

LED Color Characteristics

Color quality is an important consideration when evaluating LED-based products for general illumination. This fact sheet reviews the basics regarding light and color and summarizes the most important color issues related to white-light LED systems.

LED Emission Attributes

Individual LED dies, often referred to as chips, emit light in a narrow range of wavelengths, giving the appearance of a monochromatic source. LED lamps and luminaires combine multiple spectral components, which may be produced directly or through phosphor conversion, to create a mixture that appears white to the human eye. In comparison, incandescent lamps have a broad distribution and fluorescent lamps typically rely on a limited, fixed set of phosphors with specific emission characteristics. Figure 1 compares the spectral power distributions of several light sources, adjusted for equal lumen output.

Creating White Light with LEDs

Currently, white light is most often achieved with LEDs using phosphor conversion (PC), but mixed systems that use a combination of colored LEDs [typically red, green, and blue (RGB)] are also available. For LEDs, phosphor down-conversion¹ is most commonly based on a blue or near-ultraviolet emitting die that is combined with a yellow-emitting phosphor, or a combination of different phosphors that produce a broad energy distribution. The phosphor(s) may be incorporated into the LED package, or may be located remotely. Fluorescent lamps also utilize phosphor down-conversion. Earlier versions of the technology relied on broad emitting halophosphors, but most current lamps, called triphosphor fluorescent, utilize a combination of red-, blue-, and green-emitting phosphors.

Mixed LED sources produce white light by mixing two or more colors, called primaries. Although only two primaries are necessary, such systems have very poor color rendition properties and therefore three-primary RGB systems are typically considered a minimum for acceptable performance. Additional primaries, such as amber, can be added to potentially improve the color characteristics, though efficacy is often sacrificed. This is analogous to the practice of adding additional phosphors to broaden the range of emitted wavelengths. Hybrid systems—which might combine PC LEDs with red LEDs, for example—are also possible. PC LEDs utilize the same color mixing principle, but combine a blue component with a broad phosphor emission. This results in a different

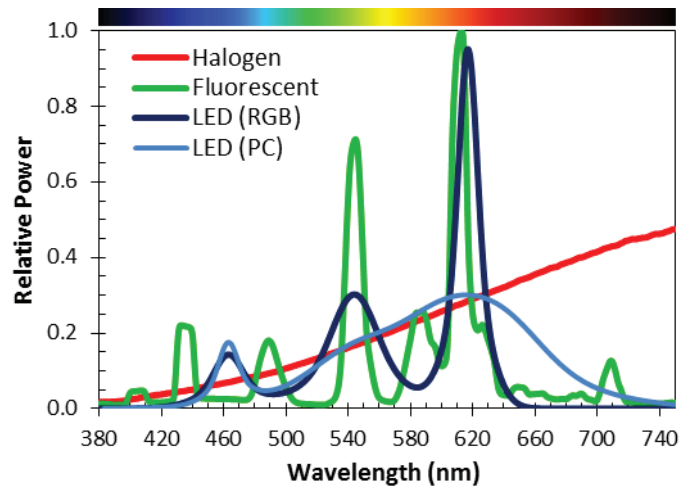


Figure 1. Due to the trichromatic nature of the human visual system, white light of equal appearance can be created with different spectral power distributions. This chart shows the spectral power distributions for four different light sources, all producing 2700 K white light with a CRI > 80.

spectral power distribution, although the light is still nominally white in appearance.

Mixed LED sources have a higher theoretical maximum efficiency, potentially longer life, and allow for dynamic control of color.² However, they generally have less color consistency both initially and over time, require more elaborate optical systems to ensure proper mixing, and are generally more complex and expensive to manufacture. Currently, mixed LED efficacy is typically lower than PC LED efficacy, limiting their use in general lighting applications. It is important to remember that even within a family of LED sources, or within the products offered by a given manufacturer, color characteristics can vary widely based on the choice of primaries or phosphors. Each individual product should be evaluated on its own merits, regardless of the technology.

