercial expediency (or reluctance to change) [CIE 1999; Pointer 2004; Sandor and Schanda 2006].

Two classes of deficiencies with CRI and the broader CIE 13.3 method have been identified over decades of investigation. First, the underlying calculation framework—never updated despite advances in color science—relies on an inaccurate model of color vision that is officially considered obsolete by the CIE [2018] and a small set of color samples that are not capable of capturing the full effect of a light source. Second, CRI and the broader CIE 13.3 method only attempt to address color fidelity (see Section 3.8). Measures of average color fidelity do not convey how different colors change in appearance or distinguish between desirable and undesirable changes to color appearance, as was recognized even when CIE 13.2 was published in 1974. Combined, these technical and breadth deficiencies became an impediment to the development and specification of more efficient and higher quality solid-state lighting devices. When performance ratings do not match visual assessments, and when performance is not accurately distinguished by specification criteria, it creates unnecessary challenges for lighting producers and specifiers. TM-30 was developed to address this situation and provide a practical solution to a decades-old issue, enabling higher-quality lighting and reducing energy use.

2.5 How was TM-30 developed?

With the issues to be addressed identified (Section 2.4), the plan of the working group was to establish the core calculation framework based on the latest color science research and then establish a suite of measures derived from the calculation framework to address various aspects of color appearance. The first step was to

examine and synthesize the research of numerous other groups—the novelty of the method lies primarily in the combination of ideas, rather than any one aspect. Among other details, the group examined the performance of available models of color vision [Luo et al. 2006; Sandor and Schanda 2006; Luo et al. 2015; Smet et al. 2015c; Xu et al. 2016; Gu et al. 2017; Royer 2017b; Jost et al. 2018; Royer 2018; Wei et al. 2019] and the effect of the quantity and type of color samples [Davis and Ohno 2010; Whitehead and Mossman 2012; David 2013; Smet et al. 2013; Smet et al. 2015c; Smet et al. 2016b; Royer 2017b; Royer 2018]. In each case, the best available options were merged into the core calculation framework of TM-30, with each decision made via consensus vote. More details are provided in Section 4. The various outputs of TM-30 were also informed by existing approaches, with the goal of providing as much information as possible. Each output is described further in Section 5.

With the initial publication of TM-30-15, the method only specified how to perform the calculations to determine the outputs and excluded any guidance on what performance thresholds should be set. Intentionally, the method focused on establishing a vocabulary of quantifications that could be used to perform psychophysical experiments, as well as benchmark existing and future products, all while providing an opportunity for users to test the method. With new experimental evidence, it was possible for specification guidance to be formalized in 2019, when Annex E and Annex F were added to TM-30. This guidance again followed the consensus process, utilizing data, experience, and negotiation to establish a system suitable for a wide range of users. More information is provided in Section 7.

2.6 Who are the intended users of TM-30?

TM-30 was developed for the benefit of lighting producers, specifiers, researchers, and users. It is intended to be used in all situations where quantification of color rendition is necessary. This includes companies working to engineer and produce lighting equipment, people specifying lighting equipment, organizations or government agencies setting performance standards, researchers conducting experiments, and end users trying to select a lighting product.

2.7 Is TM-30 approved by the CIE?

TM-30 was developed by the IES. IES documents are analogous to CIE documents, and either can be developed as, or incorporated into, national or international standards like those of ANSI or ISO (International Standards Organization).

CIE 224:2017 and ANSI/IES TM-30-20 share the same core calculation framework, meaning there is one such framework recognized as scientifically accurate by both organizations. As of 2020, CIE has only adopted the Fidelity Index (R_f), described in Section 5.3, for accurate scientific use and has been unable to agree on one or more characterizations of color rendition focused on aspects other than color fidelity, or make any new recommendations for lighting practice. CIE Technical Committee 1-90 has been attempting to address measures beyond color fidelity for more than eight years, but is not expected to formally endorse any method, leaving the choice up to users.

2.8 Does TM-30 replace CRI?

ANSI/IES TM-30 and CRI, as defined in CIE 13.3-1995, are published by different organizations and therefore one cannot officially replace the other. What becomes the predominant method for rating the performance of lighting products and specifying color rendition characteristics is ultimately up to the broader lighting community. Neither are mandatory standards themselves, but they may be included in mandatory or voluntary standards established by governments or other organizations.

TM-30 includes a measure, R_f (see Section 5.3), that is analogous to CRI in that both are intended to be measures of average color fidelity (see Section 5.4 for a detailed comparison). The IES recommends that users transition from CRI to R_f [IES 2018]. Simultaneously, it is important to understand that TM-30 goes far beyond color fidelity to convey important information that should be considered in most lighting applications.

2.9 How is TM-30 being used today?

TM-30 has been used by lighting producers to engineer new light sources, by energy efficiency and government organizations to establish specifications for color rendition performance (see Section 7.9), by lighting specifiers to choose products, and by researchers to investigate visual assessments of color rendition qualities. TM-30 is supported by a wide range of users [Ashdown et al. 2015], and is expected to increase its reach and use in the coming years [Boyce and Stampfli 2019].

2.10 Will TM-30 continue to evolve over time?

It is expected that TM-30 will evolve over time. This may include the addition of new output measures derived from the same calculation framework or updates to the underlying calculation framework as other branches of color science advance. For example, a new metric based on the TM-30 calculation framework, the Metameric Uncertainty Index (R_t), was recently proposed [David et al. 2019], and new models of color vision have been established [Li et al. 2017]. For now, there is no recommended notation system to indicate the specific version used in calculation, partially because changes to values with the revisions have been minimal and generally in the positive direction.

3. Color Rendering Fundamentals

This section provides a brief overview of the basics of color science that are pertinent to color rendition. For more background, see David, Smet, and Whitehead [2019b] or Houser et al. [2016]. Additional background and historical record is provided by Wyszecki and Stiles [1982].

3.1 What is color rendering?

Objects or surfaces do not have an inherent color, but rather reflect different proportions of energy over the visible spectrum. When the spectrum emitted by a light source changes, the light reflecting off a surface (the visual stimulus reaching the eye) also changes, which alters how the stimulus is interpreted by the brain. Figures 2 and 3 provide two examples of how color rendition can influence appearance using digitally manipulated images that simulate real color rendition conditions. Officially, the IES and CIE define color *rendering* as the “effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant.” CIE also defines color *rendition* as the “effect of an illuminant spectral power distribution on the color appearance of objects” [CIE 2017], which provides a less restrictive definition, even though rendering and rendition are typically considered synonyms.

Methods for evaluating color rendition are used by producers to assign quantitative ratings to light sources and by specifiers to establish suitable performance for a given installation. They utilize standardized parameters to facilitate comparison while predicting performance in unknown real settings. Methods for evaluating color rendition are a way to communicate performance without visually assessing every product-application combination. Although some alternative approaches exist, methods for evaluating light source color rendition typically rely on three fundamental components:

1. a standardized model of average human color vision,
2. a set of standardized color samples,
3. and a scheme to define a reference(s) to which calculated colors for a given test light source can be compared.

In this way, color rendition can be determined purely mathematically, even if it is a simplification of a more complex issue. In order to establish color rendition as a property of a light source, it must be disassociated from a specific scene and viewer. That is, methods for evaluating light source color rendition predict the influence of a light source without knowledge of the specific objects that will be illuminated or their arrangement. Some known phenomena that influence the appearance of objects, such as the surrounding field, are held constant across calculations so that they are effectively unaccounted for. Likewise, the intensity of the light (that is, the illuminance or luminance) is disregarded in existing methods, although it can strongly influence color appearance [Hunt 1952; Bao and Wei 2019; Kawashima and Ohno 2019; Wei et al. 2020] and has potential to be integrated into specification criteria or more advanced methods. While methods for evaluating light source color rendition play an important role in the lighting industry, it is important to remember that they are not calculations of how a specific room or object will appear, but rather an educated prediction. To understand the color appearance of a specific object in a specific viewing condition, a color appearance model is used, as covered by Fairchild [2013].

Methods for evaluating light source color rendition can focus on one or more aspects of color rendition, including color fidelity, gamut area, color naturalness, color preference, color vividness, chroma shifts, or hue shifts, each of which is described in subsequent sections. There are different approaches that can be taken to quantify some of these concepts. For more background information on previously proposed measures of color rendition, see Guo and Houser [2004], Pointer [2004], Davis and Ohno [2009], or Houser et al. [2013].



Figure 2. Theoretical illustration of the effect of color rendition on human complexion. Variations in wood tone are also notable.

3.2 Why is color rendition important?

Color rendition, particularly its accurate quantification, is important because it can influence occupant wellbeing, task performance, and energy efficiency. Varying color rendition has been demonstrated to

influence the acceptability of an illuminated environment [e.g., Royer et al. 2018c; Royer et al. 2019d]. Other research has linked environmental satisfaction with productivity [e.g., Veitch et al. 2008; Veitch et al. 2011].

Fundamentally, delivering appropriate color rendition is at odds with maximizing luminous efficacy. Maximizing lumen output suggests maximizing energy around 555 nm (nominally green-yellow light), but a light source optimized for luminous efficacy alone is unsuitable for almost all visual tasks and uncomfortable for habitation—an example is the low-pressure sodium lamp. Establishing minimum performance thresholds for color rendition helps to balance lighting quality with energy efficiency, ensuring the light is appropriate for the tasks to be performed by providing color contrast, enabling object identification, and creating a pleasant and comfortable environment to occupy. These characteristics ultimately can help energy-efficient technologies to reduce energy use by increasing their acceptance and use. Without accurate methods for evaluating color rendition, assessing tradeoffs between color rendition and energy efficiency, or other performance characteristics, is more difficult and can result in non-optimized solutions that do not maximize the benefit delivered per Watt.

3.3 What are chromaticity, CCT, and D_{uv} ?

Chromaticity is a numerical specification of color, regardless of luminance (brightness), and is defined as part of the CIE system of colorimetry [CIE 2018; David et al. 2019b]. Its primary use is to determine if the light from two or more sources match in appearance. When two spectra have the same chromaticity coordinates, are of equal luminance, and are viewed under identical conditions, their perceived color is predicted to match; however, chromaticity does not take into account the adaptive processes of the eye-brain system that make color vision non-linear and context-dependent. For example, the light emitted by an incandescent lamp can appear white when viewed alone, but yellowish when viewed simultaneously with midday daylight. Importantly, two light sources with the same chromaticity—which are called metamers—may have different spectral power distributions, and therefore render object colors differently.

Correlated color temperature (CCT) is calculated as the color temperature of the Planckian radiator nearest the chromaticity coordinates of the test source. It is calculated in the CIE 1960 (u , v) chromaticity diagram, which is a legacy of when it was developed as measure [Robertson 1968]. It indicates whether the apparent color is warmer (lower CCT) or cooler (higher CCT). For interior architectural lighting applications, sources typically range between 2700 K and 6500 K. Importantly, two light sources with the same CCT can have



Figure 3. Illustration of the effect of color rendition on food.

different chromaticities and not match in appearance, as illustrated in Figure 4. This is addressed with a complimentary measure called D_{uv} , which is a measure of the distance between the chromaticity of the light source and that of the nearest Planckian radiator in the CIE 1960 (u , v) chromaticity diagram [Ohno 2013]—the same Planckian radiator used to calculate CCT. D_{uv} conveys the relative greenness (more positive values) or pinkness (more negative values) of the light. CCT and D_{uv} provide a complete specification of chromaticity, with axes that are more closely linked to a visual perception.

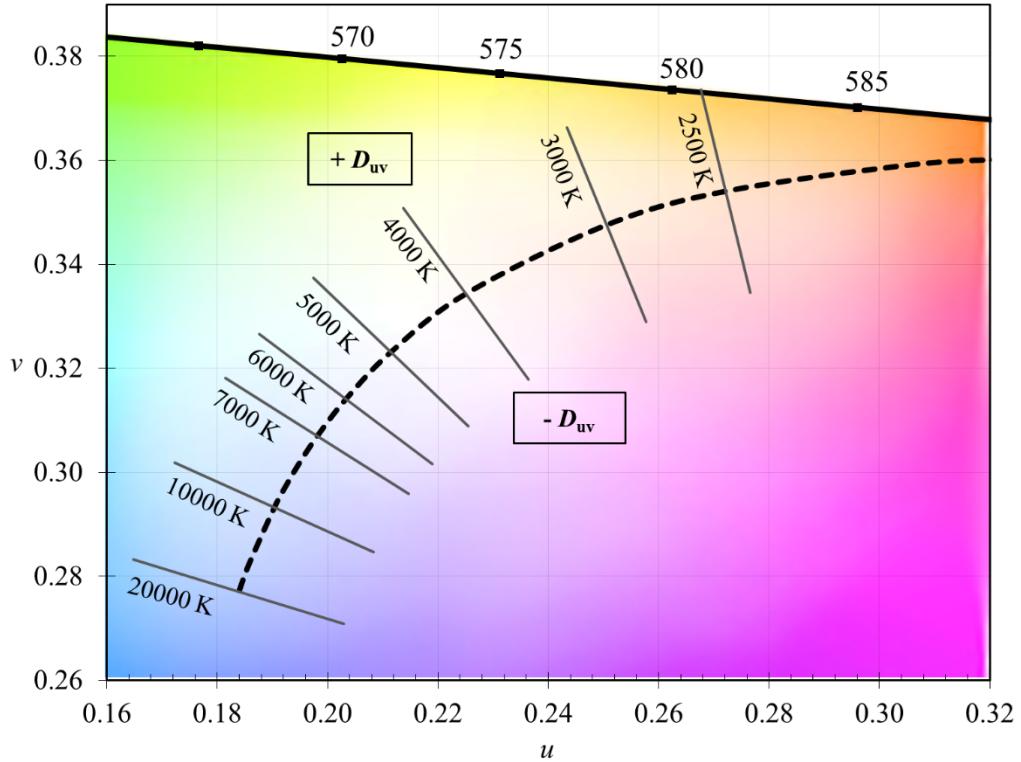


Figure 4. CCT and D_{uv} in the 1960 (u , v) chromaticity diagram. All points along each of the lines perpendicular to the Planckian locus (dashed line) have the same CCT. Colored background for illustration only.

3.4 How is color vision modelled for the purpose of evaluating color rendition?

One of the most consequential components of a framework to evaluate light source color rendition is the model of color vision, or the mathematical system that characterizes how humans see color. Although there is considerable variation in color vision from person to person [Asano et al. 2014, 2016, 2016b; Murdoch and Fairchild 2019], like other lighting characterizations a single average representation is used to evaluate color rendition. The overall model has several important components, including color matching functions, a mechanism to account for the adaptation of the visual system to different illumination (chromatic adaptation), and a projective transformation and system of equations that establish a three-dimensional coordinate system that intends to accurately describe perceived color differences.

Color matching functions are a way to represent the sensitivity of the human visual system; they can be derived from psychophysical experiments and are also a linear transformation of the spectral sensitivity of the three cone photoreceptors in the eye that are responsible for color vision. The set of three functions is known as a Standard Colorimetric Observer [CIE 2018]. Color matching functions are used to calculate tristimulus values by integrating the product of each function and the spectral power distribution of the

stimulus. The tristimulus values are then input to the remainder of the color vision model. The CIE has standardized four sets of color matching functions: 1931 2°, 1964 10°, 2015 2°, and 2015 10° [CIE 2006; CIE 2015; CIE 2018]. They differ slightly based on the method and data used for derivation and the field of view that they quantify. The 1931 2° color matching functions are the accepted standard for calculating chromaticity, although proposals have been made to change this, and other methods, such as TM-30, use alternatives (see Section 4).

One important visual phenomenon that must be addressed in methods for evaluating light source color rendition is chromatic adaptation. Chromatic adaptation is the process by which the visual system attempts to adapt to the color of the light to make it appear white and facilitate color constancy, whereby object colors generally maintain their appearance across a wide range of illumination to assist with object identification and evaluation [Smithson 2005; Foster 2011]. Color rendition is sometimes considered the breakdown of color constancy, when the shifts exceed what the human visual system is capable of adapting away. This occurs at least in part because the visual system features three broadband color detectors, and therefore cannot distinguish individual wavelengths.

The final key component is the definition of the color coordinates that are derived from tristimulus values, which determines the color space. As shown in Figure 5, the range of possible coordinates in a color space forms a three-dimensional volume, which is described further in Section 3.7. Numerous such color spaces—which are often optimized based on a specific set of color matching functions and have a native chromatic adaptation transformation—have been standardized, including CIE U*V*W* (now deemed obsolete) [CIE 2018], CIE LAB [CIE 2018], and CAM02-UCS [Luo et al. 2006; CIE 2018]. More background is available from Fairchild [2013]. New color spaces continue to be proposed, including CAM16-UCS [Li et al. 2017]. An important, or perhaps defining, characteristic of a color space is its *uniformity*. Uniformity means that any given Euclidian distance in the color space corresponds to the same degree of perceived color difference—Luo et al. [2006] provided comparisons of different color spaces. Color difference spaces are typically derived from and tested against extensive sets of data from psychophysical experiments, where participants evaluated the magnitude of difference between two color samples. As explained by Smet, David, and Whitehead [2015c] color space uniformity is important for accurately characterizing color rendition.

