NLPIP :: Lighting *Answers*
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Light Sources and Color

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Introduction

The phrase, "Color is only a pigment of your imagination" (Ingling, circa 1977), is a humorous and convenient way to remember that color is not a physical property of objects, but rather a human physiological and psychological response to light.

Out of the lighting industry's need to quantify color properties, lighting scientists have developed methods that allow us to approximate color perceptions. A host of measurements are now available to describe such factors as the **color appearance** of light sources and objects, the ability of a light source to render colors accurately, and the stability of color properties over a lamp's lifetime. However, due to the complexity of the visual system, these measures are only approximations, and their usefulness is limited.

In order to provide information useful for specifying electric light sources properly, *Lighting Answers: Light Sources and Color* describes many of the methods for characterizing the color properties of light sources. It also addresses these methods' strengths and weaknesses.

Part I of this report focuses on the metrics used to describe the appearance of light emitted from a light source. To provide a technical background, it also describes the human color vision system.

Part II focuses on the color appearance of objects when illuminated by a light source. It proposes a "triangulation" method for describing color rendering to aid in the selection of light sources based on their ability to show object colors. This section also discusses the relationship between color rendering and luminous **efficacy** (lumens per watt). Although older light source technologies forced a trade-off between the two, many products now available can provide both good color properties and high efficacy.

PART I

When is color important to lighting applications?

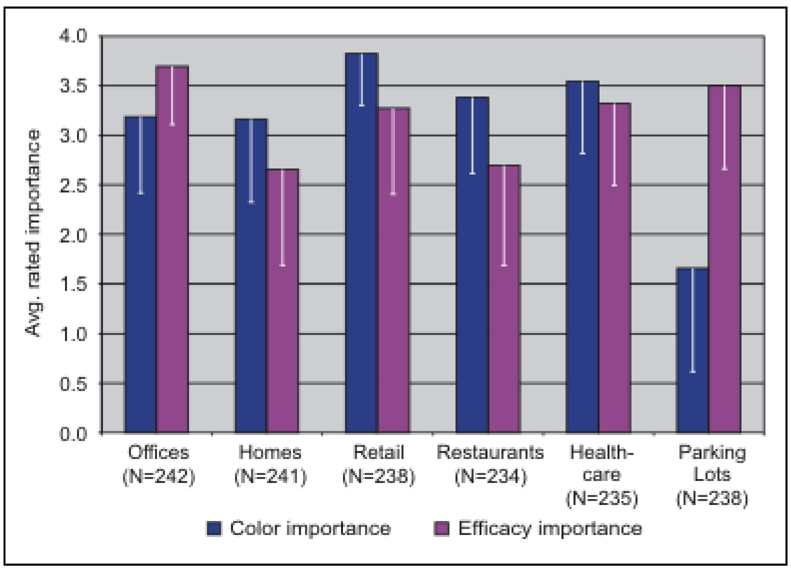
The National Lighting Product Information Program (NLPIP) conducted a survey of its registered online users in January 2004. NLPIP asked lighting professionals to indicate the importance of color and **efficacy** for several lighting applications. The question appeared as follows on the original web questionnaire, which can be viewed in its entirety at http://www.lrc.rpi.edu/survey/color.

For each of the following space types, please indicate how important the light source characteristics color (left) and efficacy (right) are when specifying light sources. (0=Not important at all, 4=Very important)

	Importance of Lamp Color					Importance of Lamp Efficacy (lm/W)				
Offices	0	1	2	3	4	0	1	2	3	4
Homes	0	1	2	3	4	0	1	2	3	4
Retail Stores	0	1	2	3	4	0	1	2	3	4
Restaurants	0	1	2	3	4	0	1	2	3	4
Healthcare	0	1	2	3	4	0	1	2	3	4
Parking Lots	0	1	2	3	4	0	1	2	3	4

Figure 1 summarizes the results of this survey. According to the surveyed lighting professionals, color is an important consideration in nearly every identified application, and in four of the six identified applications color is more important than efficacy. The average response to the importance of color on a 0-4 scale was less than 3 for only one application—parking lots.

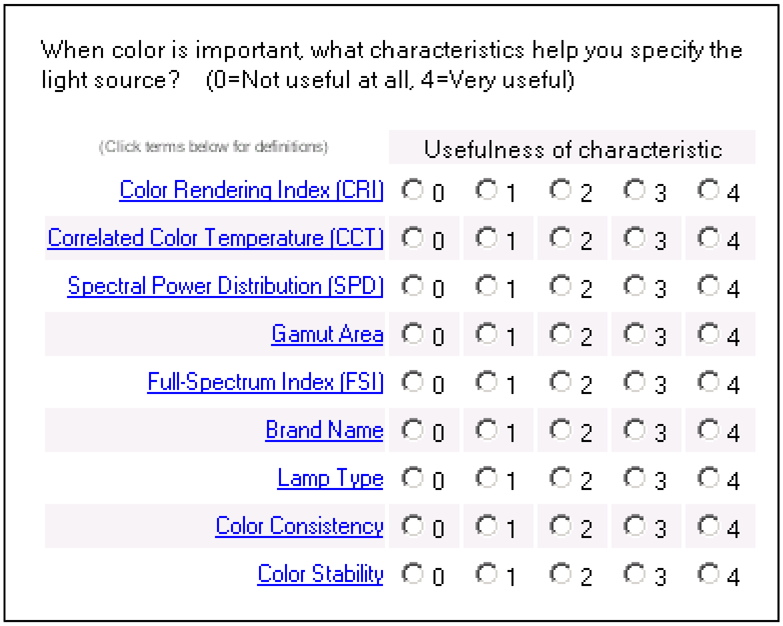
Figure 1. Importance of color and efficacy in different lighting applications



Results from January 2004 online survey of 243 registered NLPIP web site users. Error bars superimposed on histograms represent one standard deviation.

What lamp color characteristics do lighting specifiers use to select light sources?

The January 2004 NLPIP survey referred to in the previous question (When is color important to lighting applications?) asked its online users which color characteristics they use to select light sources. The question appeared in the original survey as follows, with definitions for each characteristic provided through hyperlinks.


When color is important, what characteristics help you specify the light source? (0=Not useful at all, 4=Very useful)

(Click terms below for definitions)	Usefulness of characteristic				
Color Rendering Index (CRI)	0	1	2	3	4
Correlated Color Temperature (CCT)	0	1	2	3	4
Spectral Power Distribution (SPD)	0	1	2	3	4
Gamut Area	0	1	2	3	4
Full-Spectrum Index (FSI)	0	1	2	3	4
Brand Name	0	1	2	3	4
Lamp Type	0	1	2	3	4
Color Consistency	0	1	2	3	4
Color Stability	0	1	2	3	4

Table 1 summarizes the responses from 243 registered NLPIP web site users, who see **color rendering index (CRI)** as the most important color criterion to consider, with **correlated color temperature (CCT)** the next most important criterion. The measures currently promulgated by the lighting industry are seen as the most useful measures of light source color. **Color stability** and **color consistency** were also highly rated by survey respondents. This report discusses these measures in detail, as well as other potentially important aspects of lamp color performance.

Table 1. Most useful light source color characteristics.

Characteristic	Average Usefulness Rating	Standard Deviation	Number of Responses
Color Rendering Index (CRI)	3.5	0.7	237
Correlated Color Temperature (CCT)	3.2	1.0	233
Color Stability	3.2	1.0	232
Lamp Type	3.1	1.0	235
Color Consistency	3.1	1.0	228
Spectral Power Distribution (SPD)	2.4	1.2	226
Full-Spectrum Index (FSI)	2.0	1.3	204
Brand Name	1.9	1.2	226
Gamut Area	1.5	1.2	189

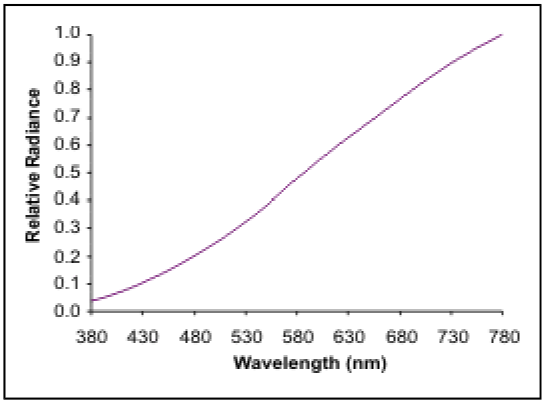
(Rating Key: 0 = Not useful; 4 = Very useful)

How do we see color?

Electromagnetic radiation, varying in wavelength from gamma rays to microwaves, is constantly bombarding us from all directions. Our eyes are able to detect how much radiation is entering them, and from what direction, only if that radiation is within the visible spectrum, which is between approximately 380 and 780 nanometers (nm).

The **spectral power distribution (SPD)** of a light source is graphical or tabulated data representing the amount of radiation emitted by a light source at each wavelength in the visible spectrum only. For example, Figure 2 shows the SPD of an incandescent lamp. The SPD provides the basic physical data needed to calculate light source color.

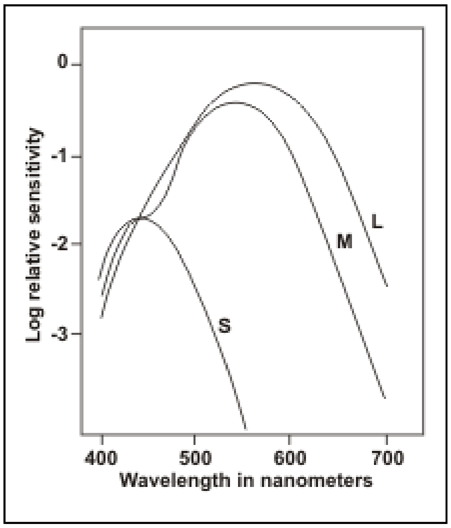
Figure 2. Spectral power distribution of an incandescent lamp



When people speak of color, they are usually discussing the appearance of an object (red, pink, purple, brown, white) or a light source (e.g., warm-white, cool-white). Although **color appearance** seems to come from the physical characteristics of the electromagnetic radiation reaching the retina, it is actually the result of signal processing performed by the visual system. More specifically, color appearance is the result of calculations performed by three separate "color channels" in the visual system. Each channel takes the same radiant power falling on the retina and processes it slightly differently. Research has produced a general model of the visual system, which provides a basic explanation of color appearance (CIE 2004).

For light to stimulate the brain it must be absorbed by photoreceptors in the eye's retina. There are three types of cone photoreceptors responsible for color vision, each defined in large part by the photopigment contained within that photoreceptor. Figure 3 shows the spectral sensitivity of the three cone photoreceptors, L, M, and S. The letters symbolize the photoreceptors' peak spectral sensitivities to Long, Medium and Short wavelength radiation, respectively.

Figure 3. The spectral absorption curves of the three cone types



Source: IESNA Handbook 2000

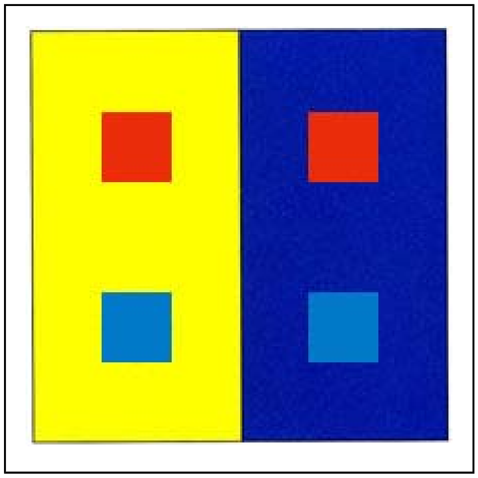
The neural signals generated by these photoreceptors are combined in different ways by the three color channels. One channel, the achromatic or luminance channel, calculates the amount of light falling on the retina from the sum of the outputs of the L and M cones. This luminance channel is related to the perceived brightness of the object or the light source. The other two channels, known as the color opponent channels, calculate the **hues**. One opponent channel subtracts the response of the L cones from that of the M cones to produce a Red versus Green response. When the signal strength of the channel is, for example, greater than zero, the channel signals "Red" to the brain; when the response is less than zero, it signals "Green" to the brain. The other opponent channel subtracts the response of the S cone from the sum of the L and M cones to produce a Blue versus Yellow response.

All colors are seen by the brain as the following combinations: red *or* green; and blue *or* yellow. For example, orange is seen as reddish-yellow, while turquoise is seen as greenish-blue. Since both reds and greens are formed by only one color opponent channel, we can never see reddish-greens. Similarly, we can never see bluish-yellows. The color "white" is seen when both color opponent channels are balanced (i.e., the light is neither red or green, nor blue or yellow), so only the achromatic channel is signaling the brain.

Although this model forms the foundation of color appearance, the actual appearance of a given color is based upon a much more complicated set of subtle interactions in the visual system. For example, a light may appear white when briefly flashed, but yellow when steadily viewed. A more common example of these neural interactions is the change in appearance of the same light at different adaptation levels. A light that looks orange at high light levels may look amber or brown under low light levels. A vivid example of how color appearance can change as a result of other neural activities in the brain is illustrated in Figure 4.

