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A practical and predictive two-metric system for characterizing the color rendering properties of light sources used for architectural applications

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ABSTRACT
A source of illumination with good color properties, daylight or electric, should reveal a full range of colors, should enable good color discrimination between objects of similar spectral reflectance, and should not distort colors. We presently have only one recognized measure of color rendering in the lighting industry, color rendering index (CRI), developed in the early 1960s. However, CRI should not be used alone as a predictive measure of the color rendering properties of a light source. First, CRI is a poor predictor of color discrimination. Gamut area index (GAI), another measure of color rendering, is consistently better at predicting performance on the Farnsworth-Munsell 100 Hue test than is CRI. GAI is also better at predicting subjective judgments of "vividness" than CRI. On the other hand, when measuring the ability of a light source to display colors "naturally," neither the GAI nor the CRI performs consistently. In fact, sometimes GAI is a better predictor of "naturalness" than CRI, and sometimes the opposite is true. When GAI and CRI are used jointly in characterizing the color rendering characteristics of a light source used for illumination, high values on both metrics appear to ensure subjective impressions of both "naturalness" and "vividness." In general, this two-metric system appears to be predictive of an average individual's "preference." A priori tests of this two-metric system of color rendering were conducted, lending support to the validity of this approach for characterizing the color rendering properties of electric light sources.

Keywords: Color rendering, color rendering index (CRI), correlated color temperature (CCT), daylight, gamut area index (GAI), solid state lighting, LED

Electric light sources used for interior applications are expected to provide observers with color information about the objects illuminated by that source.

"Are the bananas ripe?"
"Is that a blue or a black suit?"
"What have you done to your hair?"

In fact, the color rendering characteristics of a light source are considered more important than energy efficiency (i.e., luminous efficacy) for many applications, particularly in retail.[1,2] The lighting industry uses color rendering index (CRI)[*] as the standard, and only, measure of a source's ability to provide color information.[3] CRI was developed in the early

[*] For the purposes of this report, CRI is used synonymously with general CRI.[3]

1960s through a collaborative effort among interested scientists and manufacturers.[4,5] These leaders in the lighting industry developed CRI as a measure of how "true" objects were rendered by electric light sources. When they created the CRI metric, they assumed that daylight and incandescent light should be used as reference illuminants when gauging color rendering because these were the most familiar light sources. When they were creating CRI in the 1960s, they believed that other less familiar sources might render object colors less "truly" or "naturally." CRI of an electric light source is defined in terms of the net shift in color space for eight standard chips with different spectral reflectances relative to the coordinates for these standard chips under the reference light source of the same correlated color temperature (CCT). The general CRI scale was normalized to 100 (maximum value) for reference illuminants and set at 50 for a warm-white halophosphor fluorescent lamp, which was common at the time. Table 1 shows CRI values for a variety of light sources.

Although CRI has a precise definition, color rendering is an imprecise construct with several different aspects. For example, in 1948 Bouma[6] identified three aspects of color rendering that he considered important and ones that he believed were provided by daylight: "It [daylight] displays (1) a great variety of colours, (2) makes it easy to distinguish slight shades of colour, and (3) the colours of objects around us obviously look natural."[4] A source with good color rendering properties, like daylight, should then reveal a full range of colors ("Is this a blue or a black suit?"), should enable good color discrimination between objects of similar spectral reflectance ("Are these bananas ripe?"), and should not distort colors ("What have you done to your hair?"). Therefore, in the context of Bouma's early description, color rendering should not be measured along a single dimension, but, rather, should be evaluated along two or more dimensions so that lighting specifiers (engineers, architects, etc.) may predict how well a light source might provide color information to observers when objects are illuminated by a source.

A half-century ago, Judd argued that in addition to CRI, another metric for color rendering was needed in order to provide a more thorough analysis of a light source's color rendering, but until recent developments in solid state lighting, his concerns have been largely ignored by the lighting industry. The development of narrowband spectra for sources of general illumination have led to several psychophysical studies of color rendering; these studies have repeatedly revealed that CRI is a poor predictor of a source's ability to provide good hue discrimination, perceived color saturation, and preference.[7-16] Several attempts have been made to improve CRI, perhaps most notably by Davis and Ohno[17] who have developed the color quality scale (CQS) as a potential replacement. A different approach has been taken by Rea and Freyssinier[18] who have argued, as did Judd in 1967, that the well-established industry metric, CRI, should be supplemented by another measure of color rendering.

While multiple metrics can potentially inform users better, too many metrics may not provide the right kind of information or even confuse lighting specifiers. To be effective then, an additional color rendering metric should measure relevant aspects of color information important to observers not presently characterized by CRI. In other words, any new metric should be both predictive of an important color characteristic and it should *not* be well correlated with CRI. If a second metric was irrelevant to color rendering there would be no point in adding it, and if it was well correlated with CRI, it would simply be measuring the same characteristics as the current standard metric used by the industry. In either case, there would be no need to have more than CRI. If on the other hand, a second metric was predictive of an aspect of color rendering not well represented by CRI and it was not well correlated with CRI, there would be a compelling reason to augment CRI with another measure of color rendering.

