ASSIST *recommends...*

Guide to Light and Color in Retail Merchandising

Volume 8, Issue 1
March 2010

A publication of the Alliance for Solid-State Illumination Systems and Technologies

Lighting Research Center

Rensselaer

Published by the Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY 12180, USA. Online at http://www.lrc.rpi.edu.

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Introduction

Lighting plays an important role in supporting retail operations, from attracting customers, to enabling the evaluation of merchandise, to facilitating the completion of the sale. Lighting also contributes to the identity, comfort, and visual quality of a retail store. Ideally then, lighting should support the retailer's desired image and work in concert with other design components to promote sales.[1]

Architects, designers, store owners, and marketing professionals have recognized the power of light and color as prominent tools to support the goals of retail advertising and merchandising since the early days of electric lighting.[2] A recent survey of lighting designers and specifiers by the National Lighting Product Information Program showed that for retail applications, the color appearance and the color rendering properties of light sources were considered more important than any other criterion, including the luminous efficacy of the source.[3] Chapter 10 of the *IES Lighting Handbook*[1] is devoted to a discussion of what constitutes a high-quality visual environment. This chapter introduced the then-new IESNA Lighting Design Guide, which includes 18 design issues (criteria) to consider for the creation of high-quality visual environments. The design guide is divided by applications and ranks the design issues for each situation using four levels of importance, from *not important* to *very important*. For retail merchandising applications, color appearance is ranked *very important* more often than any other design issue for merchandising.

Color is not a physical property of objects, but rather a human perception enabled by light.[3] Nevertheless, the color of light sources is described by the industry primarily in terms of two metrics, correlated color temperature (CCT) and color rendering index* (CRI), that are only indirectly related to human perception. CCT is intended to characterize the appearance of the illumination generated by the source, and CRI is intended to characterize the appearance of objects illuminated by the source. These two color metrics, developed nearly a half-century ago, are increasingly being challenged because new sources are being developed with increasingly exotic spectral power distributions.[3-7]

This volume of *ASSIST recommends* discusses the two main color metrics used by the industry today and provides guidance as to how they each might be augmented to better use them in support of the design objectives for retail merchandising with new as well as traditional light sources. The companion publication, *ASSIST recommends…Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising* (Vol. 8, Iss. 2), offers specific guidance on how to specify light sources for a desired appearance of the illumination provided by the source and for good color rendering of objects illuminated by the source in retail applications.

Background

The term *color* can be used in two surprisingly distinct ways, one perceptual and one physical. First, color is used to describe the appearance of light or illuminated objects and is often used as a synonym for hue (e.g., red, blue, yellow).[3,7] Second, color can be used to quantify, in very simple terms, the spectral radiance distribution of a light source or of light reflected from an object. Color in this latter sense is a formal and internationally accepted method for

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* For the purpose of this document, CRI is used synonymously with general CRI, also denoted as R_a.[8]

characterizing light in strictly physical terms, and is known as *colorimetry*. Color in the former sense is always a contextual interpretation by a person's visual system of the spectral radiance distribution. This perceptual interpretation takes into account variables such as the individual's own photopigments, the size of the visual stimulus, the spectral radiance distribution of the stimulus surround, the light level, and the temporal-spatial properties of the visual stimulus. Because of the non-linear interactions among all these variables, it is very difficult to precisely predict color appearance and can be done so only under very specific conditions.[7,9] Colorimetry, however, is independent of all of these complicated factors and is strictly limited to characterizing the spectral radiance distribution of the light, independent of the context under which these objects are being illuminated and independent of the individual viewing the objects being illuminated. Both CCT and CRI are based upon colorimetry, so it should not be surprising that both are inherently limited in their ability to predict color appearance.

In 1931 the CIE adopted the first formal system of colorimetry, a simple computational procedure to quantify the color, in physical terms, of any spectral radiance distribution.[1,10-12] The CIE system of colorimetry is based upon the tri-chromatic nature of the human visual system, whereby the appearance of any light can be matched by the relative contribution of three so-called primary lights. The CIE system is based on the normalized contributions of three imaginary primaries known as the standard color-matching functions (the right panel of Figure 1). The spectral radiance distribution of any light source is multiplied by each of the three color-matching functions and then normalized so that the sum of the three products equals unity (i.e., 1.0). These color-matching functions are not based on human physiology or perception, but rather they are convenient mathematical constructs that allow any spectral radiance distribution to be specified simply in terms of a pair of planar (x,y) coordinates or a point in the left panel of Figure 1. In this system, the specific pair of planar coordinates that characterize the spectral radiance distribution of the light is referred to as its color or, more specifically, its chromaticity.

