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# The Class A Color Designation for Light Sources

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## Introduction

Lighting manufacturers currently rely on two metrics to communicate to consumers the color qualities of light sources used for general illumination. Color rendering index (CRI) is used to describe how well the light source reveals, or renders, the colors of illuminated objects, and correlated color temperature (CCT) is used to describe the tint of the illumination provided by the light source. Those manufacturers interested in selling “high-quality color” illumination are at a disadvantage for two reasons: first, most consumers do not understand the current metrics used to describe color, and second, the current metrics are not entirely useful for predicting color perception. To the first point, most consumers are not lighting specialists and are only concerned with lighting occasionally (e.g., when purchasing or remodeling a home), so it is not economically feasible for the industry to undertake educational programs about color for consumers (Horner 2012). To the second point, a wide variety of studies have shown experimentally that CRI is poorly correlated with color preference (ASSIST 2010; CIE 2007; Narendran and Deng 2002), and more recently, it has been shown that people prefer “white” illumination, which is unrelated to CCT (Rea and Freyssinier 2012).

Proposed here is a simple way to *inform* consumers about the color-rendering properties of a light source and about the tint of illumination that is intuitive and immediately obvious, thereby obviating expensive educational programs, materials, and labels related to color. The proposed “class A color” designation bundles several metrics shown to be predictive of viewer color preferences, and the designation is intuitively obvious to consumers as one connoting a high-quality light source for color.

## Fundamentals

The basic problem with CRI and CCT is that they are both based on orthodox colorimetry, a system of color measurement based upon color matching, not upon color appearance (CIE 1995, 2004; Rea 2000; Wyszecki and Stiles 1982).

Briefly, colorimetry is based upon the fact that any arbitrary spectral power distribution (SPD) can be matched perfectly to a unique mixture of three primary lights. By normalizing the amounts of the three primaries to sum to unity, it is possible to fully characterize the SPD of the matching light with the relative amounts of just two of the three primary lights. Thus, any SPD can be fully characterized in colorimetry with just a pair of chromaticity coordinates. Important for this discussion, however, is that chromaticity does not unambiguously describe color appearance. Indeed, light of a specific chromaticity may appear very different depending upon the person and the conditions under which the light is viewed.

Colorimetry is based solely upon the spectral characteristics of the light source. Apparent color is not. Color appearance depends not simply on the physical properties of the light but upon the visual infrastructure of the observer as well. Individuals with pre-retinal filters (e.g., cataract) or with only two cone photopigments will perceive a light differently than a young adult with all three cone photopigments. The amount of irradiance incident on an object also impacts its color appearance, even though the chromaticity is unchanged. Under very dim light levels, no hues (red, green, blue, etc.) can be perceived. Even at higher light levels where hue perception is possible, chromaticity does not predict color appearance. For example, the very same chromaticity can appear brown at low light levels and orange at high light levels. Most importantly, however, the spatial and temporal characteristics of the viewing conditions affect color perception. The same chromaticity can appear red or green, blue or yellow, depending upon the chromaticity placed next to it or seen prior to it. Therefore, it is inherently impossible to expect colorimetry, a color measurement system based upon color matching, to be predictive of color appearance.

Since both CRI and CCT are based upon colorimetry, they should not be expected to be, nor are they, predictive of color appearance. CRI is based upon the chromaticity shifts of eight (or 14) reference color chips when alternatively illuminated by a practical light source and by a reference light source. If there is a large net shift in chromaticity, CRI is low whether or not real objects (e.g., fruits and vegetables) illuminated by the practical source are seen as more appealing than when illuminated by the reference source. CCT is based upon the chromaticity of a practical light source with respect to the chromaticity of a reference source located on the line of blackbody radiation. Lights of exactly the same CCT but of different chromaticity can appear very different and none of them will necessarily appear "white," including the light with a chromaticity on the line of blackbody radiation.