3.5 What are color samples?

Almost all methods for evaluating light source color rendition are based on “color samples.” For the purpose of color rendition calculations, these samples are not physical specimens, but rather spectral reflectance functions—defined as the percentage of light reflected at each wavelength over the visible range—for measured real or theoretical objects. Figure 6 illustrates a measured object, a spectral reflectance function, and a digitally rendered color swatch based on an estimated appearance. Note that spectral reflectance functions, and thus rendered swatches, have a uniform color, which is based on the average spectral reflectance over a small area; thus, they are a limited representation of specific objects, for which color is often varied over the

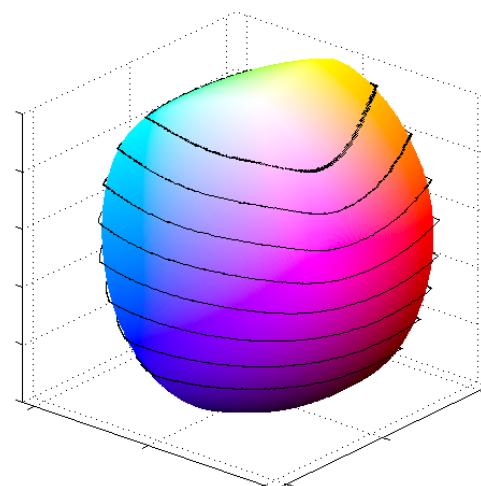


Figure 5. Illustration of the theoretical volume of visible colors.

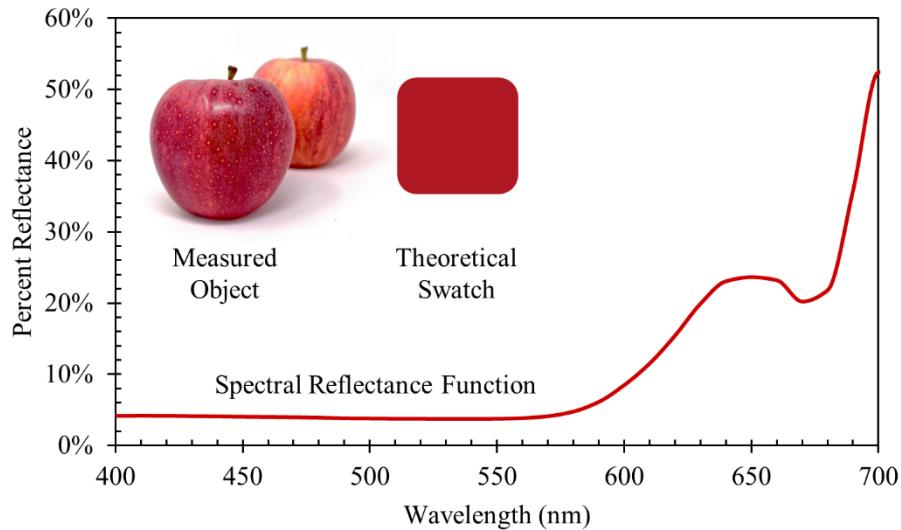


Figure 6. A real object, a color swatch representing that object (an average of the color over a small area), and a spectral reflectance function for the color swatch.

surface. The use of spectral reflectance functions allows color rendition to be repeatably calculated from a spectral power distribution, without the need for visual evaluation or physical measurement of illuminated swatches or objects.

The concept of using color samples to evaluate color rendition dates to at least the 1950s [Jerome and Judd 1953; Nickerson 1958, 1960; Ouweltjes 1960]; attempts prior to that focused on the amount of energy within regions of the visible spectrum [Bouma 1937; CIE 1948; Winch and Ruff 1951; Barnes 1957]. At that time, the color samples were chosen from the Munsell library so they physically existed and could be used for visual evaluation too—visual experiments informed development of new methods and metrics. While having physical color samples was important in the past for method development and validation, today there is considerably more data available that support color space uniformity, so color rendition methods can rely directly on the accuracy of the models, eliminating the need to have physically reproducible samples.

Over time, considerable effort has been made to develop new sets of color samples by varying the quantity or type of color samples [Opstelten 1980; Seim 1985; Van Kemenade and Van der Burgt 1988; van der Burgt and van Kemenade 2010; Davis and Ohno 2010; Smet et al. 2010; Zukauskas et al. 2010; Whitehead and Mossman 2012; Smet et al. 2013; Vick and Allen 2014; Smet et al. 2015c], with the ultimate goal being a set that is representative of the built environment. A challenge, however, is that the built environment cannot be completely characterized because there is no reasonable way to determine the statistical distribution of colors. Further complicating the choice of color samples is the fact that lighting products are used in a variety of environments, which are themselves comprised of surfaces with different color characteristics. Consequently, there will always be mismatch between the influence of a light source on the color appearance of a set of standardized color samples used for the purpose of rating product performance and the color appearance of objects in an environment where the product is installed [Royer and Wei 2017c]. Nonetheless, there are important theoretical goals that have been established to help ensure that the color samples selected for a method provide the greatest value [Smet et al. 2015c]. These include sampling of the complete range of possible colors with sufficient resolution, and consideration for the “features” of the

spectral reflectance functions so that sensitivity to changes in spectral power are approximately even across the visible wavelengths.

3.6 What is a reference-based color rendering measure?

Most methods for evaluating color rendition, including CIE 13.3 and IES TM-30, are based on comparing how colors are rendered by a light source in question to how they are rendered by a reference condition, which is usually a mathematically defined light source, known as an illuminant, having the same CCT as the test source [Royer 2016]. In other cases, the reference is a single illuminant for all light sources, or a small number of illuminants.

Reference illuminants are usually either a CIE D Series illuminant or a Planckian radiator. CIE D Series illuminants [CIE 2018] are mathematical representations of daylight that are calculated with a formula given the input of a color temperature between 4000 and 25000 K. A Planckian radiator, also called a blackbody radiator, is calculated using a formula known as Planck's law based on the temperature of a black body. Incandescent lamp filaments are a close approximation of a Planckian radiator.

The CCT-matched (i.e., relative) reference-based approach allows color rendering to be considered independent of CCT, because chromatic adaptation mechanisms do not completely address difference in appearance induced by changes in CCT [Pointer 2004; Royer 2016]. For example, a 5000 K source may be too cool in appearance for the atmosphere of a home furnishings store, so it may not be appropriate to compare a 2700 K light source to a 5000 K reference illuminant. Fixed-reference measures often result in inherent differences in ratings for products of different CCTs. Whether or not these effects are perceived by humans, they can create confusion because different CCTs have different possible ranges.

Importantly, depending on the features of the method, the role of the reference illuminant can vary. For methods that assign the maximum value to the reference illuminant, like CIE 13.3, the reference serves as the gold standard and takes on increased importance [Davis and Ohno 2009]. For methods that provide a combination of values that can be used to describe the deviation from the reference, the reference serves more as an anchor or guidepost than an ideal. In the latter case, it is important that the reference illuminant(s) represent a common experience that can be recalled from memory.

One alternative to reference-based methods is to evaluate the spectral power distribution directly, as has been proposed several times in the distant and recent past [Bouma 1937; CIE 1948; Kirkpatrick 2004; Holm et al. 2016; Acosta et al. 2018]. Another option is to examine the range of colors that can be created, measured with an area or volume, which does not require a reference for the initial calculation but often utilizes a reference for scaling the output values to a specific range. For more background, see Davis and Ohno [2009] or Houser et al. [2013].

3.7 What are the dimensions of perceived color?

Three dimensions are needed to describe human perception of color, given its trichromatic nature, although the exact terms can vary based on the color description model. For example, colors may be classified using hue, saturation, value (HSV) or hue, chroma, lightness (HCL), among others. Figure 7 illustrates hue, chroma, and lightness in a discretized diagram.

Hue is a more precise term for what one might call "color"; it is the differentiation among red, yellow, green, blue, and the shades in between. Hue is typically described as an angle of rotation in a polar coordinate system—this is called the *hue angle*. Lightness is the brightness of an area judged relative to a similarly

illuminated area that appears to be white.

Finally, chroma is defined as the colorfulness of an area relative to a similarly illuminated area that appears white—it can be thought of as the intensity of the color.

Changes to the color appearance of an object in any direction can be consequential. Some shifts in color can influence object detection, either enhancing or obscuring information about an object, such as the ripeness of a fruit. Other shifts can make a surface look old and dull, as opposed to vibrant or vivid.

For any given color sample (or real object) the change in color appearance versus the reference illuminant can be calculated in all three dimensions. The total magnitude of the color shift can also be calculated.

Early concepts in color rendition focused on distilling all color shifts to a single number, discarding information about the direction of the shifts. In the 1980s, several researchers proposed new methods focused on describing, at least to some degree, the direction of color shifts, including Worthey [1982], Pointer [1986; 2004], and van Kemenade and van der Burgt [Van Kemenade and Van der Burgt 1988; van Kemenade and van der Burgt 1995; van der Burgt and van Kemenade 2010]. These ideas were later expanded on by Zukauskas et al. [2009; 2010] and Davis and Ohno as part of the Color Quality Scale [2010]. TM-30 includes measures to describe the hue shift, chroma shift, and total magnitude of shift for color samples with different hues: Local Hue Shift, Local Chroma Shift [Royer et al. 2018b], and Local Color Fidelity, as described in Sections 5.7 to 5.9.

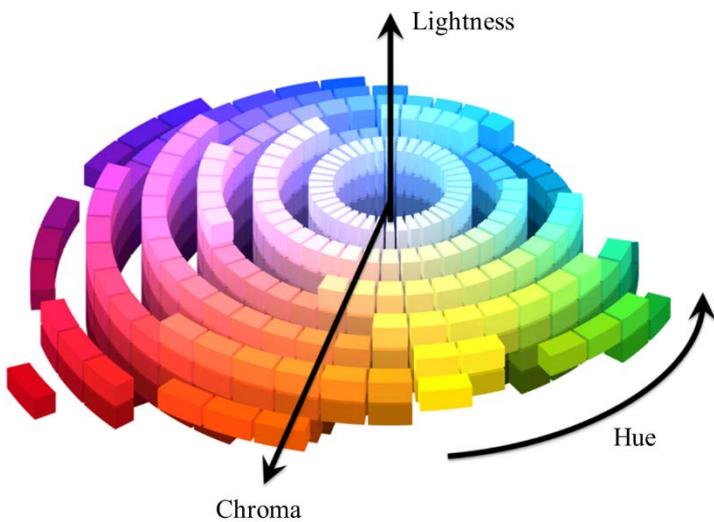


Figure 7. Illustration of hue, chroma, and lightness.

3.8 What is color fidelity?

Color fidelity refers to the degree of similarity between a color or colors rendered by a light source and a reference Illuminant. Color fidelity describes only the magnitude of the color difference, not *how* the colors are different. It is often formulated as an average, whereby the color differences for a set of color samples are averaged to provide a single value characterizing the light source. For example, CRI (CIE General Color Rendering Index R_a) is determined based on the average color difference for eight color samples. (The average difference is multiplied by a scaling factor and subtracted from 100.)

Color fidelity, illustrated in Figure 8, is one of the older concepts in the field, originating in the 1950s and standardized by the CIE in 1965. The benefit of calculating average color fidelity is the single number facilitates easy product comparisons. Major downsides are that it does not convey the magnitude or direction of any of the individual color shifts and that light sources with very different individual color shifts can have the same average color fidelity value. CIE 13.3 states: “The importance of the directions of colour shifts is recognized but not included in the Colour Rendering Indices” [CIE 1995].

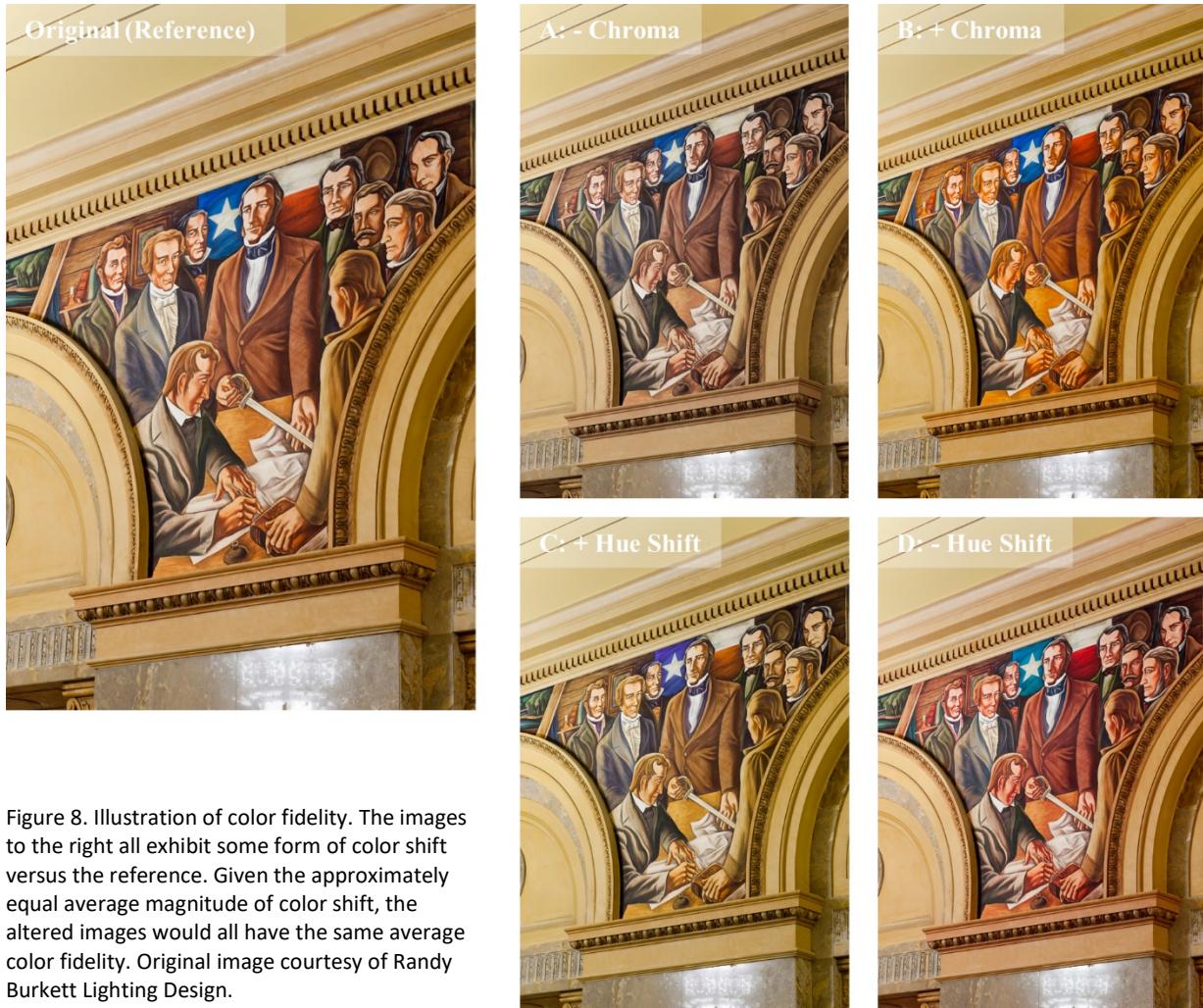


Figure 8. Illustration of color fidelity. The images to the right all exhibit some form of color shift versus the reference. Given the approximately equal average magnitude of color shift, the altered images would all have the same average color fidelity. Original image courtesy of Randy Burkett Lighting Design.

Color fidelity has often been thought to characterize color naturalness and been used inappropriately as an “overall color quality measure,” [CIE 2017] but most psychophysical experiments have found measures of average color fidelity insufficient for these purposes. Nonetheless, characterizing color fidelity helps ensure that colors are not too distorted compared to what we expect; if distortion is too great, the environment may be uncomfortable or confusing. However, light sources with the same average color fidelity may make surfaces appear vivid or dull, natural or unnatural, acceptable or unacceptable.

The color samples, color space, and reference illuminant scheme influence the accuracy and precision of color fidelity measures, many variants of which have been proposed [Jerome 1974; Seim 1985; Pointer 1986; CIE 1999; Geisler-Moroder and Dur 2009; Zukauskas et al. 2009; Davis and Ohno 2010; Bodrogi et al. 2011; Smet et al. 2013; Smet et al. 2016b]. They also influence how applicable the results are to real illuminated environments. For a systematic exploration of how these factors influence characterizations, see articles from Royer [2016, 2017b].

