Metamer Mismatching as a Measure of the Color Rendering of Lights

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ABSTRACT

We propose a new method for evaluating the colour rendering properties of lights. The new method uses the degree of metamer mismatching for the CIE XYZ corresponding to flat grey (constant reflectance of 0.5) quantified in terms of the metamer mismatch volume index proposed by Logvinenko et al. (Logvinenko 2014). A major advantage of this method is that unlike many previous color rendering indices it does not depend on the properties of a chosen set of representative test objects.

1. INTRODUCTION

Evaluating the colour rendering properties of lights is an important issue in the lighting industry. It is well known that the colours of objects viewed under lights of identical correlated colour temperature may look very different under the different lights. Several color rendering indices have been used in the past. Perhaps the most widely used is the CIE colour rendering index CIE Ra (CIE 1995), which is based on computing the average color difference induced by the illuminant for a fixed set of reflectances. The CIE Ra is a color fidelity measure. There have also been preference-based measures such as Judd's flattery index (Judd 1967) and Thornton's colour preference index (Thornton, 1972), in which the focus is more on the subjective preferability of lights. More recently Smet et al. (Smet 2010, Smet 2015) have suggested a memory-color-similarity measures, Sa and Rm (a non-linear scaling of Sa), based on how a light affects the colors of a sample set of familiar objects (green apple, banana, orange, lavender, Smurf, strawberry yoghurt, sliced cucumber, cauliflower, Caucasian skin, sphere painted Munsell N4 grey) in comparison to the average subject's memory of the colors of those objects as determined by psychophysical experiments.

The CIE Ra is defined in terms of a reference illuminant and the test light being evaluated. For test lights of CCT less than 5000K the reference illuminant is chosen to be the ideal blackbody radiator of the same CCT. For test lights with CCT of 5000K or greater, the reference light is chosen to be the standard CIE daylight D-series illuminant of the same CCT. There are 8 test color samples (Munsell papers) whose color differences, after an adjustment for chromatic adaptation, under the test and reference lights are evaluated.

The CIE Ra has been widely criticized, especially for the evaluation of LED lights. One of the key problems with it is that it is based on measuring the colour differences that arise across a small sample of 8 (sometimes generalized to 14) coloured papers. Not only may such a sample not represent what the colour differences for all other possible surface reflectances may be, it also gives manufacturers the opportunity to tune the spectra of their lights to perform well on the standard sample.

Variants of metamer mismatching have been previously used as a measure of the color rendering of daylight simulators. In particular, the CIE Metamerism index is a measure based on calculating the average color difference between each of a set of reflectance pairs that are initially metameric matches under the reference light but not necessarily metameric matches under the target light. However, this method is limited to the specific reflectances used. Whitehead et al. (Whitehead 2012) extend this general idea by using a large number of randomly generated metameric spectra and then assessing the fraction of them that noticeably change colour when the illuminant changes. In contrast, the method proposed here is based on measuring the size of the metamer mismatch volume, which is the volume of colour signals (i.e., XYZs) induced under the second light by the set of all theoretically possible reflectances that make a metameric match under the first light.

1. METAMER MISMATCH INDEX

The background for the proposed measure of colour rendering is the concept of metamer mismatching. Consider a colour signal XYZ (in CIE standard coordinates) observed under a first light. Metamer mismatching refers to the fact that the possible XYZ that might be observed under a second light is only constrained to lie within a convex volume of possible XYZ values. The size of the volume depends on the XYZ and the lights involved; however, the volume for the XYZ of flat grey is the largest. The metamer mismatch volume represents the range of possible XYZ that can arise under the second light and so provides a measure of how varied the XYZ under the second light can be—the less the variation, the better the color rendering.

The boundary of the metamer mismatch volume can be calculated using the code of Logvinenko et al. (Logvinenko 2014), which finds the maximum amount of metamer mismatching that can occur for any given XYZ and pair of lights. Figure 1 shows an example of the metamer mismatch volume for the XYZ of flat grey for a change in illuminant from an ideal 2900K blackbody radiator to a 2900K LED. Even though the two illuminants are of the same CCT the metamer mismatch volume is quite large: it fills a sizable fraction of the entire object-color solid. The object-colour solid is the set of all possible XYZ that can arise for all possible reflectance functions $\rho(\lambda)$ (i.e., $0 \leq \rho(\lambda) \leq 1, 380 \leq \lambda \leq 780$nm). The metamer mismatch volume depicted is the set of all possible XYZ that could arise under the second illuminant for any reflectance that is metameric to flat grey under the first illuminant.

