Assessing Color Rendering Without Test Samples

Lorne Whitehead
University of British Columbia
Vancouver, British Columbia, Canada

Introduction

Although the concept of color rendering is fairly simple, methods for quantifying it have become increasingly complex. It seems plausible that there could be a simple way to evaluate color rendering by directly comparing the spectral power distribution (SPD) of a test source with that of a reference source, but previously no such direct method has agreed well with observers' perceptions of color rendering.

Instead, the current CIE CRI procedure (1) uses an indirect method which calculates, for each of eight color test samples, the changes of observed color that would be caused by switching illumination from a reference source to a test source, and then calculates the average size of those changes. This method works fairly well for sources having smoothly varying SPDs, but performs less well for those having narrow bands of emission. Consequently, new color rendering metrics have been proposed based upon larger numbers of more carefully-selected test color samples (2). The increase in sample number unfortunately increases the complexity further.

This paper presents a simple color rendering calculation method that does not use test color samples at all. Instead, it assesses changes in the retinal cone sensitivity functions arising from differences between the SPDs of the test and reference sources.

Definitions

The proposed method uses the sensitivity functions for the retinal cone cells, denoted here as $L(\lambda)$, $M(\lambda)$, $S(\lambda)$. As is customary for assessing color rendering, the test source SPD is represented here as $E_t(\lambda)$ and the CIE reference SPD having matching color temperature is represented as $E_r(\lambda)$.

Introduced here is a simple way to smooth fine spectral features of $E_t(\lambda)$. Smoothing is required because fine features are not generally found in the spectral reflectance functions of ordinary materials and consequently equivalently fine features in the source SPD do not impair color rendering. Smoothing is carried out by convolution with a blur function, $B(\lambda)$ - a symmetrical triangle function centered about zero, defined as follows:

$$B(\lambda) = \max\left(1 - \frac{|\lambda|}{150\text{nm}}, 0\right) \qquad (1)$$

Using these definitions, the LMS sample-free CRI calculation has three simple steps:

Step 1 - Calculating Effective Cone Sensitivity Functions

For both the test source and the reference source, an effective cone sensitivity function is computed for each of the L, M, and S cones. This is done by multiplying the cone sensitivity function by the source SPD, convoluting with the blur function, and exponentiating to a power representing the non-linearity of the cone responses:

$$L'_t(\lambda) = n_{L,t}\left[\left(L(\lambda)E_t(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{2}$$
$$M'_t(\lambda) = n_{M,t}\left[\left(M(\lambda)E_t(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{3}$$
$$S'_t(\lambda) = n_{S,t}\left[\left(S(\lambda)E_t(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{4}$$

$$L'_r(\lambda) = n_{L,r}\left[\left(L(\lambda)E_r(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{5}$$
$$M'_r(\lambda) = n_{M,r}\left[\left(M(\lambda)E_r(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{6}$$
$$S'_r(\lambda) = n_{S,r}\left[\left(S(\lambda)E_r(\lambda)\right) * B(\lambda)\right]^{0.42} \tag{7}$$

The, n values are for normalization – they are set so that each of the functions integrate to unity. The selected compression exponent is 0.42, matching the compression exponent used in CIECAM02, the well-established CIE color appearance model (3).

Step 2 - Determining the Color Difference Components at Each Wavelength

In CIECAM02, the red-green, yellow-blue and achromatic color components are based on linear combinations of the cone sensitivity functions:

Red-green component: $L + \frac{-12}{11}M + \frac{1}{11}S$ (8)
Yellow-blue component: $L + M - 2S$ (9)
Achromatic component: $2L + M + \frac{1}{20}S$ (10)

Accordingly, three color difference measures are expressed by the matrix equation:

$$\begin{pmatrix} \Delta a(\lambda) \\ \Delta b(\lambda) \\ \Delta j(\lambda) \end{pmatrix} = \begin{bmatrix} g_a(1, -12/11, 1/11) \\ g_b(1, \quad 1 \quad, -2\ ) \\ g_j(2, \quad 1 \quad, 1/20) \end{bmatrix} \begin{pmatrix} L'_t(\lambda) - L'_r(\lambda) \\ M'_t(\lambda) - M'_r(\lambda) \\ S'_t(\lambda) - S'_r(\lambda) \end{pmatrix} \tag{11}$$

The gain coefficients g_a, g_b, g_j are the only free parameters in this calculation – they can be adjusted so as to best fit either observational data or the output of indirect metrics that have previously been shown to agree well with observational data.

