NIST Facility for Color Rendering Simulation

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ABSTRACT

The color rendering index (CRI) does not adequately assess the color rendering properties of solid-state light sources. An improved metric will be critical to the development of such new light sources for general lighting applications. A facility for color rendering simulation of real objects has been developed at NIST, which measures the spectral reflectance of object surfaces, calculates the spectrum of each pixel when illuminated by a given light source, and displays the resultant color image on a computer monitor. Based on these simulations, a number of modifications of the CRI have been developed for an improved color rendering metric.

1. INTRODUCTION

Color rendering is an increasingly important issue in solid-state lighting as novel spectra, produced by new technologies, are developed and compared. The CIE Color Rendering Index (CRI)[1] is unable to accurately assess some LED light sources. Such sources cannot be simply evaluated by the general CRI, R_a. Color rendering performance of white LEDs of various designs (RGB, 4-chip, phosphor) were studied by calculation analysis and simulation. [2,3] We previously developed a simulation program to display, on a computer monitor, the colors of samples (of known spectral reflectance) illuminated by simulated white LED sources. While this system is useful for obtaining an impression of the color differences between standard samples, it does not present an impression of how real objects appear under a given illumination. To extend our research, we have enhanced this simulation to include use of real object images.

A facility for color rendering simulation of real objects has been developed at NIST. This system measures the spectral reflectance of object surfaces by obtaining a number of images at many wavelengths, calculates the spectrum of each pixel when illuminated by a given light source, and displays the resultant color image on the computer monitor. The image can also be adjusted to correct for chromatic adaptation, as though the light source were illuminating the observer's entire environment.

This simulation facility offers some advantages over traditional means of color rendering testing using real light sources. This system does not require the user to obtain and set up many different real light sources and also allows the use of theoretical and other non-existent sources (e.g, Planckian radiation of 5000 K, equal energy white). This system will be particularly useful in the design of new light sources, since color rendering performance can be assessed visually before the new light sources are actually developed. It may also allow visual experiments on color rendering. Illumination spectra can be quickly and precisely manipulated, and rendering simulations can be performed on any real-world object, providing a highly applicable sample set for experimentation. One limitation of the system is the gamut area of the display monitor, when evaluating samples of high chromatic saturation. A warning should be given when this occurs, and the objects samples may need to be reselected depending on the extent of color shifts.

2. METHOD

An imaging photometer combined with a spectrally-tunable liquid crystal filter (LCF) is used to acquire spectrally resolved images. The imaging photometer has 1360 x 1306 image resolution and 12-bit analog-to-digital conversion, with a capability of bracketing operation to further extend dynamic range. It is used without a $V(\lambda)$ filter. Figure 1 shows the relative spectral transmittance of the LCF at several wavelength settings. The bandwidth (half-maximum) is from 5 nm to 15 nm in the visible region. The imaging photometer with LCF is calibrated by measuring a large white paper board, whose spectral reflectance factor has been calibrated, under illumination by a tungsten halogen

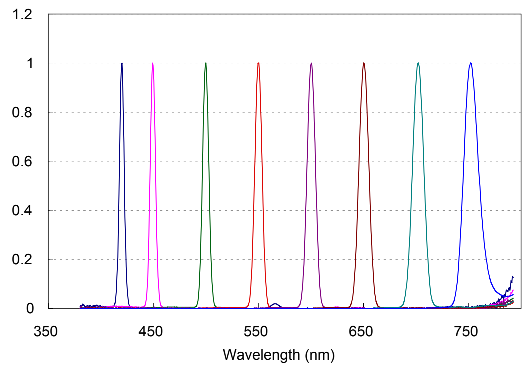

Figure 1. Relative spectral transmittance of the LCF.

lamp in a color viewing booth. The measurements are taken by spectrally tuning the LCF in 10 nm intervals in the 400 nm to 750 nm range. After the imaging photometer is calibrated, the white board is replaced with a target object (e.g., color samples, fruit, flower, etc.), which is then measured by the imaging photometer at the same wavelengths under the same illumination. The ratio of the value of each pixel of the target object to the white board (corrected by the reflectance factor of the board) gives the spectral reflectance factor of the object surface at each pixel in the given geometry set by the light source and the imaging photometer. The spectral reflectance factor data (35 images per scene) are stored in a computer file, where they are accessed by software developed to perform the color rendering simulations. Spectral distribution data of any light source can be used to calculate the reflected spectrum and subsequently the tristimulus values X, Y, Z of light reflected at each pixel of the object. After further possible changes to the spectrum to account for chromatic adaptation, the final X, Y, Z tristimulus values of each pixel are determined. They are then transformed to RGB values by a conversion matrix based on the measured tristimulus values of the display's primary colors and gamma correction.[4] The simulation program allows for selection of Von Kries transform, Bradford transform, or no correction. Chromatic adaptation correction is important because in real-world scenarios the entire surrounding environment would be illuminated by the light sources and the observer's visual system would adapt accordingly. Since the influence of the illuminant is limited to the image on the display monitor in the simulation, the effect of chromatic adaptation must be accounted for within the system.