CRI is a metric of the change in chromaticity of a standard set of color objects relative to a standard source. CRI was never intended to be a measure of color discrimination or saturation. With regard to these two aspects of color rendering, Thornton proposed gamut area as a measure of color rendering.[20-22] Indeed, the work by Thornton a quarter-century ago led to the development of the tri-phosphor fluorescent lamps that dominate the market today. The gamut area of a light source is that area enclosed by a polygon within a chromaticity diagram; the points of the polygon correspond to the chromaticity coordinates of selected spectral reflectances when illuminated by the source. The greater the separation among the selected points, the greater the gamut area. Generally too, the greater the gamut area, the greater the perceived saturation of hues and the better the discrimination among hues under that source of illumination. Gamut area index (GAI) was developed and defined, for convenience, in terms of the eight standard spectral reflectance chips used in the CRI calculation.[23] The chromaticity coordinates of the standard eight chips when illuminated by the source define the points of the polygon in the CIE u',v' space, and therefore the gamut area of the source. An equal energy spectrum is arbitrarily assigned a GAI value of 100 and the gamut areas defined by all other sources in the u', v' color space are normalized to this value. Unlike CRI, values of GAI greater than 100 are possible.

Rea and Freyssinier[18] showed that GAI is better than CRI at predicting color discrimination on a standard test (Farnsworth-Munsell 100 Hue test),[24,25] which is an important aspect of color rendering. They also showed that GAI is predictive of color saturation, another important aspect of color rendering.[18,19] However, they discovered that object colors can be rendered poorly because the hues appear to be too saturated; thus, GAI can be too high for observer preference. Studies have indicated that people tend to prefer slightly saturated colors for natural objects, but not when the saturation levels make the objects appear artificial. Given these observations, and following recommendations offered by Figueiro et al.,[26] Rea and Freyssinier[18,19] recommended a lower and an upper limit to GAI. They were able to demonstrate in an *a priori* test of this idea that, when used in conjunction with one another, sources with high CRI values and high (but not too high) values of GAI tend to be preferred over light sources that have high values of only one measure.[19] Thus, the two-metric approach to characterizing the color rendering characteristics of fabricated sources of illumination appears to successfully meet the expectations for daylight identified by Bouma 60 years ago. Table 1 lists, in addition to CRI values, GAI values for some commercially available light sources.

Figure 1 shows the correlation between GAI and CRI for a variety of commercial and theoretical light sources described in a recent paper by Szabó et al.[27] As noted above, it is important that a second metric for color rendering *not* be well correlated with CRI. Indeed, the correlation with GAI is rather poor when compared to the correlation between CRI and CQS, a proposed replacement for CRI, shown in Figure 2. CQS is very similar to CRI, so it adds little additional information about the color rendering characteristics of the light source. GAI is less well correlated, suggesting that it measures different color rendering attributes than those captured by CRI. GAI characterizes saturation and discrimination better than CRI; these attributes are important aspects of color rendering missed by CRI. Consequently, GAI in conjunction with CRI adds predictive power for lighting specifiers as compared to using CRI alone. Again, since objects can appear too saturated, and therefore unnatural, limits were placed on GAI by Rea and Freyssinier. Presently Rea and Freyssinier[19] recommend that light sources used for general illumination where color rendering is important should meet two color rendering criteria: a CRI between 80 and 100 and a GAI between 80 and100. The sources in Table 1 are examples (but not necessarily a complete list) that meet the two-metric criteria recommended by Rea and Freyssinier.

More empirical tests are needed to refine these specific recommended levels of GAI and CRI, but it appears clear that a two-metric system of color rendering is needed by the lighting industry so that specifiers can be reasonably assured that the sources they choose for installation in commercial, health-care, and retail applications will be accepted. Further empirical tests should not be without end, even though they could be. It must be understood that color rendering is a broad, imprecise construct and does not factor in the particular objects being illuminated, the observer's color vision system, or the observer's cultural color preferences. Therefore, any recommended criteria for color rendering will reflect a compromise between practical utility and a complete characterization of the source, the object, and the observer.