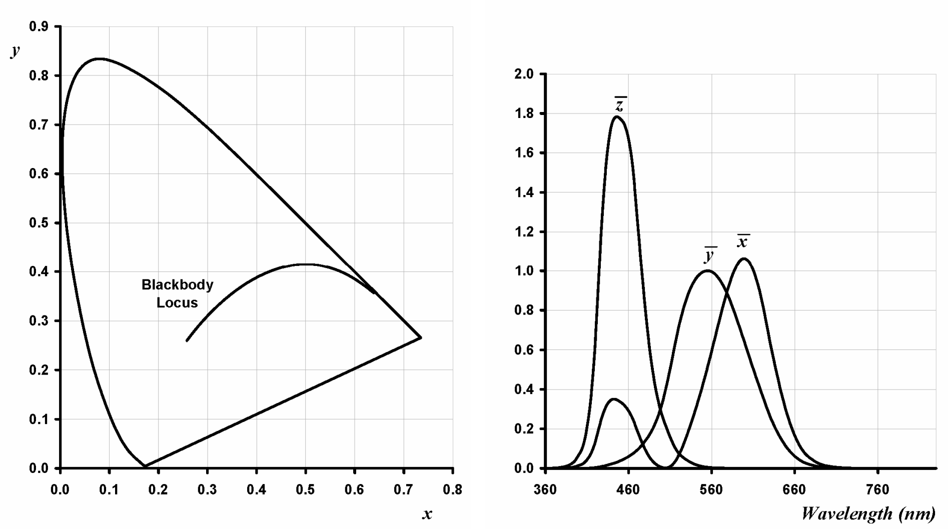

Figure 1. CIE 1931 (xy) chromaticity diagram (left) and the three color-matching functions used to derive x,y chromaticities (right).[13]

Although any system of colorimetry can only be an approximation of human color perception, the CIE transformed the x,y chromaticity diagram, first in 1960 and subsequently in 1976, to meet a specific goal; namely, to create a chromaticity diagram more consistent with the perception of *differences* among light sources of different chromaticities. In this revised system, a given distance between any two chromaticities is assumed to be of equal psychological or perceived difference. Equal psychological or perceived distances are measured in terms of "just noticeable differences (jnds)." The jnd is based upon controlled experiments with humans where two sources could be shown to be statistically different upon repeated trials where the observer was asked to say *either* "these two lights look the same" *or* "these two lights look different." The CIE 1960 (uv) and CIE 1976 (u'v') uniform color spaces are shown in Figure 2.[1,11]

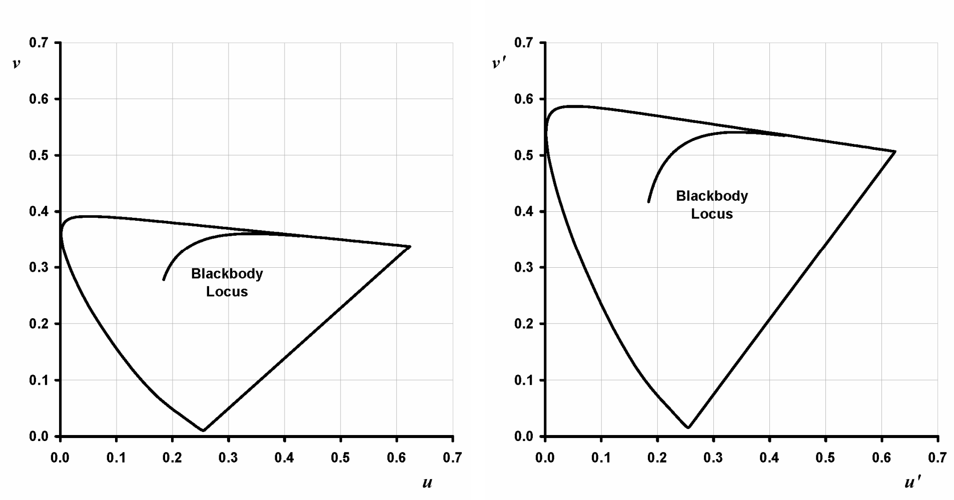

Figure 2. CIE 1960 (uv) (left) and CIE 1976 (u'v') (right) uniform color spaces.[1,11]

Again, colorimetry is, strictly speaking, independent of color appearance, but it nevertheless forms the foundation for the two most widely used metrics in the lighting industry to describe color appearance.[3] The appearance of the light emitted by a source is described in terms of its correlated color temperature (CCT), and the ability of that source to have object colors appear "natural" when illuminated by the source is described in terms of its color rendering index (CRI). The following sections describe these two metrics in more detail in the context of retail merchandising applications.