Until the initial publication of TM-30 in 2015, CRI was the only standardized measure attempting to quantify average color fidelity. TM-30 features a measure of average color fidelity, the Fidelity Index (R_f) (see Section

5.3), and specifies how to calculate color fidelity for each color sample (see Section 5.10) or small subsets of samples grouped by hue angle (Local Color Fidelity) (see Section 5.9). R_f was also adopted by the CIE in 2017.

3.9 What is gamut area?

Gamut can mean different things depending on its specific use. In the printing and display industries, gamut refers to the colors that can be created based on the inks or display primaries; that is, the points represent primaries for color mixing. For color rendering measures, gamut refers to the area enclosed by the color coordinates of a set of color samples and is unrelated to the number or range of visible colors. As with other measures of color rendition, the behavior of the color samples is predictive of the effect of the light source on real objects.

Unlike with print or display, there is no such thing as an object that cannot be rendered by a light source, just various levels of difference in color appearance between the test and reference conditions. Gamut area approximates the overall change in chroma: a larger area enclosed by the hue-chroma coordinates of a set of color samples indicates an average increase in chroma across all hues. Given the nature of the calculation, however, gamut area is not only influenced by changes in chroma, but also by hue shifts, especially when large color shifts occur [Royer 2018]. Images A and B in Figure 8 illustrates the effect of decreasing or increasing gamut area, respectively.

Gamut area can be a coarse indicator of vividness, and has also been linked to color discrimination [Thornton 1972; Davis and Ohno 2009; Houser et al. 2013], visual clarity [Hashimoto and Nayatani 1994; Hashimoto et al. 2007], and color preference [Hashimoto et al. 2007; Rea and Freyssinier-Nova 2008; Rea and Freyssinier 2010; Liu et al. 2017]. Newer research has demonstrated that it can be insufficient to completely describe these phenomena, however [Royer et al. 2017; Esposito and Houser 2017; Zhang et al. 2017; Esposito and Houser 2019]. Many light sources will increase the chroma compared to the reference for some hues but decrease it for others, and these variations can lead to differences in perception. Figure 9 includes three images that illustrate potential color rendition conditions with equal gamut area resulting from different shifts.

Although gamut area measures date to at least the 1970s, TM-30's Gamut Index (R_g) is the only measure of gamut area that is currently formalized by a lighting standards organization (see Section 5.5). Several other measures, like the Color Discrimination Index (CDI) [Thornton 1972], Feelings of Contrast Index (FCI) [Hashimoto and Nayatani 1994; Hashimoto et al. 2007], Gamut Area Index (GAI) [Rea and Freyssinier-Nova 2008], and Color Quality Scale Gamut Index (Q_g) [Davis and Ohno 2010] have been proposed. Royer [2018] provided a review of how different aspects of the calculation framework, including the color samples and color space, influence quantification of gamut area.

Gamut area has been discussed as a complement to average color fidelity, and two-measure systems have been described [Rea and Freyssinier-Nova 2008; Rea and Freyssinier 2010; Houser et al. 2013]. Whereas color fidelity quantifies the magnitude of color shifts, gamut area partially quantifies the direction. However, it has now been shown that light sources with the same average color fidelity and gamut area can be perceived differently [e.g., Royer et al. 2016]. For complete characterization, more information is needed about the color shifts for different hues than can be conveyed with two average values.

3.10 What is gamut shape?

As knowledge of the limitations of average measures of color rendition has grown among researchers, the concept of *gamut shape* has become more prominent. Developed gradually since the late 1980s [van



Figure 9. Illustration of gamut area. These images were edited to theoretical show lighting with equal gamut area but appear different because they have different color shifts for different hues. Original image courtesy of Randy Burkett Lighting Design.

Kemenade and van der Burgt 1988; van Kemenade and van der Burgt 1995; van der Burgt and van Kemenade 2010; Davis and Ohno 2010; de Beer et al. 2015; David et al. 2015; Wei et al. 2017; Royer et al. 2018b; David et al. 2019], gamut shape refers to the pattern of hue and chroma shifts with changing hue—that is, how do colors shifts vary with hue angle. It has often been captured pictorially rather than numerically, although it has been demonstrated that the pattern can be fit with a polynomial equation, with some variability overlaid [David, Esposito, et al. 2019]. Gamut shape is important because it distinguishes between light sources with equal color fidelity and gamut area that render colors differently and can be perceived differently. The center and right images in Figure 9 have opposing gamut shapes: the one in the center shows increases in the chroma of blue and yellow objects relative to the reference on the left, whereas the one on the right increases the chroma of red and green objects. Both show the accompanying hue shifts toward the colors where chroma is being increased compared to the reference condition.

Although gamut shape is an important concept, it is difficult to distill to a single number. Some information about gamut shape can be conveyed by using one or more value of chroma shift for a specific hue. It is also possible to quantify using parameters of an ellipse fit to the pattern of shifts [Esposito and Houser 2019]. Work on this topic is ongoing. TM-30 conveys gamut shape through the Color Vector Graphic (see Section 5.6) as well as Local Chroma Shift and Local Hue Shift values.

3.11 What are Color Naturalness, Color Vividness, and Color Preference?

Color naturalness, color vividness, and color preference are examples of subjectively evaluated attributes of an illuminated environment that are influenced by color rendition. Other variants include normalness, acceptability, vibrancy, and appreciation, among others. A long-time goal of color rendition research has been to develop metrics for these aspects of the visual environment, since they are the direct experience of building occupants and potential goals for lighting specification. Several metrics developed from the 1950s to 2010s have tried to directly quantify color preference with a single number [Sanders 1959; Judd 1967; Jerome 1972; Thornton 1974; Szabó et al. 2009; Davis and Ohno 2010; Smet et al. 2010; Vick and Allen

2014]. However, other research has shown that there are several factors that can influence color preference, including the objects being illuminated [Lin et al. 2015; Wei et al. 2017; Tang and Teunissen 2018], light level [Ohno et al. 2015; Bao and Wei 2019; Wei et al. 2020], and perhaps culture [Liu et al. 2013; Smet et al. 2014b; Tang and Teunissen 2018]. Undoubtedly, there is some individual variation in preferences, just as there is with food and artwork, for example.

Color preference, color naturalness, and color vividness are not independent concepts. A large body of research has shown that at light levels typically found in architectural interiors, humans prefer and find more natural scenes that are also rated as slightly more vivid—although not too vivid [Sanders 1959b; Judd 1967; Thornton 1974; Ohno 2005; Islam et al. 2013; Liu et al. 2013; Jost-Boissard et al. 2014; Szabó et al. 2014; Wei et al. 2014; Ohno et al. 2015; Royer et al. 2016; Teunissen et al. 2016; Wei et al. 2017; Wei and Houser 2017b; Zhang et al. 2017; Royer et al. 2018c; Esposito and Houser 2019; Royer et al. 2019d]. The vividness (or chroma) of reds is particularly important, which aligns with color psychology research [Elliot and Maier 2014]. Maximum color preference tends to occur at a slightly higher vividness than maximum color naturalness, although color naturalness, color preference, and acceptability are all closely related. These relationships are dependent on illuminance level [Bao and Wei 2019; Wei et al. 2020].

4. TM-30 Calculation Framework Details

This section describes the underlying components that are common to the calculation of all the outputs of TM-30. Please refer to ANSI/IES TM-30-20 for all calculation specifics; this document does not provide the information needed to perform the calculations. ANSI/IES TM-30-20 is a free download from the IES webpage.

4.1 What is the TM-30 calculation framework?

At the core of TM-30 is a calculation framework, which is a set of models that are used to calculate color shifts. The framework includes four components: the CIE 1964 10° color matching functions, the CAM02-UCS color space, a set of 99 color evaluation samples (CES), and the CCT-dependent definition of the reference. All outputs are determined using this framework. The four components of the calculation framework are independent, meaning any could be updated individually based on a new advancement of color science. Such a change could influence the values of the outputs, but it would not change their conceptual underpinnings. Some work has been done to examine how much different components influence output values [Royer 2016, 2017b, 2018]. For end-users of TM-30, it is not necessary to understand the calculation framework in detail; it is more important to understand the interpretation of the outputs, which is described in Section 5.

4.2 What is CAM02-UCS?

First introduced in 2006, CAM02-UCS [Luo et al. 2006; CIE 2018] is a color space based on the CIE CAM02 color appearance model [Fairchild 2013]. In numerous experiments during and after its development, it has been shown to have greater uniformity than predecessor color spaces, such as CIE U*V*W* (1960) or CIE LAB (1976), meaning that it more correctly maps human assessments of color difference [Luo et al. 2006; Xu et al. 2016; Gu et al. 2017; Jost et al. 2018; Wei et al. 2019]. Improved uniformity can have substantial effects on all types of color rendition measures [Smet et al. 2015c; Royer 2017b, 2018]. CAM02-UCS was chosen for TM-30 because of this improvement. Using CAM02-UCS had previously been proposed as a way to update CRI [Li et al. 2012] without the other changes implemented in TM-30.

CAM02-UCS has coordinates J' , a' , b' , where (a', b') characterizes the hue-chroma plane and J' specifies lightness. These values modify the perceptual correlates of CIE CAM02 so that the resulting color space better fits existing color difference data. The underlying CIE CAM02 model includes many adjustable parameters that can be used to predict color appearance in specific circumstances. Because color rendition is held to be a property of the light source and not an entire viewing scenario, these parameters, such as luminance and adaptation factors, are held constant in all TM-30 calculations. Advanced users could perform “custom” calculations by adjusting the parameters to better capture a specific viewing scenario, but this is outside the scope of the ANSI/IES TM-30-20 standard.

4.3 What are the 99 Color Evaluation Samples?

The 99 color evaluations samples (CES) are spectral reflectance functions for real objects. These color samples, or subsets of them, are used in calculating all the measures included in TM-30. This standardized set of color samples allows for consistent product rating and effective predictions of how a light source will influence color appearance when it is installed in a real environment. Figure 10 provides an approximate visual representation of the color samples.

The 99 CES, developed specifically for TM-30, were downselected from a set of more than 100,000 object spectral reflectance measurements previously documented in scientific literature. The large set of 100,000 measurements was considered to represent the extent of possible colors, but it is not an even sampling of all colors because it is comprised of several specific databases (e.g., flowers, skin tones, and paints). Thus, a process was established for generating a smaller set that evenly covered the volume of possible colors and included a balanced set of spectral features. The process, described by David et al. [2015], generated a set of approximately 4,880 spectral reflectance functions, called the reference set.

While the 4,880-sample reference set had desirable properties for being an average characterization of the colors in the world, some felt it was too large for rapid calculations. A tolerance of plus or minus one point for calculating average color fidelity for a smaller set versus the reference set, among other factors, was established to guide further reduction in quantity. An optimization routine was used to establish the final set

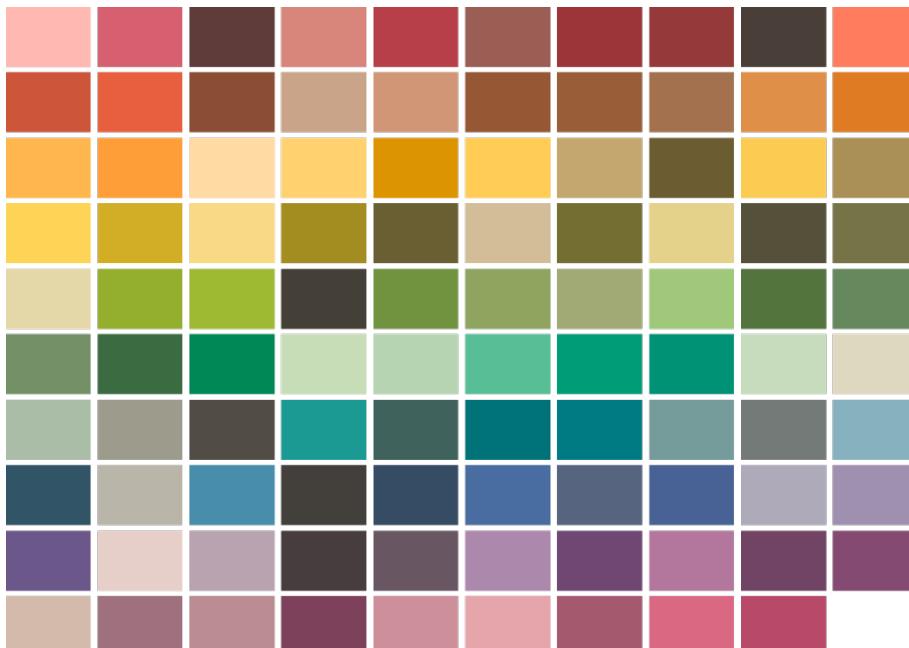


Figure 10. Visual representation of the 99 color evaluation samples used in TM-30.

of samples, the 99 CES. Note that two reflectance functions representing human skin tones that provided the greatest correlation to a larger set of skin reflectance measurements were forced into the set of 99. The 99 CES were numbered according to their hue angle under the 5000 K reference illuminant of IES TM-30-15, which was an even blend of 5000 K Planckian radiation and CIE D50.

The 99 CES represent a wide variety of objects, including paints, textiles, inks, skin tones, natural objects (e.g., food, flowers, foliage), and plastics. The CES cover a wide range of hue, chroma, and lightness, although some of the most saturated and darkest samples were excluded in the process of establishing the reference set to ensure the validity of color difference formulae, and to make sure the samples were representative of typical architectural environments. Still, Figures 10 and 11 show that the TM-30 samples cover a wide range of the hue-chroma plane of the color volume. They also cover a wide range of lightness, but that is not shown.

TM-30 users must remember that the objects in any given environment will always differ from the 99 CES to some degree. Sometimes, measures for specific hues (e.g., red) may provide more useful information than average values (that is, average color fidelity or gamut area), due to an uneven balance of hues in the space or scene (e.g., a tomato display). Because each space is different and there is no way to characterize an average architectural space, a color sample set like the 99 CES that covers the likely range of colors and does not favor any spectral feature is appropriate for determining generalized predictions of color rendition of a light source. Sets of color samples that are small, do not evenly sample the color volume, or that favor certain spectral features are more likely to incorrectly predict performance in a real environment, and incentivize targeted optimization by light source developers; this was a common criticism of the eight pastel color samples from the Munsell library that are used to calculate CRI.

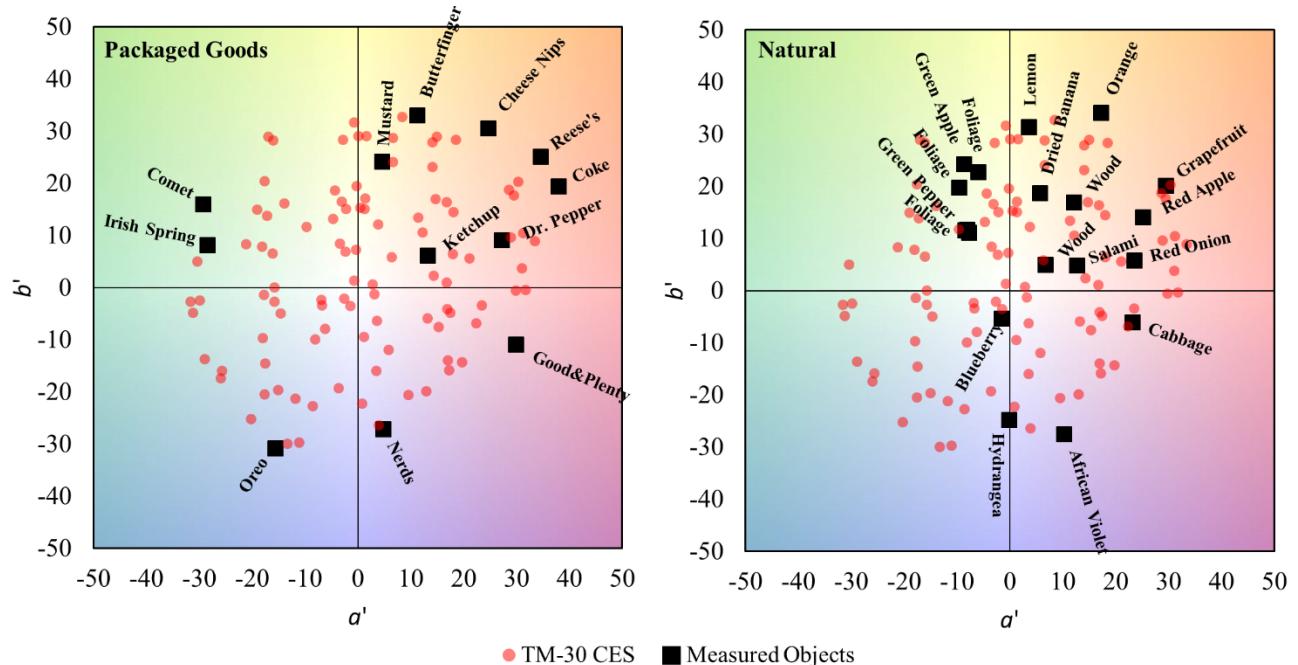


Figure 11. Comparison of the (a' , b') coordinates of the 99 color evaluation samples used in TM-30 calculations and the coordinates of measurements of familiar objects.

