Improved Method for Evaluating and Specifying the Chromaticity of Light Sources

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Abstract

This article describes a method for calculating and specifying light source chromaticity using the International Commission on Illumination (CIE) 2015 10° color matching functions (CMFs), which, according to analysis of existing psychophysical experiment data, can reduce visual mismatch compared to specifications based on the traditional CIE 1931 2° CMFs in architectural lighting applications. Specifically, this work evaluates, documents, and recommends for adoption by lighting standards organizations a supporting system of measures to be used with the CIE 2015 10° CMFs: a new uniform chromaticity scale (UCS) diagram with coordinates (s, t), a measure of correlated color temperature (CCTst), and a measure of distance from the Planckian locus (Dst). It also presents options for updating nominal classification quadrangles. A complete method of this nature has not yet been standardized, which may be contributing to the slow uptake of the CIE 2015 CMFs.

The proposed tools are analogous to u, v, CCT, Duv, and the American National Standards Institute (ANSI) C78.377 chromaticity specifications that are all currently defined in the CIE 1960 UCS diagram using the CIE 1931 2° CMFs. While conceptually equivalent, the differences between the current standard method and the proposed *st* system are important for reducing unintended visual mismatch in the chromaticity of light. The implications of changing chromaticity specification methods are identified by a comparison over a diverse set of real light source spectral power distributions.

Key Words

Chromaticity, CCT, Duv, CCTst, Dst, color matching functions

1. Introduction

One of the critical aspects of lighting design is specifying the chromaticity of a light source. Chromaticity assesses the color of light, separate from its luminance, and is used to predict if the tint of the light from two or more sources will be the same. The current standard practice for evaluating and specifying the chromaticity of light sources has not changed in almost 50 years, yet many people have become increasingly dissatisfied because it can lead to mismatches in perceived appearance between theoretically metameric light sources. Potential improvements for some elements of the chromaticity specification system have already been documented in scientific literature, but substantive uptake by producers and practitioners has not occurred. This article examines all stages of the chromaticity specification system, recommending a cohesive, updated method that could substantially improve chromaticity matching across light sources.

1.1 Background

A chromaticity specification system has several components, which should collectively yield satisfactory agreement with human perception. Chromaticity is derived from a light source's spectral power distribution (SPD) using three color matching functions (CMFs) that together define a standard colorimetric observer. The three CMFs, also known as tristimulus functions, are a linear transformation of the spectral sensitivities—after considering various absorptions in the lens, ocular media, and macular pigment as well as self-screening—of the three cone photoreceptors of the human visual system, which are typically referred to as cone fundamentals. The International Commission on Illumination (CIE) has four standardized colorimetric observers (1931 2°, 1964 10°, 2015 2°, 2015 10°) as part of its system of colorimetry (CIE 2018), and others have been proposed by researchers (Lozano and Palmer 1968; Vos 1978; Borbély and Schanda 2004; Hu and Houser 2006; Csuti et al. 2011).

CMFs are used to calculate tristimulus values—denoted X, Y, and Z for the CIE 1931 2° CMFs—which are the integral of the product of the respective CMF and SPD. Chromaticity is represented by a pair of values (coordinates) generated from a two-dimensional projective transformation of the three-dimensional tristimulus space. The two chromaticity values can be plotted in a chromaticity diagram, which is a graphical depiction using the Cartesian coordinate system. Figure 1 shows one such diagram, the CIE 1960 (u, v) uniform chromaticity scale (UCS) diagram—further description is provided in Section 2.2. When two light sources have the same chromaticity coordinates, are of equal luminance, and are viewed under identical conditions, their perceived color is *predicted* to match. However, these predictions may fail due to the limitations described in Section 1.2.

Chromaticity itself can never be a predictor of overall color appearance because human color perception is non-linear and context-dependent, which sometimes calls for more sophisticated models (*e.g.*, color appearance models) (Fairchild 2013). Nonetheless, chromaticity is useful for conveying the appearance of emitted light and, roughly, a light source's chromaticity corresponds to its perceived tint or shade. In many settings, people expect adjacent light sources to match in this sense, making an accurate system for characterizing chromaticity important.

Although chromaticity does not fully describe appearance, familiar landmarks can be shown in a chromaticity diagram to orient the user, as illustrated in Figure 1. The overall shape of the diagram is often described as a horseshoe, with the chromaticity values of monochromatic lights, over the visible range of wavelengths, plotted along the curved perimeter known as the spectrum locus. The chromaticity values for Planckian radiators (*i.e.*, a heated blackbody) can be plotted as the Planckian locus, which serves as a baseline that enables calculation of correlated color temperature (CCT), symbol T_{cp}, and distance from the Planckian locus (Duv), symbol D_{uv}. CCT corresponds to the temperature, T_c, of the closest Planckian radiator to the SPD of interest, according to Euclidean distance. D_{uv} identifies the

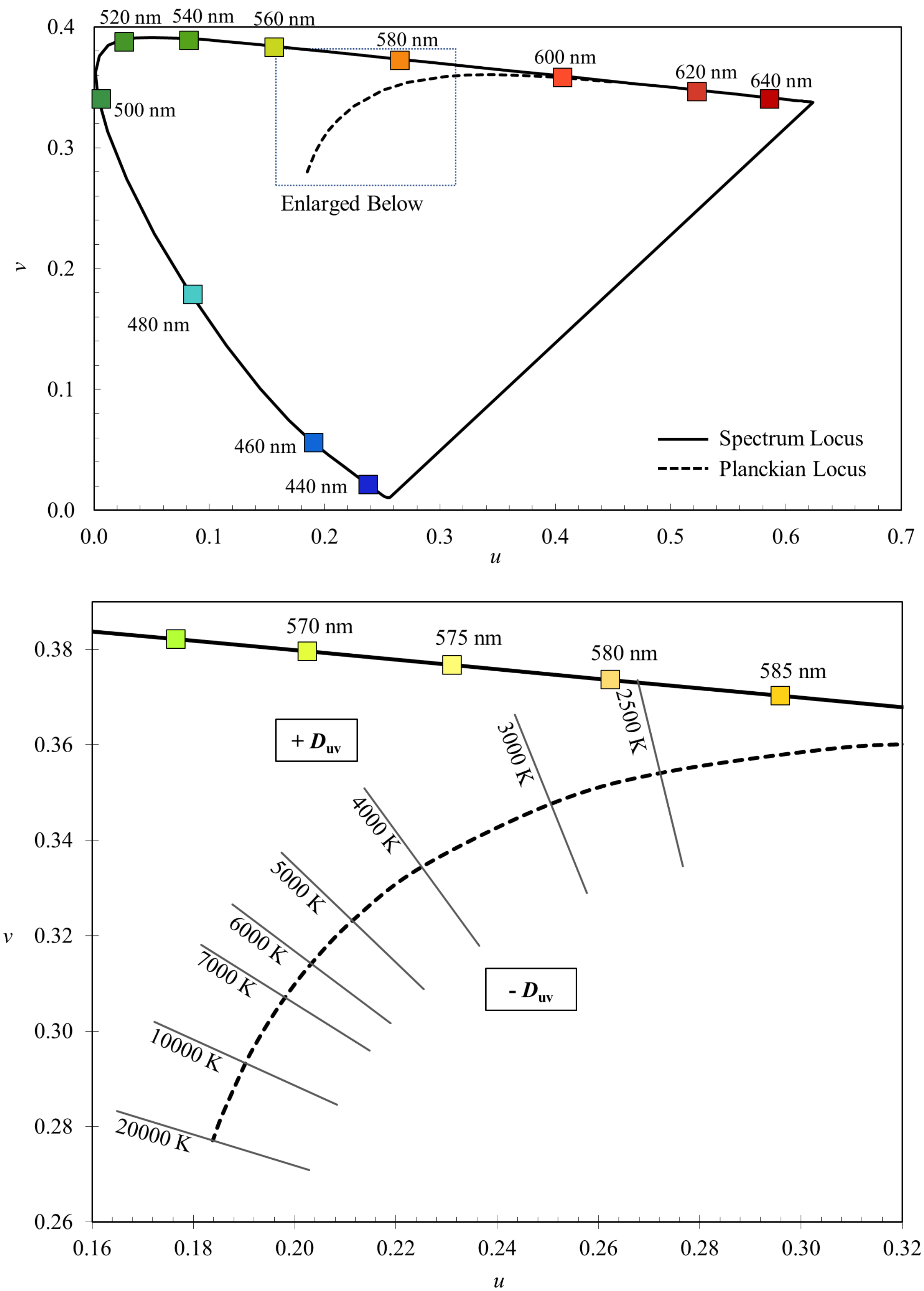


Figure 1. CIE 1960 (u, v) chromaticity diagram with enlargement of nominally white region.

tint as pinker for relatively lower values or greener for relatively higher values (Ohno 2014). More background is provided by David and colleagues (David, Smet, and Whitehead 2019). As defined by the CIE, T_{cp} (*i.e.*, CCT) and D_{uv} are calculated in the CIE 1960 (u, v) UCS diagram—which is officially the (u', 2/3 v') UCS because the 1960 UCS is obsolete according to the CIE. This article uses the generic abbreviations CCTxx and Dxx to refer to these quantities when they are used without reference to a specific UCS diagram.

American National Standards Institute (ANSI) C78.377 (NEMA 2017) uses CCT and Duv to establish "quadrangles," which are bounded areas of chromaticity. Light sources within a specific range of CCT and Duv values are assigned a nominal CCT value, such as 4000 K. The quadrangles, which cover a range of chromaticity deemed reasonably white (*i.e.*, suitable for ambient indoor architectural lighting) are used for product labelling and sorting. It is not the purpose of these quadrangles, by themselves, to ensure acceptable chromaticity matches, so manufacturers often use smaller quadrangles to bin products more precisely. The boundaries of the quadrangles can be transferred to any chromaticity diagram and have the same effect, as long as the same CMFs are used.

The origin of the quadrangles of ANSI C78.377 can be traced to MacAdam ellipses (MacAdam 1942; Brown and MacAdam 1949; Wyszecki and Stiles 1982), which describe the size of a "just noticeable difference" (JND) of chromaticity under the experimental conditions used in their development. One goal of MacAdam's work was to enable the design of a more perceptually uniform chromaticity diagram. In such an ideal diagram, for a pair of light sources, there would be reasonable consistency between the perceived difference in color tint and Euclidean distance between them and MacAdam's ellipses would be circles. Today, MacAdam ellipses are widely used to specify chromaticity variation, either between products or over time, but they are also frequently misused or misunderstood. For this reason, the CIE recommends specifying chromaticity difference using the distance in the CIE 1976 (u', v') UCS diagram, denoted $\Delta_{u'v'}$, and using circles in the (u', v') diagram to specify tolerances (CIE 2014).

Since the initial work of MacAdam and colleagues, several efforts have been made to improve standardized chromaticity diagrams by adjusting the coefficients in the pair of projective transformation formulas that convert the tristimulus values into chromaticity coordinates. The twelve numerical coefficients in those formulas, eight of which are unique, are adjusted so that they more accurately depict chromaticity matching or difference data. The CIE 1960 UCS diagram and the CIE 1976 UCS diagram are examples of the outcome of this process. However, there are no projective transformation coefficients that achieve perfect performance across all SPDs—this ideal is not possible in a simple, linear calculation system.

Importantly, whenever a pair of light sources have the same coordinates in one chromaticity diagram, and are therefore predicted to match in color, this will also be true in other chromaticity diagrams derived from the same CMFs. In contrast, if the CMFs change, the coordinates for SPDs will almost always change, to varying degrees. Thus, the CMFs are critical for predicting chromaticity matches, while the formulas generating chromaticity coordinates are important for yielding reasonably uniform tolerances throughout their associated diagram.