Unfortunately, an accurate measurement system for color appearance under natural viewing conditions does not exist. Such a measurement system of color appearance would be inherently complex and distinctly non-linear. Cognizant of this problem, the industry has traditionally imposed a number of color appearance attributes onto the simple, additive system of colorimetry. These impositions on colorimetry have met with some, but not complete, success, as is the case for CRI and CCT. Proposed here for the "class A color" designation is a set of incrementally better, but still imperfect, impositions on colorimetry to better characterize the color-rendering properties and the apparent tint of illumination of a light source. By bundling these colorimetric metrics into a single color "class," consumers should be better able to choose light sources with "high-color quality" for general illumination.

## Experimental results

*"White" illumination*

Chromaticities associated with blackbody radiation are universally used as the reference points for all light source types used for general illumination (ANSI 2001, 2011). Implicitly, chromaticities along the line of blackbody radiation are considered to be "white" even though the perception of "white" illumination had never been formally studied. Recent research has shown that perceptions of "white" illumination do not in fact lie on the line of blackbody radiation (Rea and Freyssinier 2011). Figure 1 shows the line of minimum tint from Rea and Freyssinier while observers viewed an empty box illuminated to 300 lx by sources of different chromaticities. It is important to note that there is a chromaticity of minimum tint at *every* CCT tested from 2700 K to 6500 K and these chromaticities usually look more alike (i.e., "white") than chromaticities of the same CCT on the line of blackbody radiation (Rea and Freyssinier 2011).

Subsequent research (Rea and Freyssinier 2012) has shown that when asked to view a scale model of a residential scene illuminated by two light sources of the same CCT, subjects preferred the one that provided "white" illumination and not the "yellow" illumination generated by incandescent sources (Figure 2).

It is important to point out that sources along the line of minimum tint in Figure 1 are not metamers. They look very similar (i.e., "white"), but they do not look identical. Theoretically, these sources should all be ones where the outputs from the neural channels in the brain that define hue are minimized. In other words, neural outputs from both the yellow-blue (y-b) and red-green (r-g) color channels are minimized when subjects look at illumination provided by sources with chromaticities on the line of minimum tint in Figure 1. The "class A color" designation should help consumers

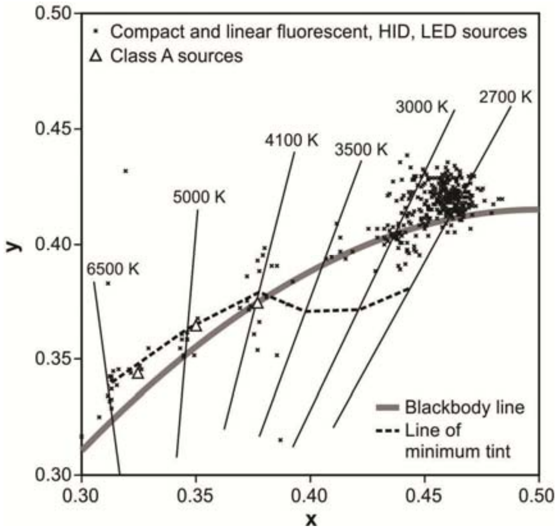


*Fig. 1: Line of minimum tint and chromaticities of selected commercially available light sources used for illumination (after Rea and Freyssinier 2011). Three "class A color" sources that provide both "white" illumination and good color rendering are indicated with open triangles.*

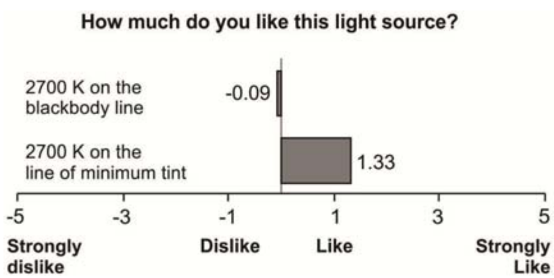


*Fig. 2: Preference ratings for two light sources of the same CCT but different chromaticities when used to illuminate a scale model of a residential living room (after Rea and Freyssinier 2012).*

choose "white" light for their homes, which they seem to prefer over "yellow" illumination from incandescent sources.