Objectives and Considerations for Lighting in Retail Merchandising

Two goals must be met when designing the lighting for retail merchandising:

- set the atmosphere of the store
- help customers evaluate the products for sale

The industry recommends CCT to help designers meet the first goal and CRI to meet the second. As already noted, both measures are based upon colorimetry and both have been used with some success over the past half-century in guiding practitioners toward meeting the two design goals. Since both metrics are based upon colorimetry, they are both an inherently incomplete specification of color appearance, so both are inherently limited for ensuring that these two design goals will in fact be met. The liabilities of CCT and CRI have become more evident as new lighting technologies appear on the market, but it is highly unlikely, given their long-standing use, that they will be soon abandoned by the industry. To help keep pace with light source developments, however, both CCT and CRI can be augmented to make it less likely that users will be disappointed in a) the appearance of the light generated by the source and b) the appearance of the objects being illuminated by the source.

Correlated Color Temperature

Correlated color temperature (CCT) is an indication of the color appearance of the light emitted by a light source. In practice, CCT ratings should be limited to "white" light sources used in general illumination (not sodium sources, for example). CCT is commonly understood to be and is used as an indication of the apparent "warmth" or "coolness" of the light emitted by a source.[1,3,12] Light from warm-white light sources appear yellow-white and will have a CCT between about 2700 K and 3500 K. Cool-white light is seen as blue-white with CCTs ranging from about 4500 K to 7500 K. Light sources with CCTs in the middle range (3500 K to 4500 K) are described as neutral-white. Many specific descriptive names have been proposed in the past to aid in the communication of CCTs of fluorescent lamps with little success in achieving meaningful descriptors or consistency among manufacturers.[5,14,15] Presently, the lighting industry formally refers to "warm white" (3000 K), "white" (3500 K), "cool white" (4000/4100 K), and "daylight" (6500 K), based on the standing version of the ANSI standard for the specification of chromaticities of linear fluorescent lamps.[16]

CCT is defined in terms of the chromaticity of a reference source, a blackbody radiator of a given absolute temperature, with the same color appearance.[10] The spectral power distribution, and thus the chromaticity, of a blackbody radiator can be precisely determined by its absolute temperature in kelvin (K) alone. Each of the chromaticity diagrams in Figures 1 and 2 includes the blackbody locus, the continuous line joining the chromaticities of blackbody radiators at different color temperatures in kelvin.[1,12] The chromaticities of practical light sources do not plot on the blackbody locus. Formally then, the CCT of a practical light source is defined in CIE 1960 uv space in terms of an imaginary line perpendicular to the blackbody locus that intersects with the chromaticity of the source under consideration.[†]

There are several problems with CCT as a measure of the color appearance of the light emitted by a source. First, CCT is a potentially confusing metric because higher color temperatures are associated with "cooler" color appearance, and lower color temperatures are associated with "warmer" color appearance.[5] This counterintuitive relationship between CCT and tactile sensation appears to be an artifact of the association people have between the radiant warmth and the yellow color of an open flame.

Second, CCT is a not a good representation of the color appearance of light emitted from a source having a chromaticity some distance from the reference blackbody locus. Fortunately, the chromaticities of most commercially available white light sources plot very near the blackbody locus, so light emitted from these sources will in fact look similar to light emitted by the corresponding reference source. Therefore, even though a CCT can be calculated for any light source, the farther its chromaticity is from the blackbody locus, the less meaningful CCT is in characterizing the appearance of the light emitted by that source.

[†] Because of the mathematical transformations among the different CIE color spaces, the isotemperature lines are not perpendicular to the blackbody locus in diagrams other than the CIE 1960 uv diagram.