The same physical stimuli (the colored squares) appear to be different depending upon the color of their surrounding.

Figure 4. A demonstration of the complexity of color appearance



The two squares on the left are physically identical to those on the right, but appear to be different because of their respective surrounding colors.

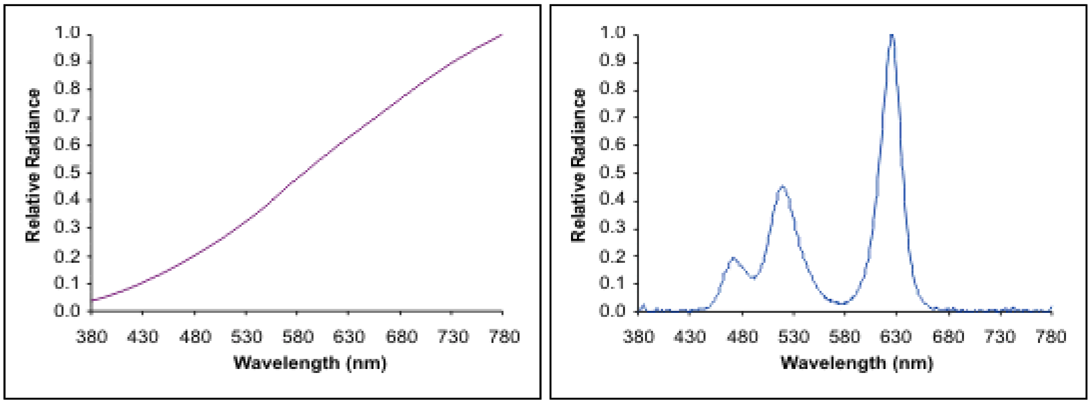
How does the lighting industry measure color appearance?

Researchers and scientists, despite many attempts, have not been able to predict **color appearance** precisely, except under fairly restricted conditions (CIE 2004, 1986; Moroney et al. 2002; Fairchild 1998; Hunt, 1998; Nayatani 1997; Luo et al. 1996). However, the International Lighting Commission (Commission Internationale de l'Eclariage, referred to as CIE) established a colorimetry system for **color matching** that has, with minor changes, remained in use for nearly a century. Human color vision begins with absorption of light by the eyes' three cone photoreceptors. In the 19th century, scientists discovered that any light can be exactly matched in appearance with the proper combination of three different colored lights, known as **primaries**. They also discovered that color matching followed all the rules of linear algebra; addition, subtraction, multiplication, and division. The CIE system has been the foundation for all color calculations used by the lighting industry, in large part because color matching follows these algebraic rules. This three-primary principle is utilized today with color television and other electronic displays. By incorporating different amounts of just three highly saturated, red, green and blue primaries, a wide array of color perceptions can be created on the display.

Although lighting manufacturers publish **spectral power distribution (SPD)** data for their light sources, these data are cumbersome and more detailed than necessary for accurate, unambiguous color representation. Instead, the industry most commonly describes a light source's color appearance using **chromaticity**, which is derived from the SPD of the light source using the CIE system (CIE 1986). In that system the absolute amounts of the three primaries needed to match a given light are normalized so the sum of the amounts of the three primary lights equals one. In this way, any two of the normalized numbers give a complete description of a light source color. The two numbers used to describe a light source color mathematically are known as its chromaticity coordinates, or simply its chromaticity.

Light sources that have different SPDs but produce identical relative absorptions by the three cone types will have the same chromaticity. At the same luminance, these lights will also appear to be identical under the same viewing conditions. Light sources of this type are known as **metamers**; one metameric pair of light sources is shown in Figure 5.

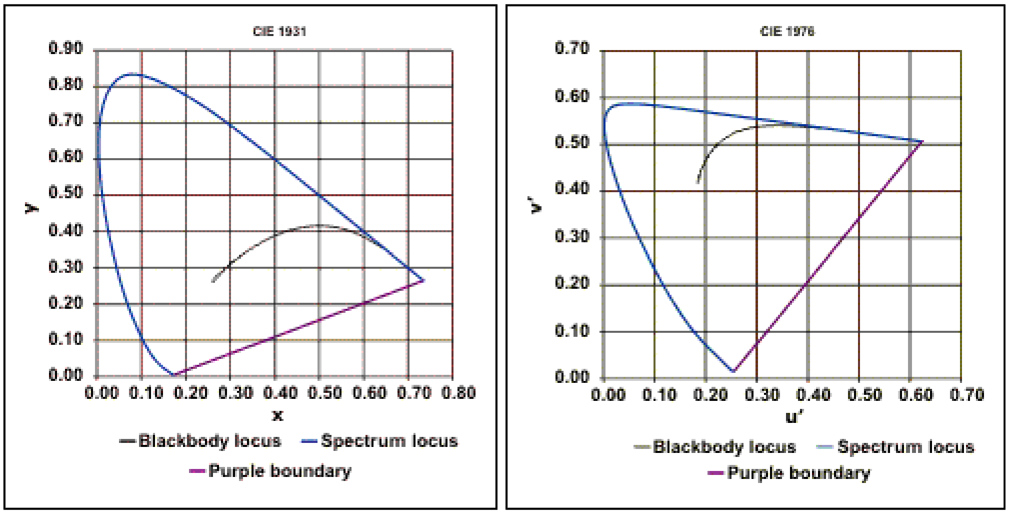
Figure 5. Spectral power distribution of two metameric light sources



The SPD on the left is that of an incandescent lamp with a CCT of 2856 K. The SPD on the right is of a red, green and blue LED mixed spectrum that is metameric with the incandescent lamp.

Since it is known that the chromaticity of any light source can be determined by a linear combination of three primaries, it is possible to abandon the use of real primaries in favor of imaginary primaries that have some useful characteristics. The CIE 1931 system of colorimetry uses the **photopic** luminous efficiency function $V(\lambda)$ as one of the three imaginary primaries. In this way the CIE system of colorimetry was simultaneously integrated with the CIE system of photometry. Figure 6 compares the CIE 1931 two-dimensional chromaticity diagram with the CIE 1976 diagram, both of which utilize imaginary primaries. Also plotted in the diagrams is the blackbody locus, which represents the chromaticities of a **blackbody radiator** source, heated to incandescence.

Figure 6. The CIE 1931 and CIE 1976 Chromaticity Diagrams

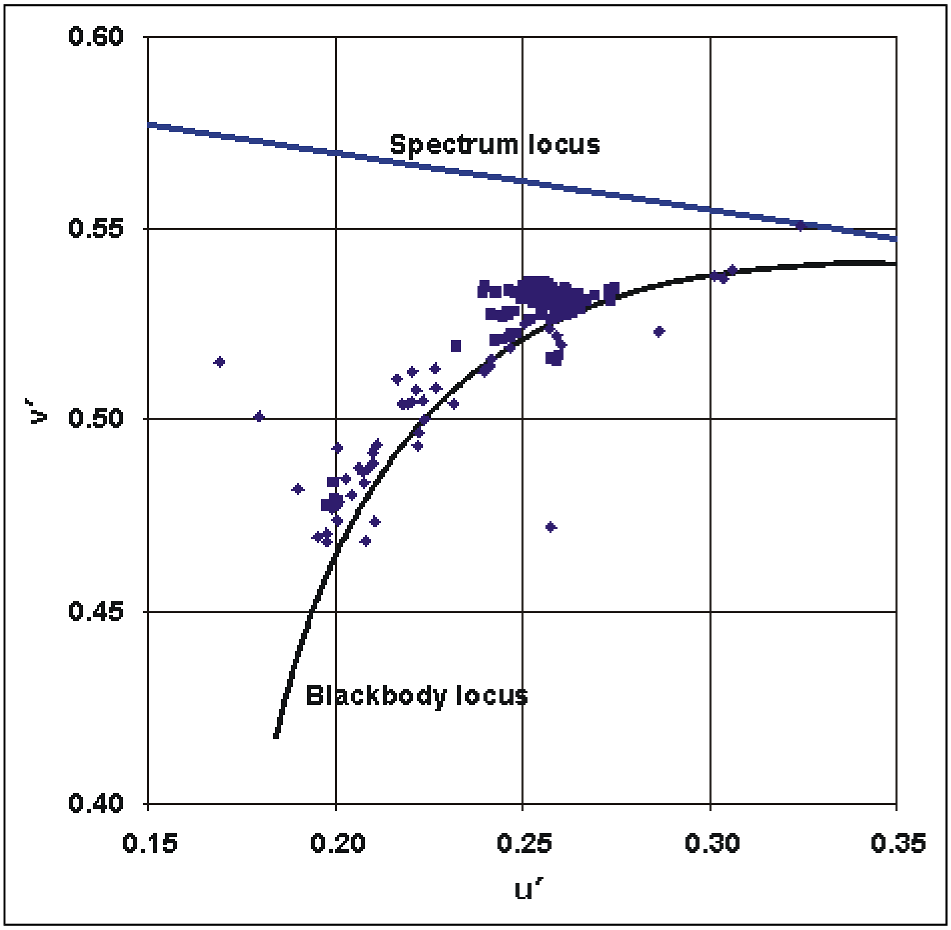


Appendix A demonstrates how the chromaticity of a light source can be calculated from its SPD and the three CIE 1931 color matching functions. Also included are the linear transformation equations for converting the color-matching functions in the CIE 1931 system into those for the CIE 1976 system. The main advantage of the CIE 1976 system of colorimetry is that distances within the chromaticity space are approximately "perceptually equal." That is, pairs of chromaticities separated by the same distance are presumed to be equally different in perceived color, no matter where on the CIE 1976 space they occur.

The true color appearance of a light source is too complex to be represented precisely by chromaticity for reasons previously discussed. However, the chromaticity of a light source is useful as an *approximate* representation of its color appearance. Lights with chromaticity coordinates at the bottom left of the diagram will generally appear blue, while those in the far right will appear red. Those near the blackbody locus will appear "white." Chromaticity diagrams like those in Figure 6 are often produced in color so that they resemble an artist's palette, but this approach is technically inappropriate despite its visual appeal.

Figure 7 shows the chromaticities of 67 commercially available "white" light sources (fluorescent, metal halide, mercury, and incandescent) plotted in a small portion of the CIE 1976 color space. Nearly all of the "white" light sources in Figure 7 fall close to the blackbody locus even though they are not incandescent sources. Given this close relationship between the blackbody locus and the chromaticities of "white" light emitted by these sources, the blackbody locus has become a useful reference line for describing the apparent colors of light emitted from electric light sources.

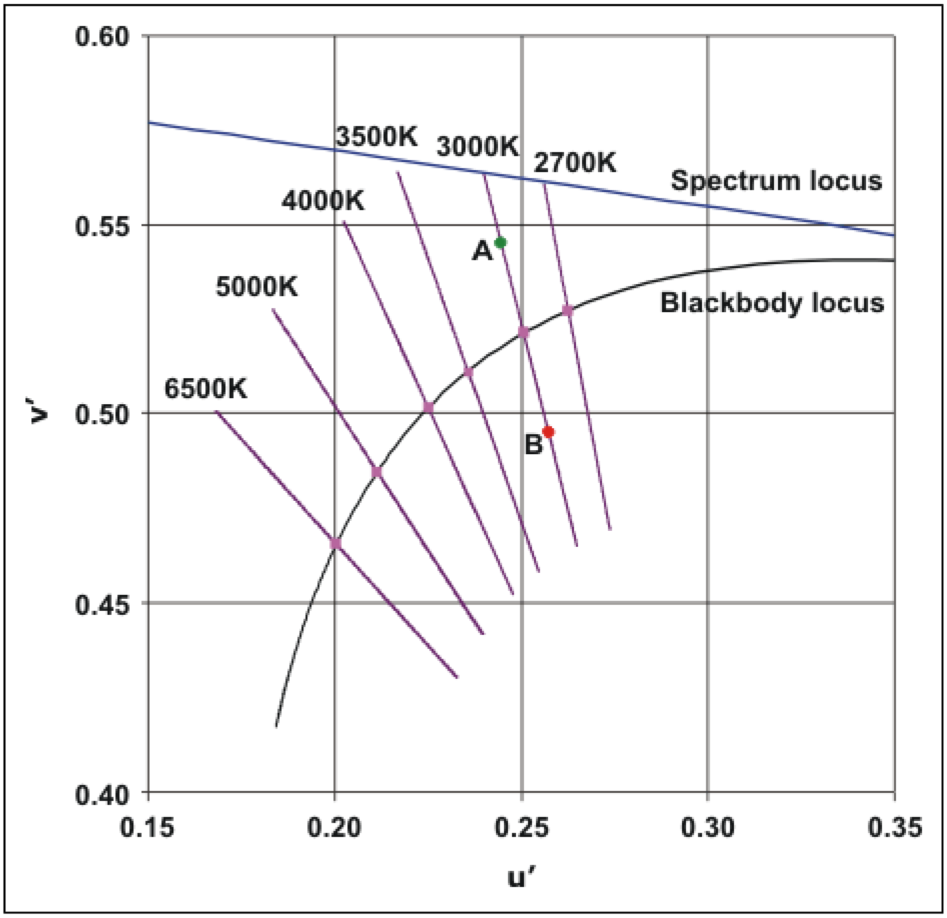
Figure 7. Chromaticities of 67 commercial light sources plotted in the CIE 1976 color space



What is correlated color temperature?