4.4 What are the hue-angle bins?

To facilitate some of the TM-30 output measures (see Sections 5.5 to 5.9), 16 hue-angle bins were defined. They are equally sized, 22.5° slices of the flattened color space (the a' - b' plane of CAM02-UCS). The bins were numbered sequentially beginning with the positive a' axis, or the red region. Bins 4-5 are nominally yellow, 8-9 nominally green, and 12-13 nominally blue, as shown in Figure 12. The precise quantity of bins was an arbitrary choice, balancing precision with practicality.

With each calculation, the color samples are assigned to a bin based on the coordinates of each sample under the reference illuminant. There are between 2 and 11 color samples in each bin, with variation occurring based on the CCT of the reference illuminant. Figure 12 also shows the distribution of samples for two reference conditions, 2700 K (Planckian radiation) and 6500 K (CIE D65). While the uneven and unequal distribution of color samples may seem concerning at first, it is important to remember the 99 CES were purposefully selected to match the performance of the 4,880-sample reference set, which evenly sampled the voxelated color space.

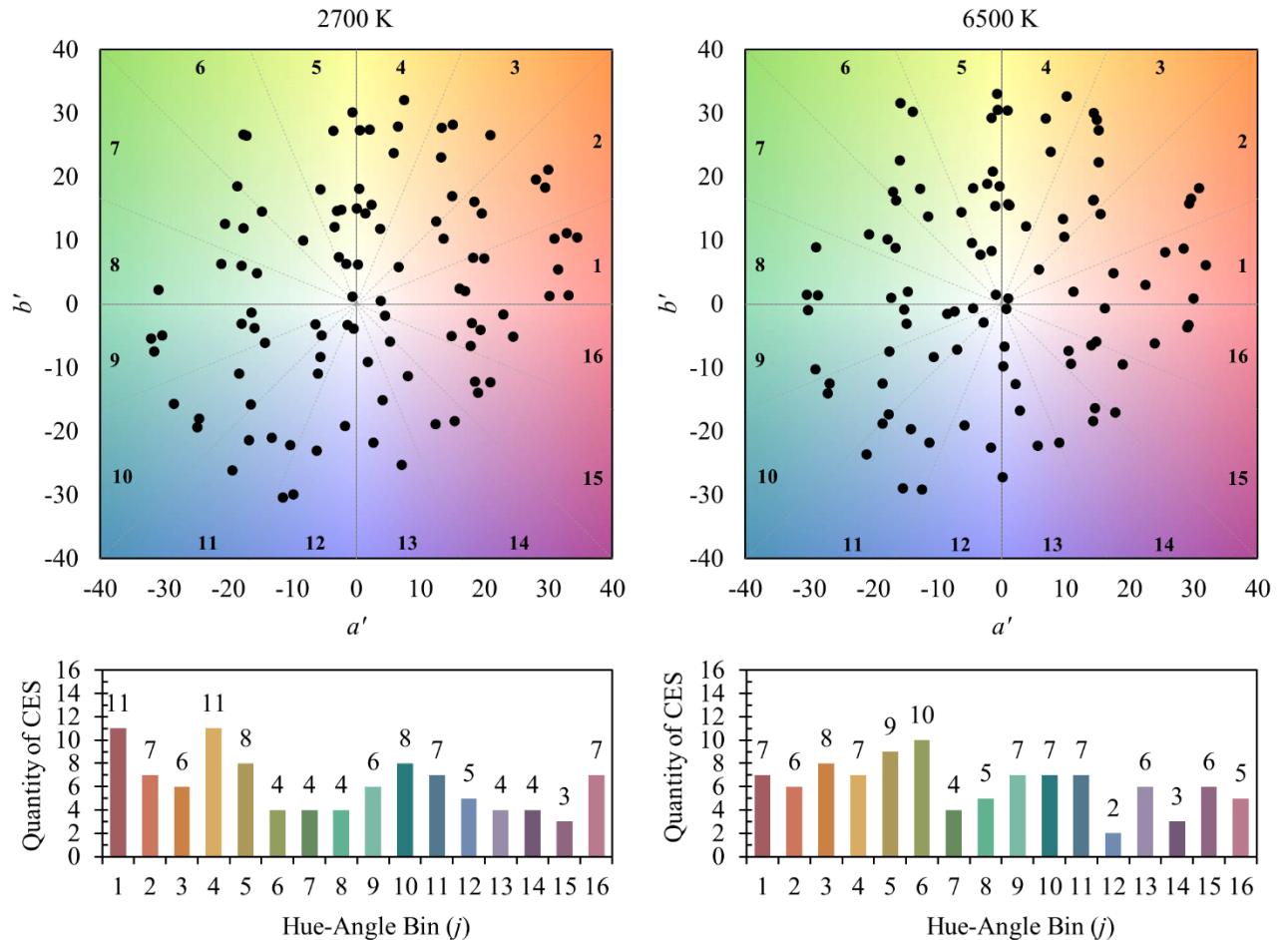


Figure 12. Top: The CAM02-UCS (a' , b') coordinates of the 99 color evaluation samples used in TM-30 and associated hue-angle bins (dashed lines, numbered at perimeter). Bottom: Distribution of color samples within each bin for two example reference conditions.

4.5 What are the reference illuminants?

TM-30 is a reference-based method that compares a test source to a reference illuminant at the same CCT. That is, there is a unique, but systematically defined reference illuminant corresponding to each CCT. For sources with a CCT of 4000 K or less, the reference is a Planckian radiator at the same CCT. At 5000 K or above, the reference illuminant is from the CIE D Series. Between 4000 K and 5000 K, the reference illuminant is a proportional blend of Planckian radiation and the D Series illuminant, each at the specified CCT. For example, at 4750 K, the reference illuminant is 75% Planckian radiation (at 4750 K) and 25% CIE D4750.

Except for the blending aspect, which alleviates a discontinuity in values for the output measures, the TM-30 reference scheme is the same as the one specified in CIE 13.3. Some people have suggested that the references should be all Planckian radiation or all CIE D series illuminants, but in fact this change would have minor effects on the values of output measures [Royer 2016]. The sun is a Planckian radiator, and daylight only differs from Planckian radiation because the Earth's atmosphere slightly filters some wavelengths.

Others have suggested that the reference sources should not be on the Planckian locus, because off-Planckian sources with a negative value for D_{uv} may be viewed as more neutral or be more preferred, according to some research [Dikel et al. 2013; Rea and Freyssinier 2013; Smet et al. 2014; Smet et al. 2015; Ohno and Oh 2016; Smet 2018]. However, there are no defined standard illuminants with chromaticity in this range, which makes establishing reference spectral power distributions more difficult. Ultimately, the choice of a reference illuminant scheme—for which there is no right or wrong—is less consequential because TM-30 does not depict the reference as an ideal light source.

5. TM-30 Measures and their Meaning

This section describes each of the outputs of TM-30, focusing on interpretation of the values rather than the calculation details, which are provided in the technical memorandum itself. Information about desirable or target values is provided in Section 7 .

5.1 What is the difference between a measure and a metric?

The terms measure, metric, index, and method are all used in relation to quantification. The specific definitions of these terms are not universally agreed upon, particularly the distinction between measure and metric, where the definitions may be reversed according to different sources. In this article, *measure* is used to describe a quantification that is objective and repeatable, such as quantifications of color shifts like color fidelity, gamut area, or chroma shift. *Metric* is used to describe quantifications that are more subjective in nature, like for color preference, color naturalness, or color vividness. The term *index*, used in the name of some specific measures or metrics, is reserved for quantifications based on changes to a group of individual datapoints, or those that aggregate multiple indicators. Stock market indices are a good example of this, and many quantifications of color rendition are appropriately deemed an index because they aggregate the color shifts of multiple color samples. Finally, *method* is used here to refer to general approaches to evaluation or to collections of measures or metrics that can be generated from a common framework. That is, the TM-30 method includes many individual measures which are intended to be used in various combinations to evaluate and communicate color rendition performance.

5.2 How many outputs are part of TM-30?

Although it is sometimes erroneously referred to as having just two measures (R_f and R_g), ANSI/IES TM-30-20 specifies 149 distinct numerical output measures and one graphical output. While R_f and R_g have received more attention, other parts of TM-30 are often more important for describing and specifying color rendition. These other tools, such as the 16 Local Chroma Shift measures, are an important part of what distinguishes TM-30 from most other methods for evaluating light source color rendition. Each type of output is described in subsequent sections. Figure 13 documents the current scope of TM-30, whereas Table 1 provides a basic overview of the TM-30 outputs.

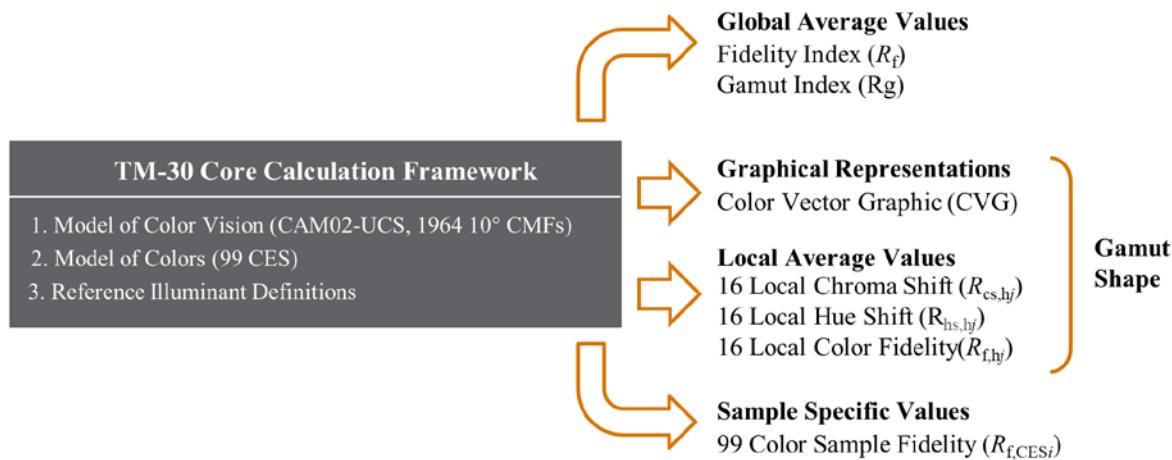


Figure 13. The scope of the TM-30 core calculation framework and outputs.

Table 1. Summary of TM-30 Outputs

Measure		What it Characterizes (Relative to reference)	Interpretation	Typical Values
Fidelity Index	R_f	Overall average similarity	Values closer to 100 indicate greater similarity to the reference	70 to 100
Gamut Index	R_g	Approximation of the average change in chroma	Values above 100 increase in chroma; values below 100 decrease in chroma	80 to 120
Color Vector Graphic	CVG	Visual representation of gamut shape	Radial arrows for chroma shift, tangential arrows for hue shift	NA
Local Chroma Shift (16 Values)	$R_{cs,hj}$	Average relative change in chroma for a specific hue-angle bin	Values above 0% for increased chroma, values below 0% for decreased chroma	Approx. -20% to 20% (varies by hue)
Local Hue Shift (16 Values)	$R_{hs,hj}$	Average change in hue angle (in radians) for a specific hue-angle bin	Positive values for counterclockwise shift (e.g., yellow to green), negative values for clockwise shift	Approx. -0.2 to 0.2 (varies by hue)
Local Color Fidelity (16 Values)	$R_{f,hj}$	Average similarity for a specific hue-angle bin	Values closer to 100 indicate greater similarity to the reference	60 to 100
Sample Color Fidelity (99 Values)	$R_{f,CESi}$	Average similarity for a specific color sample	Values closer to 100 indicate greater similarity to the reference	60 to 100

5.3 What is the TM-30 Fidelity Index (R_f)?

The Fidelity Index (R_f) is the TM-30 measure for average color fidelity, describing the overall similarity in the appearance of colors for the test and reference conditions. It is analogous to CRI but uses significantly more

modern color science that makes it a more representative of human perception and more generalizable as a tool for characterizing light sources.

R_f averages the magnitude of the difference in color coordinates between the test and reference conditions for all 99 CES. This average difference is multiplied by a scaling factor and subtracted from 100. A logarithmic transformation is applied so values do not go below 0, making the total range 0 to 100. A value of 100 indicates an exact match with the reference, and the lower the value, the more difference is calculated compared to the reference. For architectural interiors, R_f values below 60 are not typically considered appropriate, although fidelity alone is not necessarily a good indicator of the appropriateness of a source for an application. In some cases, targeted deviations from the reference, such as increasing the chroma of reds versus the reference, can be preferable. The old paradigm that higher color fidelity is “better” has become an overly simplistic approach to a complex phenomenon.

Some color samples may be rendered more similarly to the reference than others, as shown in a two dimensional representation in Figure 14, but this information is not conveyed in the final average value. Likewise, some hues can shift one way, while others shift in the opposite direction, as occurs for both examples in Figure 14. No matter the direction of shifts, if the average magnitude is the same, the R_f value will be the same, as occurs for the two examples in Figure 14. This is a substantial limitation of all average color fidelity measures. Note that R_f is not an exact average of the 99 individual fidelity values, $R_{f,CESi}$, due to the transformation that is applied to every fidelity value included in TM-30 to prevent negative numbers.

5.4 How is TM-30 R_f different from CRI (CIE R_a)?

CRI (officially the CIE’s General Color Rendering Index R_a) and R_f share the intent of characterizing average color fidelity; however, TM-30 R_f addresses many of the scientific shortcomings of CRI. Two of the main differences are the color space (CIE U*V*W* versus CAM02-UCS), and the number and type of color samples

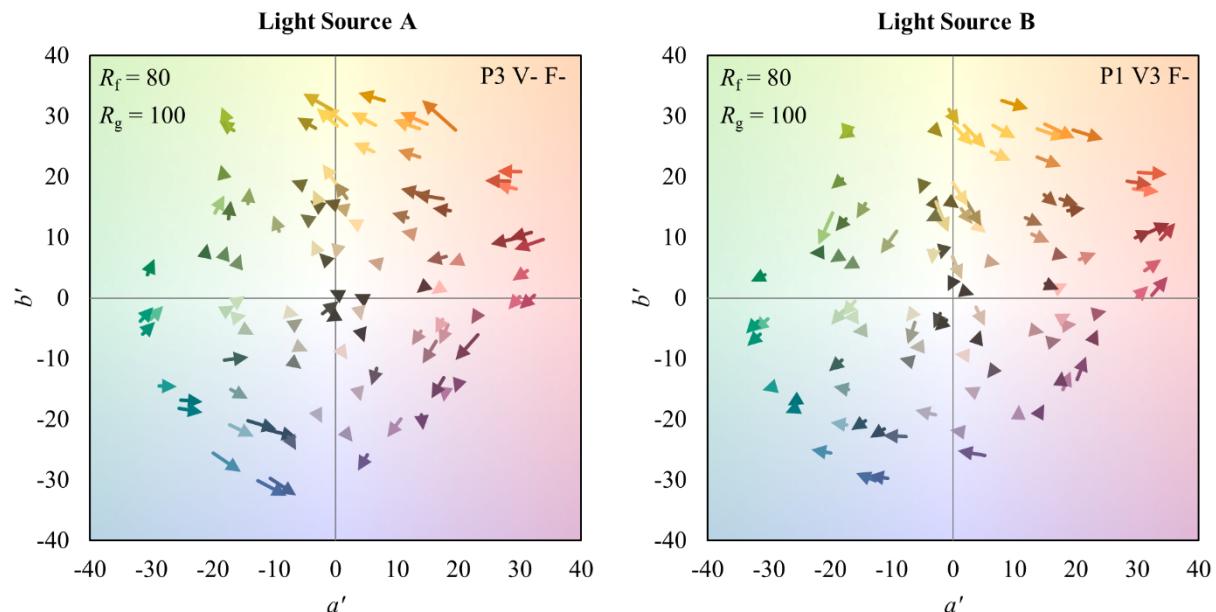


Figure 14. Vectors for each color sample showing the reference coordinate and test coordinate (arrowhead). The light source represented on the left side and the light source represented on the right side have the same R_f value, but the individual color samples shift in different ways. These two LED light sources also have the same chromaticity.

considered (8 versus 99), as demonstrated in systematic comparisons of the two measures [David et al. 2015; Smet et al. 2015c; Royer 2017b].