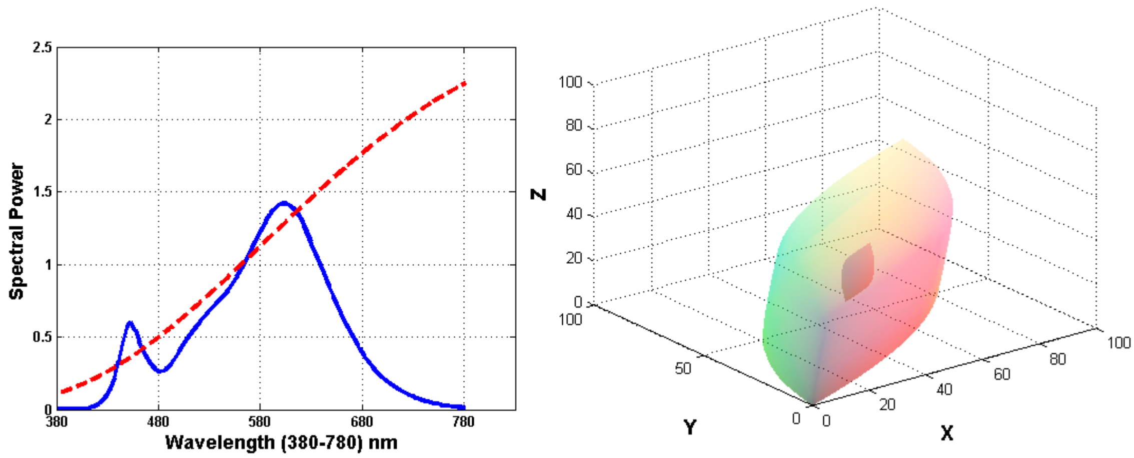


Figure 1: Left: Spectra of a 2900K LED (blue) and that of an ideal 2900K blackbody radiator (dashed red). Right: Metamer mismatch volume (for the XYZ of flat grey lit by a 2900K blackbody) shown inside the object-colour solid of the 2900K LED for the case when the illuminant is changed from the blackbody to the LED. Coordinates are the CIE 1931 XYZ space.

Since both the object color solid and the metamer mismatch volume change with the second illuminant, we consider size of the metamer mismatch volume relative to the size of the object color solid it generates. In particular, both scale with the intensity of the second illuminant. Hence, the metamer mismatch volume index (MMVI) (see Logvinenko et al., 2014 Eq. 15 for a formal definition) for a given XYZ and a pair of illuminants is defined as the ratio:

$$MMVI = \frac{\text{volume of the metamer mismatch volume for the given illuminant pair}}{\text{volume of the object color solid under the second illuminant}} \qquad (1)$$

Note that this ratio is also independent of any linear transformation of the color coordinate space and so will be the same for any LMS space obtained as a linear transform of CIE XYZ as for CIE XYZ itself.

In terms of colour rendering, the larger the MMVI, the poorer the colour rendering of the second light relative to the first light is likely to be. Since the MMVI is volume based, we find it more intuitive to consider MMVI^(1/3). The Metamer Mismatching Colour Rendering Index (MMCRI) is then defined as:

$$MMCRI = (1 - \sqrt[3]{MMVI}) \times 100 \qquad (2)$$

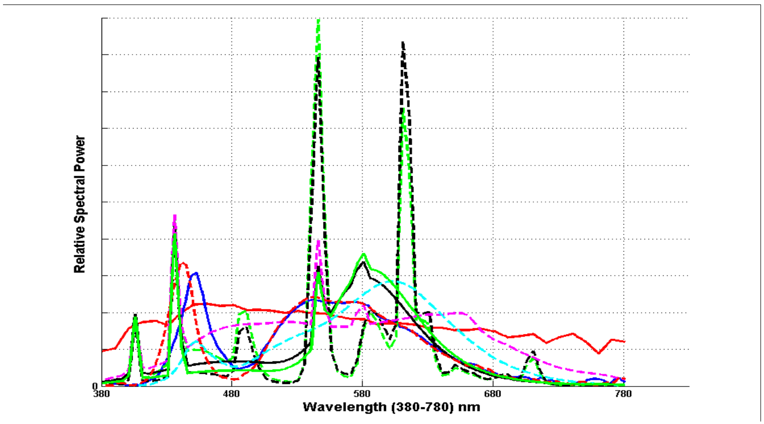
where the MMVI is for that of the XYZ of flat grey under the first illuminant. The scaling by 100 is simply to make its range match that of the CIE CRI Ra.

4. COMPARISON TO OTHER COLOR RENDERING INDICES

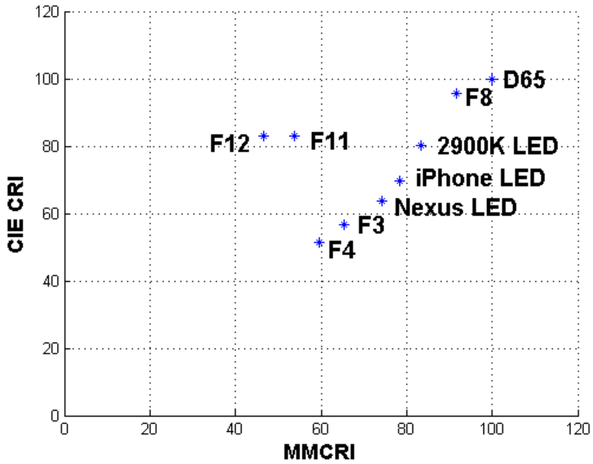
The MMCRI can be computed for any pair of illuminants as a measure of the color rendering properties of the second light relative to the first. However, the CIE CRI Ra for a light L is defined relative to an 'ideal' illuminant (blackbody or D-series) of the same CCT as L. For comparison with Ra we use the same choice of 'ideal' illuminant as the first illuminant when computing the MMCRI of L.

We have computed the MMCRI and CIE Ra for several light spectra across a range of CCTs and technologies and compared them. In particular, we measured the spectra of several commercially available LED lights and also used the spectra of the CIE standard illuminants. When plotted as in Figure 2 we see a good correlation between the two indices—an indication that the MMCRI behaves reasonably—but with notable differences for some illuminants. It is exactly such differences that the proposed new method is intended to reveal. In particular, we note that F11 and F12 have a high CIE Ra but a low MMCRI. Since F11 and F12 are both dominated by three narrowband peaks, it seems unlikely that their color rendering properties are very good, and this is confirmed by the MMCRI.

As second test, we make use of the set of lights Smet et al. included in their paired comparison experiment (Smet 2010). Smet's set contains: a halogen lamp (H), a fluorescent lamp approximating CIE F4 (F4), a Neodymium incandescent lamp (Nd), a Philips Fortimo LED module with a green filter (FG), an RGB LED lamp (RGB) and a LED cluster (LC) optimized to obtain a high Sa, all of which are plotted in Figure 3. The various color rendering measures are compared in Table 1.



(2a)



(2b)

Figure 2: (2a) The illuminant spectra used for testing: D65 (red), F3 (black), F4 (dashed green), F8 (dashed magenta), F11 (dashed green), F12 (dashed black), 2900K LED (dashed cyan), Nexus LED (dashed red) and iPhone LED (blue). (2b) CIE CRI versus MMCRI.