1.2 Current System and its Limitations

The current common practice for specifying chromaticity for architectural lighting uses the 1931 2° CMFs. The original CIE 1931 (x, y) chromaticity diagram is still often used for specification and presentation of chromaticity coordinates. The CIE 1960 (u,v) UCS diagram is used to define CCT, Duv, and nominal classification quadrangles, due to the time period when those metrics were developed, even though it is now obsolete (Robertson 1968; Wyszecki and Stiles 1982). Finally, the CIE 1976 (u',v')

UCS diagram is generally recommended for calculating chromaticity difference (*i.e.*, $\Delta_{u'v'}$) (CIE 2014). This system for specifying chromaticity for architectural lighting—a de facto standard in practice, but not explicitly recommended in combination by a lighting authority—has long been known to have limitations, but they are often ignored in practice. The known deficiencies include:

(a) The 1931 2° CMFs are scientifically outdated (Stockman and Sharpe 2000; CIE 2006, 2015) and not the best representation of color vision for an average color-normal observer;

(b) The 2° field of view is arguably not the most relevant condition for normal viewing by occupants in an architectural environment;

(c) The standard observer methodology does not capture individual variability (Asano et al. 2014; Asano et al. 2016; Asano, Fairchild, and Blondé 2016; Emery and Webster 2019; Asano and Fairchild 2020) in color perception;

(d) The current system is not cohesive in that different chromaticity diagrams are used for different purposes;

(e) The CIE 1960 (u, v) UCS diagram is not the most uniform and has been labelled obsolete by the CIE but remains in use to calculate CCT and Duv.

The first three deficiencies all lead to observer-induced metameric mismatch, whereby light sources with the same chromaticity coordinates do not visually match for all observers. There is considerable evidence—subsequently described—that improvements to the chromaticity specification system can address points (a) and (b), providing a significant practical benefit. This is especially true for modern light sources with more structured SPDs, which have exacerbated the deficiencies of existing methods for characterizing chromaticity. A better evaluation method can help ensure that the calculated chromaticity is closer to the center of the distribution of human perception for viewing conditions typical of architectural interiors. While an improved method cannot reduce inter-observer variability (c)—which creates some degree of metameric mismatch that is unavoidable—it can help product developers and specifiers to reduce the overall level of mismatch. Addressing points (d) and (e) can easily be done together, simplifying the overall system with a long overdue unification.

1.3 Scope

This article considers an improved system for calculating and specifying the chromaticity of light sources used in architectural applications, though it may be applicable to other areas. Architectural lighting is primarily white light, but as with the existing system, the proposed improvement is intended for use with both colored and white light.

The system for calculating and specifying chromaticity has five components. These are the CMFs, the coefficients of the formulas for calculating chromaticity coordinates from tristimulus values, the definitions of correlated color temperature (CCTxx) and distance from the Planckian locus (Dxx), the quadrangle boundaries for nominal classification, and the method for calculating chromaticity differences or chromaticity tolerances. This article explores each component, discussing options for addressing the identified deficiencies of the current system and presenting data to illustrate how updates change existing characterizations. Collectively, we believe the recommended updates comprise a substantial and needed improvement. We acknowledge, however, that these changes cannot eliminate all metameric mismatch arising from inter-observer variability. Methods for specifying object colors, which often already use CMFs other than the 1931 2°, are not discussed in this article.

2. Analysis

2.1 Color Matching Functions

The first step toward an improved system for specifying chromaticity is identifying CMFs that are more representative of an average observer, for general purposes, in common architectural environments. The CIE 1931 2° CMFs—denoted $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$—originated from matching experiments conducted by several researchers between 1918 and 1931, all of which used a 2° field of view. A summary of these early developments is provided by Wyszecki and Stiles (1982). Although the CIE originally did not limit the applicability of these CMFs to any field size, by 1964 a second standard colorimetric observer was adopted—CMFs denoted $\bar{x}_{10}(\lambda)$, $\bar{y}_{10}(\lambda)$, $\bar{z}_{10}(\lambda)$—based on research featuring a 10° field of view. It was then recommended that the 1931 2° CMFs be used only in applications with a field of view between 1° and 4°, which still holds true (CIE 2018). However, the CIE 1931 2° CMFs have continued to be the default set used for colorimetric calculations in architectural lighting applications.

Work to improve CMFs has continued (Thornton 1973; Stockman and Sharpe 2000; Oulton 2004; Hu and Houser 2006; Brill and Worthey 2007), and in 2006, the CIE published report 170-1 (CIE 2006), establishing a system that allows for derivation of average cone fundamentals for any field size between 1° and 10° and any age between 20 years and 80 years. Those two parameters describe a large range of expected variability, with visual field size accounting for typical macular pigment and cone distribution differences between foveal and extra-foveal vision, and age accounting for typical age-related yellowing of the eye's components. In 2015, CIE report 170-2 (CIE 2015) provided documentation for transforming the cone fundamentals to CMFs in line with the XYZ tristimulus colorimetry system. A good summary of this new system is provided by Stockman (2019). Specific CMFs (technically called cone fundamental based tristimulus functions) have been reported for 2° and 10° field sizes for a 32-year-old observer; these are referred to as the 2015 CMFs in this article. Work is ongoing within the CIE to address other ages. A notation system has also been recommended by the CIE, such that these CMFs carry an *F* subscript, as do quantities derived from them. Figure 2 shows four sets of CMFs that have been documented by the CIE. Regrettably, the 2015 CMFs have seen limited use in practical applications.

Matching observer-specific CMFs with the intended viewing conditions would be one approach to avoiding metameric mismatch. However, commerce induces the need to rate products independent of application and observer, and thus demands the use of a single standard set of CMFs. There is no single

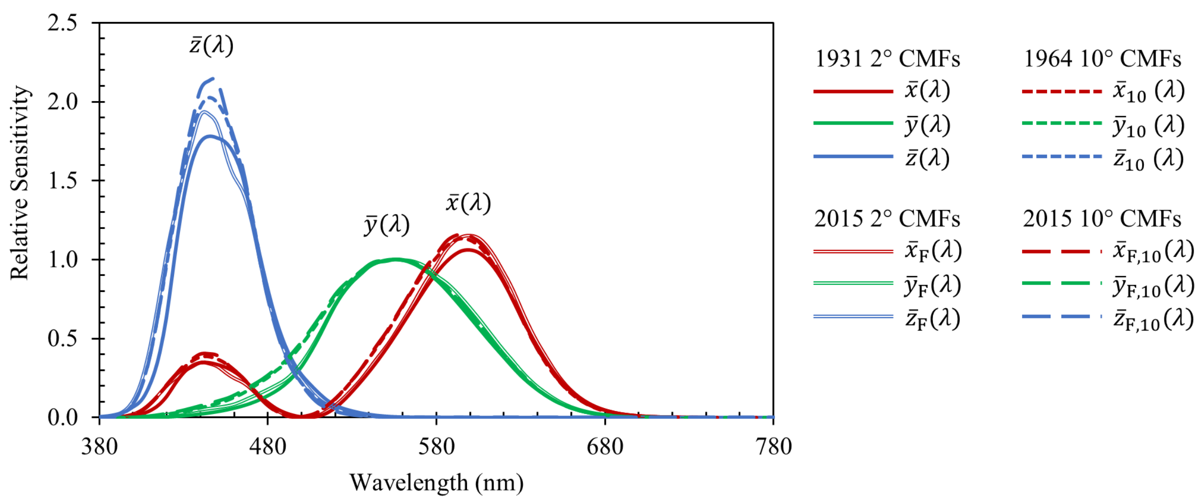


Figure 2. Comparison of four CMF sets standardized by the CIE. The discrepancy is largest at the short wavelengths side of each function.

measure for establishing the “best” CMFs to use for rating products, but considerable efforts have been made to compare the performance of the 1931/1964 CMFs with the 2015 versions, including the following psychophysical studies:

- Ohno et al. (2019) found the 2015 10° CMFs predicted chromaticity matches better than the 1931 2° CMFs overall when observers viewed an illuminated piece of white paper in a booth. The improvement was especially pronounced for younger observers but was less clear for older observers, although statistical analyses were not reported, and age-modified CMFs were not considered.
- David, Sahlhoff, and Wisser(2019) found that the 2015 10° CMFs provided substantial improvement for characterizing perceived chromaticity for observers viewing light projected onto a wall from prototype lamps. They also found that age-adjusted CMFs were particularly useful for predicting the responses of age-grouped study participants.
- Li et al. (2019) studied the impact of the peak wavelength of spectrally narrowband primaries on color matching accuracy with a broadband halogen lamp with filter. They found that the visual matches for a 3° match field were better predicted with the 1964 10° and 2015 CMFs than the 1931 2° CMFs. The 1964 and 2015 10° CMFs showed very similar match predictions, both in the position of the mean, as well as the size, shape, and orientation of the standard error ellipses of the visual matches. However, the 1931 and 2015 2° CMFs resulted in very different matches for many primary sets, especially for the sets containing a primary with a very short peak wavelength (404 nm). A subsequent study (Li et al. 2021, 2021b) with 54 observers, using various narrowband primaries in a 10° bipartite matching field, confirmed earlier results about the improved matching accuracy of the CIE 2015 and 1964 10° CMFs compared to the 1931 2° CMFs, although small but statistically significant differences remained between primary sets with different peak wavelengths.

Beyond these studies, CIE 170-2 (2015) states: “The cone fundamentals are grounded on the best experimental colour-matching data collected to date. It is likely that no large database will be collected in the near future. Careful analysis of the colour-matching data and comparison with physiological and other psychophysical procedures makes secure the precision of the cone fundamentals as representative of an average observer.” In combination, there is strong evidence that the correct application of the 2015 CMFs can help address observer-induced metameric mismatch and aid engineering of lighting products. Some lighting manufacturers have already started implementing these or similar CMFs due to their benefits, but the inconsistent execution resulting from the lack of a single standardized method is problematic for commerce.

In selecting a specific new standard CMF set from the 2015 system to be used for lighting product rating, it is necessary to select a representative field size and age. After careful consideration, and consistent with CIE recommendations for fields larger than 4°, we recommend using the 2015 10° CMFs, as we believe they are representative of more general viewing conditions in the built environment, where surfaces of uniform color often have a visual angular size exceeding 10°. Large field situations include, for example, when comparing the appearance of luminaires across a ceiling, when scanning a room, or when evaluating the consistency of a washed wall. These are scenarios where chromaticity mismatch can be noticeable and objectionable. We do not suggest using the 2015 10° CMFs in specific calculations for scenarios with a field size less than 4°. The best solution is always to choose the correct CMFs for the visual field, but current commercial practices demonstrate that only one set of CMFs will predominate product rating, and thus we make a single recommendation for such use. Some additional information comparing 2° and 10° CMFs is provided in Supplement 1.

For the representative age, we recommend 32 years because it is a reasonable approximation of the median age of humans (UN 2019), and because the transformation for cone fundamentals to CMFs described in CIE 170-2 (2015) was initially completed for a 32-year-old standard observer.

2.2 Chromaticity Diagram

Once a decision is made to implement new CMFs, all systems reliant on CMFs should be reevaluated, starting with chromaticity diagrams. The original 1931 (*x*, *y*) chromaticity diagram, developed around the 1931 2° CMFs, is determined by Equations 1 and 2, where *X*, *Y*, and *Z* are tristimulus values and (*x*, *y*) are chromaticity coordinates:

$$x = \frac{X}{X+Y+Z} \qquad (1)$$

$$y = \frac{Y}{X+Y+Z} \qquad (2)$$

New projective transformations were later introduced to "stretch" the diagram, improving its perceptual uniformity based on the chromaticity discrimination experiments of MacAdam (which used a 2° field of view) (1942). Several transformation formulas were proposed over time (Wyszecki and Stiles 1982), including non-linear transformations that improved uniformity but created other limitations for use of the resulting chromaticity spaces (MacAdam 1971). In 1960, the CIE first adopted a chromaticity diagram with improved perceptual uniformity, the 1960 (*u*, *v*) UCS diagram, which results from the calculation of chromaticity coordinates according to Equations 3 and 4:

$$u = \frac{4X}{X+15Y+3Z} \qquad (3)$$

$$v = \frac{6Y}{X+15Y+3Z} \qquad (4)$$

In 1976 the CIE adopted the 1976 (*u*', *v*') UCS diagram, defined in Equations 5 and 6, which simply scaled the *v* coordinate by a factor of 1.5 to further increase uniformity:

$$u' = \frac{4X}{X+15Y+3Z} \qquad (5)$$

$$v' = \frac{9Y}{X+15Y+3Z} \qquad (6)$$

Since 1976, there have been no new chromaticity diagrams recommended by a lighting standards organization, likely because efforts shifted to the development of more complex and accurate color appearance models, which are used for purposes other than specifying light source chromaticity.