Third, CCT is defined in terms of a line, not a point, in chromaticity space. Therefore, an infinite number of sources, each with a different chromaticity, can all have the same CCT. Figure 3 shows six isotemperature lines used to represent light emitted by commercially available linear fluorescent lamps. In this example, lamps A and B have the same 3000 K designation; however, their chromaticity points are located on opposite sides of the blackbody locus, meaning that their color appearances are likely to be different from one another, with one looking more pinkish while the other more greenish.

Fourth, CCT designations used by the industry are rather coarse, usually no finer than in 500 K increments. Thus, two lamps with the same designated CCT may look very different in a side-by-side comparison, even if both are quite close to the blackbody locus. This is a common problem, as illustrated in Figure 4.

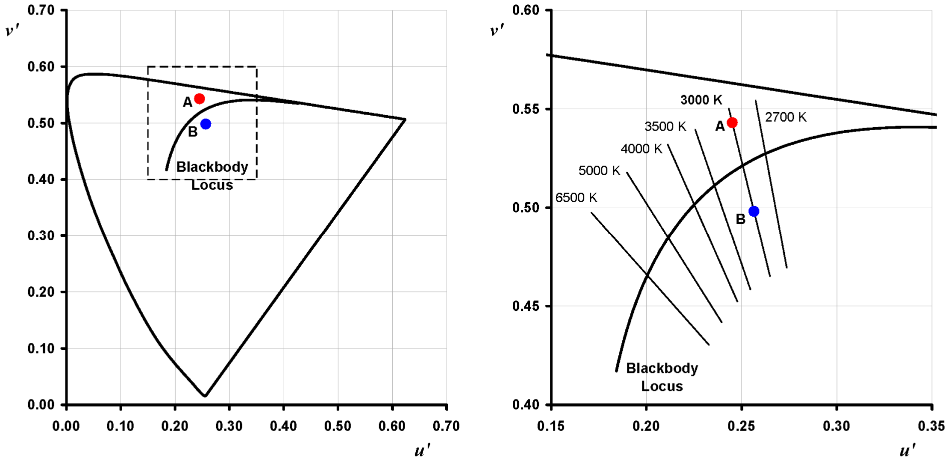

Figure 3. CIE 1976 (u'v') uniform color space showing six isotemperature lines to represent commercially available fluorescent lamps. In the example, light sources A and B have the same 3000 K designation in spite of their vastly different chromaticities (after Rea et al. 2004[3]).

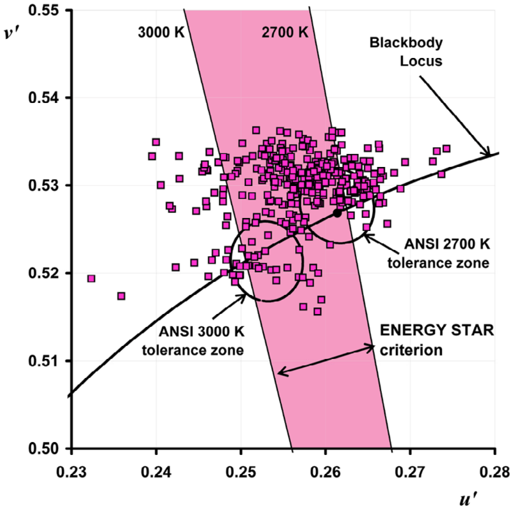

Figure 4. Chromaticities of 345 commercially available compact fluorescent lamps and the ANSI tolerance zones for linear fluorescent lamps of nominal 2700 K and 3000 K CCTs (after Rea et al. 2004[3]). Also shown for reference are the blackbody locus, and the 2700 K and 3000 K isotemperature lines, which are used to define the ENERGY STAR® criterion for compact fluorescent lamps.[17]

In practice then, it is necessary to augment CCT with a practical measure of a person's ability to discriminate between sources of the same nominal CCT but of different chromaticities, In this regard, the industry has created standard tolerance zones to augment six specific CCT values for linear fluorescent lamps, as illustrated in the left panel of Figure 5.[16] The tolerance zones, rooted in color discrimination experiments conducted in the early 1940s,[18] are approximately 8 jnds in diameter. Ideally, of course, the tolerance zones would be very small (e.g., 1 jnd), but their size reflects a consensus compromise between perceptual discriminability and manufacturing tolerances. Therefore, two linear fluorescent lamps of the same CCT, both having chromaticities within the tolerance zone, may still be seen as having different colors under some situations. For example, it is easier to discriminate between sources with slightly different chromaticities when they illuminate juxtaposed sections of a blank, white wall than when they are widely spaced and illuminate a colored and textured wall.[19,20] Despite this potential problem, this two-metric method of specifying the appearance of the light emitted by linear fluorescent sources has worked extremely well.