Color Temperature

Color temperature is an important aspect of color appearance that characterizes how “cool” (bluish) or how “warm” (yellowish) nominally white light appears. Correlated Color Temperature (CCT) is a metric that relates the appearance of a light source to the appearance of a theoretical black body heated to high temperatures. As a black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source, given in Kelvin (K), is the temperature at which the heated black body most closely matches the color of the light source in question. It characterizes the color of the emitted light, not the color of illuminated objects.

¹ Phosphor down-conversion is the process by which a phosphor absorbs shorter-wavelength energy and emits it at a longer wavelength. This is also known as Stoke's shift.

² For more on the differences between PC and mixed LED systems, including future performance projections, see the Solid-State Lighting Research and Development Multi Year Program Plan, available from http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2011_web.pdf.

Like many color appearance metrics, CCT distills a complex spectral power distribution to a single number. This can create discord between numerical measurements and human perception. For example, two sources with the same CCT can look different, one appearing greenish and the other appearing pinkish (see Figure 2). To address this issue, the American National Standards Institute (ANSI) references Duv, a metric that quantifies the distance between the chromaticity of a given light source and a blackbody radiator of equal CCT.³ ANSI has established Duv tolerances for LED lighting products producing white light.

Today's LED systems can produce white light throughout the range of CCTs typically used in general lighting, including both interior and exterior applications. Due to differences in quantum efficiencies, higher-CCT LED sources tend to be more efficacious than lower-CCT alternatives within the same product family. Some mixed or hybrid LED products feature independent control of the different components to allow for dynamic adjustment of CCT.

Color Rendition

At least three aspects of color rendition are relevant to light source selection and application. These include the accurate rendition of colors so that they appear as they would under a familiar (reference) source, the rendition of colors such that objects appear more pleasing (often referred to as vivid or flattering), and the ability of a source to allow for a subject to distinguish between a large variety of colors when viewed simultaneously. For simplicity, these three facets of color rendering may be called fidelity, appeal, and discrimination. The relative significance of these different elements of color rendition depends on the application.

Color rendition metrics attempt to characterize human perception of one or more of these elements using numerical methods, but they are not perfect. Some of the imperfections of well-established metrics have been revealed by the emergence of LED lighting products, which often have spectral power distributions that are different from those that were common when the metrics were developed.

Color Rendition Metrics

Color rendition metrics have several distinct forms, including systems that use a comparison (reference) source, systems that are area based (gamut based), systems that are built upon advanced color appearance models, or systems that divide the visible spectrum into bands. While dozens of metrics have been proposed, only the International Commission on Illumination (CIE) Test-Color Method⁴ [most notably the Color Rendering Index (CRI)] has been officially adopted by a standards organization. CRI is a measure of fidelity (i.e., how “true” a light source is when compared to the reference source), but it does not address the other two aspects of color rendering listed above: appeal and discrimination.