3. APPLICATIONS

A series of simulations were performed to compare the appearance of various test objects under several light sources. In particular, various RGB white LED models and four-color white LED models (with various combinations of peak wavelengths) were tested. Visual simulations have been generated for the white LED models studied previously.[3] The test object sample set was a combination of various fruits and natural flowers, as well as a Macbeth ColorChecker chart. Though rigorous visual experiments have not been done on this system, the visual impressions of the object colors under these LED models support the conclusions from the previous study.[3] For example, one of the four-color white LED models renders colors with nearly the same quality as a broadband daylight spectra (of the same CCT). Additionally, the appearance of saturated colors was found to be very important for color rendering impression.

These simulations are based completely on the 1931 CIE colorimetry system and do not examine any possible effects beyond the CIE system. Furthermore, the simulation system does not allow visual experiments involving real task performance. We plan to build experimental booths using a real spectrally tuneable source in the near future, extending one that has been developed for radiometric applications[5]. The visual accuracy of our color image simulation system will be tested and validated by comparison with such a real facility. However, relying on the validity of the current CIE colorimetry system, this simulation provides analysis of the problems of the current CRI by examining the color images under various theoretical and modelled SPDs, and suggests solutions to the problems of CRI.

Based on this simulation work, several improvements for the current CRI are developed and proposed. The proposed modifications include changes to the reflective sample set, the color space used to calculate perceptual color differences (ΔE), and the scaling factor used in calculation of the general color rendering index, as well as the addition of a saturation factor, CCT factor, use of RMS, and conversion to a 0-100 scale. These improvements were implemented in an improved color rendering index program developed at NIST, which addresses most of the problems identified in the previous study[2]. The details of these changes and new factors introduced are given below.

Samples

The eight moderately saturated reflective samples of the CRI were replaced with 15 samples of high chromatic saturation spanning the entire hue circle. The chromaticity a*, b* of these samples under illumination by D65 are shown in Figure 2. All are Munsell samples of the following hue value/chroma: 7.5 P 4 / 10; 10 PB 4 / 10; 5 PB 4 / 12; 7.5 B 5 / 10; 10 BG 6 / 8; 2.5 BG 6 / 10; 2.5 G 6 / 12; 7.5 GY 7 / 10; 2.5 GY 8 / 10; 5 Y 8.5 / 12; 10 YR 7 / 12; 5 YR 7 / 12; 10 R 6 / 12; 5 R 4 / 14; 7.5 RP 4 / 12.

Highly saturated samples were chosen because accurate rendering of highly saturated colors by a lamp ensures accurate rendering of less saturated object colors. The inverse is not true however; accurate color rendering of objects of low saturation by a particular lamp does not guarantee good rendering of more saturated colors. This is particularly important for the peaked spectra of LEDs. Adequate representation of all the hues is also important for this reason, which is why the sample set was increased from eight to 15.

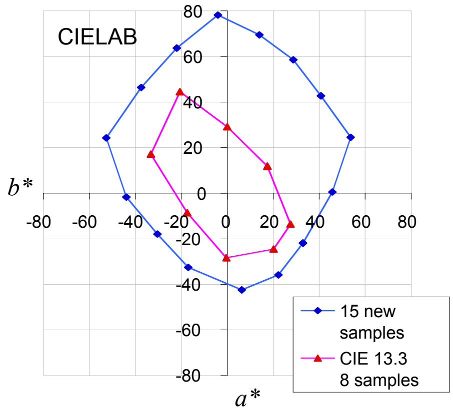

Figure 2. Chromaticities a*, b* of the 15 samples used in the NIST program and those of the 8 samples of CIE 13.3 plotted on CIELAB space.

Object Color Space

The 1964 W*U*V* space used in the current CRI is very nonuniform and color differences are extremely exaggerated in the red region and suppressed in yellow and blue regions. W*U*V* is no longer recommended by CIE. We chose CIE 1976 L*a*b* ("CIELAB") to replace W*U*V*,as CIELAB is the current recommendation by CIE and widely used in many applications.