The spectral power distribution (SPD) of a blackbody radiator can be completely determined from its absolute, or color temperature in Kelvin (K). Correlated color temperature (CCT) is a measure of light source color appearance defined by the proximity of the light source's chromaticity coordinates to the blackbody locus, as a single number rather than the two required to specify a chromaticity. Practical light sources of different SPD but identical chromaticities will also have identical CCTs. Six isotemperature lines are plotted in the CIE 1976 chromaticity diagram in Figure 8. The CCT of a light source can be determined by extending an isotemperature line from the blackbody locus out to the chromaticity coordinates of the source. For example, Point A in figure 8 represents a light source with chromaticity coordinates of (0.24, 0.59). This point lies on the 3000 K isotemperature line, thus the light source has a CCT of 3000 K.

Figure 8. The CIE 1976 chromaticity diagram with six isotemperature lines used by manufacturers to represent light emitted by commercially available fluorescent lamps



Since it is a single number, CCT is simpler to communicate than chromaticity or SPD, leading the lighting industry to accept CCT as a shorthand means of reporting the color appearance of "white" light emitted from electric light sources. CCT values of most commercially available light sources usually range from 2700 K to 6500 K. CCT values are intended by the lighting industry to give specifiers a general indication of the apparent "warmth" or "coolness" of the light emitted by the source. According to lighting industry convention, lamps with low CCT values (2700 K to 3000 K) provide light that appears "warm," while lamps having high CCT values (4000 K to 6500 K) provide light that appears "cool." This convention may have been established because non-electric light sources with low CCTs, such as fire, connote warmth. However, this industry convention may be confusing to many people because the higher the CCT of the lamp, the "cooler" the light appears.

Another weakness of CCT is illustrated in Figure 8 by points A and B, representing two light sources with the same CCT (3000 K). Although lights A and B have exactly the same CCT they have very different chromaticities and will look very different to the eye. The light emitted by source A will look greenish-white, while the light emitted by source B will look purplish-white. To address the potential problem of lamps with the same CCT having a different color appearance, the lighting industry utilizes a color tolerance system in conjunction with CCT to specify **color consistency**.

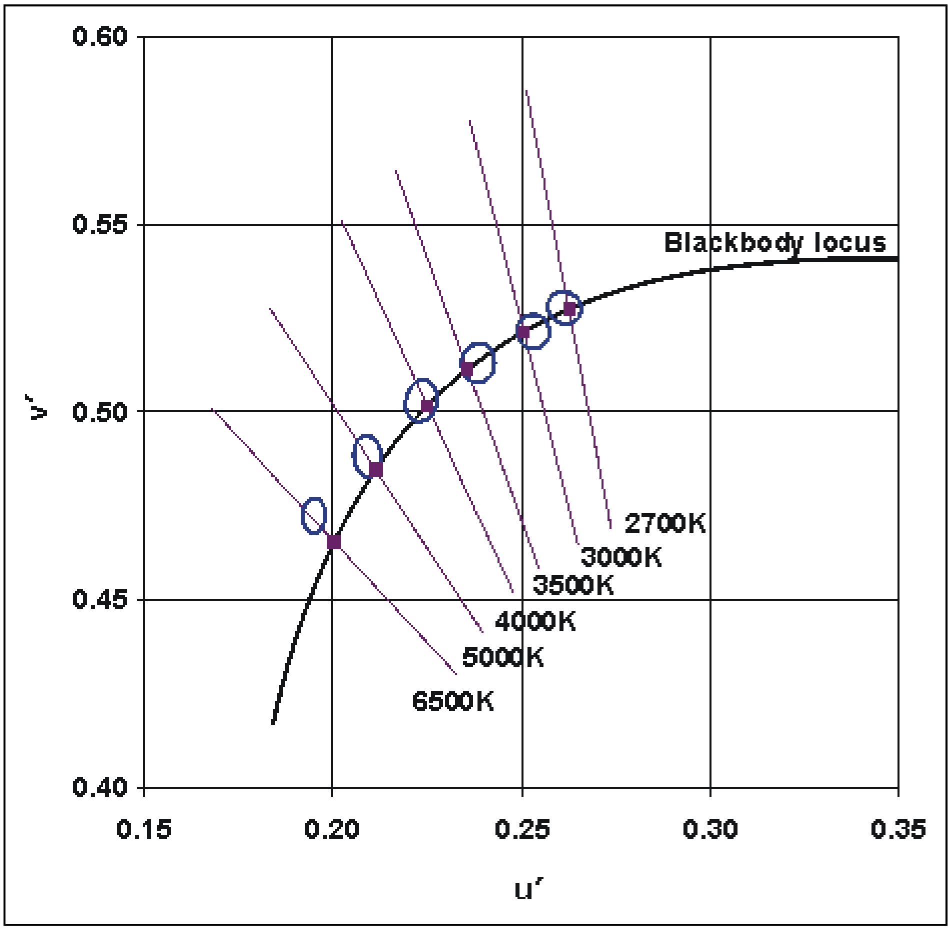
What is color consistency?

Color consistency refers to the average amount of variation in **chromaticity** among a batch of supposedly identical lamp samples. Generally speaking, the more complicated the physics and chemistry of the light source, the more difficult it is to manufacture with consistent color properties. This is why consistency is a problem for discharge light sources, particularly metal halide. Different samples from the same batch of metal halide lamps may exhibit different chromaticities. To limit this variation, the lighting industry uses a color consistency system based on MacAdam ellipses (Wyszecki and Stiles 1982).

People frequently exhibit some error when attempting to match the colors of two lights. This implies that two lights of slightly, but measurably, different chromaticities may not be detected as different by everyone. A number of researchers, most notably D.L. MacAdam, showed that a just noticeable difference (JND) in the colors of two lights placed side-by-side was about three times the standard deviation associated with making color matches between a reference light and a test light (MacAdam 1942, Wyszecki and Stiles 1982). MacAdam also argued that these JNDs form an elliptical pattern of "constant discriminability" in chromaticity space, centered on the chromaticity of a reference light. Thus, a human observer should not reliably detect a color difference between a reference light having a chromaticity at the center of the ellipse and any other light within the elliptical pattern of constant discriminability. Because the elliptical pattern was defined in terms of three standard deviations when making color matches it has been termed the 3-step MacAdam ellipse.

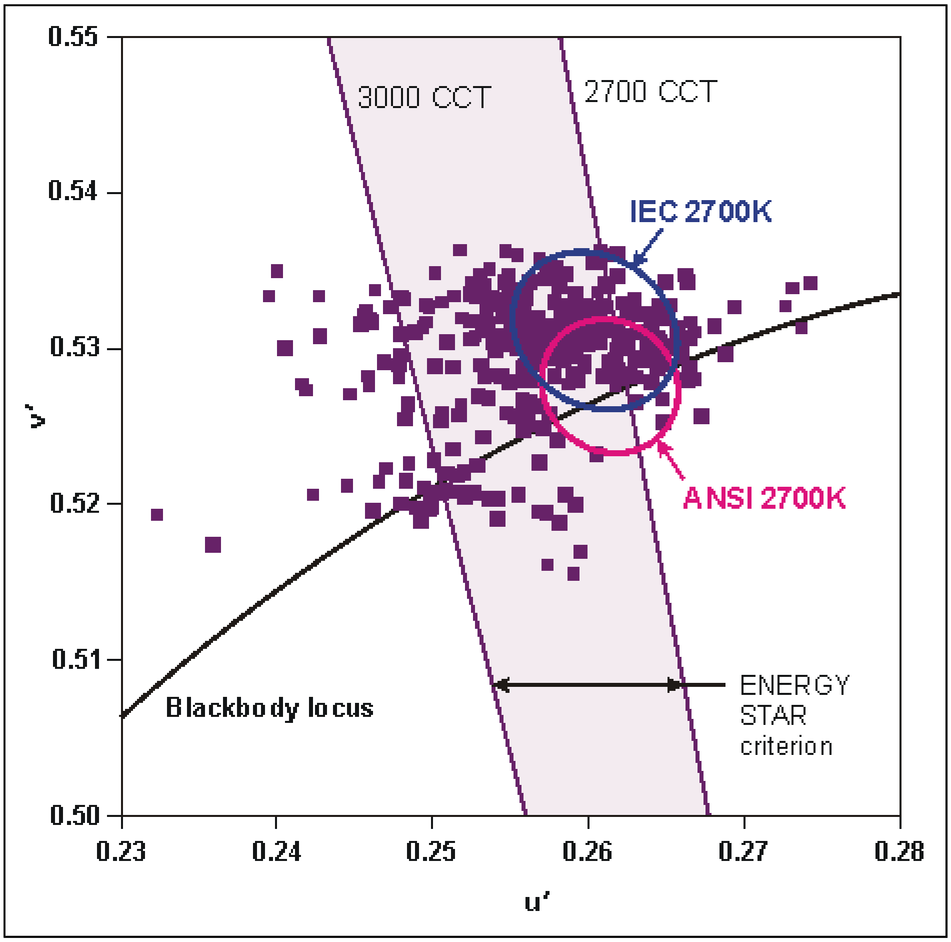
For reasons that may include variations in manufacturing processes over time and limitations in human perception in practical applications compared to a laboratory setting, industry standards for color consistency are more liberal than the 3-step MacAdam ellipse. The American National Standards Institute (ANSI) has formalized six, 4-step MacAdam ellipses, centered on specific chromaticity coordinates, for T8, T10, T12 and some CFL fluorescent lamps (ANSI 2000); these are shown in Figure 9. The International Electrotechnical Commission (IEC) standard (IEC 2002) specifies six, 5-step MacAdam ellipses as color consistency criteria for double-capped fluorescent lamps. According to these standards the chromaticity of fluorescent lamps of a stated CCT must also fall within the color consistency criterion associated with that CCT. Requiring a color consistency criterion together with the stated CCT eliminates the problem of lamps with identical CCT values having vastly different **color appearances**, such as the lamps illustrated by Points A and B in Figure 8 (discussed in "What is correlated color temperature?").

Figure 9. ANSI specifications on the chromaticity tolerance for fluorescent lamps



Loose adherences to CCT and color consistency criteria currently plague the compact fluorescent lamp (CFL) market in North America. Figure 10 shows the chromaticity coordinates of many CFLs that are claimed to meet the requirements of the ENERGY STAR® program from several different manufacturers. It also shows the ANSI 2700 K 4-step MacAdam ellipse and the IEC 2700 K 5-step MacAdam ellipse. To meet the ENERGY STAR specification, the CFLs' CCT must be between 2700 K and 3000 K. If it is not, the lamp packaging must clearly designate the color temperature and color tone of the product in terms of "cool" or "warm" (ENERGY STAR 2003). The chromaticities of many CFLs in Figure 10 lie outside the ANSI and IEC color consistency criterion (ANSI 2001; IEC 2002). This results in noticeable differences in the color of light emitted by these lamps. Their scatter exceeds even the more lenient ENERGY STAR color consistency criterion, defined by the region between the 3000 K and 2700 K CCT **isotemperature** lines.

Figure 10. Chromaticity coordinates of 375 CFLs (meeting ENERGY STAR program requirements) from different manufacturers



Three factors create the variation in chromaticities shown in Figure 10. Some manufacturers have different target points within the ENERGY STAR zone, so there may be perceived color variation in the lamps produced by any two manufacturers. A given manufacturer may also have different target points for different lamp wattages. For example, the same manufacturer may have a 13 W lamp that produces a noticeable color difference from its 26 W lamp with the same CCT rating. Finally, some manufacturers have difficulty controlling the color of the lamps they produce, so different lamps of the same wattage from the same manufacturer may produce noticeably different colors of light.

What is color stability?

Color properties of lamps may change over the life of those lamps, even when they are manufactured with consistent **correlated color tempatures (CCTs)**. **Color stability** describes the ability of a light source to maintain its color properties over time. As shown in Table 1, survey respondents rated color stability as high as CCT, the second most important criterion for lighting specifiers when selecting light sources.