2.2.1 Chromaticity Diagram with the 2015 10° CMFs

Satisfying the goal of reducing observer-induced metameric mismatch by implementing the 2015 10° CMFs means some SPDs that plot at the same point using 1931 2° CMFs will diverge to different points; the exact coordinates of those points in the UCS diagram are determined by the specific projective transformation that is chosen. Any system based on the 2015 10° CMFs will achieve the primary goal of better accounting for observer-induced metameric mismatch; the specific choice of projective transformation, defining the chromaticity diagram, is important for assessing CCTxx and Dxx, establishing nominal classification quadrangles, and the function of chromaticity tolerances.

CIE 15:2018 notes that existing projective transformations can be used with CMFs other than the 1931 2°, provided that the CMFs being used are denoted with a subscript, such as (u'_{10}, v'_{10}) for the 1976 diagram using the 1964 10° CMFs. Here, we propose that the new system have chromaticity coordinates (*s, t*) instead of relying on a subscript, superscript, or other notation scheme, which reduces overlap with existing methods while still relying on two consecutive letters. This further allows a simplified *st* to be used with downstream quantities, such as quantity abbreviations CCTst and Dst as well as symbols T_{st} and D_{st}; this will facilitate clear communication during a transition period having multiple methods in use.

Three approaches to establishing a projective transformation were considered: (A) using the existing CIE 1976 transformation identified in Equations 5 and 6, (B) optimizing the projective transformation to minimize changes to the chromaticity coordinates of important benchmarks like the spectrum and Planckian loci when using the 2015 10° CMFs instead of the 1931 2° CMFs, and (C) optimizing the numerical coefficients within the projective transformation to increase perceptual uniformity.

Approach (A) retains the coefficients of the XYZ to (u', v') projective transformation (Equations 5 and 6), with their application to the 2015 10° CMFs denoted by the subscript *F,10*. New chromaticity coordinates (*s, t*) are calculated as:

$$s = \frac{4X_{F,10}}{X_{F,10}+15Y_{F,10}+3Z_{F,10}} \tag{7}$$

$$t = \frac{9Y_{F,10}}{X_{F,10}+15Y_{F,10}+3Z_{F,10}} \tag{8}$$

Figure 3 demonstrates how this method compares to the (u', v') diagram of the current standard system, showing the Planckian locus and a set of 1,528 real SPDs (Royer 2020) that includes 1,376 LED (821 phosphor-converted [pcLED], 453 color-mixed [cmLED], 102 other [either unidentified or hybrid products employing both pcLEDs and cmLEDs]), 73 fluorescent, 36 high-intensity discharge, and 43 other SPDs. The set of real SPDs has CCTs between 1629 K and 9086 K (95% between 2570 K and 6561 K) with Duv values between -0.0288 and 0.0394 (95% between -0.0132 and 0.0086). This figure demonstrates how the chromaticity diagram changes from the 2° to 10° CMFs for both the SPDs and the Planckian locus, reflecting the variable interaction of SPDs and CMFs.

Approach (B) takes a different form depending on which chromaticity changes are minimized. One possibility minimizes changes to the Planckian radiators, D Series Illuminants, and monochromatic radiation (*i.e.*, the spectrum locus)—the specific details are provided in Supplement 2—resulting in a projective transformation of:

$$s = \frac{4.0000X_{F,10}+0.2100Y_{F,10}+0.0807Z_{F,10}}{-0.1859X_{F,10}+17.5009Y_{F,10}+3.1197Z_{F,10}} \tag{9}$$

$$t = \frac{-0.7141X_{F,10}+10.4756Y_{F,10}-0.0969Z_{F,10}}{-0.1859X_{F,10}+17.5009Y_{F,10}+3.1197Z_{F,10}} \tag{10}$$

Figure 4 shows this approach is somewhat successful in minimizing changes in chromaticity coordinates for important features. However, the differences between approaches (A) and (B) are far smaller—particularly in the areas of greatest interest for nominally white light—than are the differences between either approach and the current standard. That is, the change in CMFs results in most of the change in chromaticity coordinates and optimizing the projective transformation only slightly reduces the overall difference. Further, approach (B) does not reduce changes to CCTxx and Dxx (see Supplement 2)

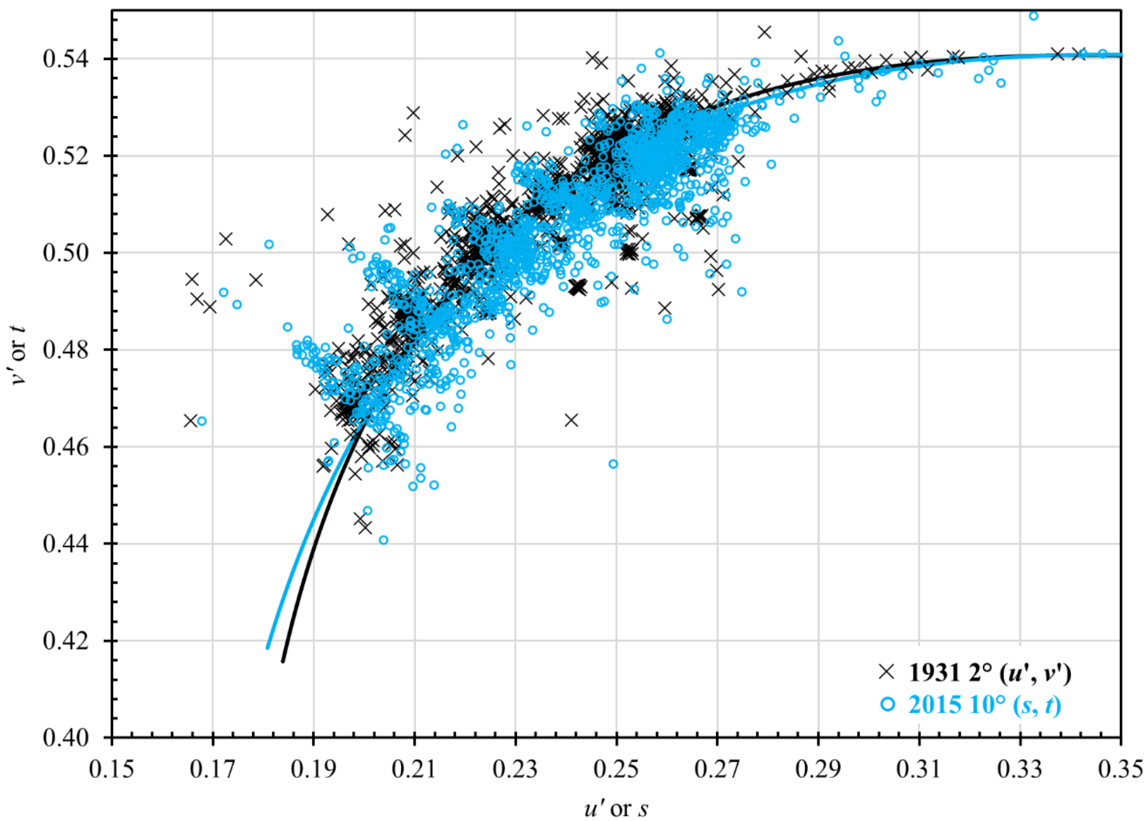


Figure 3. Close-up including the nominally white region of the (*u*′, *v*′) chromaticity diagram versus the (*s*, *t*) chromaticity diagram. The change in CMFs results in changes to the coordinates of both reference locations (i.e., Planckian locus) and SPDs. It is most important to evaluate relative positions.

because they are relative measures. Another issue with this approach is that it might suggest the need for a different projective transformation for every set of CMFs, which could be cumbersome. For these reasons, we do not recommend approach (B).

Figure 5 shows color matching ellipses, based on data from a prior experiment previously described (Li et al. 2021), plotted for the existing standard system—1931 2° CMFs in (*u*', *v*')—and approaches (A) and (B). Using the 2015 10° CMFs substantially reduces the difference between the reference (origin) and the mean of matches across participants (center of ellipses), while approximately maintaining the level of variation in the size and shape of the average 95% confidence interval for the matches (the ellipses) compared to the current standard system. The difference between approaches (A) and (B) is relatively small.

In Figure 5, the different shape and size of the ellipses for different primary sets suggest it would be impossible to create a universally uniform chromaticity diagram via linear transformation; that is, not all ellipses can simultaneously be made more circular with a single transformation. Thus, there is no practical path toward approach (C), even though it may initially seem like a reasonable goal. The CIE 1976 diagram established by Equations 5 and 6, as well as those of approaches (A) and (B), appear to be sufficiently uniform, and the best that can be accomplished, for the intended use.

An important consideration when examining Figure 5 is that it is possible for different chromaticity diagrams to have different scales for chromaticity difference calculations. The scales can be compared

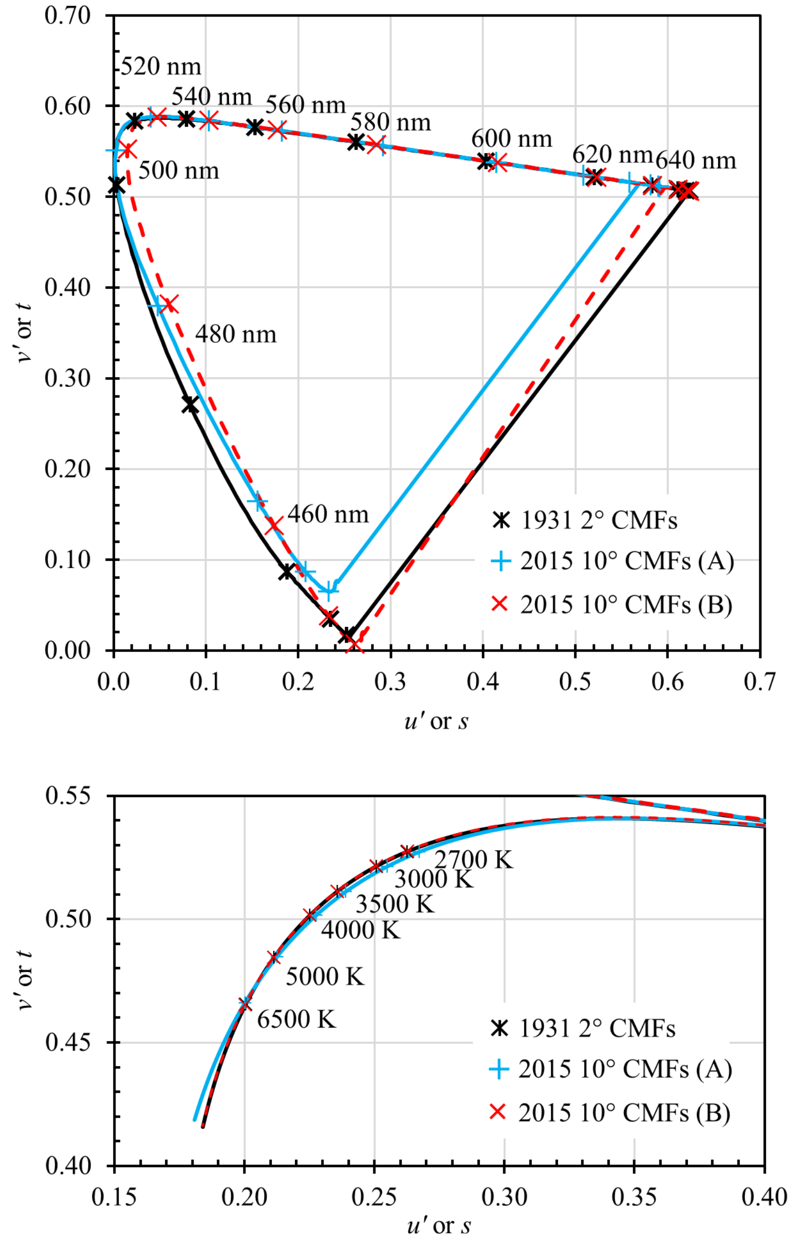


Figure 4. Comparison of the performance of two projective transformation option in replicating the chromaticity coordinates of reference features.

by evaluating the difference between two SPDs. For example, if the difference between 2700 K Planckian radiation and D65 for the current system is 1.00, the same difference would be 0.994 for (A) and 1.002 for (B). Other pairs reveal similar results.