Scaling Factor

In the current CRI, the scaling factor 4.6 is used to convert color differences into color rendering indices. This factor needs to be changed when the sample set and color space are changed, in order to maintain the consistency with the current CRI. With our test program for a new index, a new scaling factor is chosen so that the average score of the new index for the CIE standard fluorescent lamp spectra (F1 through F12 in CIE 15.2) is equal to the average score of the current CRI R_a (75.1) for these sources. This scaling maintains consistency of the new color rendering metric scale with the current CRI scale for existing lamps.

Saturation Factor

The CRI penalizes lamps for color shifts of hue and chromatic saturation in any direction between samples under reference and test sources. However, an increase in object color saturation (chroma) under the test source is considered desirable. Increases in chroma yield better visual clarity and enhance perceived brightness[6]. These are positive effects and are generally preferred, though they cause deviations in color fidelity (compared to reference). In the improved color rendering metric, lamps are not penalized for increasing object chroma relative to the reference source, though their scores are also not increased. The net result is that a lamp's score is only penalized for hue shifts, lightness shifts, and reductions in chroma. This is a way to take color preference into account in the new color rendering index.

CCT Factor

As with the CRI, the CCT of the reference light is matched to that of the test light. Therefore the CRI score is perfect (100) for reference illuminants of any CCT. Color rendering, however, is degraded at extremely low or high CCTs. To account for this effect, a CCT correction factor is included in the improved metric. A multiplication factor is based on the gamut area in CIELAB space for the 15 samples under the reference sources (Plankian) for each CCT, which are shown in Figure 3. The multiplication factor was normalized to give 6500 K a value of one. All other multiplication factors were determined by the ratio of a given CCT's gamut to the gamut area of 6500 K and are shown in Figure 3. With this normalization, the multiplication factors at certain CCT ranges (e.g., 5000 K) give values slightly higher than 1, but these are truncated to 1, so that the new CRI value will never be higher than 100. The exact effect of CCT on color rendering is difficult to quantify, but this method offers at least a temporary solution for sources at extremely low or high CCT.

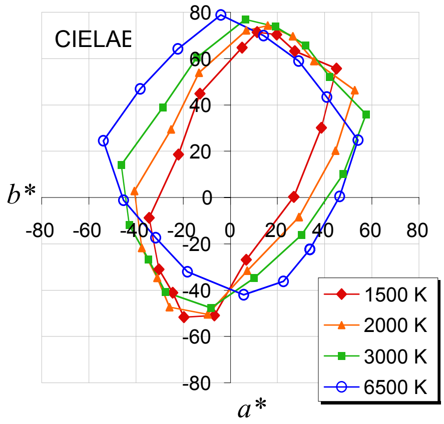

Figure 3. Gamut area produced by the 15 samples under Planckian source.

Use of RMS

In the current CRI, the color differences (ΔE) for each of the samples is averaged. This makes it possible for a lamp to score quite well, even when it renders one or two samples very poorly. This situation is even more likely with SPDs having narrowband peaks. To ensure that large hue shifts of any sample have notable influence on the general color rendering index, the root-mean-square (RMS) of color shifts of each individual sample is used (rather than arithmetic mean). The RMS color differences of the 15 samples are calculated by

$$\Delta E_{\mathrm{RMS}} = \sqrt{\sum_{i=1}^{15} \Delta E_i^{\,2} / 15} \tag{1}$$

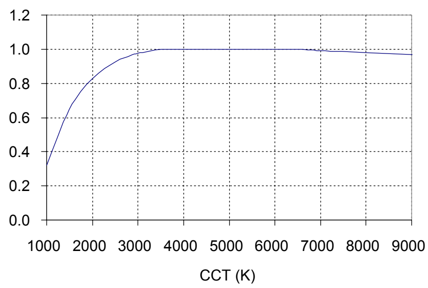

Figure 4. CCT scaling factor (normalized gamut area).

0-100 Scale

This correction was made to avoid the often confusing negative values that the current CRI reports for certain lamps. CRI scores lower than 20 or 30 are already very poor and the linearity of the scale below these low scores is not considered important. A scale from 0 to 100 would be better understood by users and was implemented by using the formula,

$$R_{\mathrm{out}} = 10 * \ln\left[\exp(R_{\mathrm{in}}/10) + 1\right] \tag{2}$$

where R_{in} is the input value (which can be a negative number) and R_{out} is the output value of the conversion. Only values lower than about 20 are changed by this conversion, and values above 20 are not considerably affected. As such, all values within the range for usable lamps are unchanged.

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