Figure 11. Color stability of CFLs

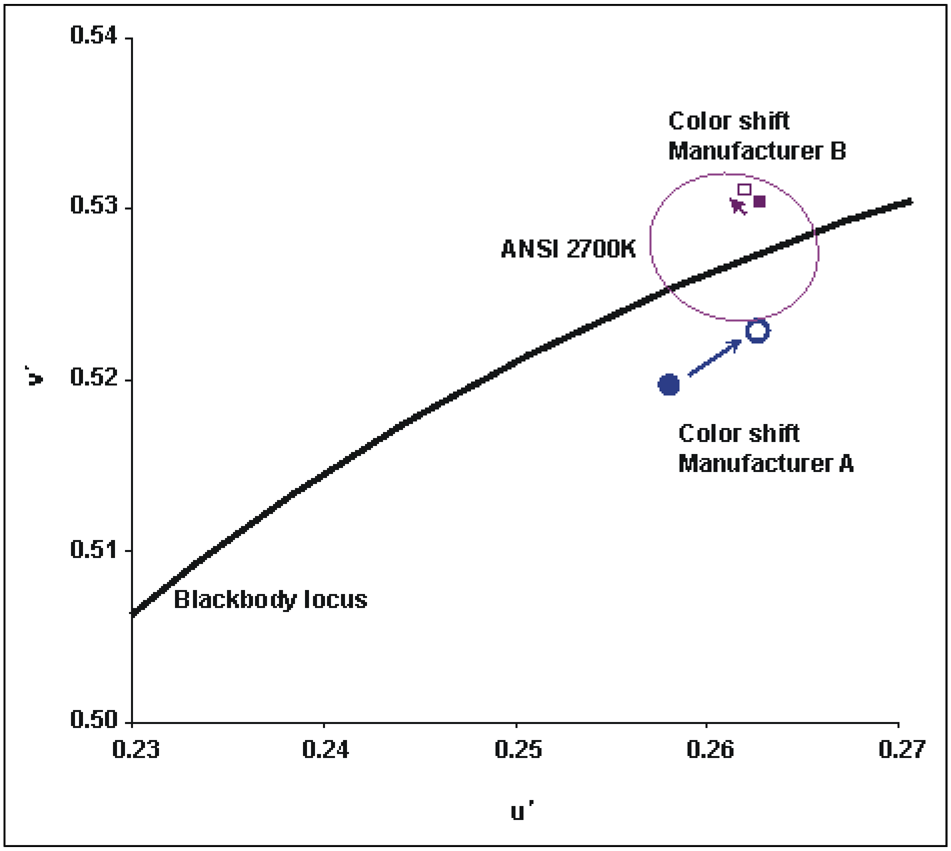
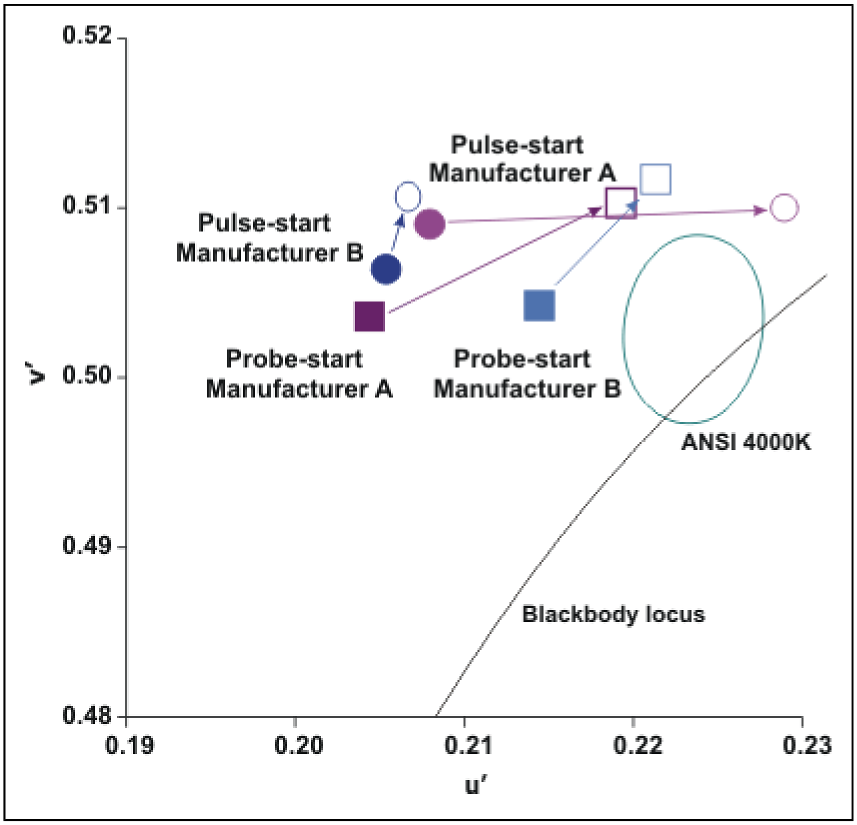


Figure 11 illustrates the average shift in CIE 1976 color space of CFLs from two different manufacturers, A and B, along with the ANSI 2700 K 4-step MacAdam ellipse. The chromaticity coordinates of 100 lamps produced by 10 manufacturers were measured in NLPIP's laboratory. The data from the two manufacturers shown in Figure 11 were chosen to illustrate the extremes in measured color shift between 100 and 2400 hours of operation. This time period represents 40% of rated lamp life. Compact fluorescent lamps (CFLs) from manufacturer A exhibited a much larger shift in the average chromaticity of 10 lamps over time than those from manufacturer B. For both manufacturers the movement in average chromaticity is less than a 4-step MacAdam ellipse, suggesting that color stability over time is quite good for CFLs, despite the wide variation among different lamps shown in Figure 10.

Color stability is substantially different for metal halide lamps than for CFLs. Figure 12 presents color stability measurements for both probe-start and pulse-start metal halide lamps from two manufacturers. The data were chosen to illustrate the measured color shift over 8000 hours of operation, 40% of rated lamp life. The color shift over time for both manufacturers is much larger than a 4-step MacAdam ellipse, except for the pulse-start lamps from manufacturer B. Therefore, over their lifespan, these metal halide lamps will shift in color much more than typical CFLs. So, as noted by respondents to NLPIP's survey (Table 1), lamp type can play an important role in defining a light source's color characteristics.

Figure 12. Color stability of metal halide lamps



PART II

How are the color rendering properties of light sources defined?

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. The color rendering properties of a light source cannot be accurately assessed by visual inspection of the light source or by a cursory examination of its **spectral power distribution (SPD)**. Rather, a calculation procedure must be used.

Color Rendering Index (CRI) is currently the only color rendering metric recognized internationally (CIE 1986, 1995), and it is universally used by the lighting industry. Nevertheless, many other methods for quantifying the color rendering properties of electric light sources have been proposed (Guo and Houser 2004). All of these methods, including CRI, have limitations in characterizing the various aspects of color perception associated with color rendering (e.g., vividness, discriminability, naturalness). Every method utilizes the SPD of the light source. Most, but not all, incorporate one or more reference light sources to which a particular light source is compared. Most procedures also incorporate a reference set of colored objects to be illuminated.

Three color rendering metrics are discussed here, each emphasizing a slightly different aspect of color rendering: color rendering index (CRI), **full-spectrum index (FSI)**, and color **gamut area (GA)**. As new light sources are developed, particularly light-emitting diodes (LEDs), more than one metric will be required in order to evaluate the color rendering capabilities of a light source.

What is color rendering index?

According to surveyed specifiers (Table 1), the most useful measure of a light source's color characteristics is **color rendering index (CRI)**. In general terms, CRI is a measure of a light source's ability to show object colors "realistically" or "naturally" compared to a familiar reference source, either incandescent light or daylight.

CRI is calculated from the differences in the chromaticities of eight CIE standard color samples (CIE 1995) when illuminated by a light source and by a reference illuminant of the same **correlated color temperature (CCT)**; the smaller the average difference in chromaticities, the higher the CRI. A CRI of 100 represents the maximum value. Lower CRI values indicate that some colors may appear unnatural when illuminated by the lamp. Incandescent lamps have a CRI above 95. Cool white fluorescent lamps have a CRI of 62, however fluorescent lamps containing rare-earth phosphors are available with CRI values of 80 and above.

For CCTs less than 5000 K, the reference illuminants used in the CRI calculation procedure are the SPDs of **blackbody radiators**; for CCTs above 5000 K, imaginary SPDs calculated from a mathematical model of daylight are used. These reference sources were selected to approximate incandescent lamps and daylight, respectively.

For full details on how to calculate CRI, see Appendix B.

What is full-spectrum index?

Full-spectrum index (FSI) is a mathematical measure of how much a light source's spectrum deviates from an equal-energy spectrum (NLPIP 2003). An equal-energy spectrum is an imaginary spectrum that provides the same radiant power at all wavelengths, thus representing a "full" spectrum. Therefore, for humans to see object colors, a light source must generate light from more than one region of the visible spectrum. Subtle differences in the perceived colors of objects arise from slight differences in the spectral reflectance of those objects. If a light source does not provide radiant power at those wavelengths where the spectral reflectances of those objects differ slightly, the objects will appear to have the same color. Therefore, a lamp that emits radiant power at all visible wavelengths would be expected to have good color rendering properties. For more information about color rendering, see "How are the color rendering properties of light sources defined?".

Among electric light sources, light from Xenon lamps most closely resembles a full spectrum. The same can be said for the 5500 K phase of daylight. Both of these sources have been experimentally shown to be excellent at revealing subtle differences in color that can not be seen under other types of lamp spectra (Deng et al. 2004). Light sources with deficiencies in some parts of the spectrum will have poorer FSI values and will be less effective at rendering subtle differences in object colors. Appendix B provides a calculation method for assessing FSI.

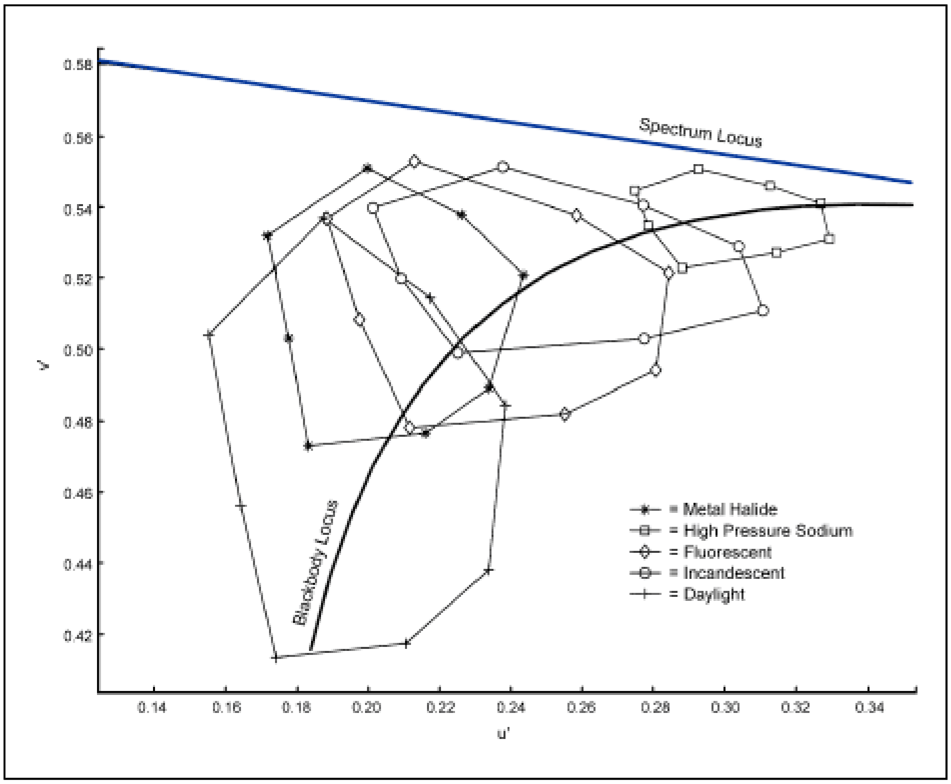
The NLPIP report *Lighting Answers: Full-Spectrum Light Sources* contains details on FSI, along with FSI values for many commercial light sources.

What is gamut area?

Gamut area (GA) is another measure of color rendering. It is more commonly used in Japan than in North America, which may explain why it was considered the least useful color metric by surveyed NLPIP members (Table 1). In principle, GA is defined as the area enclosed within three or more **chromaticity** coordinates in a given color space. For purposes of color rendering, GA is usually calculated from the area of the polygon defined by the chromaticities of the eight CIE standard color samples, the same reference samples used to calculate **color rendering index (CRI)** in CIE 1976 color space when illuminated by a given light source (Boyce 2003). The CIE 1976 color space is used because equivalent distances in this color space are assumed to be "perceptually equal."

In general, the larger the GA, the more saturated the object colors will appear. Figure 13 illustrates gamut areas associated with several commercially available light sources. Unlike CRI and **full-spectrum index (FSI)**, GA is not defined in terms of any reference light source. See Appendix B for full details on calculating GA.

Figure 13. Gamut areas for several light source technologies



Source: Boyce 2003

What is the best way to communicate the color rendering properties of a light source?

Depending upon the context, a person might ask a number of different questions about the color rendering properties of a light source, such as:

- Do objects appear natural under the light?
- Can subtle differences in shades of colors be seen?
- How colorful do objects look?

Given the present state of knowledge about predicting the **color appearance** of objects under different light sources, no single metric can capture the multidimensional aspects of color rendering implied by these questions. In very general terms, a high **color rendering index (CRI)** implies that colors will appear natural. A low **full-spectrum index (FSI)** implies that the light source will enable good discrimination between small color variations. Finally, a large **gamut area (GA)** implies colors will be highly saturated.

In practice, available measures of color rendering can at times seem to contradict each other. For example, an incandescent lamp has the highest possible CRI value of 100, but scores poorly on FSI because it is deficient in the short wavelength range. A recent study found CRI to be a poor predictor and GA to be a good predictor of color naming accuracy (Deng 2001). In another study, light sources with high values on GA and low values on CRI were highly rated in terms of color preference (Narendran and Deng 2002).