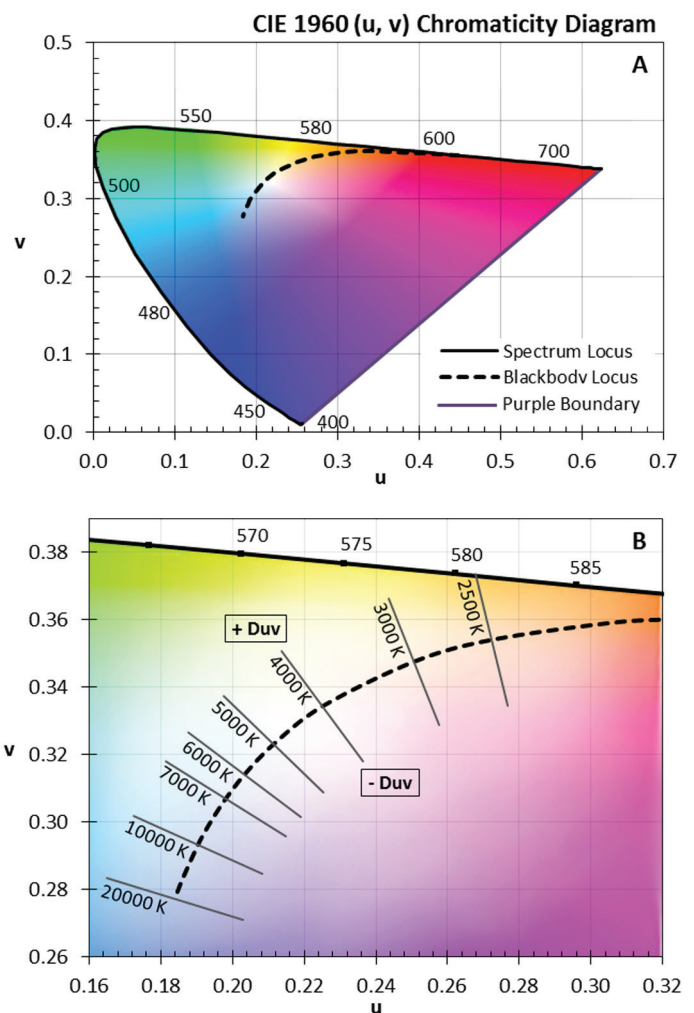


Figure 2. **A** – The CIE 1960 (u, v) chromaticity diagram, representing the Uniform Coordinate System (UCS) in which CCT, CRI, and Duv are calculated. A chromaticity diagram should not be interpreted as a two-dimensional map of color, since the bright-dim dimension (lightness) is not represented. Colored backgrounds, as are shown here, are for orientation only.

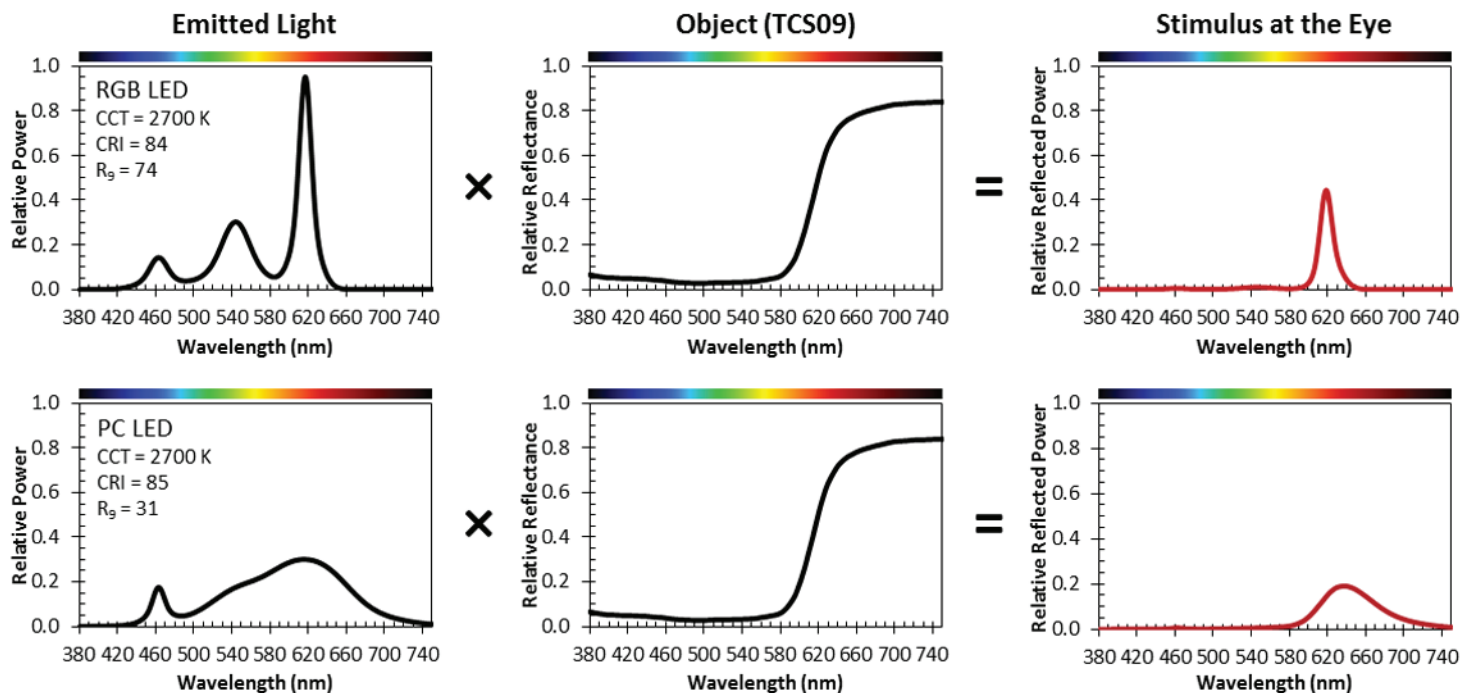
B – A close up of the CIE 1960 (u, v) chromaticity diagram showing lines of constant CCT, which are perpendicular to the blackbody locus. For a given CCT, a source with a positive value for Duv has a chromaticity that falls above the blackbody locus (appearing slightly greenish), whereas a source with a negative value for Duv has a chromaticity that falls below the blackbody locus (appearing slightly pinkish). The lines in this chart represent a Duv range of ± 0.02 , which is much greater than ANSI tolerances for white light. *Adapted from NIST data.*