Table 1: Examples of light sources that meet the criteria for CRI (≥80) and GAI (≥80 and ≤100).[19]

Light source	Manufacturer	Specification	CCT (K)	CRI (Ra)	GAI
Xenon	OSRAM Sylvania	1000W	5853	97	91
PC-LED	Cree	XRE lamp	4154	84	82
PC-LED	Sharp	Zenigata	5097	95	99
RGB-LED	Various	Peak wavelengths of 465 nm, 545 nm, and 614 nm	4000	89	82
T8	General Electric	F32T8SPX50	4751	87	86
T8	Lumiram	Lumichrome 1XX	5960	93	95
T8	Verilux	F32T8VLX	6369	85	96
T12	OSRAM Sylvania	Design50, 40W	4861	90	84
T12	General Electric	Sunshine F40C50	4944	92	87
T12	Duro-Test	Vitalite 5500	5159	88	90
T12	Lumiram	Lumichrome 1XC	5207	92	93
T12	Philips	Colortone 75	6217	90	85
T12	Duro-Test	DAYLITE 65, 40W	6588	93	95
MH	Philips	CDM100W/4K	4075	93	80
MH	Philips	CDM150W/4K	4197	92	83
Daylight		CIE D50	5000	100	88
Daylight		CIE D65	6500	100	98

PC-LED: Phosphor converted white light emitting diode
RGB-LED: Red, green and blue LEDs mixed to create white light
T8: Linear fluorescent, 1 inch diameter
T12: Linear fluorescent, 1½ inch diameter
MH: Metal halide

Figure 1: Gamut Area Index (GAI) and Color Rendering Index (CRI) of the light sources listed in Table 6 of Szabó et al.[27]

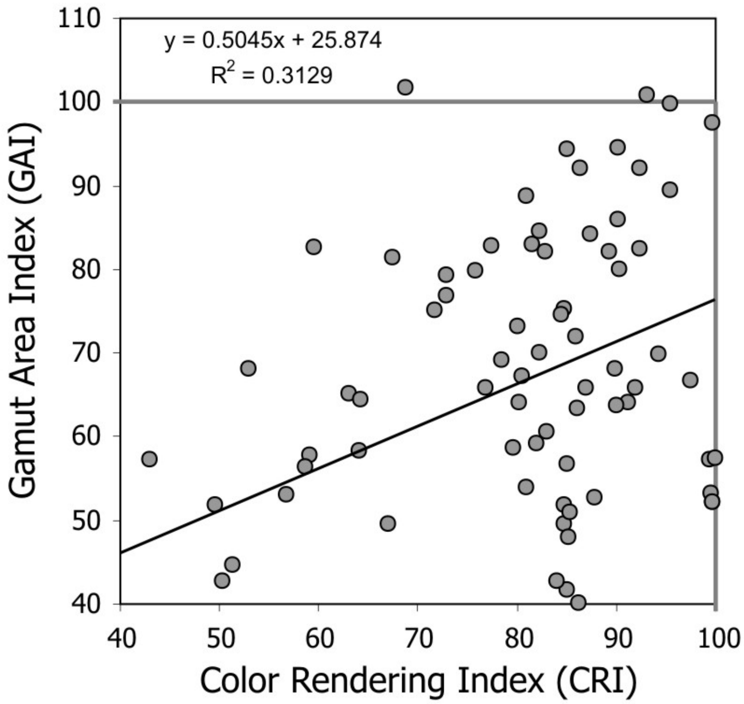
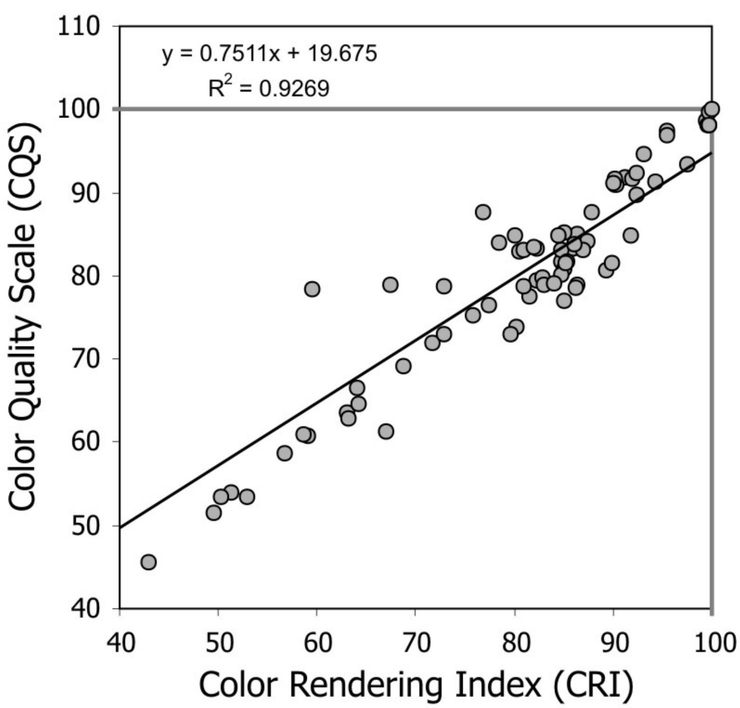


Figure 2: Color Quality Scale (CQS) and Color Rendering Index (CRI) of the light sources listed in Table 6 of Szabó et al.[27]



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