Whereas R_f was formulated to have approximately the same scale as CRI, there is usually a difference in values for individual light sources. Figure 15 shows the relationship for two data sets, one of approximately 165,000 theoretical white light SPDs [Royer 2019c] and the other with 1,529 SPDs for real lighting products, some of which are for tunable systems used in experiments [Royer 2020]. For SPDs with a CRI of 80, the difference between R_f and CRI can exceed 20 points for light sources that exist today and 40 points for light sources that could be available in the future—all despite the fact that the two are reasonably well correlated.

CRI is imprecise as a result of the small number of samples, which increase the variance of values relative to more comprehensive color sample sets [Smet et al. 2015c]. CRI is also inaccurate given that specific special features are favored and the dependence of R_f -CRI differences on gamut shape: CRI values tend to be lower than R_f values for sources that increase red chroma because of the nonuniformity of CIE U*V*W*. That is, an increase in chroma for nominally red colors that is visually equal to a decrease in chroma for the same colors will result in a greater reduction in CRI, creating a systematic bias. One visible manifestation of this nonuniformity is the different scale for R_g values compared to CRI or other R_i values.

CIE acknowledges that “ R_a [CRI] deviated from a scientifically accurate colour fidelity measure” and notes that “ R_a [CRI] values do not always correlate well with visual evaluation by general users” [CIE 2017].

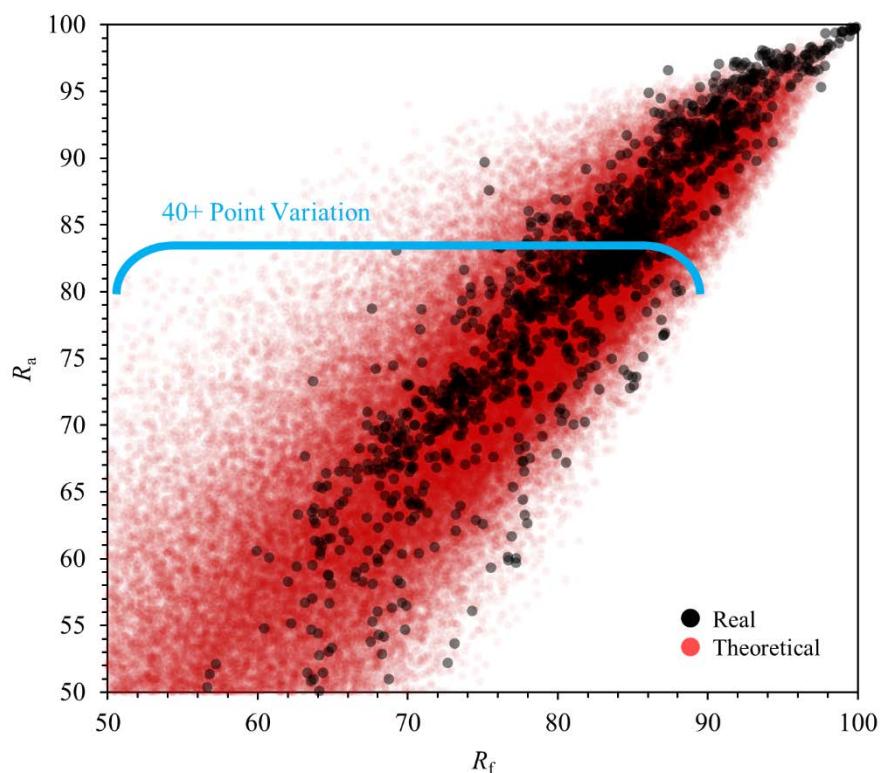


Figure 15. Relationship between R_f and R_a (CRI) for real and theoretical light sources. Despite a strong correlation ($r^2 = 0.86$ for theoretical, 0.85 for real), the range in R_f values for theoretical light sources with R_a of 80 is exceeds 40 points, and differences up to 20 points are common.

Nonetheless, CIE stopped short of recommending that R_f replace R_a [CRI] for the purpose of specifying color rendition and rating products, because color fidelity, no matter how accurately quantified, is not always related to perceived color quality. In contrast, “The IES recommends that lighting professionals transition to IES R_f ” for quantifying color fidelity, while also recommending “that the practice of creating specifications based solely on average color fidelity be reevaluated on a case-by-case basis to determine whether it is sufficient...” [IES 2018] The IES also acknowledges that providing R_a values in addition during a transition period may be useful.

5.5 What is the TM-30 Gamut Index (R_g)?

The Gamut Index (R_g) is the TM-30 measure for relative gamut area, approximating the average change in chroma for all hues. (As explained in Section 3.9, hue shifts can also influence gamut area.) Calculating R_g first requires dividing the 99 CES into the 16 hue-angle bins (see Section 4.4), so that a stable area can be calculated. The (a', b') coordinates of all samples in each bin are averaged, forming the vertices of one 16-sided polygon each for the test and reference conditions. R_g is the quotient of the area of the two polygons (the test area divided by reference area), multiplied by 100. Figure 16 illustrates the areas used in this calculation.

The range of values for R_g does not have specific limits, although the range is dependent on R_f : as average color fidelity is reduced, there is more possibility for the gamut area to be increased or decreased. When R_f is about 60, R_g is between approximately 60 and 140. Values greater than 100 indicate an increase in gamut area, whereas values less than 100 indicate a decrease in gamut area. The relationship between R_f and R_g is illustrated in Figure 17. Like all measures of gamut area, R_g does not address which hues exhibit increased or decreased changes in chroma.

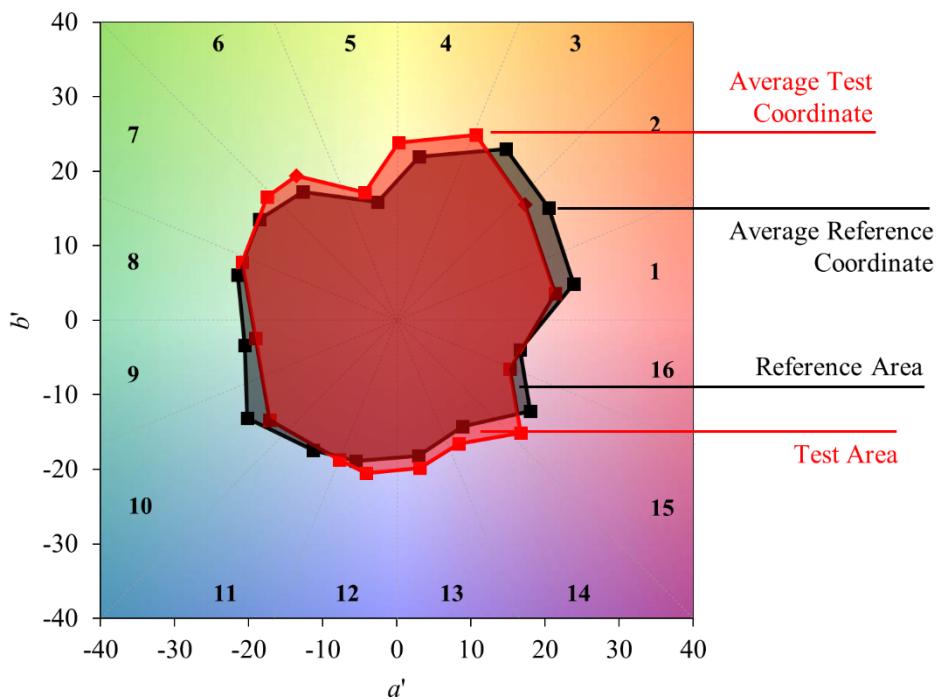


Figure 16. Illustration of hue-angle bin averaging and areas that are compared to calculate R_g .

5.6 What is the Color Vector Graphic?

The Color Vector Graphic (CVG) is a visual representation of color shifts that define the gamut shape. It is based on the average (a' , b') coordinates calculated for the color samples in each of the 16 hue-angle bins that are described in Section 4.4. The Color Vector Graphic is important because it quickly conveys what types of colors have more or less chroma under the test light source relative to the reference illuminant and where hue shifts occur.

In the Color Vector Graphic, two examples of which are shown in Figure 18, the reference illuminant is represented by a black circle. In each of the 16 hue-angle bins, the average shift created by the test source relative to the reference for the samples in the bin is plotted with an arrow that originates from the center of the bin. The ends of the arrows are connected to form a shape, shown with a red line, that characterizes the test source gamut. (Note that R_g is calculated from the raw coordinates of the samples, rather than this shape, which is plotted relative to the normalized circle of the reference.)

Where the red line for the test source is outside the black circle, the test source is increasing chroma in that hue range. Likewise, where the line for the test source is inside the circle, the test source is reducing the chroma of those hues relative to the reference. Arrows that are not purely radial indicate that a hue shift is also occurring (e.g., reds shifting toward orange). Although it does not provide easy comparison of small differences or a way to evaluate the magnitude of a difference, the Color Vector Graphic facilitates quick inspection of how a light source will render a wide variety of colors. Detailed comparisons are facilitated by the numerical counterparts to the Color Vector Graphic: Local Chroma Shift, Local Hue Shift, and Local Color Fidelity.

5.7 What is Local Chroma Shift ($R_{cs,hj}$)?

Local Chroma Shift is the quantification of typical change in chroma for specific (localized) hues. (The *Local* moniker is used throughout TM-30 to refer to averages for specific hue regions, as opposed to averages over all hues.) The average chroma shift in each hue-angle bin is determined by calculating the radial component of each vector from the Color Vector Graphic. The Local Chroma Shift values are denoted $R_{cs,hj}$, where h indicates a hue-angle bin specific value and j indicates the number of the hue-angle bin. They are expressed as a percentage because the magnitude of chroma shift is dependent on the absolute chroma of a sample. The sign of the value indicates whether chroma is increased (positive) or decreased (negative) relative to the reference, so that the measure indicates both a magnitude and a direction. Two examples are given in Figure 19, which corresponds to the same SPDs shown in Figures 14 and 18. Values for typical light sources

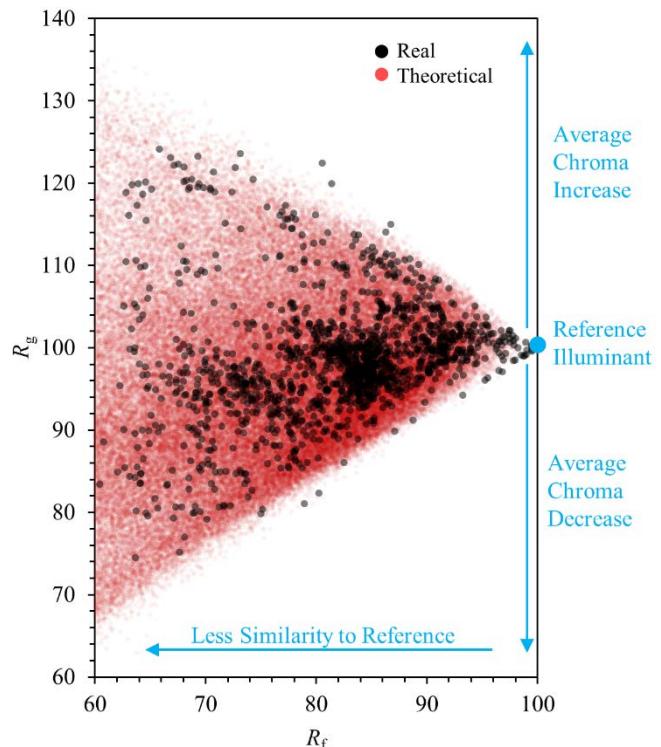


Figure 17. The relationship between R_g and R_f .

(Figure 17 is a scatter plot showing the relationship between R_g (Y-axis, ranging from 60 to 140) and R_f (X-axis, ranging from 60 to 100). The plot contains two main data series: 'Real' data points represented by black dots and 'Theoretical' data points represented by red dots. A large black circle at the point (100, 100) represents the 'Reference Illuminant'. A red line outlines the general shape of the data points. Three vertical arrows originate from the top right and point downwards, labeled 'Average Chroma Increase' (top), 'Reference Illuminant' (middle), and 'Average Chroma Decrease' (bottom). A horizontal blue arrow points to the left from the red line, labeled 'Less Similarity to Reference'.)

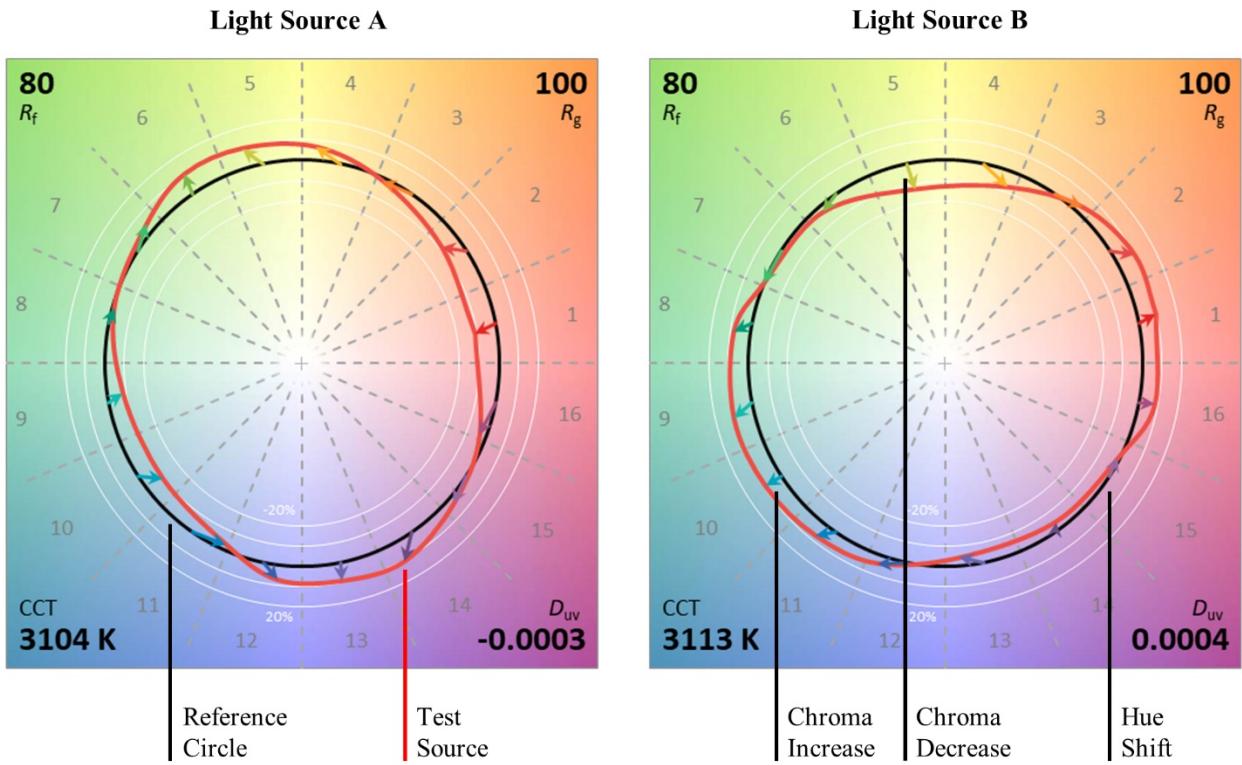


Figure 18. Two example Color Vector Graphics with annotations for the interpretation.

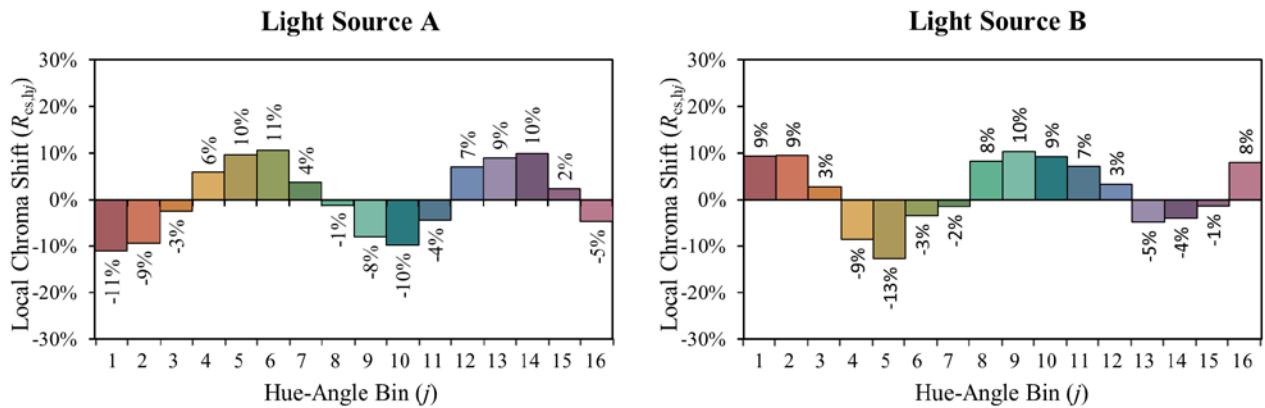


Figure 19. Local Chroma Shift values for two example light sources with the same R_f (80) and R_g (100) values.

used in architectural interiors range from -25% to 25%, and there is typically a continuous pattern to the values in different hue-angle bins going around the hue circle. Royer, Houser, and David [2018b] explored the mechanics of TM-30 Local Chroma Shift calculations.