CIE 170-2 (2015) also documents a MacLeod-Boynton chromaticity diagram, based on the standardized cone fundamentals. While more closely tied to physiology, recommending widespread implementation of this style of chromaticity diagram—which is not a UCS—would constitute a markedly greater departure from the existing standard system, and is therefore not something we suggest for architectural lighting practice. Nonetheless, the developed MacLeod-Boynton diagrams may be preferred in some scientific discussions.

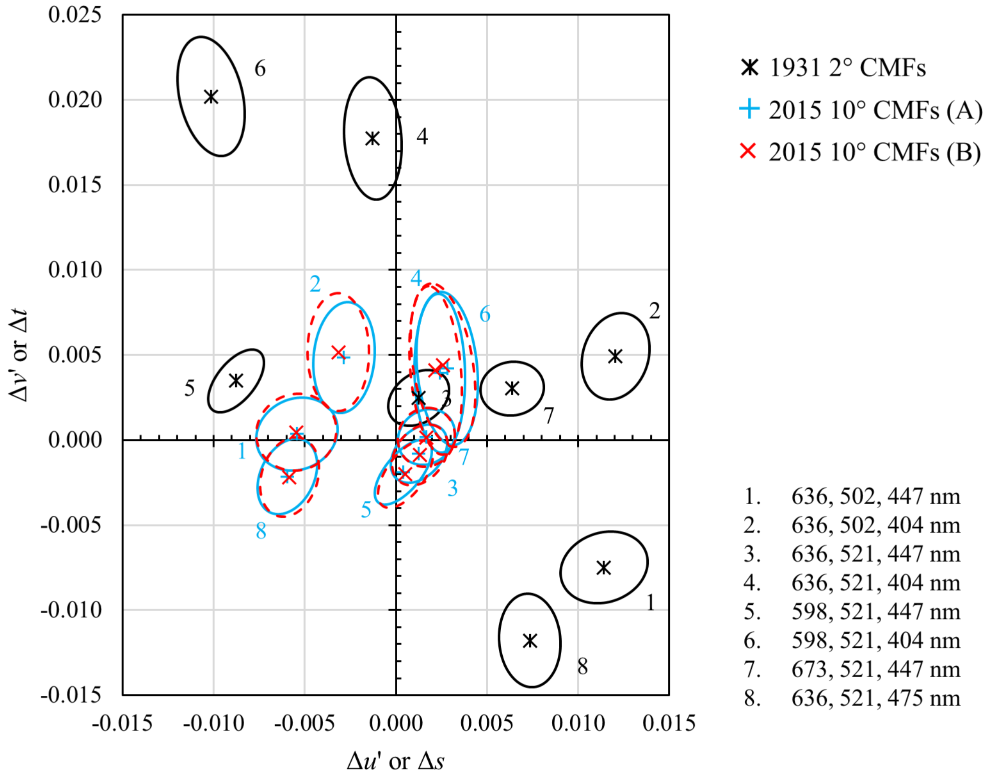


Figure 5. Mean chromaticity (center point) and 95% confidence interval (ellipse) for color matches made with eight different primary sets to a broadband reference (origin). The matches were made with a 10° viewing field by 54 observers who each made four matches to minimize starting bias. For each primary set, the ellipses were calculated using the 54 participants' mean chromaticity values. The primaries had peak wavelengths as identified. For additional explanation, see (Li et al 2021).

In summary, we recommend approach (A) using the existing projective transform of the 1976 (u', v') UCS diagram with the 2015 10° CMFs, renaming the coordinates (s, t) as defined in Equations 7 and 8. The coordinates could be (u'_{F10}, v'_{F10}), but it would be more cumbersome for widespread use in specifications than the simpler (s, t) notation. The proposal has the advantage of providing continuity with current standard practice, avoids the need to establish an optimized transform for each set of age- and field size-based CMFs in the 2015 system, and does not have a measurably detrimental effect on uniformity or chromaticity tolerances. The remainder of analyses in this article are based on this approach.

2.3 CCT and D_{uv}

Defining only the new (s, t) diagram would not necessarily aid a transition to new CMFs. To specify the chromaticity of light sources for general illumination, CCT and Duv are widely used, rather than the two numbers of chromaticity coordinates, such as (u', v'). Thus, to recommend the 2015 10° CMFs for lighting practice, it is necessary to introduce new CCT and Duv equivalents that are defined based on the new CMFs, potentially also changing the UCS diagram used in their calculation.

Wyszecki and Stiles (1982) noted that "a change…[from the 1960 (u, v) UCS diagram] to the [1976 (u', v') UCS diagram] was considered undesirable as the resulting change in the [CCT] scale would offer no advantage in practical applications….continuity of practice was considered more important." This decision has been questioned recently and stimulated some new research, the results of which favored the use of (u', v') though they were not definitive (Kwak et al. 2020, Oh et al. 2020). Given the present recommendation for a CMF change as well as the greater diversity of SPDs now available, we propose calculating CCTxx and Dxx in the (s, t) UCS diagram, with abbreviations CCTst and Dst as well as symbols T_{st} and D_{st}, as described in Table 1. This notation system will reduce the chance for confusion and avoid having multiple items denoted with a subscript. That is, the *st* suffix denotes use of *both* the 2015 10° CMFs and (s, t) UCS diagram used in the calculation. To reiterate, CCTst values are based on the nearest Planckian radiator in the (s, t) UCS—rather than the (u, v) chromaticity diagram—and thus lines of constant CCTst are perpendicular to the Planckian locus in the (s, t) diagram.

The differences between CCT/Duv and CCTst/Dst have two distinct origins. First, defining CCTxx and Dxx in the 1976 UCS diagram (denoted here as CCTu'v' and Du'v') using the 1931 CMFs results in changing values as shown in Figure 6 for the set of 1,528 real SPDs previously described. These changes are a function of chromaticity alone; that is, all SPDs with the same CCT and Duv (or u and v coordinates) shift the same amount, which is a consequence of the stretch of the chromaticity diagram. When Duv is positive Du'v' increases compared to Duv and CCTu'v' is decreased compared to CCT, whereas when Duv

Table 1. Summary of existing and proposed terminology.

Status	Written	Abbreviation	Symbol	Chromaticity Diagram	CMFs
Existing	Color temperature	CT	T_c	NA	NA
Existing	Correlated color temperature	CCT	T_{cp}*	(u, v) [u', $2/3v'$]	1931 2°
Existing	Distance from the Planckian locus	Duv	D_{uv}	(u, v) [u', $2/3v'$]	1931 2°
Proposed	*st*-based correlated color temperature	CCTst	T_{st}	(s, t)	2015 10°
Proposed	*st*-based distance from the Planckian locus	Dst	D_{st}	(s, t)	2015 10°
Proposed	Correlated color temperature	CCTxx	T_{xx}	Generic	Generic
Proposed	Distance from the Planckian locus	Dxx	D_{xx}	Generic	Generic

* Future consideration may be necessary to align existing notations with proposed use of subscripts to indicate the chromaticity diagram used for calculation.

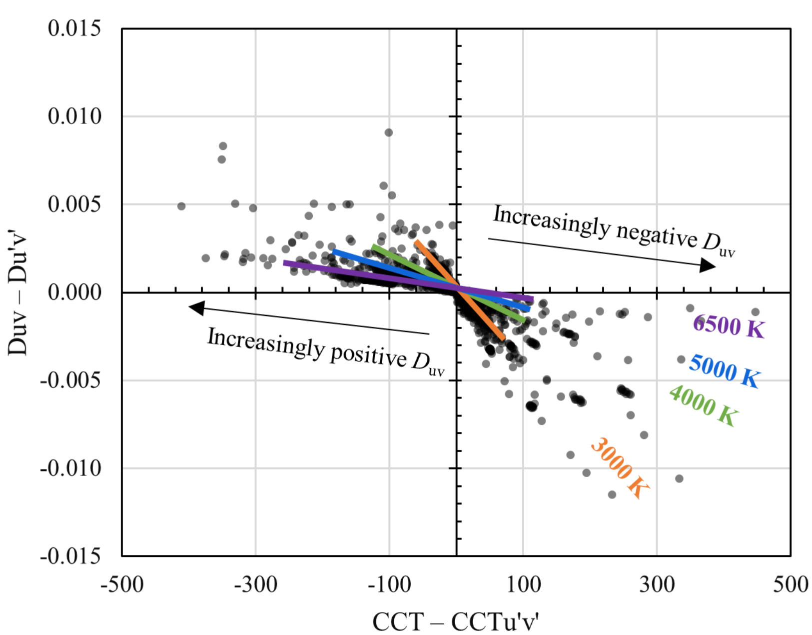


Figure 6. Changes to CCTxx and Dxx when changing the UCS diagram in which the values are calculated, with the 1931 2° CMFs held constant. The change is a function of CCT and Duv, not SPD.

is negative the opposite occurs. By definition there is no change in either measure for SPDs on the Planckian locus. For SPDs far from the Planckian locus, the scaling of the *v*' axis in 1976 UCS diagram compared to the *v* axis in the 1960 UCS diagram can mean that the closest point on the Planckian locus is a different part of the curve (*i.e.*, the nearest Planckian radiator is in a different direction and thus of a very different CCT). Eight extreme cases with CCT changes exceeding a magnitude of 500 K were found outside the range shown in Figure 6.

The change in CMFs leads to further changes in CCTxx and Dxx. Both are relative measures based on comparison to a Planckian radiator, but when CMFs change, non-Planckian SPDs almost always see some change in both values. This issue is more pronounced for SPDs that are more highly structured (*i.e.*, "spikey"). Figure 7 shows differences between CCTu'v' and CCTst as well as Du'v' and Dst for the set of 1,528 real SPDs and the subsets of 827 pcLEDs and 453 cmLEDs. These differences are due to the CMF change only, and can be quite large, particularly for Dxx. Changes perpendicular to the Planckian locus (pinkish-greenish) dominate, which contrasts Figure 6, where CCT changes are a more prevalent result, stemming from the change in UCS diagram from 1960 to 1976 with the same CMFs. Park et al. (2020) documented why pink-green variation is more common with changes in CMFs. The CMF-induced changes for the pcLEDs are consistently in one direction (toward lower Dxx values), but the changes for the cmLEDs, which have more varied SPDs, are less predictable. Finally, Ohno et al. (2019) noted that the change in CCTxx increased with increasing CCT, but this is not the case here when evaluating mired (reciprocal megakelvin, MK^{-1}) shifts, which are more perceptually uniform (Wyszecki and Stiles 1982). The combined effects of the CMF change and projective transformation change on CCTxx and Dxx are documented in Figure 8 and Figure 9. Figure 8 demonstrates that the overall average change for the 1,528 SPD set is slightly toward a more negative Dxx and lower CCTxx but is highly dependent on the specific SPD.

We believe implementation of CCTst and Dst will produce more perceptually accurate results; in particular, Dst should be more consistent than Duv at describing perceived tint across the range of nominally white CCTxx values. Of course, the actual appearance of any light source does not change, regardless of the characterization; changing the characterization is intended to make it more closely align with the existing perception, aiding in the prediction of metamers. For example, the *st* system would more accurately characterize typical pcLEDs as slightly pinker than the current standard system—and slightly more pink than incandescent lamps—which aligns with the experimental evidence previously described (Park et al. 2020, Ohno et al. 2019).