Depending on the application and the desired effect, one of these color rendering metrics may be more appropriate than the others. In residential lighting, for example, CRI may be the most relevant metric, while GA may be the most appropriate metric for enhancing the color of meat in a supermarket. Thus, a light source with a high value on one metric but low on the other two will not necessarily render colors poorly for a specific application. Nevertheless, a single metric can be misleading. NLPIP recommends the use of all three metrics to represent the color rendering properties of light sources. By recommending all three, NLPIP suggests that specifiers will be more likely to "triangulate" to the most useful light source for a particular color application.

The NLPIP report Lighting Answers: Full-Spectrum Light Sources (revised in 2004) also includes CRI, FSI, and **efficacy** values for many commercial light sources. For sources not listed in the report, it will be necessary to obtain **spectral power distribution (SPD)** data from the manufacturer to calculate FSI and GA in order to supplement published CRI values.

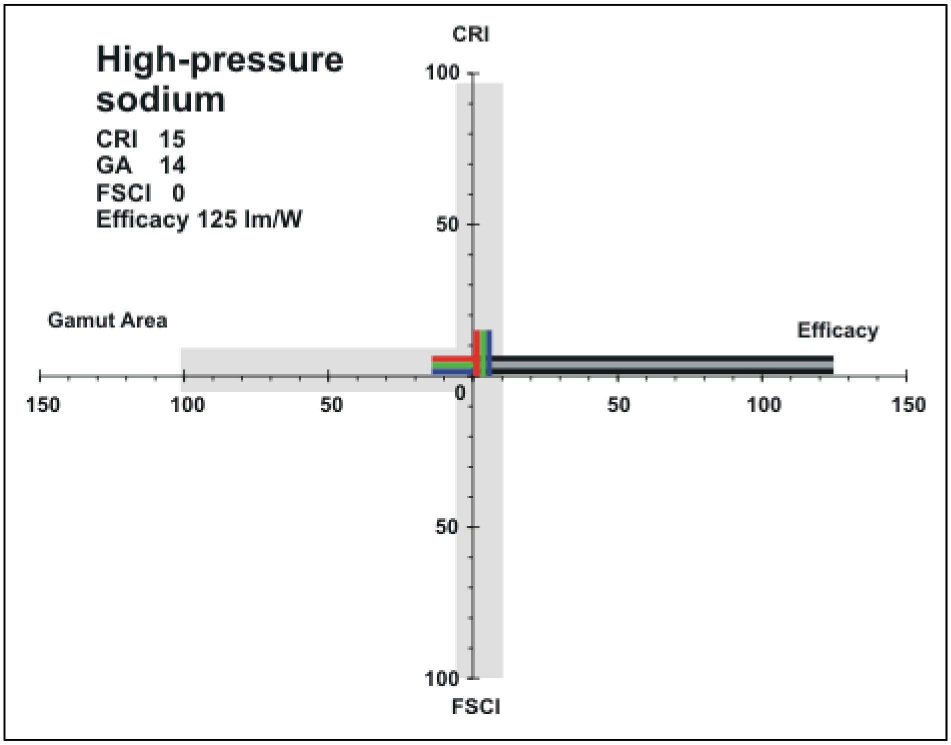
What is the relationship between lamp efficacy and color rendering?

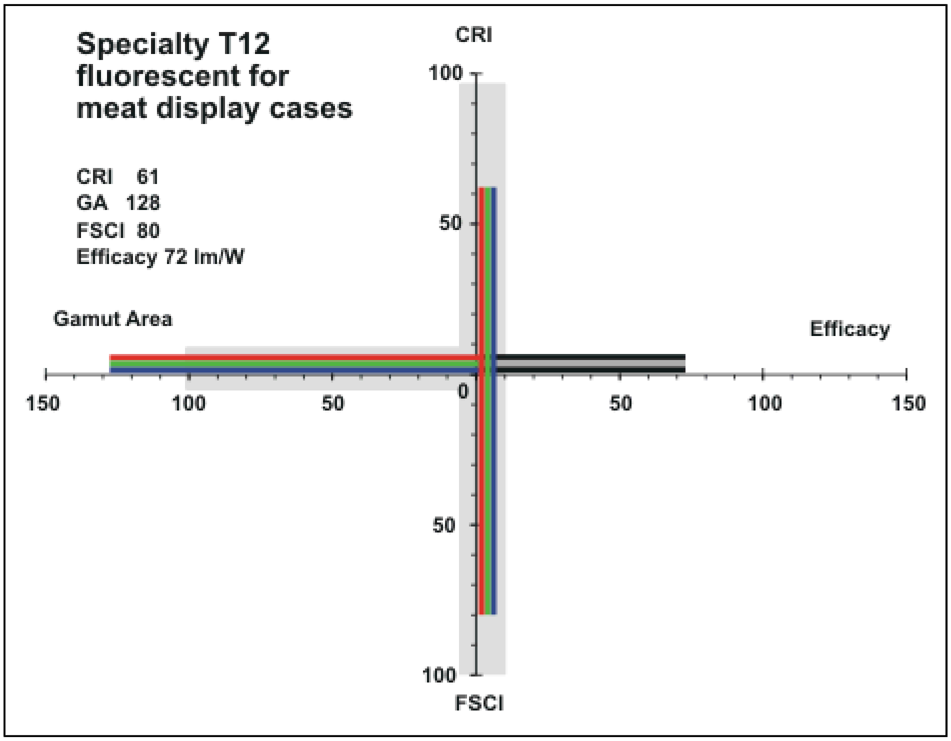
Among practical light sources, lamp **efficacy**, expressed in lumens/watt (lm/W), is highest when it provides radiant power within a narrow range of wavelengths near the peak of the **photopic** luminous efficacy function V (λ) (Rea 2000). This typically results in limited color rendering. For example, high-pressure sodium (HPS) lamps have very high efficacy (125 lm/W) but low values of color rendering (CRI, FSI and GA). However, more modern lighting technologies, including T5 and rare-earth phosphor T8 fluorescent lamps and metal halide lamps, provide light across the visible spectrum, exhibit good luminous efficacy, and render colors well.

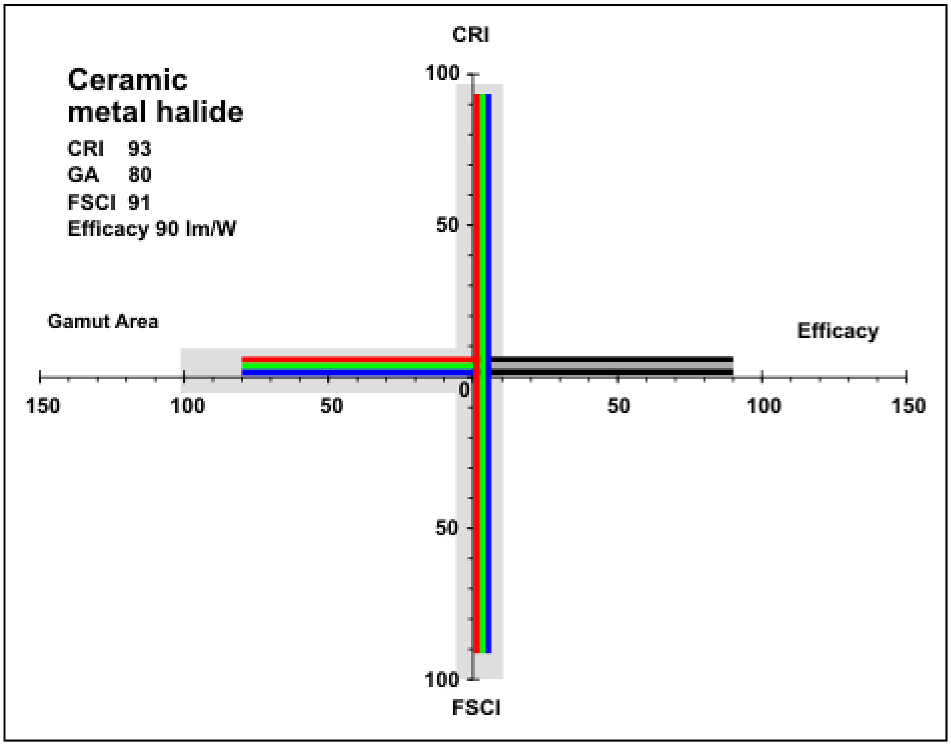
Figure 14, which consists of a series of seven graphs, illustrates a new method devised by NLPIP to represent values of **color rendering index (CRI)**, **full-spectrum color index (FSCI)**, **gamut area (GA)**, and lamp efficacy for various electric light sources. For a selected light source, the three color rendering metric values are shown as tri-color vectors while the lamp efficacy value is shown as an achromatic (gray or black) vector. To make full-spectrum index (FSI) more directly comparable to CRI, FSI values have been converted to a 0-100 scale, to be called full-spectrum color index (FSCI), where, by definition, an equal energy spectrum has the maximum FSCI value of 100 and a "standard warm white" fluorescent lamp has an FSCI value of 50, and any values less than zero (e.g. monochromatic light) are set to zero.

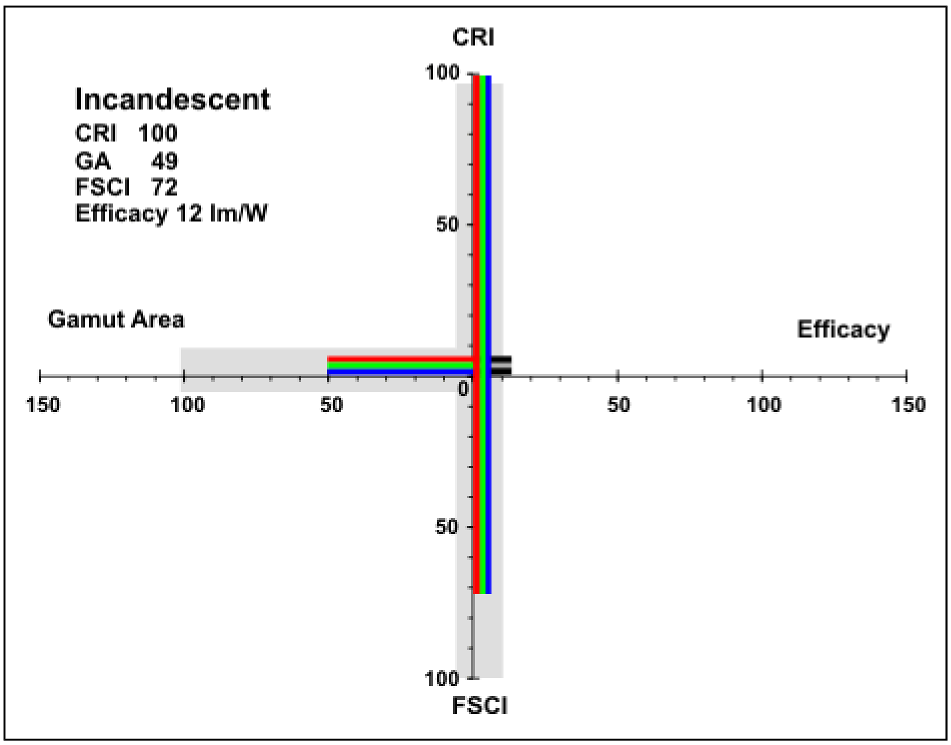
To make GA more directly comparable to CRI and FSCI, GA values have been scaled so that an equal energy spectrum has a GA value of 100. Electric light sources cannot have CRI or FSCI values greater than 100, but both GA and lamp efficacy values can exceed 100. Also illustrated in these plots with light gray shading are the three color rendering metric values for an equal energy spectrum, which serves as a convenient, but arbitrary, reference source. An equal energy spectrum has a CRI value of 95, an FSCI value of 100 and a GA value of 100. Despite the fact that an equal energy spectrum can render all colors, its CRI is less than 100, because only CRI's reference sources (incandescent and daylight) can achieve an ideal CRI score. Several sources (e.g., ceramic metal-halide and some T8 fluorescent lamps) have CRI, FSCI and GA values close to those calculated for an equal energy spectrum.