*Color rendering*

The industry has relied upon CRI as the primary metric for characterizing the color-rendering properties of light sources used for illumination since the 1960s. The developers of CRI, in particular Deane Judd (1967), pointed out that CRI could not be used as the only measure of color rendering. Rather, color rendering was a multi-dimensional construct whereby a single measure would not suffice to predict preference. Wide-spread use of solid-state lighting for illumination has made Judd's caution more acute. In fact, recent research has reinforced his early caution by showing that at least two-dimensions are necessary to predict user acceptance of color rendering (Davis and Ohno 2010; Rea and Freyssinier 2008, 2010; Smet et al. 2011; Žukauskas et al. 2011).

Observers prefer illumination that makes natural objects vivid without distorting colors. These responses are consistent with the inference that CRI can continue to serve as a practical, and certainly orthodox, measure of color fidelity, and that gamut area index (GAI) is a practical adjunct measure to CRI for characterizing the vividness of illuminated objects and color discriminability among illuminated objects (Rea and Freyssinier 2008, 2010). Neither metric alone will predict color preference, but combined they do. Several human factors studies with individuals from different cultural backgrounds have shown consistently that light sources with CRI equal or greater than 80 and GAI between 80 and 100 will meet the expectations of good color rendering. Figure 3 shows the results of these studies. Although there are subtle differences among cultures (e.g., people from Nordic countries prefer less saturated colors than those in South Asia), in general, two dimensions are better than one for predicting color preference. Therefore, a light source with a CRI equal or greater than 80 and GAI between 80 and 100 should meet the color-rendering requirements for a "class A color" light source.

**Practical examples**

Figure 1 also shows the chromaticities of a variety of commercially available light sources. Only three of those sources, two fluorescent and one HID, meet the proposed "class A color" designation. No commercially available "warm" light sources could be found that meet the "class A color" designation. Nevertheless, practical light sources with CCTs of 2900 K, 3000 K and 3500 K that do meet the "class A color" designation have been fabricated for laboratory purposes and could be developed for residential and commercial applications by manufacturers.

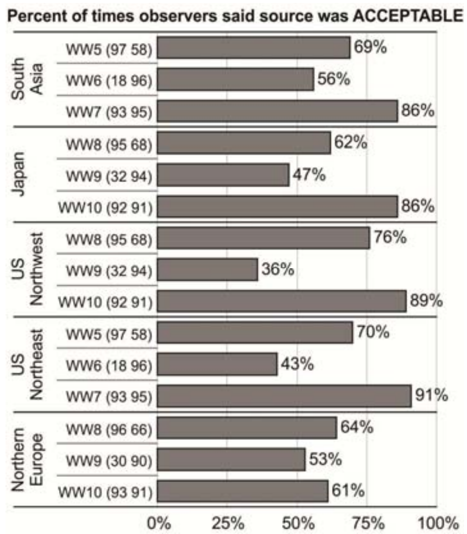


*Fig. 3: Acceptability ratings of "warm white (WW)" sources of illumination with different color-rendering properties from five subject populations. The numbers in brackets correspond to the CRI and GAI values of the light source, respectively.*

## Conclusions

Consumers have limited knowledge and sophistication about the color characteristics of light sources. The current metrics used by the industry, CRI and CCT, cannot be readily understood by consumers, and more importantly, they are not predictive of the color characteristics they purport to measure. The proposed "class A color" designation for general illumination ("*white" illumination with CRI≥80 and 80≤GAI≤100)* reflects a bundled set of metrics demonstrated to be predictive of color preference and should be readily understood by consumers. This simple method of communication should help manufacturers interested in selling, and indeed providing, sources of "high-quality color" general illumination to consumers.

## Acknowledgements

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