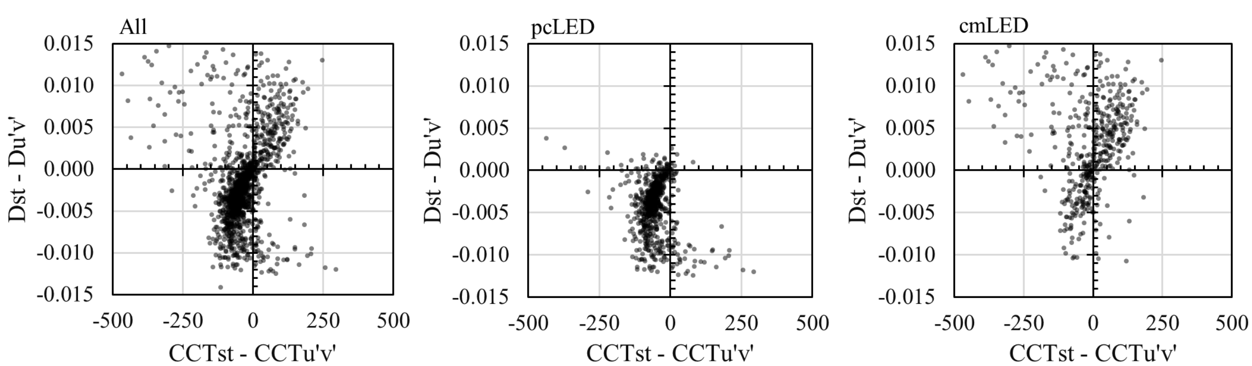


Figure 7. Difference between CCTst and CCTu'v' and Dst and Du'v' for 1,528 real SPDs (left) and subsets of 827 phosphor converted LED (pcLED) SPDs (middle), and 453 color-mixed LED (cmLED) SPDs (right). CCTst and Dst were calculated with the 2015 10°, whereas CCTu'v' and Du'v' were calculated with the 1931 2° CMFs.

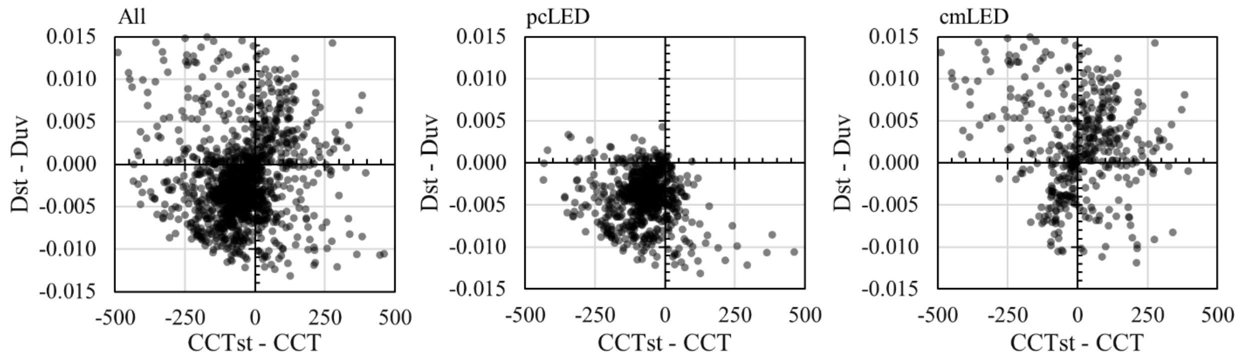
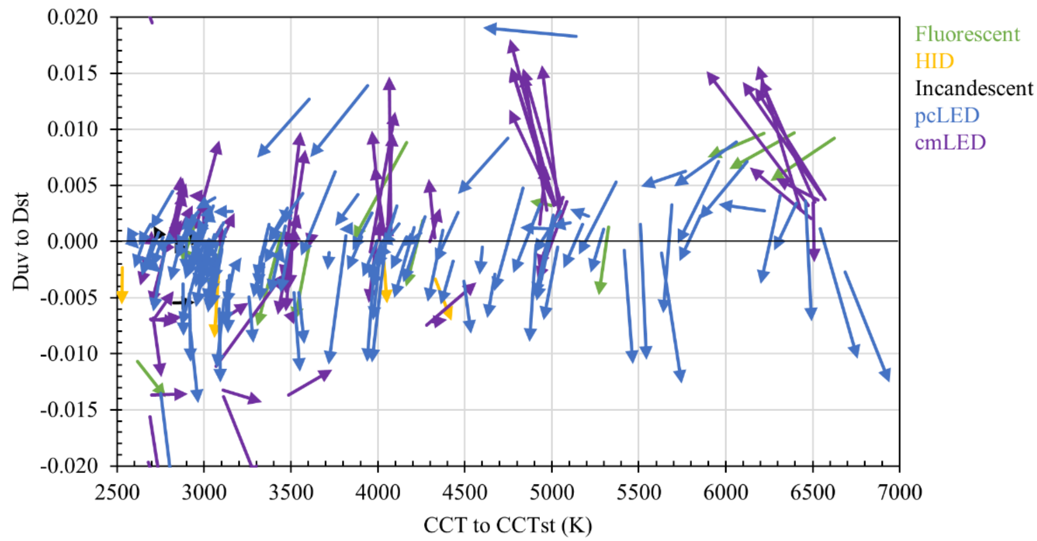


Figure 8. Total change from the current to the proposed system, or difference between CCTst and CCT and Dst and Duv for 1,528 real SPDs (left) and subsets of 827 phosphor converted LED (pcLED) SPDs (middle), and 453 color-mixed LED (cmLED) SPDs (right).



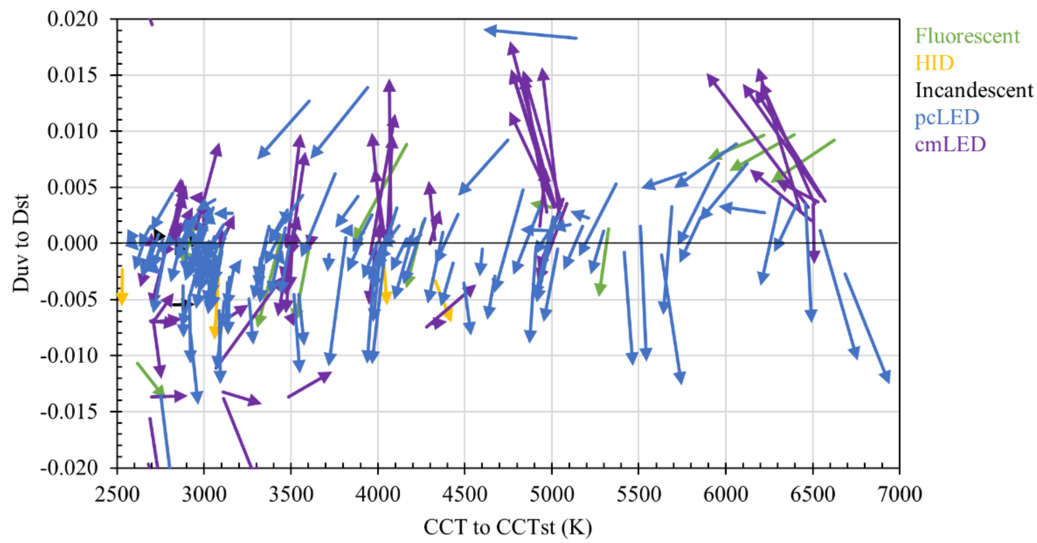


Figure 9. Change in values for the current standard to the *st* system for specifying CCTxx and Dxx.

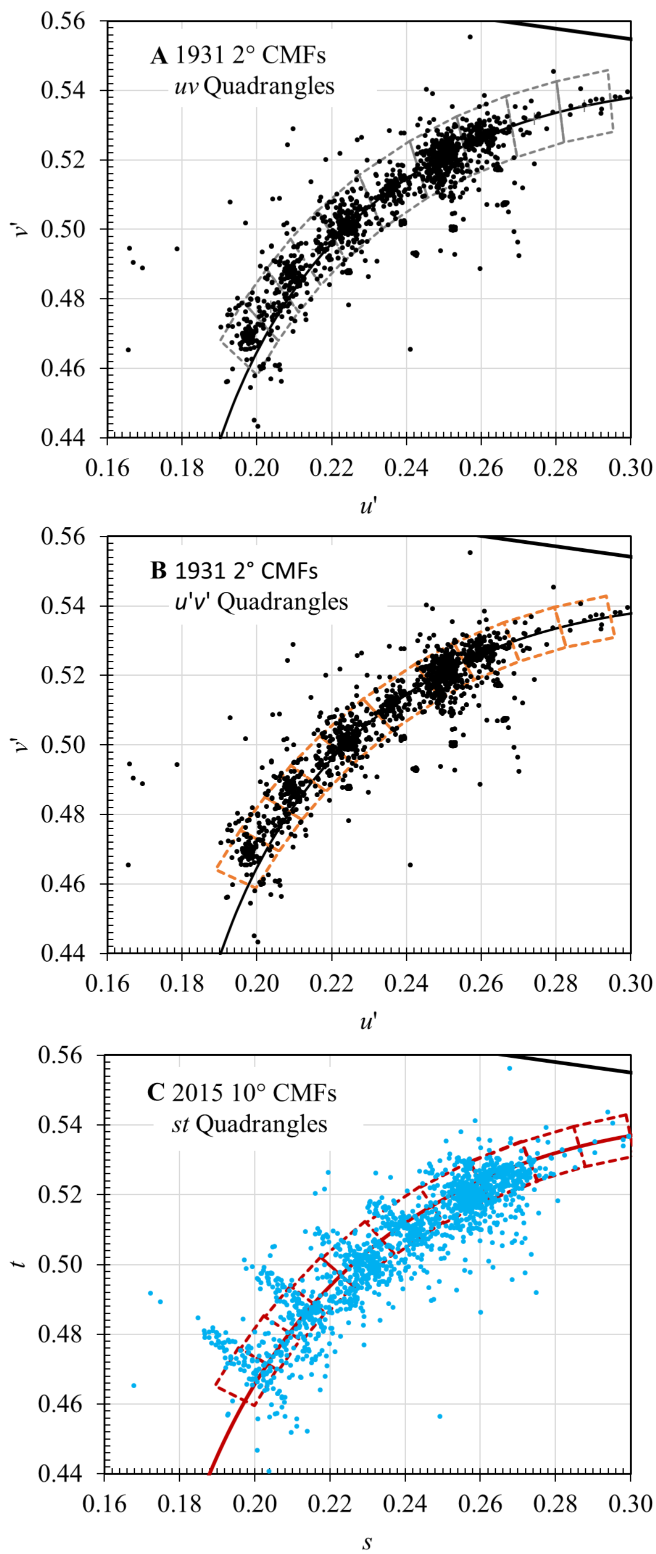


Figure 10. Interaction of quadrangles and CMFs. (A) Data using 1931 2° CMFs with existing quadrangles and CCT defined in the 1960 UCS. (B) Data using 1931 2° CMFs with new quadrangles defined in 1976 UCS using CCTu'v'. (C) Data using 2015 10° CMFs with new quadrangles based on CCTst and Dst.

Again, shifts in CCTxx and Dxx do not represent a change in the light sources, but a change in the colorimetric description. Therefore, if two light sources diverge from one another due to the proposed change in CMFs, it is not because they suddenly become different; it is because the difference between them was hidden by the use of CMFs that are less representative of typical color vision in typical architectural lighting applications.

2.4 Quadrangles and Binning

The quadrangles in ANSI C78.377-2017 are based on CCT and Duv such that the divisions are perpendicular to the Planckian locus in the 1960 (*u*, *v*) UCS diagram and skewed in the 1976 (*u*', *v*') UCS diagram, as shown in Figure 10A. Any changes to CMFs, chromaticity diagrams, or CCTxx and Dxx definitions will influence the position of specific SPDs relative to the quadrangle boundaries—which can also be varied. For example, if the definitions of CCTxx and Dxx were updated to use the 1976 (*u*', *v*') UCS diagram (without CMF change) while the CCTxx and Dxx tolerances specified in ANSI C78.377-2017 were held constant, 8% of the 1,528 real SPDs in the example set would change designation (Figure 10B). This is due to the effective shrinking of the bins, mostly in the Dxx direction, caused by the scaling of the vertical axis.