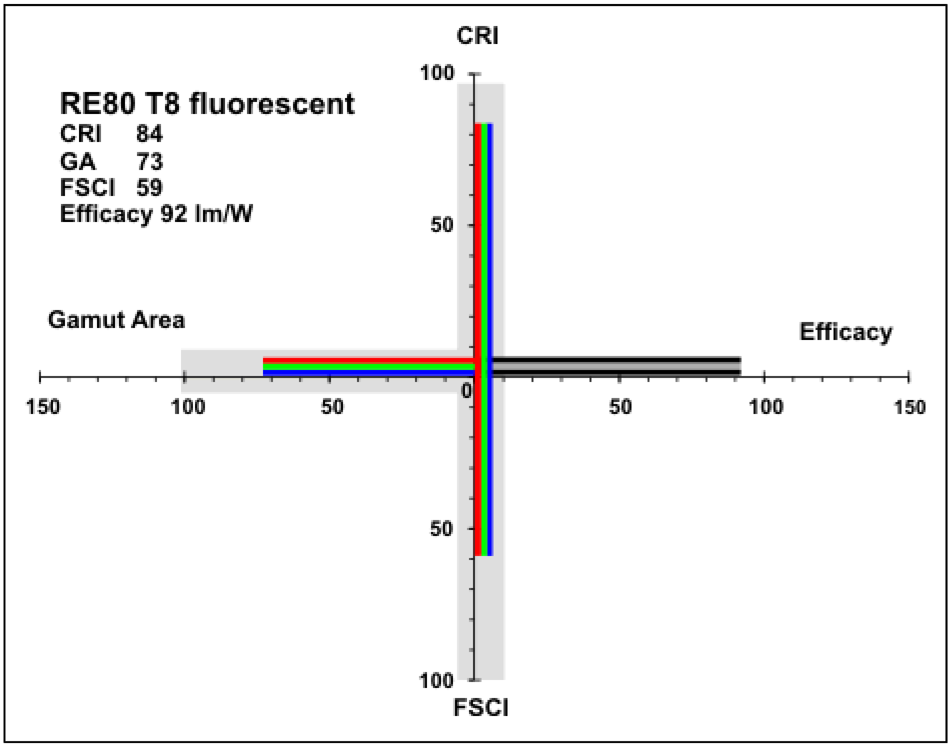
Figure 14. Color characteristics of several light sources

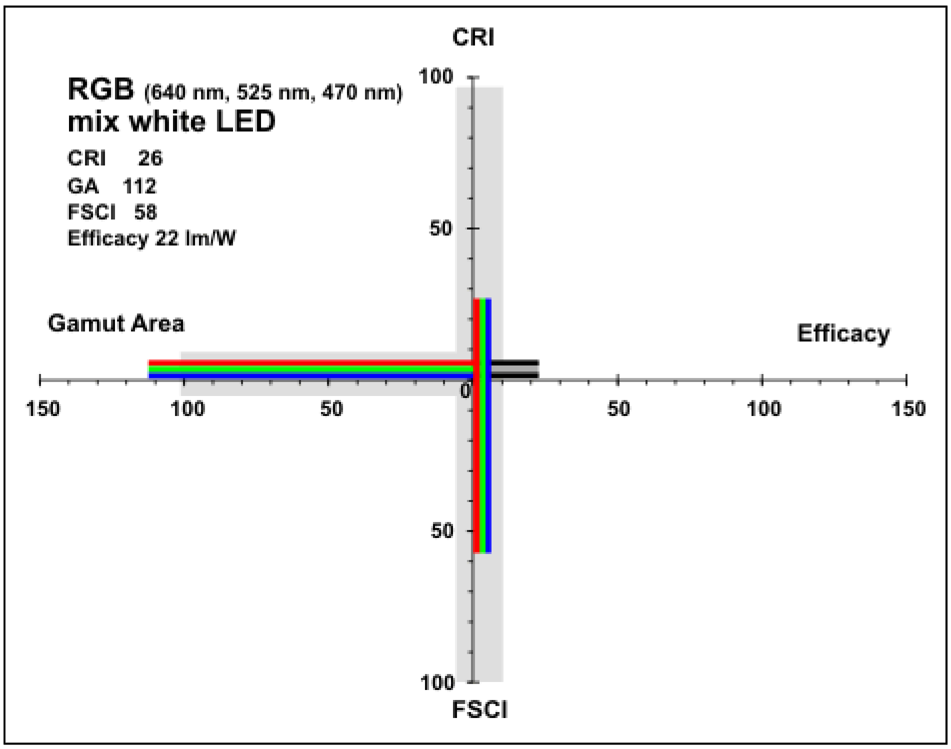


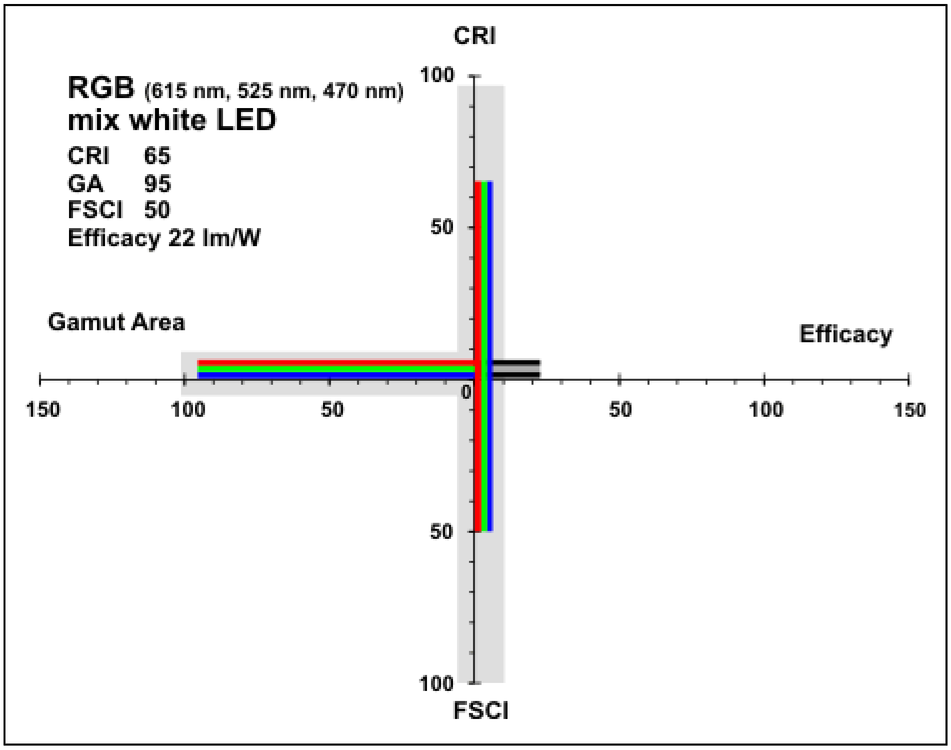



Ceramic metal halide
CRI 93
GA 80
FSCI 91
Efficacy 90 lm/W
CRI
100
50
Gamut Area
Efficacy
150
100
50
0
50
100
150
50
100
FSCI


Incandescent
CRI 100
GA 49
FSCI 72
Efficacy 12 lm/W
CRI
100
50
Gamut Area
Efficacy
150
100
50
0
50
100
150
50
100
FSCI


CRI
RE80 T8 fluorescent
CRI 84
GA 73
FSCI 59
Efficacy 92 lm/W
Gamut Area
Efficacy
FSCI
150
100
50
0
50
100
150
100
50
50
100


CRI
RGB (640 nm, 525 nm, 470 nm)
mix white LED
CRI 26
GA 112
FSCI 58
Efficacy 22 lm/W
Gamut Area
Efficacy
FSCI
150
100
50
0
50
100
150
100
50
50
100


RGB (615 nm, 525 nm, 470 nm)
mix white LED
CRI 65
GA 95
FSCI 50
Efficacy 22 lm/W
CRI
100
50
Gamut Area
Efficacy
150
100
50
0
50
100
150
50
100
FSCI

 6/8/2007

What is the relationship between lamp efficacy and color rendering? - cont'd

The **CRI**, **FSCI**, and **GA** values of 55 light sources are plotted with their lamp efficacies in Figures 15a, 15b and 15c, respectively. The figures illustrate how the same light source can perform quite differently on these three color rendering metrics. In particular, the relative positions of the incandescent lamp and the specialty T12 fluorescent lamp, identified by green diamonds (◆), change for each color rendering metric. The incandescent lamp is a general service, 60W, A-lamp; the specialty T12 fluorescent lamp is used to enhance the appearance of meat in a grocer's refrigerated case. The A-lamp has a high CRI value, while the CRI of the specialty T12 fluorescent lamp is low (Figure 15a). Conversely, the incandescent lamp has a low GA value, but the specialty T12 fluorescent lamp has a very high GA value (Figure 15c). They both have approximately the same FSCI value (Figure 15b).

Some light sources, designated by red diamonds (◆) in Figures 15a, 15b, and 15c, provide high values for all three color rendering metrics. Although these lamps may not be ideally suited for every application (such as enhancing the appearance of meat) they can be expected to render colors well for nearly any application because they rank high on all three metrics. It should also be noted that these sources have good lamp **efficacy**, so this family of light sources can provide good color rendering and high lamp efficacy.