Recently, the American National Standards Institute (ANSI) and the National Electrical Manufacturers Association (NEMA) adopted a two-metric approach for solid-state lighting systems,[21] an approach very similar to the one used for linear fluorescent lamps. In this system, eight nominal CCT values are accompanied by quadrangle tolerance zones, as shown in the right panel of Figure 5.

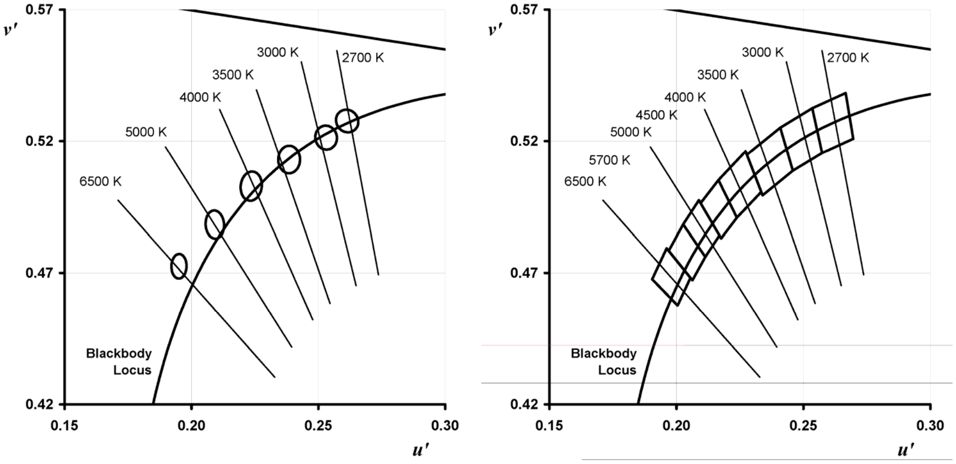

Figure 5. ANSI/NEMA specifications for the tolerance of linear fluorescent[16] (left) and solid-state light[21] lamp chromaticities (right).

These quadrangles are sized based on ellipses approximately 14 jnds wide. However, light sources plotting in opposite corners of the quadrangles would be approximately 24 jnds apart (Figure 6). As with the consensus process preceding the adoption of 8 jnds for linear fluorescent sources, this more liberal tolerance zone for solid-state lighting reflects poorer manufacturing tolerances than those associated with linear fluorescent lamps. It should also be noted too that this new set of recommendations for solid-state lighting products enables manufacturers to adopt nominal CCT values in 100 K steps between 2700 K and 6500 K, each with an accompanying 14 jnd (actually, 24 jnd) quadrangle tolerance zone. In practice then, there can be 39 CCT values provided by solid-state lighting manufacturers, each with its own liberal tolerance zone.

Undoubtedly, ANSI/NEMA's new set of recommendations will considerably improve the acceptance of solid-state lighting systems for retail applications where color appearance of the illumination is such an important aspect of marketing and sales. It remains to be determined, however, whether the very large (up to 39) number of nominal CCT values and the large tolerance zones will be sufficient for ensuring good practice for solid-state lighting in retail applications.

A companion document, *ASSIST recommends…Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising* (Vol. 8, Iss. 2), provides users with a slightly less complicated, yet more restrictive, method of specifying color tolerances for solid-state lighting products intended for retail applications.

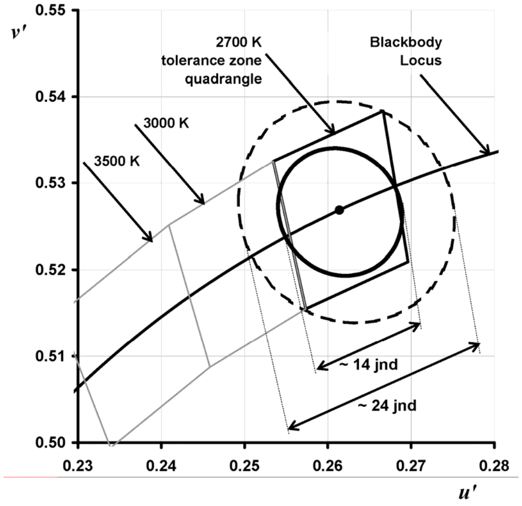

Figure 6. ANSI tolerance zone for solid-state light lamps with a nominal CCT of 2700 K.[21] The figure shows the 14 jnds-wide tolerance zone on which the ANSI 2700 K quadrangle is based, and a larger (24 jnds wide) tolerance zone needed to encompass all points within the quadrangle.