If a full update to the *st* system is to be implemented—remedying deficiencies (d) and (e) that were mentioned in the introduction—without adjustment to quadrangle tolerances, 35% of the SPDs in the real set would change designation (Figure 10C). There are only relatively small variations in this number for different light source technologies. The dominant factor in this comparison is the SPD-specific variation in chromaticity as the SPDs interact with the different CMFs, with the UCS diagram change playing a minor role. Field size is a major factor, with the 2015 10° CMFs causing a designation change for a far greater percentage than the 2015 2° CMFs (15%) in the same scenario. It is worth reiterating that the spread shown in Figure 10C is expected to be more representative of human perception—typical pcLED light sources often appear pinker than incandescent lamps of the same CCT in architectural lighting applications.

Given the ubiquity of pcLEDs, Figure 11 demonstrates their change with a focus on 4000 K for clarity. Here again, it is apparent that the *st* method characterizes these light sources as pinker than the existing method. Of the 120 SPDs in the group, 42 (35%) move out of the nominal designation quadrangle according to the *st* method, if no changes are made to the Dxx limits. In other words, if quadrangles with the same CCTxx and Dxx tolerances are used in the new *st* system, pcLED products designed to be at the center of the quadrangle would be more green than current products, and quadrangles would be effectively smaller. Such changes could be concerning because current LED products are well accepted in the market and a shift in the greenish direction is generally not preferred, especially at low CCTs (Ohno and Fein 2013; Rea and Freyssinier 2013;Dikel et al. 2014; Smet 2018).

Having a substantial percentage of SPDs change nominal classification may be a concern for some lighting manufacturers. Resizing and repositioning of the quadrangles for the *st* system could be considered if the *st* system is introduced to the ANSI C78.377 specification, with the exact changes depending on the desired effect. For example, the "target" Dst values (*i.e.*, the center of the quadrangles) could be shifted to a Dst of approximately -0.003 to address the average change for pcLEDs. This could be done at all CCTst values, or in a graduated fashion, with more of a shift for lower CCTst quadrangles. Both options would substantially reduce the number of SPDs that change nominal classification but would also mean that the target Dst differs from an incandescent lamp. Another option for target Dst values would be the ANSI/IES TM-30-20 reference illuminant coordinates, which would create a more unified system for evaluating color quality. The desirability of each of these solutions depends in part on individuals' beliefs on whether matching Planckian radiation or having negative Dxx

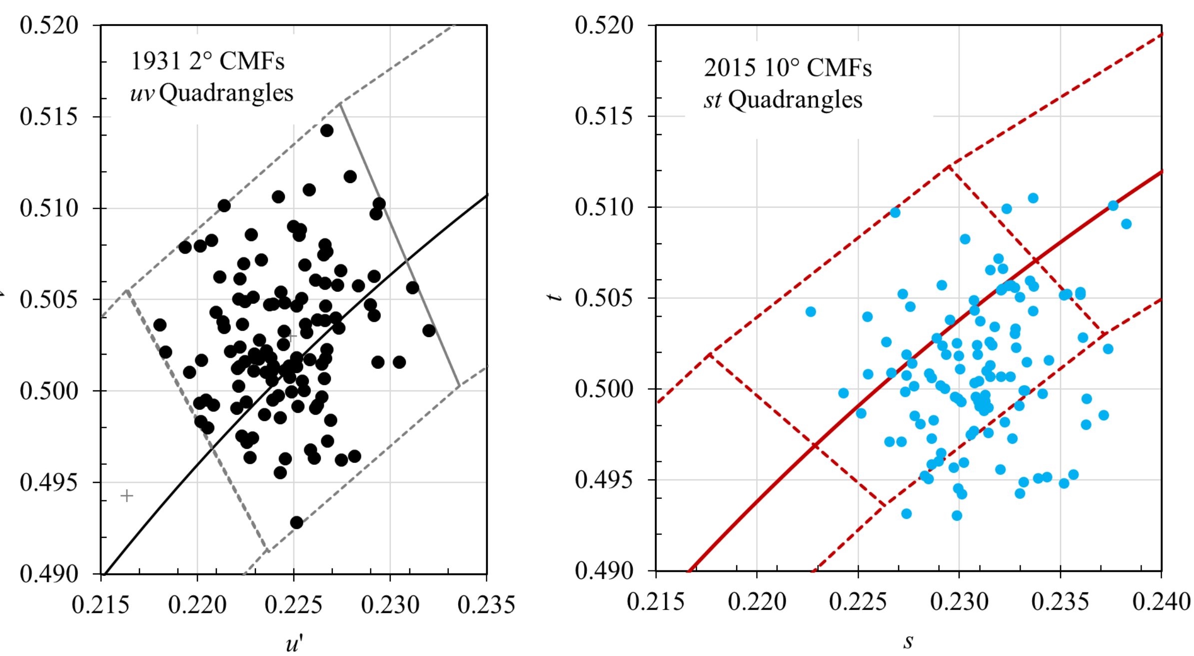


Figure 11. Comparison of current and proposed (*st*-based) methods for classification of pcLEDs (nominally 4000 K in current system).

values are the best approach for architectural lighting products, and there is significant disagreement on this topic.

2.5 Tolerances

We concur with the recommendations made in CIE TN001:2014 that chromaticity circles—in this case *st* circles—be used to specify chromaticity tolerances, and Δst be used for chromaticity change or difference. This is in lieu of specifying these items in terms of MacAdam ellipse steps, or related terms like standard deviation of color matching (SDCM) or just noticeable difference (JND). For conceptual scaling, a one-step MacAdam ellipse can still be approximated by a distance of 0.001, which would be in (s, t). All points within a circle with a *diameter* of 0.001 would be within a one-step MacAdam ellipse. The noticeability of difference is highly context dependent. As with all color vision phenomena, there is substantial inter-observer variability, which obviates the need for greater precision.

Some may question whether chromaticity tolerances when matching with a 10° field of view are equivalent to those when matching a 2° field, which have been the basis for past recommendations. Brown (1957) found that matches made at 10° led to only slightly smaller sized tolerances compared to the original MacAdam ellipses. Likewise, there is no evidence that the 2015 CMFs lead to substantially different tolerances compared to their predecessors (Li et al. 2021; Li et al. 2021b) as shown in Figure 5. It must be recognized that any tolerance for visual discrimination in a chromaticity diagram is an approximation because discrimination ability can vary considerably with age (Li et al. 2021) surround (Brown 1952, 1957), SPD (Li et al. 2021), field size (Brown 1957), and observer (Brown 1957; Li et al. 2021b).

3. Discussion

3.1. A new system for chromaticity specification

In summary, this proposal to update the de facto standard method for evaluating and specifying the chromaticity of light sources includes:

- implementation of the CIE 2015 10° CMFs,
- use of a UCS diagram with symbols (s, t) that uses the same projective transformation as the existing (u', v') UCS diagram,
- calculation of correlated color temperature and distance from the Planckian locus in the (s, t) UCS diagram, and denoted CCTst and Dst, respectively,
- use of circles in the (s, t) UCS diagram to quantify chromaticity differences, and
- several options for nominal classification quadrangles, which warrant further discussion.

The 2015 CMFs have extensive supporting evidence, and their application in architectural lighting specification and development is promising. However, they have seen only very limited use in practice because critical quantities for light sources, such as CCT and D_{uv}, are defined based on 1931 2° CMFs. This proposal, which defines analogous quantities based on the 2015 10° CMFs, is a key step toward standardization and widespread implementation.

We recommend that appropriate lighting authorities consider standardizing the *st* system or otherwise formalize guidance for using updated methods for assessing chromaticity. Such efforts should also provide guidance on performing calculations tailored to a specific population of observers and viewing condition.

3.2 Implications for industry and practice

For some practical uses of the existing chromaticity specification system, such as choosing a CCT to establish the mood of an interior, updating the system will have little effect. For others, such as trying to match the appearance of light emitted from two luminaires with different SPDs or developing a new light source with minimal metameric mismatch to existing light sources, an updated system can be very beneficial. For example, lighting specifiers are often vexed by chromaticity mismatch when utilizing different products in a single space, such as pendants, downlights, and wallwashers; the improved *st* system, along with proper chromaticity tolerances, can reduce the mismatch.

Regardless of the characterization, the *perceived* chromaticity of products by real observers does not change, and there is the same distribution across observers. The difference is that with the current standard system, the calculated chromaticity for a standard observer may not fall at the center of the distribution. Theoretically, the current system may predict a match but the updated *st* system, which in theory places the calculated chromaticity closer to the center of the distribution of real observers, would not. Knowing this, a lighting manufacturer or specifier could appropriately engineer or choose products to reduce mismatch.

Another situation where having an accurate method for evaluating light source chromaticity is important is when researchers are examining SPD as a design variable (*e.g.*, color rendition experiments) but trying to hold the chromaticity constant. Many of the cmLED SPDs used in the analysis for this article came from this type of work (e.g., Royer et al. 2017; Royer et al. 2018; Esposito and Houser 2019; Royer et al. 2020). When matched using the current standard system with 2° CMFs, chromaticity mismatch was sometimes visually apparent to the experimenters even when the numbers indicated otherwise. Using the updated *st* method could greatly reduce the severity of the issue and would be more defensible if standardized.

It is worth reiterating that for typical pcLEDs, the proposed system generally indicates a slightly more pinkish/less greenish tint compared to the reference, which is consistent with anecdotal observation of their appearance compared to incandescent lamps. The implication is that the current standard system has been incorrectly assessing how well these SPDs match Planckian references, and that the proposed use of the 2015 10° CMFs exposes this mismatch. At the same time, experimentally derived neutral white points and preferred white points are below the Planckian locus, especially at lower CCTs, meaning the error in the chromaticity specification system may have produced a desirable result, excluding issues of mismatch. Future light source development with the proposed system will reduce the error between performance and intended color: if matching Planckian references is the goal, that can more readily be accomplished, as can producing neutral or preferred chromaticities. This will ultimately lead to products that better meet the expectations of consumers and specifiers.

Given the limitations of the existing standard system for specifying chromaticity, some lighting manufacturers have started to use various alternative systems as a workaround; this fragmentation causes miscommunication and uncertainty. The current state of practice justifies our recommendation to standardize an improved chromaticity specification system for widespread use, comprising simultaneous updates for all components of the system. This single update would avoid continued disruption that would arise from incremental changes and a non-unified system in which different CMFs and chromaticity diagrams serve different purposes. It will be important to plan a phase-in period during which the existing and new systems could be used simultaneously, which will require careful use of the *st* notation to indicate the updated quantities (see Table 1). Eventually, the existing standard system should be dropped altogether because of its undisputed significant shortcomings.

3.3 Limitations and Future Research Opportunities

Additional research that would support future recommendations is warranted. This does not suggest that the present recommendation for an upgrade is premature, as there is already clear benefit to be had. One potential line of inquiry is further investigations of large field CMFs. Another is understanding how individual color matching varies with field size, because current literature requires comparing field sizes across different people. Finally, work is needed to produce better guidance on chromaticity tolerances in architectural lighting applications, expanding on what is known about a just noticeable difference in controlled laboratory conditions with trained observers. An improved chromaticity specification system will aid this development.

The proposal's implications have been studied in-depth for white light, and the *st* system is expected to be an improvement for colored light because the CMF benefits are universal. However, performance of the *st* system for colored light has not been thoroughly investigated.

One note of caution is that the ability to create analogous chromaticity coordinates with a variety of CMFs does not imply that the chromaticity differences calculated *between* diagrams are meaningful. Comparing differences relative to a reference is a better approach. Adaptive visual processes are constantly working to produce stable visual images, and chromaticity is a simple model that cannot account for these complexities. Its best use is as a tool for understanding match in appearance under equal viewing conditions.