Figure 15a. Comparing CRI to efficacy for several lamp types

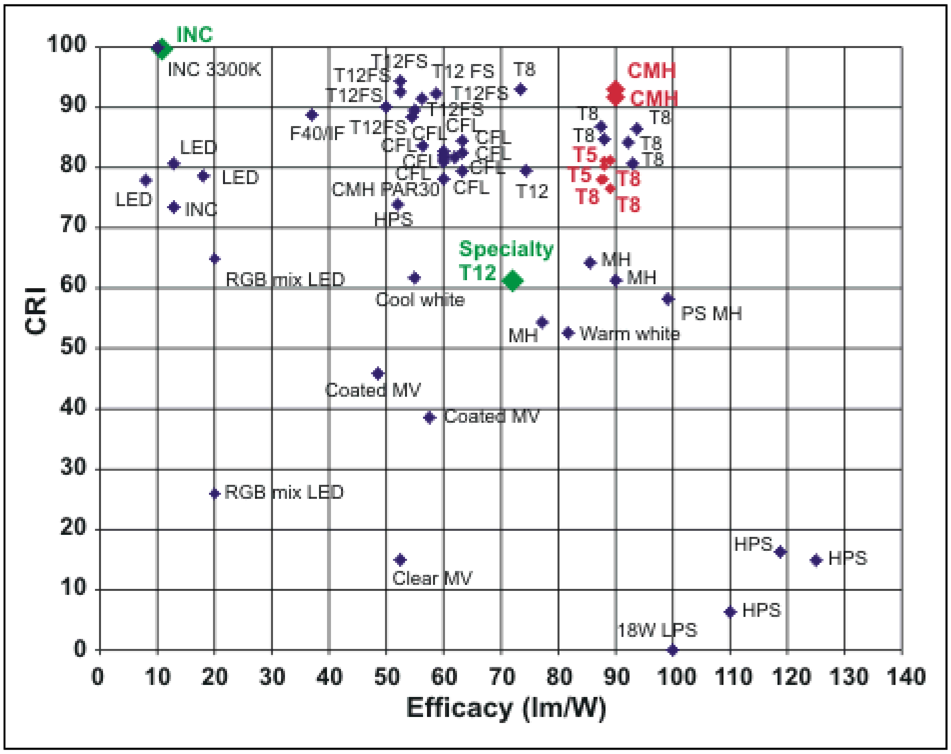


Figure 15b. Comparing FSCI to efficacy for several lamp types

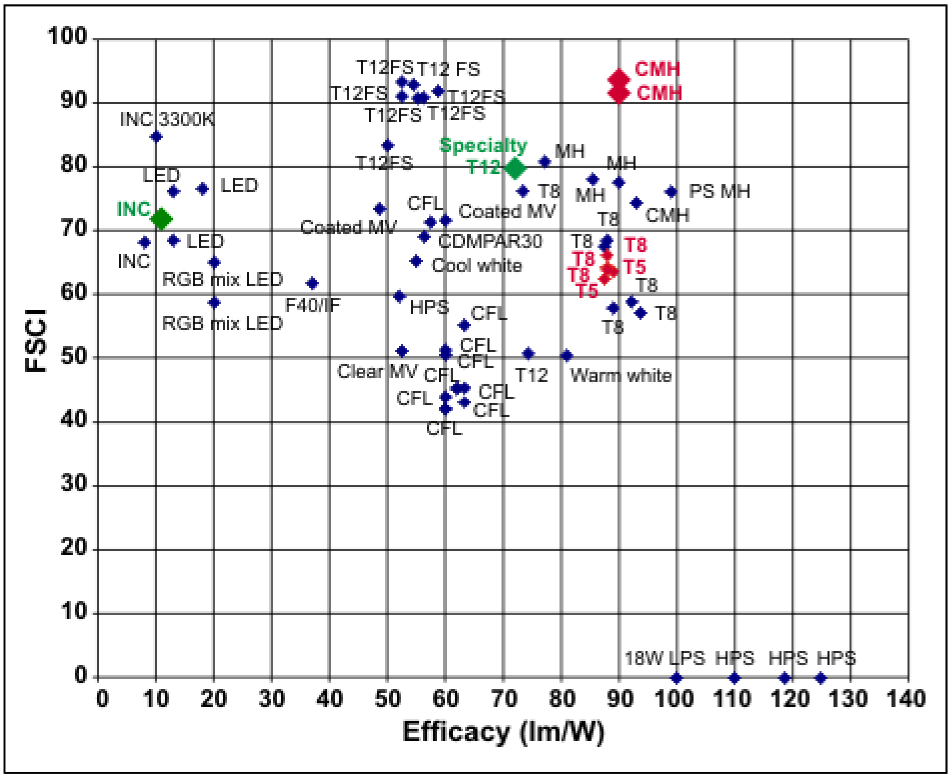
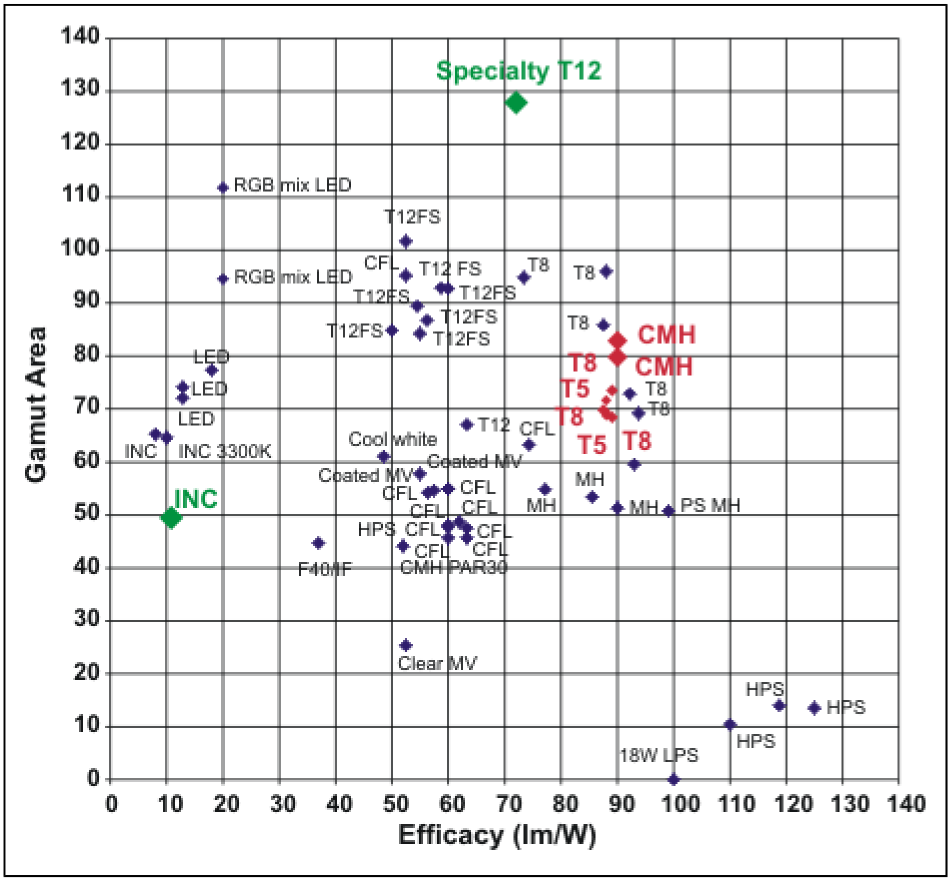


Figure 15c. Comparing GA to efficacy for several lamp types



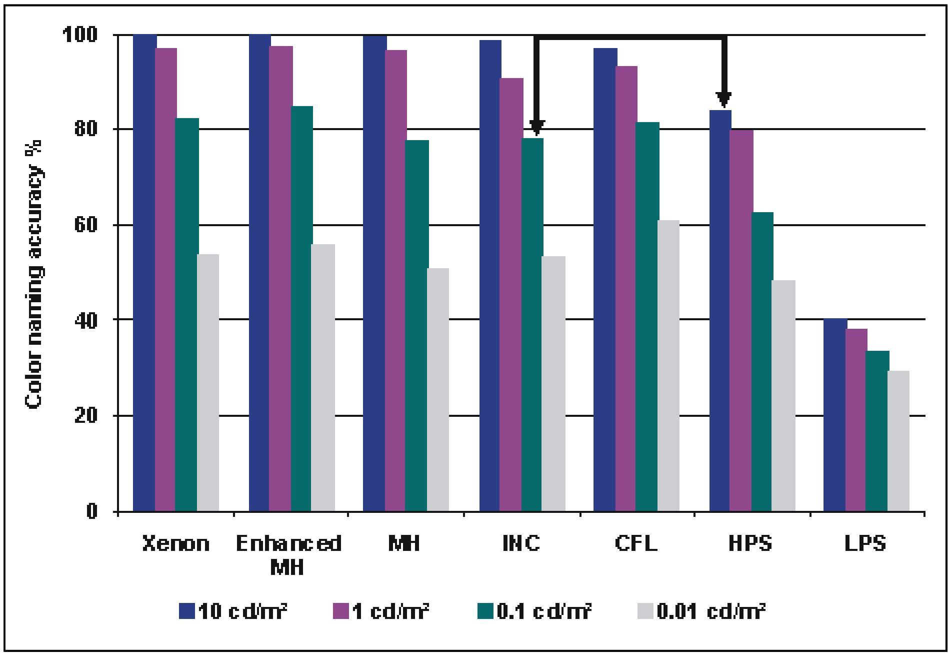
What is the relationship between color rendering and light levels?

In general, both light level and lamp color rendering play crucial roles in color perception. At low light levels, good color rendering is difficult regardless of the light source used. At high light levels, nearly every light source will provide some level of color rendering (excluding monochromatic lights such as low-pressure sodium). Even a light source with very low color rendering values can perform better at high light levels than a light source with high color rendering values at low light levels.

For example, high-pressure sodium lamps score poorly on all three color rendering metrics (**color rendering index (CRI)**, **gamut area (GA)** and **full-spectrum color index (FSCI)**. However, they have very high luminous **efficacy**. In an application where lighting power loads must be kept low, this lamp type, which can provide higher illuminance levels with less power, may provide adequate color rendering. To produce enough light to enable good color rendering, other light sources might exceed the power restrictions.

Figure 16 shows color naming accuracy for objects viewed individually under different light sources and at different light levels. In the experiment, people were asked to name the **color appearance** of 20 color chips in terms of their **primary** and secondary **hues**. For example, when a person was shown a violet chip, a correct answer would have been "Blue is the primary hue; red is the secondary hue." The average percentage of correct responses for all 20 color chips is shown on the vertical axis in the figure for seven light sources at four light levels (blind chance is 25%). The black arrows show one example where an incandescent lamp with a CRI of 100 performs worse at 0.1 cd/m^2 than a HPS lamp with a CRI of 22 at 10 cd/m^2 (Deng et al. 2004). This example illustrates that at high enough light levels, even a light source with a very low CRI can render colors better than a lamp with a CRI of 100 can at lower light levels.

Figure 16. Color naming accuracy of light sources at different light levels



Source: Deng et al. 2004

Conclusions

In many lighting applications, including residences, restaurants and retail stores, good color characteristics are often considered more important than lamp **efficacy** (Figure 1). Lighting specifiers consider the most important color performance characteristics of a light source to be the **color appearance** of the source, most often expressed by **CCT**, and the color rendering ability of the light source, most often expressed by **CRI**.

Given the present state of knowledge about predicting objects' color appearance under different light sources, no single metric can capture the multidimensional aspects of color rendering. NLPIP recommends the use of three metrics (CRI, **GA**, and **FSCI**) to represent the color rendering properties of light sources. A high CRI implies that colors will appear natural; a high FSCI implies that the light source will enable good discrimination between small color variations; and a large GA implies colors will be highly saturated. By recommending all three, NLPIP suggests that specifiers will be more likely to "triangulate" to the most useful light source for a particular color application.

Light level is as important as the color rendering properties of a lamp; at high light levels, many non-monochromatic light sources will render colors well, and at very low light levels no light source can render colors well.

Appendix A: Calculating chromaticity coordinates

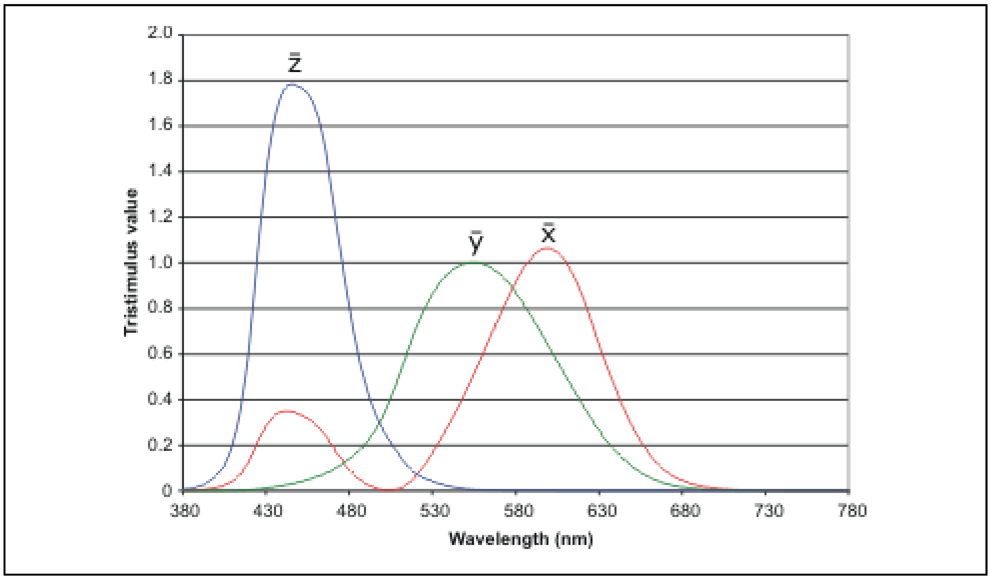
The 1931 CIE (x, y) **chromaticity** coordinates are calculated from the spectral power distribution of the light source and the CIE color-matching functions (Figure A-1). The color-matching functions give the tristimulus $\bar{x}, \bar{y}, \bar{z},$ value X,Y and Z:

$$X=\int p\bar{x}\, d\lambda, \quad Y=\int p\bar{y}\, d\lambda, \quad Z=\int p\bar{z}\, d\lambda$$

where p is the SPD of the light source. From X, Y and Z, the chromaticity coordinates x, y, z can be obtained as follows:

$$x=\frac{X}{X+Y+Z} \qquad y=\frac{Y}{X+Y+Z}$$

Figure A-1. The CIE color-matching functions



Using x, y as the coordinates, a two-dimensional chromaticity diagram (the CIE 1931 color space diagram) can be plotted as shown in Figure 6. In Figure 6, the spectral locus, the purple boundary, and the blackbody locus comprise the chromaticity diagram. The blackbody locus represents the chromaticities of blackbodies having various (color) temperatures.

The CIE 1976 chromaticity diagram was constructed by mathematically transforming the x, y chromaticity coordinates to u', v':

$$u'=\frac{4x}{12y-2x+3} \quad v'=\frac{9y}{12y-2x+3}$$

In the u', v' color space, the same distance between any two points are presumed to be perceptually equal.

Appendix B: Calculating color rendering metrics

This appendix discusses four major color rendering metrics: **color rendering index (CRI)**; **full-spectrum index (FSI)**; **full-spectrum color index (FSCI)**; and color **gamut area (GA)**. Each color rendering metric emphasizes a slightly different aspect of color rendering.

Color rendering index

Color rendering index is a measure of a light source's ability to show object colors "realistically" or "naturally" compared to a familiar reference source, either incandescent light or daylight. CRI is calculated using eight reference samples in CIE 1995 color space (Technical Report No. 13.3-1995) when illuminated by a given light source (Boyce 2003). The CIE 1995 color space is used because equivalent distances in this color space are assumed to be "perceptually equal."

Full-spectrum index

Full-spectrum index (FSI) is a mathematical measure of how much a light source's spectrum deviates from an equal-energy spectrum. The following is a step-by-step procedure for calculating FSI:

1. Begin with a relative **spectral power distribution (SPD)**. Normalize the values so the total power from 380 to 730 nm is equal to 1.

$$SPD(\lambda)_{normalized} = \frac{SPD(\lambda)}{\int_{380}^{730} SPD(\lambda)\,d\lambda}$$

2. Calculate the cumulative power as a function of wavelength from short to long wavelengths.

$$C(\lambda_C) = \int_{380}^{\lambda_C} SPD(\lambda)\,d\lambda$$

3. Calculate the squared difference of the cumulative power distribution of the SPD and the cumulative power distribution of an equal energy spectrum, also with a total power of 1, over the wavelength range 380 to 730 nm.

$$D(\lambda_C) = \left(C(\lambda_C) - C_{EE}(\lambda_C)\right)^2$$

Where the cumulative equal energy spectrum, C_{EE} is calculated as

$$EE(\lambda) = k$$

$$k = \frac{1}{\int_{380}^{730} d\lambda} = \frac{1}{350}$$

$$C_{EE}(\lambda_C) = \int_{380}^{\lambda_C} EE(\lambda)\,d\lambda = \frac{\lambda_C - 380}{730 - 380}$$

4. Integrate the squared difference from 380 to 730 nm.

$$I = \int_{380}^{730} D(\lambda)\,d\lambda$$

-->

5. Circularly shift the SPD values a delta wavelength unit and repeat steps 2 through 4 for one complete circular cycle. A circular shift amounts to moving the first SPD value in the series to the end of that series. For example, using a delta wavelength of 1 nm and an SPD defined from 380 to 730 nm, the value at 380 nm is moved to the 730 nm position and the former 381 nm value now becomes the new 380 nm value. This is repeated until the series starts with what was originally the 730 nm value. In this example, this is repeated 350 times for the delta and wavelength limits.