5.8 What are the Local Hue Shift values?

Local Hue Shift is the quantification of typical hue shifts for specific (localized) hues. It is calculated as the tangential component of the vector in each hue-angle bin of the Color Vector Graphic. The Local Hue Shift values are denoted $R_{hs,hj}$, where h indicates a hue-angle bin specific value and j indicates the number of the

hue angle bin. A negative value indicates a clockwise shift (blue to green on the Color Vector Graphic) and a positive shift indicates a counterclockwise shift (red to orange on the Color Vector Graphic). Values are expressed in radians and are typically between -0.20 and 0.20. Figure 20 provides the Local Hue Shift values for two light sources, which are the same as shown in Figures 14, 18, and 19.

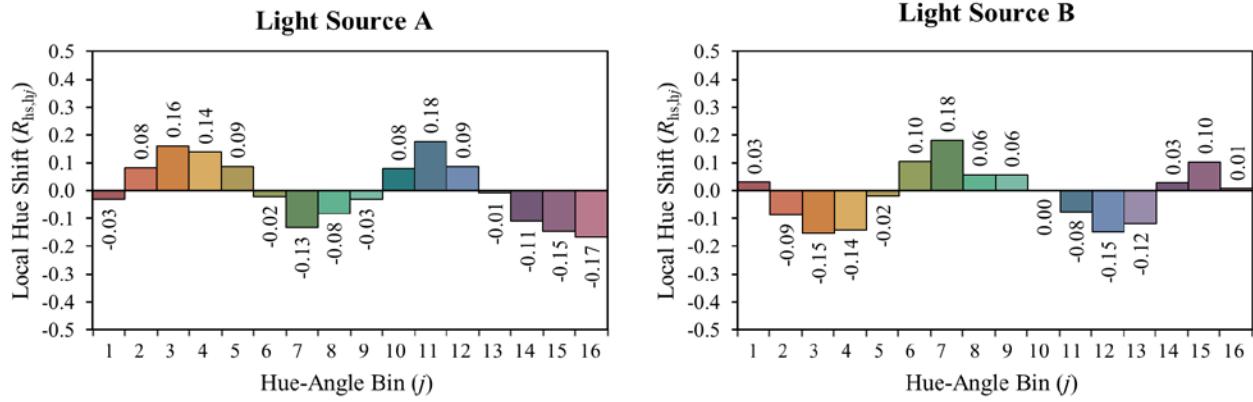


Figure 20. Local Hue Shift values for two example light sources with the same R_f (80) and R_g (100) values.

5.9 What are the Local Color Fidelity values?

Local Color Fidelity is the quantification of the magnitude of the typical shift for specific (localized) hues. It is calculated as the average color shift for the color evaluation samples within a hue-angle bin, transformed to have a range of 0 to 100. The values are abbreviated $R_{f,hj}$, where h stands for hue and j is the number of the hue angle bin, from 1 to 16. The $R_{f,hj}$ values provide more granular information than R_f that may be more relevant to a specific application where the object colors are known. For example, if fidelity of reds is very important, it is possible to examine $R_{f,h1}$. The hue angle bin fidelity values can also reveal differences between sources with the same R_f value, as shown in Figure 21. Importantly, equal $R_{f,hj}$ values may be caused by a variety of different combinations of chroma, hue, and lightness shifts. A light source with a positive $R_{cs,h1}$ value can have the same $R_{f,h1}$ value as a light source with a negative $R_{cs,h1}$ value, as shown in Figure 22.

Local Color Fidelity values function similarly to the special color rendering indices of CIE 13.3 that supplement CRI. For example, $R_{f,h1}$ shares an intended purpose with R_9 from the CIE 13.3 method. A key

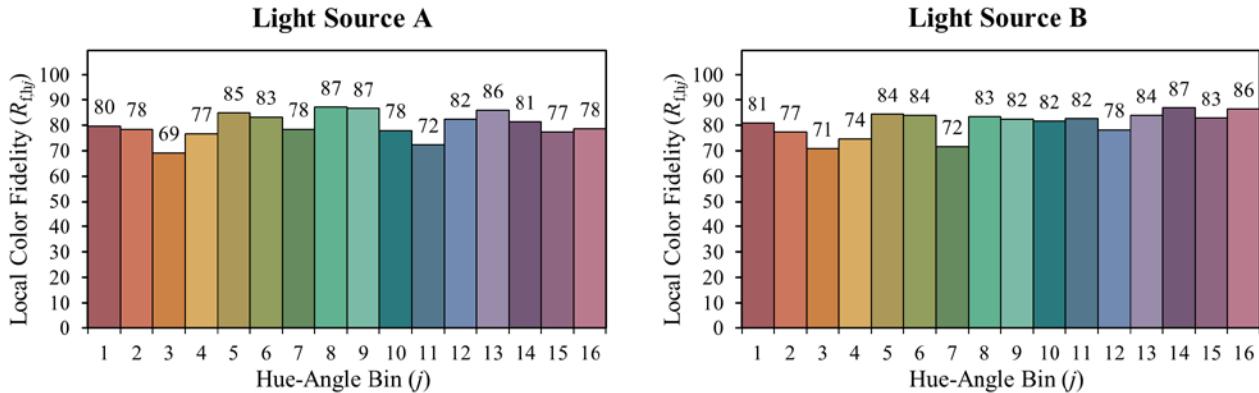


Figure 21. Local Color Fidelity values for two example light sources with the same R_f (80) and R_g (100) values.

difference, however, is that the TM-30 versions are averages of a small number of similar color samples and the scale of the values is consistent across all hues, which makes for more generalizable results and facilitates comparison.

5.10 What are the individual sample fidelity values?

A color fidelity value can be calculated for each individual color evaluation sample (CES). These values are denoted R_{f,CES_i} , where i is the number of the sample. Like all color fidelity values in the TM-30 method, the possible range is 0 to 100. Figure 23 illustrates these measures. The individual sample fidelity values may on rare occasions be useful for predicting the color rendering of a particular object with slightly greater granularity than Local Color Fidelity. For example, the single sample with fidelity values that are most correlated with CIE TCS 9—used to calculate CIE R_9 —is CES 7. Note, however, that the scale for the R_{f,CES_7} is the same as for TM-30 R_f , rather than the unusual scale that exists for CIE R_9 .

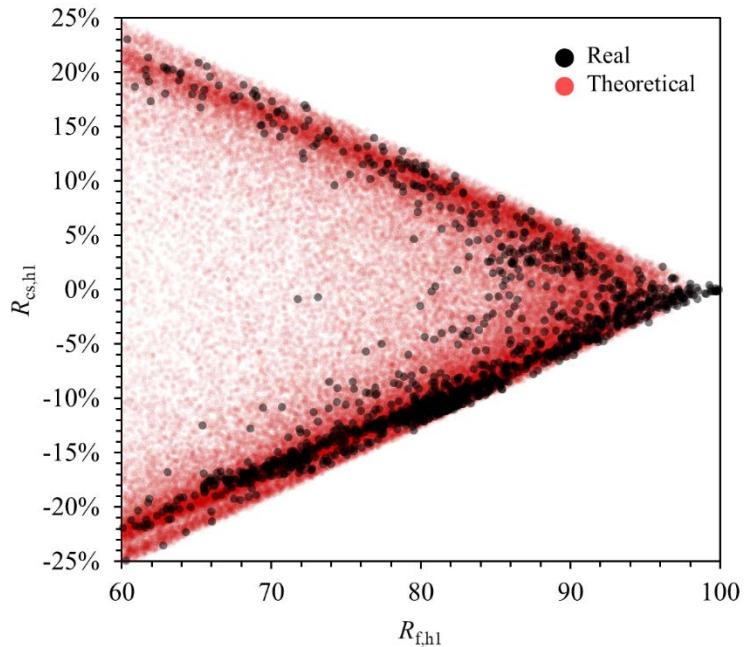


Figure 22. Relationship between Local Chroma Shift and Local Color Fidelity.

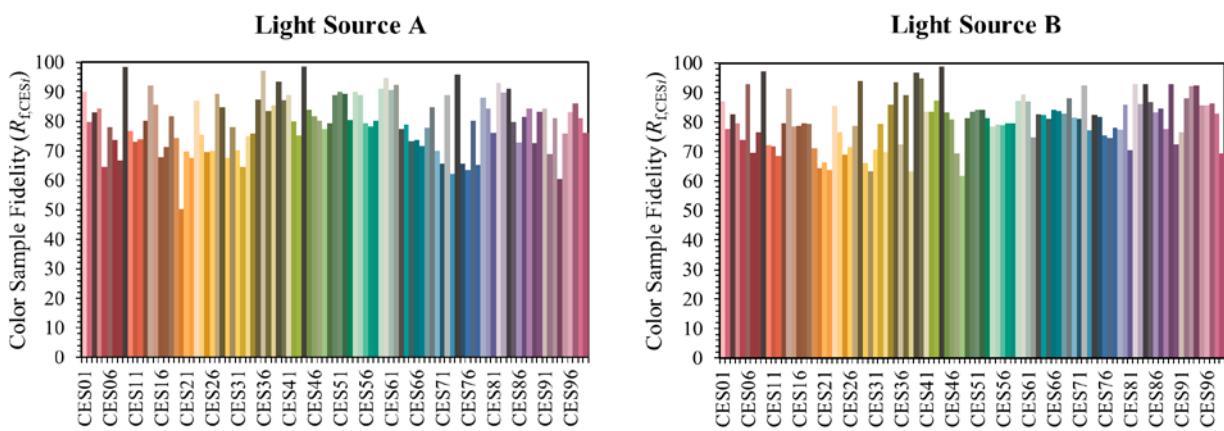


Figure 23. Color Sample Color Fidelity values for two example light sources with the same R_f (80) and R_g (100) values.

6. TM-30 Calculation Considerations

This section covers details about what is excluded from TM-30 and how it can be used in non-standard ways.

6.1 What are the technical differences between IES TM-30-15, ANSI/IES TM-30-18, and ANSI/IES TM-30-20?

After its initial publication of TM-30 in 2015, CIE published 224:2017, which adopted the TM-30 calculation framework with slight modifications. These modifications included adjusting a scaling factor to increase all color fidelity values (R_f , $R_{f,hj}$, and $R_{f,CESi}$), adjusting the extrapolation method used when color samples had no data outside 400-700 nm, and adjusting the blending range for the reference illuminant from 4501-5499 K to 4001-4999 K. Only the change in scaling factor significantly influenced any of the values, causing fidelity values to increase—typically less than 2 points for common lighting products [Royer 2017b]. The publication of ANSI/IES TM-30-18 unified the two calculation frameworks, updating IES TM-30-15 to match the calculation framework in CIE 224:2017 in order to have one global standard.

ANSI/IES TM-30-18 also provided additional detail on various output measures and recommended layouts for presenting the data but did not add any new output measures. One of the most visible changes is new formatting guidance for the Color Vector Graphic. Because essentially all output values went up or remained unchanged, it was determined that no system would be needed to identify which version of TM-30 was used to calculate a specific value.

ANSI/IES TM-30-20 is simply a republication of ANSI/IES TM-30-18 in conjunction with the publication of the 2020 IES online lighting library.

6.2 Can a different reference illuminant be used?

TM-30 specifies the reference illuminant that must be used for calculation given the CCT of the test light source. Defined references facilitate commerce and using a reference other than the one that is specified is not in compliance with the method.

Nonetheless, the specified reference illuminant is not necessarily the most important point of comparison for a given application. For example, if one wants to render the colors in a painting to match what the artist saw while painting under a different lighting condition, the artist's lighting condition can be used as a reference and *custom* measures could be calculated. Going a step further, one could perform calculations using the actual colors in the painting, rather than the generic sample set used in TM-30. It is possible to use the TM-30 framework to perform these types of calculations, but the results should not be presented without clearly distinguishing that they are not standard TM-30 calculations.

6.3 Can different color matching functions be used?

TM-30 specifies the use of the CIE 1964 10° color matching functions. It is possible to swap these for another set, but the calculations should not be reported using TM-30 nomenclature because they would not be following the standardized method. Relative to other components, the color matching functions tend to have a small effect on output values.

6.4 Can different color samples be used?

Custom calculations using different color samples could be performed, but the resulting values should not be reported using TM-30 nomenclature because they would not be following the standardized method. This approach of customized calculations has been followed and can be particularly useful for understanding the visual stimulus in psychophysical experiments [Royer and Wei 2017c]. Sets of color samples that do not include color samples in each hue-angle bin mean some values cannot be calculated and the Color Vector

Graphic would have to be modified. Using custom color samples may be appropriate if a specific color palette is of interest.

6.5 Are negative values possible for TM-30 output measures?

For the fidelity values in TM-30 (R_f , $R_{f,hj}$, and $R_{f,CESi}$), zero is the lower limit. Although not common, values in the CIE 13.3 method can be negative, even though zero is often mistakenly claimed as the lower limit for the scale.

Negative values are not possible for R_g . For Local Chroma Shift and Local Hue Shift, negative values carry specific meaning, as described in Sections 5.7 and 5.8.

6.6 Does TM-30 address white rendering?

TM-30 includes near-white samples, but it does not address the effect of optical brightening agents—the typical connotation of *white rendering*—which contribute to the appearance of many white objects. Other methods have been proposed for addressing white rendering.

6.7 Does TM-30 address differences in light level?

TM-30 relies upon the CIE CAM02 color appearance model, which does, as much as possible, address how light level influences color perception. However, the CIE CAM02 light level parameters input into the calculation for TM-30 are fixed to ensure that all reported values are comparable from product to product; this is necessary because color rendering measures characterize a light source, not an installation. Each situation of an object illuminated by a given light source can lead to a different object luminance, which can affect color perception. Section 7.12 provides more detail on how light level influences color perception.

6.8 TM-30 has measures for hue and chroma, but what about lightness?

TM-30 includes local measures for chroma shift, hue shift, and color fidelity, but not lightness shift. While a Local Lightness Shift measure could easily be defined in the same manner as the others, lightness shifts are generally considered less important and less noticeable to observers. Note that lightness shifts are included in all calculations of color fidelity.

6.9 How is TM-30 related to light source chromaticity?

Light source chromaticity is a basic characterization of the color of the light that does not account for chromatic adaptation. While chromatic adaptation is powerful, the chromaticity—or CCT and D_{uv} —of a light source is often still determinable at a coarse level by room occupants, and it can have some influence on the perception of the environment and the appearance of objects. This is partly because we are usually in settings with mixed chromaticities, and frequently transition from one space to another (e.g., outside to inside), which provides an indication of the chromaticity.

Because TM-30 measures are based on a reference illuminant at the same CCT, and because of the effectiveness of the chromatic adaptation transformation built into CAM02-UCS, color rendition and chromaticity can be considered independently. That is, the range of values for the TM-30 measures does not change at different CCTs, an improvement over methods using older color spaces. Recent research has shown that light sources with equivalent characterization according to TM-30 but different chromaticities produce nominally the same subjective evaluations of color rendition [Zhang et al. 2017; Royer et al. 2018c, 2019d].

6.10 Can TM-30 be used for sources off the Planckian locus?

TM-30 is applicable to all nominally white light sources. This definition is somewhat loose, but at a minimum includes the region defined in ANSI C78.377 [NEMA 2017]. The limiting factor is the range over which human vision can chromatically adapt to a new white point; at the extremes, the calculated values may be less reliable or less meaningful. Still, due to its use of CAM02-UCS, TM-30 provides more accurate predictions of off-Planckian light sources than older methods, such as CRI [CIE 2017]. This is especially true for light sources further from the Planckian locus (e.g., $D_{uv} < -0.01$).

6.11 Can TM-30 help ensure that light sources visually match?

The visual match between luminaire apertures themselves is predominantly determined based on chromaticity and luminance—although chromaticity specification systems are imperfect, which can lead to unintended mismatches. If the concern is illuminated objects matching under different light sources, TM-30 can be informative. To help achieve a visual match for objects in a polychromatic scene, at least R_f , R_g , and $R_{cs,h1}$ should be compared, although additional parameters will help. There is no specific guidance on how many or which measures to consider or their associated tolerances when trying to create a match, especially given heavy dependence on context.