Color Rendering Index

Color rendering is a general term for describing the ability of a light source to provide color information to a human observer when objects are illuminated by that source.[3] In 1947, Bouma described the color rendering properties of daylight as those of an ideal light source.[22,23] “It (daylight) displays (1) a great variety of colours, (2) makes it easy to distinguish slight shades of colour, and (3) the colours of objects around us obviously look natural.” Bouma’s description is, in fact, an articulation of the important features of color rendering for any light source, not just daylight. Thus, any natural or fabricated light source with good color rendering should make everyday objects in architectural applications appear vivid and natural, it should provide good color discrimination between subtle differences in hue, and should, from a marketing and sales perspective, be preferred as a light source over one with poor color-rendering properties.[24,25]

Like CCT, color rendering index (CRI), the most widely accepted measure of color rendering[3], is based upon the system of colorimetry. General CRI is a measure of the change in chromaticity of special pigmented chips under two light sources of the same CCT, one an ideal reference source and the other the practical light source being assessed.[8] Small shifts in chromaticity result in high values of CRI; larger shifts result in lower scores. Eight or fourteen special chips are used for the chromaticity calculations. The special chips were chosen to represent different apparent colors within the chromaticity diagram (red, green, blue, etc.) when illuminated by a broadband source like daylight. CRI is a continuous scale from 100, the maximum possible, to less than zero. In practice, CRI ratings above 80 are considered to provide good color rendering and are recommended for retail applications. Sources with a CRI rating below 70 are not considered suitable for merchandising.

Although there have been several attempts to augment or even replace CRI, it has become the sole measure of the color rendering of light sources used by the industry today.[3,26-47] CRI was not designed, however, to measure all of the color rendering properties described by Bouma. Rather, CRI was developed, through the system of colorimetry, simply to be an indication of how "natural" or "undistorted" the light source makes the color of objects appear when illuminated by the source. Despite the clearly articulated limits of CRI,[26] and the previously described limitations of colorimetry to characterize color appearance, it has nonetheless become associated with *all* of the expectations about good color rendering outlined by Bouma. Therefore, when used as the sole measure of color rendering for a light source, CRI simply cannot meet these expectations. With the advent of SSL, these limitations have become more widely recognized.[47-50]

Although not widely acknowledged, an inherent problem with any measure of color rendering, not just CRI, is that it is a light source designation irrespective of the objects being illuminated. Without a specification of the object being illuminated, as well as the source providing that illumination, it is impossible to predict color appearance. Since any measure of a light source's color-rendering properties is obtained without regard for what will actually be illuminated, all measures of color rendering will inherently be metrics of compromise. Within the context of this compromise, a practical light source characterized as having "good" color-rendering properties should never disappoint the consumer nor proprietor of a retail store, no matter what is being sold (e.g., fruits, yarn, furniture) or what objects happen to enter the store (e.g., suits and dresses or skin and hair types). A light source that maximizes the appearance of a particular object color (e.g., red for hamburger in a meat case), will not be suitable for architectural applications because it will not meet all of the expectations for good color rendering articulated by Bouma. Rather, such a light source would be, *by definition*, a "poor" color-rendering lamp, even though it provided excellent color for one or a small set of objects.

Despite CRI's recognized limitations, and indeed the inherent limitations of any measure of color rendering developed without regard for the objects actually being illuminated, it is probably unreasonable to suppose the lighting industry, given CRI's long use, will abandon it as a metric of color rendering.[51] Indeed, it should be reemphasized that CRI has served the industry well over the last half-century. Only with the development of new SSL sources are more than a few specialists even aware that CRI has fundamental limitations.[47] Like CCT then, the well-established CRI metric of color rendering needs to be augmented to better ensure successful specification of light sources for retail merchandising.