The CIE Test-Color Method (a reference based metric) utilizes eight standard color samples—having moderate lightness and of approximately equal difference in hue (i.e., equal spacing on a chromaticity diagram)—and six special color samples (see Figure 3). For each color sample, the chromaticity under a given (test) source can be compared to the chromaticity under a reference

³ For complete information, see ANSI C78.377-2008.

⁴ For complete information and calculation instructions, see CIE 15:2004.

PERCEIVING COLOR



Objects are not inherently colored, but rather reflect different proportions of radiant energy. Thus, if the light incident on a surface changes, the apparent color of the object may change. Depending on the light source, this shift can be small or large. As shown above for example RGB and PC LED sources, the stimulus at the eye can be calculated by multiplying the spectral power distribution of a lamp by the reflectance distribution of the object (in this case TCS09, which is used to calculate R_9). The four boxes below are an approximate representation of the TCS09 color sample, as rendered by four different sources, including the two shown above.



source of equal CCT,⁵ allowing for the measurement of color difference that is then mathematically adjusted and subtracted from 100 (R_i). The principal metric of the CIE system is the Color Rendering Index (CRI), which averages the R_i scores for the eight standard test colors and typically has a range from 0 to 100, though negative scores are also possible. A score of 100 indicates that the source renders colors in a manner identical to the reference. In general, a source with a CRI in the 70s would be considered acceptable for interior applications, whereas the 80s would be considered good and the 90s excellent. Because it is a reference-based metric, comparing the CRI for sources with different CCTs should only be done with great caution. Furthermore, two light sources with the same CCT and CRI may not render colors the same way (i.e., colors may still look different).

The special color rendering indices, referred to as R_9 through R_{14} , are each based on a single test color. They are not used for calculation of CRI but may be used for supplemental analysis when necessary. The “strong red” color sample, R_9 , is especially

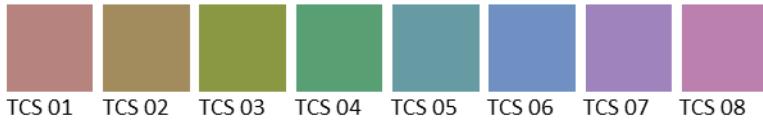
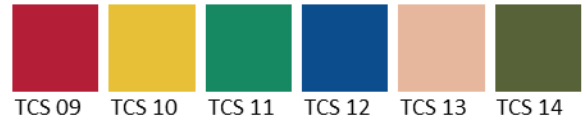
pertinent since the rendition of saturated red is particularly important for the appearance of skin tones, among other materials. An R_9 score greater than 0 is generally considered acceptable since the color space used in the CIE Test-Color Method often causes color shifts in the red region to be exaggerated.