6.12 How many points of difference are noticeable?

There is no number that represents a universal threshold for noticeability of differences for R_f or R_g . This is because both are average measures, where different individual color shifts can lead to the same resulting value. That is, two light sources with the same R_f value or the same R_g values will not necessarily produce the same color appearance for one or more objects they are illuminating. Even when combined, two lighting sources with the same R_f and R_g values do not always produce the same visual experience [Royer et al. 2017], even when all other non-color-rendition factors are held constant. Likewise, there is no number that will ensure a visual difference for either of these measures, but a difference of about five points is usually considered meaningful, such that the two would likely lead to visible differences in most scenarios.

For measures that quantify a magnitude and direction, like Local Chroma Shift or Local Hue Shift, it is easier to define a noticeable difference, but such a value is only relevant when tied to a specific viewing context. When luminance, scene composition, or viewing condition vary, the level of difference that is noticeable may also change. For example, a trained observer evaluating two color patches side by side may be able to detect much smaller differences than a typical building occupant in an architectural space. It is also not possible to adjust just one Local value without influencing adjacent values. In typical applications, anecdotal experience suggests a difference of a 3% percent (Local Chroma Shift) or 0.03 (Local Hue Shift) is likely to be noticeable given an appropriate visual target.

6.13 Does TM-30 include metrics for color preference, color naturalness, or color vividness?

By design, TM-30 does not include a single-number metric for any subjective quality of color rendition, such as preference, acceptability, naturalness, or vividness. This decision was made because subjective qualities are more difficult to quantify and involve personal discretion. Further, all single-number average color rendition metrics become less informative when values are farther from the maximum, when two light sources that render colors very differently may be rated the same. This is particularly relevant because subjective evaluations can be influenced by many factors, including the illuminance level, scene

composition, lighting application, culture, or individual differences. When hidden behind a single number, this nuance is lost. See Section 7.12 for additional information on these factors.

Rather than summarize subjective qualities with predefined metrics, multi-measure specification criteria have been established to address color preference/naturalness/acceptability, color vividness, and color fidelity (see Section 7.3). That is, these qualities are addressed via application of the objective quantities provided by TM-30. The specification criteria approach provides increased transparency and increases the opportunity for specifiers and product developers to use their own discretion. Notably, the existing recommended criteria apply in polychromatic environments with illuminance between approximately 200 and 700 lux, although it is possible to develop criteria for any situation using the common set of building blocks that is TM-30 (see Section 7.10).

6.14 How is TM-30 Data Calculated or Accessed?

TM-30 is calculated from a spectral power distribution, which is measured as part of typical photometric testing. TM-30 thus requires no extra testing or measurement beyond what is already done for lighting products, such as what is specified in the ANSI/IES LM-79-19 measurement method [IES 2019], and it is typical for TM-30 values to be included in a report provided by a photometric testing laboratory. Many of the TM-30 output measures are included in ANSI/IES TM-33-18, *Standard Format for the Electronic Transfer of Luminaire Optical Data* [IES 2018b], which provides an update to the familiar .ies file. Likewise, spectral power distributions are readily measured with handheld spectrometers, many of which now include native calculation of TM-30 within the device or within the accompanying software.

Many manufacturers provide TM-30 data as part of standard product specifications. If it is not published directly, a manufacturer should be able to provide TM-30 data if it is requested. If not provided directly, the output measures described in TM-30 can be calculated using either commercially available software or the free Excel calculator tools that are provided by IES with the technical memorandum. A web-based tool is currently under development. The DesignLights Consortium Qualified Products List publishes TM-30 data for included products as of 2019.

7. Application of TM-30

7.1 What are the best TM-30 values?

Across all the measures included in TM-30, maximum values are not necessarily the best values. In some cases, maximizing color fidelity is the most appropriate goal. In other cases, increasing chroma, which requires lower fidelity, is a more appropriate goal. Simply, the best combination of values is dependent on the situation, as well as personal preferences.

7.2 Is using R_f and R_g enough?

A limitation of any average measure is that there are multiple combinations that can lead to the same value. For example, one source could render reds with high fidelity but not blues, whereas another could render blues with high fidelity but not reds, with both having the same average performance. Even if two light sources have the same R_f and R_g , they may be perceived differently because they distort different hues in different ways (see Section 6.12) [Royer et al. 2017]. Thus, using the Color Vector Graphic along with Local Chroma Shift or Local Hue Shift values can ensure that performance is more appropriately conveyed. Of course, in some situations where color rendition is not a critical design consideration, or where average color fidelity is the key factor, additional detail beyond R_f (and R_g) may be unnecessary. In most general

architectural lighting applications, four values— R_f , R_g , $R_{cs,h1}$, and $R_{f,h1}$ —will provide sufficient information to predict color preference, color vividness, and color fidelity.

7.3 Does TM-30 provide specification guidance?

In 2019, specification guidance was added to TM-30 in two annexes. Annex E provides guidance for specifying light source color rendition using the measures defined in TM-30. It includes a table of recommended specification criteria for achieving different goals, known as *design intents*. Annex F provides additional background and evidence to support the recommendations.

Besides general guidance on factors that might influence the choice of specification criteria, Annex E provides recommended criteria for three design intents with three priority levels (i.e., criteria restrictiveness) that are applicable at typical interior light levels (200–700 lux) when the space illuminated features a variety of colors. The design intents include:

- Color Preference (P): Intent to create a pleasing, natural-looking environment. Color Preference could be the dominant color rendition design intent in retail, office, hospitality, or residential lighting applications.
- Color Vividness (V): Intent to create a vibrant scene, regardless of whether that is natural-appearing or not. Color Vividness could be the dominant color rendition design intent in specific entertainment, display, or retail lighting applications.
- Color Fidelity (F): Intent to achieve similar color appearance, at equal illuminance levels, to the reference illuminant. Color Fidelity could be the dominant color rendition design intent in manufacturing, medical, color matching, or color reproduction lighting applications.

Each design intent includes three priority levels—Levels 1-3, with 1 being the highest or most restrictive—that indicate the stringency of the criteria. Higher levels increase the likelihood of achieving the design intent while lower levels offer flexibility to account for other considerations, such as energy efficiency.

Figure 24 displays the complete matrix of recommended color rendition specification criteria that was first published in Annex E.

Each specification includes one to three measures. All of the measures have a lower limit and upper limits are added for $R_{cs,h1}$ for the Color Preference specifications. Because of the relationship between different measures, other upper limits are implicit. In order to meet the specification, all criteria within a cell must be met. The priority levels within a design intent are nested so that any light source meeting a higher priority level specification will also meet the lower priority level specification(s) for the same design intent.

Each of the nine individual specifications can be represented by a two character code combining the design intent and priority level (e.g., P1), as shown in Figure 24. In situations where no requirement is needed for a given design intent, a dash can be used in lieu of the priority level, as in P-. These codes provide a convenient shorthand intended to simplify the communication of color rendition specifications based on TM-30.

7.4 Can different specifications from TM-30 Annex E be combined?

One strategy for customizing color rendition specifications is to combine individual specifications from two or three of the design intents. For example, one could specify that a light source must meet both P3 and F3. In this example, the new composite specification would be $R_f \geq 85$, $R_g \geq 89$, $-12\% \leq R_{cs,h1} \leq 23\%$ and $R_{f,h1} \geq 85$.

Preference (P)		Vividness (V)	Fidelity (F)
P1	$R_f \geq 78$	$R_g \geq 118$	$R_f \geq 95$
	$R_g \geq 95$	$R_{cs,h1} \geq 15\%$	
	$-1\% \leq R_{cs,h1} \leq 15\%$		
P2	$R_f \geq 75$	$R_g \geq 110$	$R_f \geq 90$
	$R_g \geq 92$	$R_{cs,h1} \geq 6\%$	$R_{fh1} \geq 90$
	$-7\% \leq R_{cs,h1} \leq 19\%$		
P3	$R_f \geq 70$	$R_g \geq 100$	$R_f \geq 85$
	$R_g \geq 89$	$R_{cs,h1} \geq 0\%$	$R_{fh1} \geq 85$
	$-12\% \leq R_{cs,h1} \leq 23\%$		

Figure 24. The nine sets of criteria specified in TM-30 Annex E, covering three design intents and three priority levels. The criteria apply to polychromatic environments illuminated to between 200 and 700 lux.

The composite specification includes the most stringent criterion for each measure. Combining specifications is a way to acknowledge that more than one design intent is important for a given situation.

7.5 Can the Annex E recommended specifications be used for product rating?

The codes associated with each specification can be used as a product rating and identification system. This is a convenient and simple way to differentiate product performance that avoids the need to know the details behind TM-30 measures. It is advisable that a code for all three design intents be presented, such as P3 V- F3 or P1 V3 F-, so that a consistent and complete picture is presented.

While the specification codes are a useful shorthand, they should not be considered a substitute for the availability of numerical data for the underlying measures. Two light sources with the same designation can appear different, and the three priority levels are a relatively coarse breakdown.

7.6 What combinations of the TM-30 Annex E specifications are possible?

Not every combination of TM-30 specifications between the three design intents is possible to achieve. For example, it is not possible to achieve P1 V1 F1. This is a logical and intended outcome, because maximum vividness is not very similar to the reference, and not likely to be preferred or natural in typical architectural lighting applications—even if it is an appropriate goal in some scenarios. The following combinations are possible:

P1 V2 F3	P2 V1 F-	P3 V1 F-	P- V1 F-
P1 V2 F-	P2 V2 F-	P3 V2 F-	P- V2 F-
P1 V3 F1	P2 V3 F-	P3 V3 F-	P- V3 F-
P1 V3 F2	P2 V- F1	P3 V- F3	P- V- F-
P1 V3 F3	P2 V- F2	P3 V- F-	
P1 V3 F-	P2 V- F3		
P1 V- F1	P2 V- F-		
P1 V- F2			
P1 V- F3			
P1 V- F-			

The suitability of each combination is at the discretion of the user, specifier, or producer.

7.7 How were the criteria from Annex E developed?

The recommended criteria in Annex E were developed through a consensus-based process by evaluating current research and considering the experience of producers and specifiers. Data from several recent large-scale studies [Royer et al. 2017, 2018c, 2019, 2019d; Zhang et al. 2017; Esposito and Houser 2019] were a primary source, as explained in Annex F, but dozens of studies from the past several decades informed the discussion. Ultimately, the consensus-based outcome tried to balance specificity with usability, creating an appropriate level of granularity. It is possible that continued research and experience will lead to refinement of the recommendations in the future, and there is potential for more design intents to be added.

7.8 Why does TM-30 focus on specification criteria instead of single-number metrics?

Much of the past work on color rendition has focused on developing a single-number rating system for products. This is still a possibility—even with the increased specificity that is now demanded—but would require several single-number metrics to cover preference, vividness, and other qualities. Such metrics could be developed, for example, by using regression models fit to the same measures that are included in specification criteria, such as R_f , R_g , and $R_{cs,h1}$ for the TM-30 Color Preference criteria. However, this approach was not favored by the IES Color Committee.

When deviation from the ideal of a single-number metric increases, metric values lower, but the reason for the decrease is not apparent because multiple factors contribute. For example, if a color preference model were built from experimental data using R_f , R_g , and $R_{cs,h1}$, it would not be clear which changes caused a lower value, and multiple light sources with different characteristics could be rated the same. TM-30's recommended specification criteria shorthand notation also shares this limitation, but the shorthand codes are not intended to replace the reporting of the underlying metrics in most uses.

Another important issue is that regression models and the single-number metrics based on them imply a precision that does not exist, given all the factors that can influence perceived color rendition quality. It is often interpreted that a small difference could have a significant impact, even though correlation coefficients for such models across many experiments indicate only moderate predictive power. The implied precision and obscuration of underlying factors also make situational adjustments more difficult, whereas specification criteria present an appropriate granularity and can easily be combined and modified.

7.9 What other organizations use specification based on TM-30?

Several organizations have adopted color rendition specifications based on TM-30:

- The Technical Requirements V5.1 of the DesignLights Consortium utilize the P3 specification for indoor products (except high-bay) and a modified version of the P3 specification, with the lower limit on $R_{cs,h1}$ reduced to -18% for outdoor and high-bay products.
- ANSI/ASHRAE/USGBC/IES 189.1-2017, *Standard for the Design of High-Performance Green Buildings* uses the combination specification of P2 V- F3.
- The WELL Building Standard V2 includes a path to qualification via a modified version of the P1 specification, where the minimum R_g level is raised from 95 to 100. This specification was developed prior to the publication of TM-30 Annex E. The specification for circulation spaces is a modified version of the P2 specification.

- The U.S. Department of Defense *Unified Facilities Criteria for the Design of Military Medical Facilities* specifies $R_f \geq 80$, $97 \leq R_g \leq 110$, $-9\% \leq R_{cs,h1} \leq 9\%$, and $R_{f,h1} \geq 78$. This specification was also developed prior to the publication of TM-30 Annex E, relying on benchmarking of products previously found to be suitable for the application.

Except for ANSI/ASHRAE/USGBC/IES 189.1, paths to qualification using CRI are also available, facilitating a transition to more appropriate specifications. Over time, it is expected that more government and energy-efficiency organizations will continue to adopt and exclusively use ANSI/IES TM-30-20 specifications.

7.10 Can customized specifications for TM-30 be written?

While the recommended specifications in Annex E (see Section 7.3) are useful for many scenarios, it is also recommended that specifiers develop unique specifications to meet their precise goals. These could be combinations of the existing recommended specifications or entirely new versions tailored to an installation. For example, when a known object is being illuminated, specifications using measures relevant to the hue of the object should be considered, as they will be more informative than average measures. The same could be done if the illuminance is less than 200 lux or above 700 lux.

7.11 How should custom color rendition specifications using TM-30 be established?

The past paradigm in color rendition was simply to specify a higher CRI value if color rendition was more important. With the opportunity to use the wealth of information provided by TM-30 to target specific outcomes, a more deliberate approach is needed when establishing specification criteria. The following is a recommended set of questions to ask:

1. What is the scene being illuminated? What objects are present and what are their properties? It is important to know if specific hues are important and if people's skin will be rendered by the illumination.
2. What is the intended visual experience? Is the goal to make the colors in the illuminated environment appear dull, natural, vivid, distorted, or something else? Consider this the equivalent of a conceptual design; it will be heavily influenced by past experiences and the intentions of the specifier—there is no correct answer.
3. What measures from TM-30 are useful for achieving the desired effect for the specific scene being illuminated? This requires general knowledge of the measures and their meaning, which is provided in this document as well as in TM-30 Annex E.
4. What other lighting performance aspects are important, such as energy efficiency?
5. How important is achieving the desired color rendition effect compared to other performance aspects? If color rendition is more important, more stringent criteria are warranted.

Combining the answers to the above questions, it should be possible to identify appropriate measures and associated thresholds to achieve the desired effect while balancing competing needs. This does require knowledge and experience, however, which can take time to acquire. One tool that can be useful for understanding different color rendition effects is a spectrally tunable light source, which can be used to mockup different conditions and visually experience the outcome.

7.12 What factors can influence color rendition perception and specification criteria?

Beyond the design intent and priority level (see Section 7.3), there are many factors that can inform color rendition specification criteria, including light level, objects, scene composition, lighting application, cultural

preferences, the viewing population, and personal preferences. Some of these factors have been well studied, while others remain mostly hypothetical.

One factor that strongly influences color perception is light level [Hunt 1952; Ohno et al. 2015; Kawashima and Ohno 2019; Bao and Wei 2019; Wei et al. 2020]. As light level increases, preference for increased saturation decreases, such that at 5,000 lux or more, no increase in chroma relative to the reference is preferred [Bao and Wei 2019]. Likewise, a greater increase in chroma is necessary to achieve maximum preference at very low light levels, such as might occur in a museum. Thus, color rendition specification criteria may need to be adjusted with expected illuminance. This is also why the recommended specification criteria in TM-30 Annex E include both low (200 lux) and high (700 lux) illuminance limits.

Another important factor is the objects being illuminated, including the color properties of the objects as well as the relative importance of individual objects within the scene. An extensive body of literature supports the psychological importance of nominally red objects [Elliot and Maier 2014], which have been shown to be more influential to color rendition perception in polychromatic environments [Rea and Freyssinier 2010; Wei et al. 2016, 2017; Royer et al. 2017, 2018c, 2019d; Wei and Houser 2017b]. This supports explicit specification of color rendition for reds in most situations, but there are also situations where another hue will be the most important; for example, lighting typical tree foliage or a corporate logo. It has also been demonstrated that scene composition can influence subjective evaluations of color rendition [Lin et al. 2015; Wei et al. 2017; Tang and Teunissen 2018]. Note that scene composition is often confused with lighting application; no study has examined different lighting applications with similar distributions of object colors.