Step 3 - Calculating the Average Color Error

The average color error is calculated as the square root of the integral of the sum of the squares of the three color difference measures:

$$\Delta E = \sqrt{\int \left(\left(\Delta a(\lambda)\right)^2 + \left(\Delta b(\lambda)\right)^2 + \left(\Delta j(\lambda)\right)^2\right) d\lambda} \tag{12}$$

The average color error is the simplest and most direct way to describe the overall color rendering error arising from a light source, but for historical reasons it is usually converted into a CRI score, R_a, which is a number less than 100 whereby the difference from 100 is proportional, or approximately proportional, to ΔE. Here, we focus on comparing ΔE values, since they have the same meaning for each metric.

As can be seen in the plots below, the ΔE values computed by the LMS sample-free CRI metric for 69 different light sources match well with those calculated by the recently proposed CRI2012 metric (4), with an R^2 value of 0.99. In comparison, the match with the traditional CRI calculation is much poorer, with an R^2 value of only 0.67.

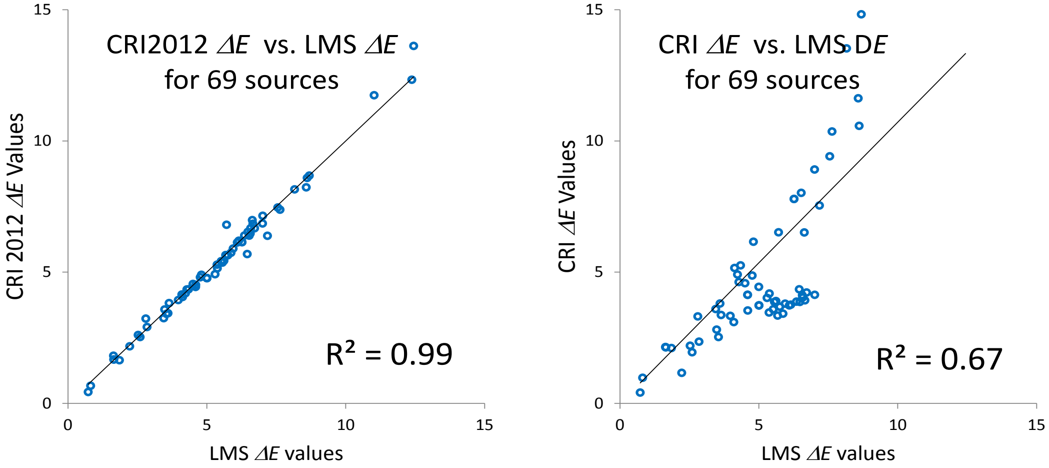

Figure 1. There is a strong correlation between CRI2012 ΔE values and LMS sample-free CRI ΔE values, and a much weaker correlation for CRI ΔE values.

Conclusion

The LMS sample-free CRI metric is simple and conceptually clear. Further, it is grounded in the basic response characteristics of the human eye and the key features of CIECAM02. It is much simpler than previous metrics for color rendering, since it has just three free parameters. In contrast, the color test sample method requires many samples each of which are defined by a great many arbitrary spectral reflectance values. It is possible that the simplicity of this new method may be helpful in establishing an international consensus on standards for color rendering.

References

1. Method of measuring and specifying colour rendering properties of light sources. Vienna, Austria: Commission Internationale de L'Eclairage, 1995.
2. Davis W., Ohno Y. Color quality scale. Opt. Eng. 2010; 49 no.3 033602-16.
3. Luo, R., Cui, G., Li, C. Uniform colour spaces based on CIECAM02 colour appearance model. Col. Res. and Appl. 2006 31, no. 4, 320–330
4. Smet, K., Schanda, J., Whitehead, L., Luo, R. CRI2012: A proposal for updating the CIE colour rendering index. Light. Res. and Technol. 2013 45 no. 6 689-709

Author Biography

Lorne A. Whitehead is a physics professor at the University of British Columbia where he is also the university's special advisor on innovation, entrepreneurship and research. Prior to joining UBC in 1994 he was the CEO of TIR System Ltd. His research focuses on discovery and innovation in the fields of illumination and information display and his research results have been commercialized in a variety of products.