While CRI is the de facto standard for evaluating color rendering, strictly speaking it only captures the ability of a source to render colors similar to the reference source. Consequently, a source with a very low CRI may actually render objects so that they are more pleasing to an observer than a source with higher CRI. Aside from this conceptual concern, CRI has many technical limitations including the chosen color space and the limited number and type of color samples. These limitations are particularly salient when white LED sources are being evaluated. It has been noted that CRI cannot predict the visual ranking of a set of lighting products when white LED sources (either PC or RGB) are included in the set.⁶ Although it is possible for LED products to have a CRI greater than 95 and many have a CRI in the 80s, numerical scores should only serve as a rough guideline for true performance.

⁵ The reference is specified as blackbody radiation for CCTs below 5000 K, or a mathematical model of daylight for higher CCTs. Because CRI is a reference based metric, it is not appropriate to compare the CRI values for sources of very different CCTs.

⁶ For complete information, see CIE 177-2007.

Color Samples for CRI

Color Samples for R_9-R_{14} 

Color Samples for CQS



Figure 3. Approximation of color samples used for the calculation of CRI, R_9-R_{14} , and CQS. Because appearance will vary based on the illumination condition, display settings, printing properties, and/or viewing conditions, these are only examples. *Adapted from NIST data.*

Ultimately, subjective visual evaluation remains the most reliable means of ensuring adequate color quality.

One of the more notable recent attempts to address the imperfections of CRI is the Color Quality Scale (CQS), developed by researchers at the National Institute of Standards and Technology (NIST). Although it makes significant updates based on current vision science—including a revised and expanded set of test color samples (see Figure 3)—the basic approach remains similar and the results are highly correlated with CRI. Despite significant initial interest, it has not yet been officially adopted by any standards organization and its use has yet to become widespread. Other recently developed metrics have utilized different methods in their approach, but although some offer significant advantages, none has achieved consensus support.

Many researchers have noted that evaluating color rendition based on a combination of several metrics tends to produce results more representative of human perception. Some newly proposed metrics have addressed this by including multiple numeric ratings to represent the different facets of color rendition, but there has been some reluctance to move away from a single-number metric. Despite the challenges of meeting the needs of different user groups, developing improved metrics remains imperative for improving the effectiveness of specifications and enabling manufacturers to optimize products. This is especially pertinent given the expanding market share of solid-state lighting.

Color Consistency (Uniformity) and Constancy (Stability)

To counter variability that is inherent in the manufacturing process, PC LEDs are sorted (binned) post-production based on chromaticity, lumen output, and sometimes forward voltage. This allows both manufacturers and specifiers of LED lamps and luminaires to receive a more consistent product. Recently, NEMA has published an LED binning standard (SSL-3-2010) based on ANSI C78.377-2008. The variability allowed by the NEMA bin sizes

and the ANSI tolerances is roughly equivalent to the chromaticity variation seen in currently available compact fluorescent lamps. Some manufacturers may hold themselves to tighter tolerances.

As LED technology continues to mature, binning tolerances remain essential to producing individual products and lighting installations with high color consistency. At this time, there is no industry-wide binning standard for colored LEDs that make up a mixed LED system. Additionally, due to the more consistent and stable output of fluorescence (i.e., the emission from phosphors), PC LED products tend to have greater consistency than mixed LED products.

In addition to the physical properties of each LED chip, differences in operating conditions may affect both initial consistency and constancy over time. Most notably, changes in operating temperature (which may change due to dimming) can result in differences in color appearance. Additionally, color characteristics may change as LED sources age, either due to phosphor degradation or variable lumen depreciation among the primaries in a mixed LED lamp or luminaire.

Where to Find Color Information

The DOE LED Lighting Facts program was established to provide specifiers and consumers with a consistent source of information on LED products. Currently, Lighting Facts labels provide information on lumen output, watts, efficacy, CRI, and CCT. Despite the limitations of CRI and CCT, these metrics generally serve as a good starting point for evaluating the color performance of an LED product. In applications where color performance is critical, additional information should be obtained from the manufacturer. Remember that when making significant purchases or specifying products for applications where color appearance is critical, there is no substitute for visual evaluation.