Some factors that have a less conclusive relationship with perceived color rendition quality include observer variability and culture. While individual variation in color vision may influence objective evaluations of color shift [Murdoch and Fairchild 2019], it is unclear if these manifest in different preferences or other subjective evaluations in real environments. Likewise, there is limited and contradictory evidence on the role of cultural or regional differences in color rendition perception [Liu et al. 2013; Smet et al. 2014b; Smet and Hanselaer 2015b; Tang and Teunissen 2018]. A specifier is best equipped to understand local preferences.

7.13 How can consumers use TM-30?

While consumers and other end-users certainly can see the effect of color rendition in architectural environments, they often lack the technical expertise to understand methods for evaluating light source color rendition. Even simple measures like CRI are often misunderstood; for example, CRI is sometimes incorrectly considered to represent the percentage of colors that are rendered accurately.

It is not expected that typical consumers will understand the intricacies of the TM-30 calculation framework or even the meaning of the output measures. Without detailed information, the Annex E recommended specifications can still be used as a categorical identification system that would allow a consumer to choose from a limited range of options. This approach would also allow consumers to identify similar-performing products to replace existing ones that they are satisfied with—although specificity does reduce at low priority levels. This change will require consistent uptake of TM-30 and the availability of TM-30 specification codes on product packaging.

7.14 How do TM-30 specifications compare to CRI-based specifications?

For many years, color rendition specifications relied on CRI, with minimum criteria ranging from 70 to 95, depending on the application [Royer 2019]. These criteria were initially established to differentiate between

existing lamp types (primarily different types of linear fluorescent lamps). The differentiating thresholds were consistent with user experiences with the limited range of lamps that were commercially available at the time but have proven problematic as the variability of light source spectral power distributions and the specificity sought with color rendition criteria have increased. More recently, CRI has been frequently supplemented with R_9 in an attempt to address the appearance of red hues, although this does not effectively address the problem because two light sources with equal red color fidelity can render red objects very differently (see Figure 22).

CRI-based criteria have held various misinterpretations from end-users as relating to color naturalness, acceptability, preference, or some overall indication of color quality, despite the original conception of CRI as a measure of color fidelity [CIE 2017]. For all of these interpretations, CRI-based criteria have been widely demonstrated to perform poorly when spectral power distributions are more varied, especially in the case of laboratory experiments [CIE 2007; Wei et al. 2014; Royer et al. 2016, 2018c, 2019d; Zhang et al. 2017; Esposito and Houser 2019; Royer 2019; Wei et al. 2019]. This problem results “from the inaccuracies of the CRI in its intended role as a colour fidelity index; and second, from the perception-related colour quality effects beyond colour fidelity” [CIE 2017].

As color rendition research has advanced, it has become clear that color fidelity is only a partial indicator of the suitability of a light source for a given application. Existing specifications based on CRI or the combination of CRI and R_9 often disqualify products, existing and theoretical, that are viewed preferably, and do not eliminate all conditions that can be evaluated poorly [Royer 2019; IES 2020]. There is essentially no relationship with vividness. Even when color fidelity is the design intent, the inaccuracies and imprecision of CRI as a measure of color fidelity make criteria that rely on it less effective when considering a broad range of light sources of the present or future.

Given all these considerations, translating existing color rendition criteria based on CRI to new methods by simply converting CRI thresholds to R_f thresholds is not recommended [IES 2018]. Instead, users should understand the specific desired outcome or primary consideration (the design intent), then utilize relevant measures from TM-30 to determine the suitability of a given product.

7.15 Where do current products fit into the Annex E recommended specification criteria?

There are commercially available LED products that meet all categories of the TM-30 Annex E recommended specification criteria. The quantity of products within these categories is not equal, which is the result of many factors including demand and tradeoffs with other performance parameters. It is at least partially a consequence of the products being developed around CRI and its common specification criteria.

Many current LED products were designed to meet a CRI ≥ 80 criterion—a particularly common threshold for energy efficiency program incentives—in the most efficient way possible, which results in a decrease in red chroma [Royer 2019, 2019b; IES 2020]. This large proportion of products was a consideration when developing the TM-30 Annex E specifications, and the P3 criteria were defined to include a vast majority of these products.

Most of the products in the higher priority levels for the Color Preference design intent are simultaneously higher color fidelity—most were designed to have CRI ≥ 90 or CRI ≥ 95 . There are, however, new products being designed that take advantage of the added specificity provided by TM-30. It is hoped that TM-30 will promote increased diversity of product offerings, so that specifiers and end users can select products that

Table 2. Color properties of an example set of lighting products. (The specific values may not be representative of all products in a family.)

Technology	Description	CCT (K)	D_{uv}	P	V	F	R_f	R_g	$R_{cs,h1}$	$R_{f,h1}$
LED	Seoul Sunlike	3440	-0.0013	P1	V3	F1	97	102	1%	98
LED	Focal Point Pref Light	3495	0.0007	P1	V3	F3	90	107	7%	87
LED	Cree CXA/CXB 935	3544	-0.0005	P1	V-	F2	92	99	0%	95
LED	Soraa Vivid	2970	-0.0002	P1	V3	F2	93	101	0%	95
LED	Xicato XSM Artist	2940	0.0012	P1	V3	F1	96	101	1%	97
LED	GE TriGain	3990	-0.0020	P2	V-	F3	87	105	-2%	93
LED	Cree LMH 930	3100	0.0008	P2	V-	F3	90	105	-2%	92
LED	ETC Series 2 Lustr+	3489	-0.0004	P1	V2	F-	80	116	14%	74
LED	ETC Series 2 Lustr+	2697	-0.0140	P3	V1	F-	70	119	20%	62
LED	Cree XTE 830	3559	-0.0042	P3	V-	F-	82	99	-11%	81
LED	Cree XP-G3 857	5691	0.0030	P3	V-	F-	84	97	-12%	78
Incandescent	A19	2812	-0.0001	P1	V-	F1	100	100	0%	100
Incandescent	A19 Neodymium	2756	-0.0048	P1	V3	F-	87	109	11%	80
Fluorescent	F32T8/930	2910	-0.0022	P2	V-	F2	90	103	-3%	92
Fluorescent	F32T8/950	5251	0.0024	P2	V-	F3	94	99	-6%	89
Fluorescent	F32T8/835	3702	-0.0002	P3	V-	F-	81	102	-9%	77
Fluorescent	F32T8/850	5398	0.0032	P3	V-	F-	84	102	-8%	82

best meet their needs. Table 2 provides key performance data for several example light sources that may be familiar to practitioners. (The specific values may not be representative of all products in a family.)

The results from an experiment published in 2014 [Wei et al.] provide an example of how past CRI-based color rendition specification criteria may have influenced currently available products. The experiment compared two lamps, one with a CRI of 78 but R_f around 84 and another having a CRI of 86 and R_f around 84. The gamut shape varied, with the lower-CRI lamp increasing the chroma of reds and the other decreasing the chroma of reds. The lower-CRI lamp was preferred, but would not meet a $\text{CRI} \geq 80$ criterion, and thus would not qualify for many incentives provided by energy efficiency organizations and would be more challenging to promote, potentially dissuading bringing this type of product to market. At the same time, the two lamps had the same R_f value. In this example, CRI fails as both a measure of color fidelity and as a measure of color preference.

7.16 Why should TM-30 be used instead of other alternatives?

Many color rendition metrics have been proposed in the past 50 years that could provide benefit over the existing practice of using CRI, and that now includes TM-30. However, there has long been a resistance to moving away from CRI from a faction of lighting producers [CIE 1999; Pointer 2004; Sandor and Schanda 2006]. Some people may wonder why this time is different.

One of the key differences between TM-30 and other proposals is that TM-30 is the only method developed through a consensus-based process and recommended for widespread use by a lighting standards organization in the past 45 years. Conceptually, what makes TM-30 unique is that it focuses on providing an extensive amount of scientifically accurate information, whereas past proposals have typically focused on one of three options:

1. Creating an improved and more accurate measure of color fidelity. Notable examples include R96a [CIE 1999], CQS Q_f [Davis and Ohno 2010], CRI-CAM02UCS [Li et al. 2012], and CRI2012 [Smet et al. 2013, 2016b].
2. Creating a single-number color preference or overall quality metric. Notable examples include the Flattery Index [Judd 1967], Color Preference Index [Thornton 1974], Feelings of Contrast Index [Hashimoto and Nayatani 1994; Hashimoto et al. 2007], CQS Q_a [Davis and Ohno 2010], and MCRI [Smet et al. 2010; Smet et al. 2011; Smet and Hanselaer 2016].
3. Creating a multi-measure system that extends the CIE 13.3 method. Notable examples include Class A [Rea and Freyssinier-Nova 2008; Rea 2010; Rea and Freyssinier 2010] and CRI-based Color Rendition Properties [GLA 2018].

All three of these paths provide benefits compared to the original CIE 13.3 method. For example, a more accurate and precise measure of color fidelity can be helpful when color fidelity is the dominant color rendition goal, and a single-number color preference metric can be useful when color preference is the goal and the application is appropriate. However, neither of these approaches offer the flexibility to address multiple design intents and varying lighting situations.

Multi-measure systems can have the flexibility to address more design intents and varying lighting situations, but when based on CIE 13.3 they do not also provide precise and accurate results because they utilize outdated color science. The limitations can be overcome in certain contexts, such as when considering a specific design intent and evaluating a limited range of existing light sources using regression models that combine measures and include red chroma shift to compensate for the nonuniformity of $U^*V^*W^*$. In these cases, it can appear that the method performs nearly the same as TM-30. However, if the design intent is changed or the range of light sources being considered is expanded, imprecision and practicality issues can become apparent. For example, replicating the specifications of TM-30 Annex E is not possible with multi-measure systems based on CIE 13.3 [i.e., GLA 2018], because the nonuniformity of CIE $U^*V^*W^*$ induces correlation between the included measures that does not exist between those based on a uniform color space; as a result, creating equivalent specifications would require non-independent specification criteria or sacrificing the accuracy of the system, as shown Figure 25 using the P2 specification

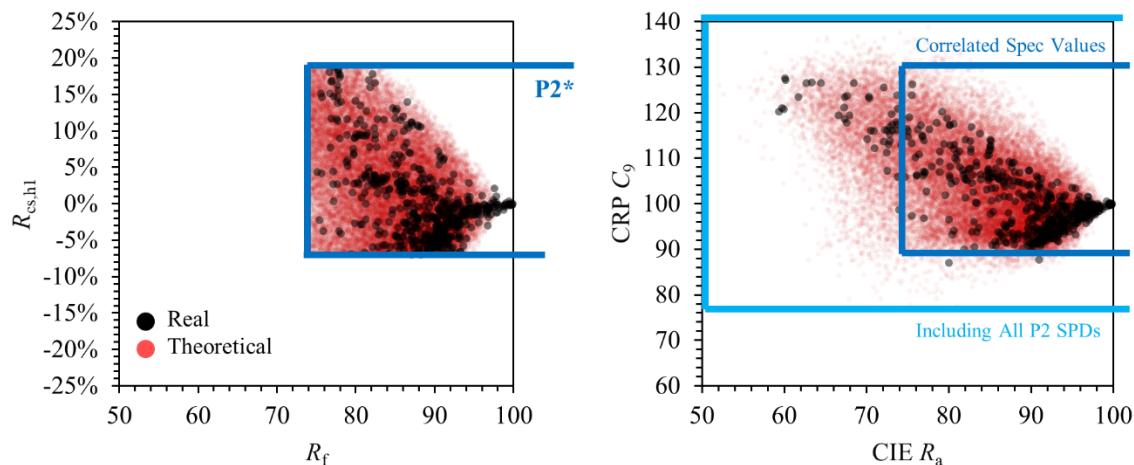


Figure 25. Light sources that meet the P2 specification (left) have more varied properties when using analogous measures based on the CIE 13.3 method, making it impossible to replicate the specifications. C_9 , a measure proposed as part of the CRI-based color rendition properties (CRP) method, refers to the change in chroma for TCS 09 of the CIE 13.3 method.

as an example. If specifications based on correlation between measures are used, many P2 sources would no longer qualify, whereas if new specification values were established to include all P2 SPDs, many SPDs not meeting P2 would qualify.

It can always be argued that more improvement is possible, but TM-30 offers considerably better precision, accuracy, and flexibility, with a demonstrated ability to improve color quality by delivering more targeted results.

7.17 Does TM-30 address the appearance of a specific object?

Standardized methods for evaluating light source color rendition are predictive of color appearance in general, but they are not intended to provide an exact characterization of the appearance of a specific object under a given lighting and viewing condition. Methods for evaluating light source color rendition are simplified to facilitate commerce, and do not consider important parts of color perception like surround conditions or illuminance. For a more accurate prediction of a known object, the use of a color appearance model, such as CIE CAM02, is a better choice. For the most complex cases, there is no substitution for visual evaluation.

7.18 How does TM-30 affect energy efficiency?

The relationship between energy efficiency and color rendition has been widely studied [Zukauskas et al. 2002; Ohno 2005; Schubert and Kim 2005; Protzman and Houser 2006; He and Yan 2011; Chalmers and Soltic 2012; Zhong et al. 2012; Soltic and Chalmers 2013, 2018; G.X. He and Tang 2014, 2014b; Bulashevich et al. 2015; David et al. 2015; Dai et al. 2016; Zan et al. 2016; Zhang et al. 2017b, 2017c, Royer 2019b]. It is an important tradeoff to consider because maximizing luminous efficacy without limits on color rendition would result in a poor visual environment and reduced visual performance for chromatic tasks. In contrast with past single-number approaches to characterizing color rendition, there is no single relationship (or Pareto boundary) between TM-30 and spectral efficiency (more specifically, luminous efficacy of radiation). The maximum possible spectral efficiency across the continuous range of values for individual TM-30 measures and specific multi-measure combinations like the TM-30 Annex E specifications has been explored [Royer 2019b]. As expected, increasing the priority level for the Color Preference or Color Fidelity design intents reduces the maximum possible efficiency (and thus efficacy). However, by being able to manipulate color quality without simply increasing color fidelity—which is associated with decreased spectral efficiency—TM-30 presents an opportunity to specify more appropriate color rendition with less of an energy penalty.

Importantly, spectral efficiency is only one component of luminous efficacy. Accurate and precise methods for evaluating light source color rendition, combined with understanding of the relationship between color rendition and spectral efficiency, can help improve electrical conversion efficiency. Specifically, identification of optimized spectra can inform emitter development that leads to more efficacious products.

8. Conclusion

The need to accurately quantify and usefully summarize color rendition has been recognized for decades. An important inflection point was the availability of fluorescent lamps, which had different characteristics compared to incumbent incandescent lamps. This scenario ultimately led to the development of CRI, which played an important role in lighting development and application for several decades, but ultimately proved to be neither an accurate quantification nor a useful summary of color rendition performance when the

spectrum of lighting products became more varied and the intended color rendition outcomes more specific.

TM-30 is unique among other past proposals for evaluating light source color rendition in that the underlying purpose was to improve the accuracy and precision of objective characterizations of colors and to provide an extensive set of measures that increase the utility and specificity of information so that it can meet a wide range of needs. It is also unique because it was developed through a consensus process that included input from various segments of the lighting community, including producers, researchers, and specifiers. These features have been well-received by a vast majority of the lighting industry, and TM-30 has been steadily added to existing institutional specifications, manufacturer data sheets, and application specifications.

Increased accuracy and precision, combined with more information output, necessarily results in a system that asks more of the user compared to the past methods of specifying color rendition with basic rules-of-thumb. This document is intended to help all users of TM-30 make the most of it.

In the five years since its initial publication, TM-30 has continued to evolve and research-backed, consensus-based guidance on its application has emerged. There are two types of development that could continue to help TM-30 evolve in the future. The first type is changes to the core calculation framework, which would include updates to the color space, color matching functions, color samples, or reference illuminant definitions. These components, particularly color spaces and color matching functions, are active areas of research—outside of the implications for color rendition evaluation methods. It is possible both could be updated in a future revision to TM-30 if a substantive difference in the resulting outputs can be demonstrated.

The more likely development to happen is new extensions of TM-30, such as an expanded set of recommended specification criteria. For example, there could be more guidance on rendition of skin tones. It is also possible that specification criteria will be revised—in either the limits set or the measures used—as new research is published and reviewed through the consensus process. Extensions to TM-30 could also take the form of new metrics developed around the TM-30 calculation framework. Undoubtedly, there are yet-to-be-developed ways to summarize the information that is provided by the core calculations of TM-30.

Ultimately, TM-30 is envisioned as a living document that will be updated when appropriate to continue to be the standard for accuracy in objective specification of color shifts and for utility in summarizing color rendition properties to predict the color quality of visual environments.

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