Nearly 30 years ago, Thornton developed *gamut area* as a measure of color rendering.[27,52-54] Rather than consider the shift in chromaticity of the eight CIE standard reflectances, Thornton was interested in the separation of their chromaticities with the expectation that the greater the separation, the greater the saturation or vividness of colors. He also showed that, as one would expect, the greater the separation, the greater the discriminability between object colors, another measure of color rendering. Thus, the greater the separation of the eight standard reflectances, the greater the gamut area created by the light source (Figure 7). The problem with gamut area, however, is that objects illuminated by a source with a greater gamut area may now appear overly saturated and thus unnatural. Inherently then, gamut area and CRI are pulling in different directions: one metric emphasizes the stability of colors with respect to familiar light sources while the other metric is sensitive to the saturation of colors.

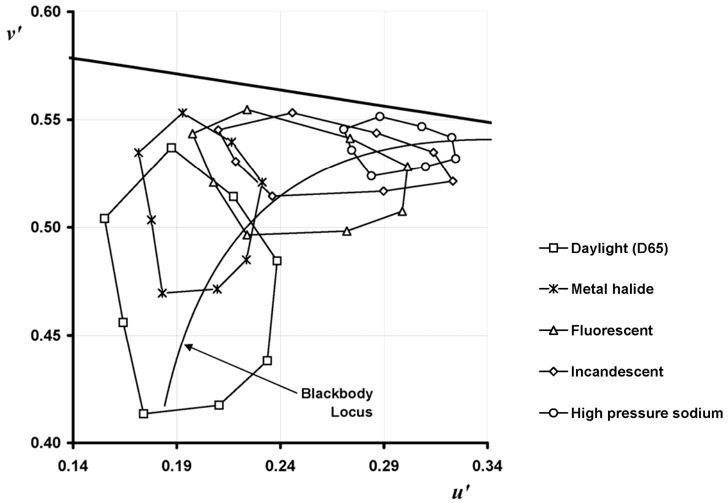

Figure 7. Gamut areas of metal halide, high-pressure sodium, fluorescent, incandescent, and CIE D65 standard illuminant simulating daylight of 6500 K (after Thornton 1972[27] and Boyce 2003[12]).

Recently, Rea and Freyssinier[25] proposed a two-metric system combining CRI, a measure of color consistency with respect to a reference source, with gamut area index (GAI), a measure of color saturation. When used together, the two metrics appear to optimize the color appearance of natural objects like fruits and vegetables, enhancing their vividness without making them appear unnatural.[25]

A companion document, *ASSIST recommends…Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising* (Vol. 8, Iss. 2), describes GAI and how to calculate it together with a calculation procedure for the more commonly used CRI.

Light levels

Finally, for good color appearance, light level must also be considered.[3,55] As already noted, color is not an inherent property of the object or the light source, but rather a physiological and psychological construct created from a person's own visual system. As such, it is necessary to have sufficient retinal irradiance for color perceptions to be formed. Given the two-metric criteria for (a) setting the atmosphere (CCT plus tolerance zones) and (b) evaluating merchandise (CRI plus GAI), illuminance levels for merchandising should usually be between 300 lx and 1000 lx, although levels between 3000 to 10000 lx are recommended for windows.[1] From an energy-use perspective, high light levels should only be used to illuminate the objects of interest when needed, not the entire retail environment.[1,56] Guidance on selecting light levels for retail applications can be found in Chapter 10 of the *IES Lighting Handbook*.[1]

Summary

Color appearance plays a major role in retail merchandising, both for setting the atmosphere in the store and helping customers evaluate products for sale. Achieving each of these retail goals requires a two-metric system, CCT plus tolerance zones for the first goal, and CRI and GAI for the second. The companion document, *ASSIST recommends…Recommendations for Specifying Color Properties of Light Sources for Retail Merchandising* (Vol. 8, Iss. 2), offers specific guidance on how to specify light sources for retail applications.

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Acknowledgments

ASSIST and the Lighting Research Center would like to thank the following for their review and feedback during the development of this publication: John Bullough and Patricia Rizzo.

About ASSIST

ASSIST was established in 2002 by the Lighting Research Center at Rensselaer Polytechnic Institute to advance the effective use of energy-efficient solid-state lighting and speed its market acceptance. ASSIST's goal is to identify and reduce major technical hurdles and help LED technology gain widespread use in lighting applications that can benefit from this rapidly advancing light source.