With an SPD defined over a finite wavelength interval (in this case 380 to 730), a circular shift can be implemented by making the SPD periodic and extending over twice the wavelength interval.

$$\begin{aligned} SPD_P(\lambda) &= SPD(\lambda) && \text{for} \quad 380 \le \lambda < 730 \\ &= SPD(\lambda - 380) && \text{for} \quad 730 \le \lambda < 380 + 730 \end{aligned}$$

6. FSI equals the average of the resulting integrated squared differences from step 4 when circularly shifted over one complete cycle. As the delta wavelength shift values approach infinitesimals the average would be calculated as an integral. Putting this together into integral form yields the following:

$$FSI = \frac{\int_{0}^{730-380} \int_{380+w}^{730+w} \left[\int_{380+w}^{\lambda_C} SPD_P(\lambda) d\lambda - C_{EE}(\lambda_C - w) \right]^2 d\lambda_C dw}{730 - 380}$$

For practical computation the delta wavelength shift values are small wavelength increments and the average is computed with a summation. The LRC used a delta wavelength shift value of 1 nm.

Full-spectrum color index

Full-spectrum color index (FSCI) is a mathematical transformation of full-spectrum index into a zero to 100 scale. The resulting values compare directly with color rendering index. FSCI is a variant of FSI that has an inverse scale starting at 100 and scaled so that a warm white fluorescent lamp has a value of approximately 50, and any values less than zero (e.g. monochromatic light) are set to zero. FSCI is calculated as follows:

$$FSCI = 100 - 5.1 \times FSI$$

Gamut Area

Gamut area (GA) is more commonly used in Japan than in North America. In principle, GA is defined as the area enclosed within three or more chromaticity coordinates in a given color space. GA is usually calculated from the area of the polygon defined by the chromaticities of eight CIE standard color samples in CIE 1995 color space (Technical Report No. 13.3-1995) when illuminated by a given light source (Boyce 2003). The CIE 1995 color space is used because equivalent distances in this color space are assumed to be "perceptually equal." In general, the larger the GA, the more saturated the object colors will appear.

```
% Second, calculate Correlated Color Temperature (CCT), Tc.

load ('isoTempLinesNewestFine.mat', 'T', 'ut', 'vt', 'tt');
% Find adjacent lines to (us, vs)
n = length (T);
index = 0;
d1 = ((v-vt(1)) - tt(1)*(u-ut(1)))/sqrt(1+tt(1)*tt(1));
for i=2:n
   d2 = ((v-vt(i)) - tt(i)*(u-ut(i)))/sqrt(1+tt(i)*tt(i));
   if (d1/d2 < 0)
      index = i;
      break;
   else
      d1 = d2;
   end
end
if index == 0
   Tc = -1; % Not able to calculate CCT, u, v coordinates outside range.
   return
end

% Calculate CCT by interpolation between isotemperature lines
Tc = 1/(1/T(index-1)+d1/(d1-d2)*(1/T(index)-1/T(index-1)));

% Third, calculate the Color Rendering Indices (CRI and its 14 indices)

% Calculate Reference Source Spectrum, spdref.
if (Tc < 5000)
   c1 = 3.7418e-16;
   c2 = 1.4388e-2;
   spdref = c1 * (1e-9*wavelength_spd).^-5 ./ (exp(c2./(Tc.* 1e-9*wavelength_spd)) - 1);
else
   if (Tc <= 25000)
      load('CIEDaySn','wavelength','S0','S1','S2');
      if (Tc <= 7000)
         xd = -4.6070e9 / Tc.^3 + 2.9678e6 / Tc.^2 + 0.09911e3 / Tc + 0.244063;
      else
         xd = -2.0064e9 / Tc.^3 + 1.9018e6 / Tc.^2 + 0.24748e3 / Tc + 0.237040;
      end
      yd = -3.000*xd*xd + 2.870*xd - 0.275;
      M1 = (-1.3515 - 1.7703*xd + 5.9114*yd) / (0.0241 + 0.2562*xd - 0.7341*yd);
      M2 = (0.0300 - 31.4424*xd + 30.0717*yd) / (0.0241 + 0.2562*xd - 0.7341*yd);
      spdref = S0 + M1*S1 + M2*S2;
      spdref = interp1(wavelength,spdref,wavelength_spd);
      spdref(isnan(spdref)) = 0.0;
   else
      R = -1;
      return
   end
end

% Load data for the spectral reflectance data of 14 color samples
TCS = load ('Tcs.txt');
TCS = TCS/1000;

% Interpolate TCS values from 5 nm to spd nm increments
TCS_1 = zeros (14,length(wavelength_spd));
wavelength_5 = 380:5:750;
for i = 1:14
```

```
    TCS_1(i,:) = interp1(wavelength_5,TCS(i,:),wavelength_spd');
    TCS_1(i,isnan(TCS_1(i,:))) = 0.0; % remove NaN from vector.
end

% Calculate u, v chromaticity coordinates of samples under test illuminant, uk, vk and
% reference illuminant, ur, vr.
uki = zeros(1,14);
vki = zeros(1,14);
uri = zeros(1,14);
vri = zeros(1,14);
Yknormal = 100 / Y;
Yk = Y*Yknormal;
uk = 4*X/(X+15*Y+3*Z);
vk = 6*Y/(X+15*Y+3*Z);
X = sum(spdref .* xbar);
Y = sum(spdref .* ybar);
Z = sum(spdref .* zbar);
Yrnormal = 100 / Y;
Yr = Y*Yrnormal;
ur = 4*X/(X+15*Y+3*Z);
vr = 6*Y/(X+15*Y+3*Z);
for i = 1:14
    X = sum(spd .* TCS_1(i,:)' .* xbar);
    Y = sum(spd .* TCS_1(i,:)' .* ybar);
    Z = sum(spd .* TCS_1(i,:)' .* zbar);
    Yki(i) = Y*Yknormal;
    uki(i) = 4*X/(X+15*Y+3*Z);
    vki(i) = 6*Y/(X+15*Y+3*Z);
X = sum(spdref .* TCS_1(i,:)' .* xbar);
    Y = sum(spdref .* TCS_1(i,:)' .* ybar);
    Z = sum(spdref .* TCS_1(i,:)' .* zbar);
    Yri(i) = Y*Yrnormal;
    uri(i) = 4*X/(X+15*Y+3*Z);
    vri(i) = 6*Y/(X+15*Y+3*Z);
end

% Check tolerance for reference illuminant
DC = sqrt((uk-ur).^2 + (vk-vr).^2);
if DC>0.0054
return
end

% Apply adaptive (perceived) color shift.
ck = (4 - uk - 10*vk) / vk;
dk = (1.708*vk + 0.404 - 1.481*uk) / vk;
cr = (4 - ur - 10*vr) / vr;
dr = (1.708*vr + 0.404 - 1.481*ur) / vr;

for i = 1:14
    cki = (4 - uki(i) - 10*vki(i)) / vki(i);
    dki = (1.708*vki(i) + 0.404 - 1.481*uki(i)) / vki(i);
    ukip(i) = (10.872 + 0.404*cr/ck*cki - 4*dr/dk*dki) / (16.518 + 1.481*cr/ck*cki - dr/dk*dki);
    vkip(i) = 5.520 / (16.518 + 1.481*cr/ck*cki - dr/dk*dki);
end

% Transformation into 1964 Uniform space coordinates.
```

```
for i = 1:14
   Wstarr(i) = 25*Yri(i).^.333333 - 17;
   Ustarr(i) = 13*Wstarr(i)*(uri(i) - ur);
   Vstarr(i) = 13*Wstarr(i)*(vri(i) - vr);

   Wstark(i) = 25*Yki(i).^.333333 - 17;
   Ustark(i) = 13*Wstark(i)*(ukip(i) - ur); % after applying the adaptive color shift, u'k = ur
   Vstark(i) = 13*Wstark(i)*(vkip(i) - vr); % after applying the adaptive color shift, v'k = vr
end

% Determination of resultant color shift, delta E.
deltaE = zeros(1,14);

for i = 1:14
   deltaE(i) = sqrt((Ustarr(i) - Ustark(i)).^2 + (Vstarr(i) - Vstark(i)).^2 + (Wstarr(i) - Wstark(i)).^2);
   Ra14(i) = 100 - 4.6*deltaE(i);
end Ra = sum(Ra14(1:8))/8;

% fourth, calculate the gamut area formed by the 8 CIE standard color samples
ukii=[uki(:,1:8),uki(1)];
vkii=1.5*[vki(:,1:8),vki(1)];
Ga=polyarea(ukii,vkii);
% Normalize gamut area to equal energy source
Ga=Ga/0.00728468*100;

% fifth, calculate the FSI (full spectrum index)
% interpolate SPD from 380nm to 730nm with 1nm internal
t=380:1:730;
spd=interp1(wavelength_spd,spd,t','spline');
spd(isnan(spd)) = 0.0;
spd=spd/max(spd);

% Equal energy accumulative spd
EEspd=(1/351:1/351:1);

% circular calculation of FSI
for j=1:351
   for i=1:351
      cum(i,:)=sum(spd(1:i,:),1)./sum(spd,1);
      leastwo(i,:)=(cum(i,:)-EEspd(i)).^2;
   end
   sumleastwo(j,:)=sum(leastwo,1);
   spd=circshift(spd,1);
end
meanleastwo=mean(sumleastwo,1);
FSI=100-4*meanleastwo;
```

% Note: To make FSI more directly comparable to CRI, FSI values in Figure 14 have been converted to a 0-100 scale, with an equal energy spectrum defined as having an FSI value of 100, and all practical light sources having FSI values lower than 100; a monochromatic light source (e.g., low pressure sodium) has a value of 0.

Resources

References

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Glossary

Blackbody radiator	A temperature radiator of uniform temperature whose radiant output in all parts of the spectrum is the maximum obtainable from any temperature radiator at the same temperature. Such a radiator is called a blackbody because it absorbs all the radiant energy that falls upon it. All other temperature radiators can be classed as non-blackbodies. Non-blackbodies radiate less in some or all wavelength intervals than a blackbody of the same size and the same temperature.
Chromaticity	The dominant or complementary wavelength and purity aspects of the color taken together, or of the aspects specified by the chromaticity coordinates of the color taken together. It describes the properties of light related to hue and saturation, but not luminance (brightness).
Color appearance	The resultant color perception that includes the effects of spectrum, background contrast, chromatic adaptation, color constancy, brightness, size and saturation.
Color consistency	The measure of how close in color appearance random samples of a lamp or source tend to be.
Color matching	The action of making a color appear the same as a given color. Often used as a method of evaluating the ability of a light source to render colors faithfully.
Color rendering index (CRI)	A measure of the degree of color shift that objects undergo when illuminated by a lamp, compared with those same objects when illuminated by a reference source of comparable correlated color temperature (CCT). A CRI of 100 represents the maximum value. A lower CRI value indicates that some colors may appear unnatural when illuminated by the lamp. Incandescent lamps have a CRI above 95. The cool white fluorescent lamp has a CRI of 62; fluorescent lamps containing rare-earth phosphors are available with CRI values of 80 and above.
Color stability	The ability of a lamp or light source to maintain its color rendering and color appearance properties over its life. The color properties of some discharge light sources may tend to shift over the life of the lamp.
Correlated color temperature (CCT)	A specification of the apparent color of a light source relative to the color appearance of an ideal incandescent source held at a particular temperature and measured on the Kelvin (K) scale. The CCT rating for a lamp is a general indication of the warmth or coolness of its appearance. As CCT increases, the appearance of the source shifts from reddish white toward bluish white; therefore, the higher the color temperature, the cooler the color appearance. Lamps with a CCT rating below 3200 K are usually considered warm sources, whereas those with a CCT above 4000 K usually considered cool in appearance.
Efficacy	The ratio of the light output of a lamp (lumens) to its active power (watts), expressed as lumens per watt.
Full-spectrum color index (FSCI)	A mathematical transformation of full-spectrum index into a zero to 100 scale, where the resulting values are directly comparable to color rendering index. An equal energy spectrum is defined as having an FSCI value of 100, a “standard warm white” fluorescent lamp has an FSCI value of 50, and a monochromatic light source (e.g., low pressure sodium) has an FSCI value of 0.
Full-spectrum index (FSI)	A mathematical measure of how much a light source's spectrum deviates from an equal energy spectrum, based on the slope of its cumulative spectrum.
Gamut area	A measure of color rendering based upon volume in color space. It is the range of colors achievable on a given color reproduction medium (or present in an image on that medium) under a given set of viewing conditions.
Hue	The attribute of a light source or illuminated object that determines whether it is red, yellow, green, blue, or the like.
Isotemperature	A set of coordinates within which all points have the same temperature. In a color space diagram, isotemperature lines represent lights with identical correlated color temperatures.
Metamers	Lights of the same color but of different spectral power distribution.

Photopic	Vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to a luminance of at least 3.4 cd/m^2.
Primary	Any one of three lights in terms of which a color is specified by giving the amount of each required to match it by additive combination.
Spectral power distribution (SPD)	A representation of the radiant power emitted by a light source as a function of wavelength.

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