None of the improvements examined in this article address the important issue of inter-observer variability. However, a more accurate system for quantifying chromaticity will assist in the development of a new measure(s) of observer-induced metameric mismatch. The new measure could evaluate the ability of SPDs to appear the same across a wide range of observers, which could be a very desirable trait. As illustrated by the data presented in this article, this ability is to some degree related to the smoothness of the SPD, because more discontinuous or highly structured SPDs exacerbate the small differences in CMFs, which can occur between people.

4 Conclusions

An updated system for specifying chromaticity has the potential to improve lighting quality by better ensuring chromaticity matches between different SPDs. The first step in the process is to implement new color matching functions (CMFs), and we recommend the 2015 10° CMFs because they are more representative of the population of observers and the field of view for general purposes in typical architectural environments. Once the decision is made to change CMFs, other components of the chromaticity specification system should likewise be updated. We propose, for consideration by appropriate lighting standards organizations, a new (*s*, *t*) uniform chromaticity scale (UCS) diagram, which can be used to calculate *st*-based correlated color temperature (CCTst) and *st*-based distance from the Planckian locus (Dst), new quadrangles to be used for the nominal classification of white light, and chromaticity difference tolerances for architectural lighting applications.

The proposed *st* system builds upon existing CIE standards and is supported by empirical evidence regarding chromaticity mismatch of nominally white light. We believe the system can perform well across the full range of chromaticity, supporting the engineering and specification of architectural lighting. It is envisioned as the standard for product rating, while alternative CMFs that match specific viewing conditions and observers can still offer optimized performance in specialized situations.

Author Contributions

Conceptualization AD LW KS | **Investigation** LW MM MR KS | **Methodology** AD JL KH KS LW MM MR TE | **Project Administration** JL LW MR | **Software** LW MM MR KS | **Investigation** LW MM MR KS | **Visualization** MR KS | **Writing – Original Draft** MR | **Writing – Review and Editing** AD JL KH KS LW MM MR TE YO

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References

Asano Y, Fairchild MD. 2020. Categorical observers for metamerism. Color Res Appl. Online before print. doi:10.1002/col.22493.

Asano Y, Fairchild MD, Blondé L. 2016. Individual colorimetric observer model. PLoS One. 11(2). doi:10.1371/journal.pone.0145671.

Asano Y, Fairchild MD, Blondé L, Morvan P. 2014. Multiple Color Matches to Estimate Human Color Vision Sensitivities. In: Elmoataz A., Lezoray O., Nouboud F., Mammass D. (eds) Image and Signal Processing. ICISP 2014. Lecture Notes in Computer Science, vol 8509. Springer, Cham.

Asano Y, Fairchild MD, Blondé L, Morvan P. 2016. Color matching experiment for highlighting interobserver variability. Color Res Appl. 41(5):530–539. doi:10.1002/col.21975.

Borbely A, Schanda J, Borbély Á, Schanda J. 2004. Colour matching using LEDs as primaries. Color Res Appl. 29(5):360–364. doi:10.1002/col.20044.

Brill MH, Worthey JA. 2007. Color matching functions when one primary wavelength is changed. Color Res Appl. 32(1):22–24. doi:10.1002/col.20283.

Brown WR. 1952. The effect of field size and chromatic surroundings on colar discrimination. J Opt Soc Am. 42(11):837–844. doi:10.1364/JOSA.42.000837.

Brown WR. 1957. Color discrimination of twelve observers. J Opt Soc Am. 47(2):137–143. doi:10.1364/JOSA.47.000137.

Brown WR, MacAdam DL. 1949. Visual sensitivities to combined chromaticity and luminance differences. J Opt Soc Am. 39(10):808–834. doi:10.1364/JOSA.39.000808.

[CIE] Commission Internationale de L'Eclairage. 2006. 170-1: Fundamental chromaticity diagram with physiological axes. Part 1. Vienna, Austria.

[CIE] Commission Internationale de L'Eclairage. 2015. 170-2: Fundamental chromaticity diagram with phsysiological axes, Part 2: Spectral luminous efficiency functions and chromaticity diagrams. Vienna, Austria.

[CIE] Commission Internationale de L'Eclairage. 2014. TN001:2014: Chromaticity Difference Specification for Light Sources. Vienna, Austria.

[CIE] Commission Internationale de L'Eclairage. 2018. CIE 15:2018: Colorimetry. Vienna, Austria.

Csuti P, Schanda J, Petluri R, McGroddy K, Harbers G. 2011. Improved color matching functions for better visual matching of LED sources. Proc 27th Sess. Sun City, South Africa. Commission Internationale de L'Eclairage.

David A, Sahlhoff D, Wisser M. 2019. Human perception of light chromaticity: short-wavelength effects in spectra with low circadian stimulation, and broader implications for general LED sources. Opt Express. 27(22):31553. doi:10.1364/oe.27.031553.

David A, Smet KAG, Whitehead L. 2019. Methods for Assessing Quantity and Quality of Illumination. Annu Rev Vis Sci. 5(1):479–502. doi:10.1146/annurev-vision-091718-015018.

Dikel EE, Burns GJ, Veitch JA, Mancini S, Newsham GR. 2014. Preferred Chromaticity of Color-Tunable LED Lighting. Leukos. 10(2):101–115. doi:10.1080/15502724.2013.855614.

Emery KJ, Webster MA. 2019. Individual differences and their implications for color perception. Curr Opin Behav Sci. 30:28–33. doi:10.1016/j.cobeha.2019.05.002.

Esposito T, Houser K. 2019. Models of colour quality over a wide range of spectral power distributions. Lighting Research and Technology. 51(3):331–352. doi:10.1177/1477153518765953.

Fairchild MD. 2013. Color Appearance Models. 3rd ed. Chichester, United Kingdom: Wiley.

Hu X, Houser KW. 2006. Large-field color matching functions. Color Res Appl. 31(1):18–29. doi:10.1002/col.20170.

Kwak Y, Ha H, Ohno Y. 2020. Vision experiment on perception of correlated color temperature. 5th CIE Symposium on Color and Visual Appearance. Hong Kong. Commission Internationale de L'Eclairage.

Li J, Hanselaer P, Smet KAG. 2019. The impact of matching primary peak wavelength on color matching accuracy and observer variability. Color Imaging Conf. doi:10.2352/issn.2169-2629.2019.27.39.

Li J, Hanselaer P, Smet KAG. 2021. Impact of Color-Matching Primaries on Observer Matching: Part I – Accuracy. LEUKOS. Online before print. doi:10.1080/15502724.2020.1864395.

Li J, Hanselaer P, Smet KAG. 2021b. Impact of Color Matching Primaries on Observer Matching: Part II – Observer Variability. LEUKOS. Online before print. doi:10.1080/15502724.2020.1864396.

Lozano RD, Palmer DA. 1968. Large-field color matching and adaptation. J Opt Soc Am. 58(12):1653–1656. doi:10.1364/josa.58.001653.

MacAdam DL. 1942. Visual sensitivities to color differences in daylight. J Opt Soc Am. 32(5):247–274. doi:Doi 10.1364/Josa.32.000247.

MacAdam DL. 1971. Geodesic Chromaticity Diagram Based on Variances of Color Matching by 14 Normal Observers. Appl Opt. doi:10.1364/ao.10.000001.

[NEMA] National Electrical Manufacturers Association. 2017. ANSI/NEMA C78.377-2017 American National Standard for Electric Lamps—Specifications for the Chromaticity of Solid State Lighting Products. Rosslyn, VA.

Oh S, Kwak Y, Ohno Y. 2020. Vision experiment II on perception of correlated colour temperature. CIE Tutorials on Colorimetry and Visual Appearance. Commission Internationale de L'Eclairage. doi:10.25039/x47.2020.OP02.

Ohno Y. 2014. Practical Use and Calculation of CCT and Duv. Leukos. 10(1):47–55. doi:10.1080/15502724.2014.839020.

Ohno Y, Kawashima Y, Oh S, Kwak Y. 2019. Visual evaluation of CIE 2015 cone fundamental-based 10° colour matching functions for lighting applications. Proc 29th CIE Session. Washington, DC. Commission Internationale de L'Eclairage. doi:10.25039/x46.2019.OP69.

Ohno Y, Fein M. 2014. Vision experiment on acceptable and preferred white light chromaticity for lighting. Proc CIE 2014 Lighting Quality and Energy Efficiency. Kuala Lumpur, Malaysia. CIE x039:2014.:192-199.

Ohno Y, Oh S. 2016. Vision Experiment II on White Light Chromaticity for Lighting. Proc CIE Lighting Quality and Energy Efficiency. Melbourne, Australia. CIE x0422016.:175–184.

Oulton DP. 2004. The properties of multiple CMF determinations using alternative primary sets part II: A data unification methodology. Color Res Appl. 29(6):438–450. doi:10.1002/col.20069.

Park Y, Murdoch MJ, Fairchild MD. 2020. Observer metamerism: Why do [mis] matches of neutral appear pinkish or greenish?. In: Color and Imaging Conference 2020. Online Conference Society for Imaging Science and Technology. doi: 10.2352/issn.2169-2629.2020.28.2.

Rea MS, Freyssinier JP. 2013. White lighting. Color Res Appl. 38(2):82–92. doi:10.1002/col.20738.

Robertson AR. 1968. Computation of Correlated Color Temperature and Distribution Temperature. J Opt Soc Am. 58(11):1528. doi:10.1364/josa.58.001528.

Royer MP, Wei M, Wilkerson A, Safranek S. 2020. Experimental validation of colour rendition specification criteria based on ANSI/IES TM-30-18. Lighting Research and Technology. 52(3):323–349. doi:10.1177/1477153519857625.

Royer MP, Wilkerson A, Wei M. 2018. Human perceptions of colour rendition at different chromaticities. Lighting Research and Technology. 50(7):965–994. doi:10.1177/1477153517725974.

Royer MP, Wilkerson A, Wei M, Houser K, Davis R. 2017. Human perceptions of colour rendition vary with average fidelity, average gamut, and gamut shape. Lighting Research and Technology. 49(8):966–991. doi:10.1177/1477153516663615.

Royer M. 2020. Real Light Source SPDs and Color Data for Use in Research. Figshare. Dataset. doi:10.6084/m9.figshare.12947240.v1.

Smet KAG. 2018. Two Neutral White Illumination Loci Based on Unique White Rating and Degree of Chromatic Adaptation. Leukos. 14(2):55–67. doi:10.1080/15502724.2017.1385400.

Stockman A. 2019. Cone fundamentals and CIE standards. Curr Opin Behav Sci. 30:87–93. doi:10.1016/j.cobeha.2019.06.005.

Stockman A, Sharpe LT. 2000. The spectral sensitivities of the middle- and long-wavelength-sensitive cones derived from measurements in observers of known genotype. Vision Res. 40(13):1711–1737. doi:10.1016/S0042-6989(00)00021-3.

Thornton WA. 1973. A System of Photometry and Colorimetry Based Directly on Visual Response. J Illum Eng Soc. 3(1):99–111. doi:10.1080/00994480.1973.10732233.

[UN] United Nations. 2019. World Population Prospects 2019. https://population.un.org/wpp/ <Accessed June 2021>

Vos JJ. 1978. Colorimetric and photometric properties of a 2° fundamental observer. Color Res Appl. 3(3):125–128. doi:10.1002/col.5080030309.

Wyszecki G, Stiles WS. 1982. Color science. Vol. 8. New York, NY: Wiley.

Supplement 1:
Comparison of CIE 2015 2° and CIE 2015 10° Color Matching Functions

In the manuscript, we proposed that 10° color matching functions (CMFs) are the most logical choice for describing the chromaticity of products intended for use in architectural lighting applications with typical viewing geometries. Consequently, we did not provide data regarding the performance of the CIE 2015 2° CMFs as an alternative basis for an updated chromaticity specification system. This supplement addresses the 2015 2° CMFs.

Figure S1-1, in conjunction with Figure 3, demonstrates a smaller change in chromaticity coordinates between the 1931 2° CMFs and 2015 2° CMFs (mean difference *u'v'* - *st* = 0.0037) than between the 1931 2° CMFS and 2015 10° CMFs (mean difference *u'v'* - *st* = 0.0068) shown in Figure 3. This is principally due to smaller shifts in the Dxx direction (pink-green axis), rather than reduced changes to Txx. This is consistent with the reported findings that the change to the *st* system with the 2015 10° CMFs most strongly shifts characterization along the pink-green Dxx axis.