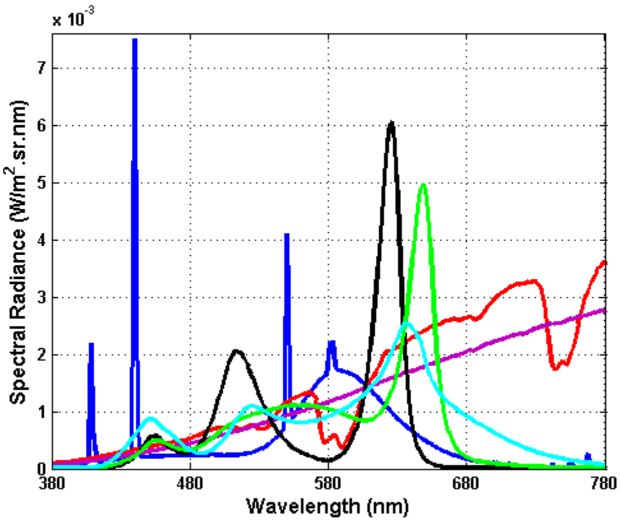


Figure 3: The spectral power distributions of the six light sources (provided by Smet) and used for the comparison of the color rendering measures listed in Table 1. The lights (see text) are F4 (blue curve), FG (green), Nd (red), LC (cyan), H (purple) and RGB (black).

Table 1. Comparison of Color Rendering Measures. Measures include: Sa, memory color similarity (Smet 2010), Ra (CIE CRI), NIST CQSa Color Quality Scale (Davis 2010), and MMCRI (proposed metamer mismatch index). The data reported in the table for Sa, CIE CRI Ra and NIST CQSa are quoted from Table 2 of Smet et al. (Smet 2010, page 26235). The MMCRI results were computed based on the MMVs for a change from the blackbody radiator having the CCT of the given illuminant to the given illuminant. The lights were approximately equal illuminance ranging from 239 to 251 lux, and CCT ranging from 2640 to 2878. The spectra of the lights are plotted in Figure 3.

Light source	Sa		CIE Ra		NIST CQSa		MMCRI	
	Sa	Rank	Ra	Rank	CQSa	Rank	MMCRI (Grey)	Rank
F4	0.6672	5	52.8	5	53.9	5	55.53	5
FG	0.7787	3	80.6	3	87.2	3	83.99	3
Nd	0.7841	2	73.7	4	87.0	4	89.46	2
LC	0.7899	1	81.0	2	89.0	2	74.95	4
H	0.7662	4	99.6	1	97.2	1	99.64	1
RGB	0.6548	6	31.9	6	50.5	6	49.30	6

The results in Table 1 show a general agreement in ranking across all the methods in that the same lights are given ranks 3 (FG), 5 (F4), and 6 (RGB). Ra and CQSa rankings for all six lights are identical. MMCRI agrees with Ra and CQSa on 4 of the rankings, but swaps the rankings of Nd and LC, ranking Nd 2nd, in agreement with Sa and the reported popularity of Neodymium lights in terms of their sales. Since LC is an LED cluster designed to optimize Sa, it is not surprising that it is ranked first by Sa. Similarly, since H is a halogen light closely approximating a blackbody radiator, it is also not surprising that MMCRI, Ra and CQSa all rank it first since they assume that a blackbody is the ideal light source in terms of color rendering. This is an assumption that Smet et al. (Smet 2012) challenge, but as yet no general alternative has been proposed.

It should be noted that the Sa rankings in Table 1 do agree with the 'preference' and 'fidelity' rankings reported in Table 3 of Smet et al. (Smet 2010, p. 26237). However, one problem Table 1 reveals about the Sa measure is that it ranks many of the lights almost identically. In particular, FG, Nd, LC and H all have Sa values of 0.778 ±0.012. Effectively, Sa divides the lights into just two groups: (FG, Nd, LC, H) and (F4, RGB). In comparison, with MMCRI there are clear differences in the scores such that there are four distinct groups: (F4, RGB), (LC), (FG, Nd) and (H).

4. CONCLUSION

A new measure of the color rendering properties of lights is proposed based on the general concept of metamer mismatching. The amount of metamer mismatching—effectively the range of theoretically possible color signals arising under a second light—is taken as an indicator of the difference in the color rendering properties of the second light relative to the first. The greater the degree of metamer mismatching, the poorer the color rendering is considered to be. Previous color rendering indices have been based on a fixed selection of object reflectances. Although there have been attempts to optimize the set of test reflectances (Smet 2013) a finite set will always remain the source of some bias. In comparison, the proposed method, through the calculation of the metamer mismatch volume, takes into account all theoretically possible reflectances

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