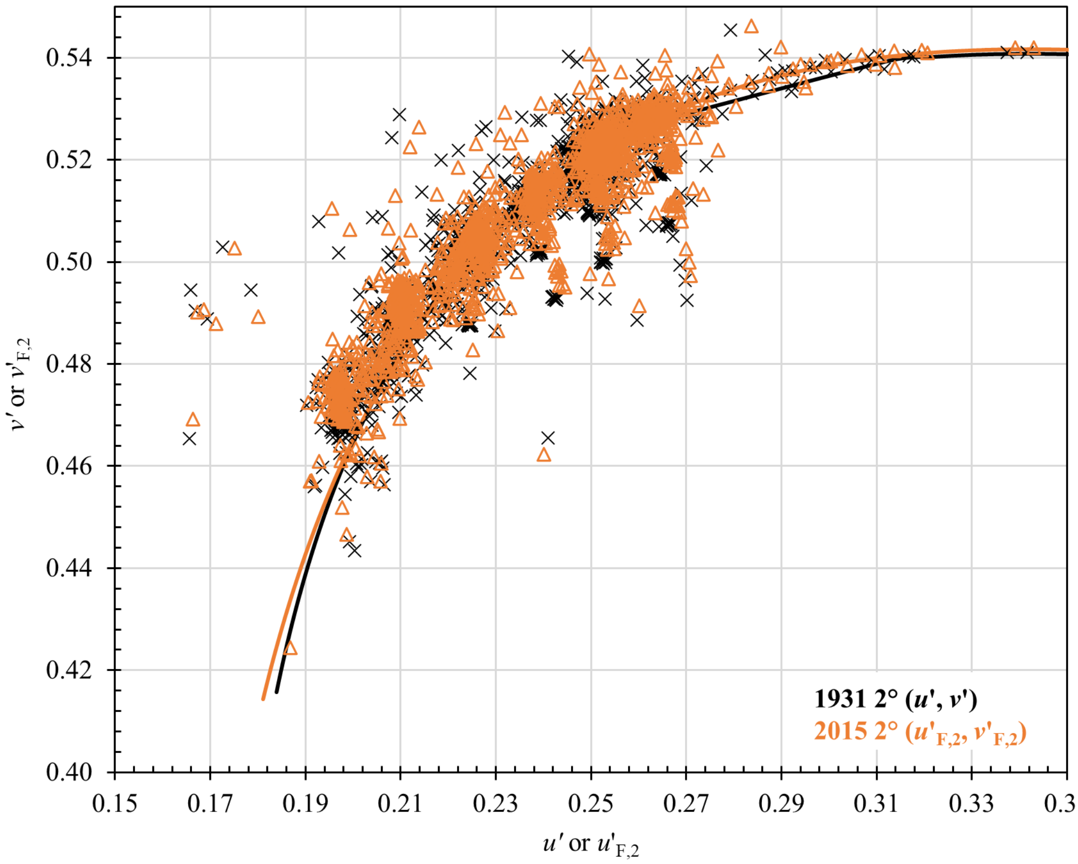

Figure S1-1. Analogous to Figure 3, change in position for chromaticity coordinates calculated using the 1931 2° CMFs and 2015 2° CMFs, both with the same projective transform.

The most important result is whether the 2015 2° CMFs or 2015 10° CMFs offer better predictions of perceived chromaticity match. Figure S1-2, which is similar to Figure 5, demonstrates that while the 2015 2° CMFs are an improvement over the 1931 2° CMFs, they are substantially outperformed by the 2015 10° CMFs for a 10° field of view matching task, using a variety of primary sets. In small field of view tasks (< 4°), we expect the 2015 2° CMFs will perform better than the 2015 10° CMFs, as has been recently reported for an experiment on matching displays (Hu, Wei, and Luo 2020). Although there is a range of viewing conditions in architectural environments, as explained in the manuscript we believe 10° is more representative of the most prevalent general use viewing conditions, which are also ones that are critical to the perception of chromaticity match by general observers. We are hopeful that future light source development can reduce unintended observer-based metameric mismatch across all viewing geometries. We also recommended the use of alternative CMFs (*e.g.*, 2015 2°) for specific calculations with a known small field of view, even if this is not used for product rating.

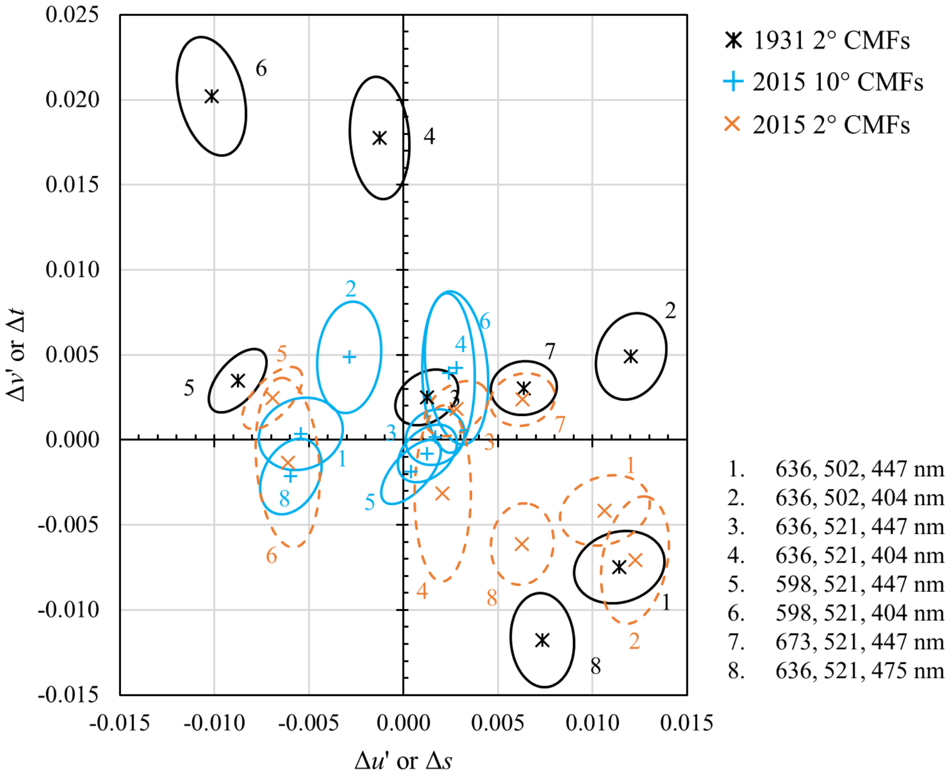

Figure S1-2. Analogous to Figure 5, mean chromaticity (center point) and 95% confidence interval (ellipse) for color matches made with eight different primary sets to a broadband reference (origin). The matches were made with a 10° viewing field by 54 observers who each made four matches to minimize starting bias. For each primary set, the ellipses were calculated using the 54 participants' mean chromaticity values. The primaries had peak wavelengths as identified. For additional explanation, see (Li et al 2021).

References

Hu Y, Wei M, Luo MR. 2020. Observer metamerism to display white point using different primary sets. Optics Express. 28(14):20305-20323. doi:10.1364/OE.395568

Li J, Hanselaer P, Smet KAG. 2021. Impact of Color-Matching Primaries on Observer Matching: Part I – Accuracy. LEUKOS. Online before print. doi:10.1080/15502724.2020.1864395.

Supplement 2:
Comparison of Projective Transformation Options (A) and (B)

This supplement provides additional data comparing options (A) and (B) for the projective transformation that converts tristimulus values generated with the 2015 10° CMFs to (*s*, *t*) coordinates. Table S2-1 summarizes differences (Euclidian distances) between (*u*', *v*') coordinates and (*s, t*) coordinates for alternatives (A) and (B) for:

- 391 spectral colors (390 to 780 nm in 1 nm increments),
- 39 Planckian radiators (2700 K to 6500 K in 100 K increments),
- 26 CIE D Series illuminants (4000 K to 6500 K in 100 K increments),
- and the set of 1,528 real SPDs, as described in the manuscript.

Alternative (B) successfully reduces changes to chromaticity coordinates compared to alternative (A). For example, the mean difference of (B) versus this existing standard system is about 50% of (A) for spectral colors, 10% for Planckian radiators, and 50% for D series illuminants. This is logical, given (B) was designed to minimize these specific changes. The benefit is considerably smaller for real SPDs, which are less smooth: the mean change with (B) is 75% of (A).

In contrast, (B) offers no benefit for reducing the range or mean change in Txx or Dxx. Table 2 documents the combined difference between CCT_{st} and CCT as well as D_{st} and D_{uv} for (A) and (B) considering the set of 1,528 real SPDs. Notably, the difference between using projective transformations (A) and (B)—$\overline{\Delta CCT}$ = -0.48, σ = 28; $\overline{\Delta D}$ = -0.00005, σ = 0.0002, not shown—is much smaller, roughly by an order of magnitude, than the difference between either one and the current standard. Given this finding, we elected to recommend (A).

Derivation of (B)

Projective transformation (B) was derived using a numerical optimization that aimed to minimize change to the chromaticity coordinates of both white illuminants and the spectrum locus. The optimization sequence began by using the existing projective transform coefficients (from Equations 7 and 8) as the initial starting values, with the objective of minimizing the shift in the coordinates of a set of spectral colors equally spaced in (*u*',*v*') (wavelengths 390, 455, 468, 475, 480, 485, 491, 498, 512, 540, 561, 576, 587, 598, 610, 627, and 780 nm). The resulting coefficients were then used as the initial starting values for a second optimization with the objective of minimization of the change in coordinates, with a weight of 0.9 on the difference in six reference illuminants (2750 K, 3200 K and 3800 K Planckian radiation; 4700 K blended Planckian and D Series from CIE 224 and IES TM-30; and 6200 and 9000 K D Series illuminants) and a weight of 0.1 on the difference in 40 spectral colors (390 to 780 nm in 10 nm increments). Matlab 2019b was used for both optimizations, the first using the *fminunc* optimizer, and the second using *fminsearch*.

Table S2-1. Change (Euclidean distance) in (*s*, *t*) chromaticity coordinates versus a (*u*', *v*') baseline for several SPD sets when using either (A) Equations 7 and 8 or (B) Equations 9 and 10 to convert from XYZ to (*s*, *t*).

SPD Set:	**Spectral Colors**		**Planckian Radiators**		**D Series**		**Real SPDs**	
Transform:	**(A)**	**(B)**	**(A)**	**(B)**	**(A)**	**(B)**	**(A)**	**(B)**
Minimum	0.0005	0.0000	0.0005	0.0000	0.0012	0.0007	0.0003	0.0002
2.5^{th} Percentile	0.0063	0.0001	0.0005	0.0000	0.0012	0.0007	0.0015	0.0006
Mean	0.0398	0.0190	0.0020	0.0002	0.0016	0.0008	0.0068	0.0051
97.5^{th} Percentile	0.1108	0.1056	0.0046	0.0003	0.0024	0.0009	0.0131	0.0122
Maximum	0.1167	0.1140	0.0047	0.0004	0.0025	0.0009	0.0214	0.0208
σ	0.0240	0.0255	0.0014	0.0001	0.0004	0.0001	0.0030	0.0031

Table S2-2. Summary statistics for 1,528 real SPDs for the combined difference in Txx and Dxx with change to the CMFs and the UCS diagram used for the calculation.

	CCTst - CCT		**Dst - Duv**	
Transform:	**(A)**	**(B)**	**(A)**	**(B)**
Minimum	-1121	-1412	-0.0225	-0.0201
2.5th Percentile	-375	-438	-0.0102	-0.0100
Mean	-56	-56	-0.0019	-0.0019
97.5th Percentile	216	232	0.0117	0.0112
Maximum	980	1300	0.0213	0.0204
σ	142	162	0.0051	0.0050