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Assessing color-rendering Differences in Cinematic Lighting with a New Metamer Mismatch Metric

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Abstract

Consistent color-rendering in motion pictures is critical for creating natural scenes that enhance storytelling and don't distract the audience's attention. In today's production environments, it is common to use a wide variety of light sources. Traditional tungsten-halogen sources—red, green, and blue light-emitting diode (RGB LED) sources and white light LEDs—are often mixed, leading to color-rendering issues. This paper introduces a new metric, the Camera Lighting Metamer Index (CLMI), rooted in the concept of metamer mismatching. The CLMI is for assessing the color-rendering differences of disparate sources when a single camera is used and the camera's spectral sensitivities are known. By leveraging the known spectral sensitivities of the camera and the spectral power distributions (SPDs) of the light sources, CLMI quantifies the potential for color discrepancies between objects lit by the different sources. We propose that this metric can serve as a useful tool for cinematographers and visual effects artists, providing more predictable and precise control over color fidelity. The metric could also be used to supplement existing generalized metrics, such as Spectral Similarity Index (SSI), when detailed camera and light source spectral characteristics are available.

Introduction

To create natural scenes that enhance storytelling in motion pictures without distracting the audience, consistent color-rendering is essential. Achieving this has always been challenging but is made more complicated when using lighting technologies with highly disparate spectral power distributions (SPDs), such as tungsten halogen, RGB LEDs, and white light LEDs, within a single scene. color-rendering becomes even more difficult to manage when integrating computer-generated imagery (CGI) with photographed images or when RGB LED walls are used as backgrounds and lighting sources for virtual productions.

For decades, daylight and tungsten incandescent lights have been the primary reference sources in photographic color-rendering[5]. However, the SPDs of modern solid-state light sources, such as LEDs, deviate significantly from these conventional sources, even if they share similar correlated color temperatures (CCTs) and chromaticity values[9]. These deviations create significant, and often hidden issues, as the SPDs of the sources used are generally not available to the photographer or cinematographer on set and, even when available, are complex to interpret. Further complicating the issue, the most common color-rendering metrics provided by lighting manufacturers, such as the color-rendering Index (CRI)[1] or the Illuminating Engineering Society (IES) TM-30[4], are inapplicable to cinematic applications because they do not consider the spectral sensitivities of digital cinema cameras. Recent advancements in color-rendering, as discussed by Schanda et al., highlight the limitations of CRI and the improvements introduced by metrics like TM-30 in general lighting applications. However, these metrics still fall short when assessing color-rendering from a camera's perspective.

Recent studies have highlighted the need for color-rendering models targeted specifically for photographic applications. Holm et al. criticized the use of CRI for light sources used in cinematography because the metric relies on the use of the CIE standard observer, a model of the human visual system, which is not applicable when the observer is a camera[2]. To account for the fact that digital camera spectral sensitivities differ significantly, not only from the eye's but also from one camera model to another, they proposed a metric, known as the Spectral Similarity Index (SSI), which compares the SPD of a test source directly with that of a reference source. Jiang et al. [6] explored the diversity in spectral sensitivity functions across different digital cameras, highlighting the variability that must be considered when assessing color-rendering, supporting the development of camera-specific metrics like CLMI.

While the SSI is appropriate when camera spectral sensitivities are unknown, it can be overly restrictive. When the camera spectral sensitivities are known, a more nuanced approach is possible. In particular, we can relax the SSI requirement that the light source SPDs match those of the reference source as closely as possible. The CLMI shows how color-rendering quality can be high without having to force the SPDs of the lights to be similar to one another.

In a similar application of metamer mismatching, Roshan et al. introduced the Camera Metamer Mismatch Radii Index (CMMRI) which introduced the use of metamer mismatch radii to measure the colorimetric accuracy of cameras[8]. The CMMRI is founded on the algorithm of Logvinenko et. al[7] and addresses the need for metrics that quantify differences in spectral sensitivities of imaging devices compared to those of the human observer.

Methods

This study introduces a theoretical metric, referred to as the Camera Lighting Metamer Index (CLMI), to evaluate the potential for metamer mismatching between two different light sources when capturing images with a digital camera. The metric is based on the concept of Metamer Mismatch Bodies (MMBs), which quantify the differences in color signals of metameric pairs under different lighting conditions.

The required input values for the algorithm are the spectral power distributions (SPDs) of the test and reference light sources, along with the spectral sensitivity functions for a camera. Similar to the CMMRI algorithm, CLMI algorithm computes both the object color solid (OCS) for the "color mechanism" of the reference source and camera spectral sensitivities combined, and the MMB for the color mechanism of the test source and camera spectral sensitivities. As described by Roshan et al., the moments of inertia tensor for the MMB are calculated by treating the MMB as a mass of uniform density and determining the principal radii of its equivalent ellipsoid. These radii characterize the dominant aspects of the shape of the MMB, providing insights into the degree of metamer mismatching.

To ensure invariance to any linear transformation of the sensor space, the MMB is normalized relative to the OCS. The principal moments of the OCS are used to derive a unique linear transformation that normalizes the MMB, transforming its equivalent ellipsoid into a unit sphere.

The calculation of CLMI involves several key steps. Both the test and reference illuminants are normalized to a maximum value of one, and the camera spectral sensitivities are normalized to a sum of 100, similar to the normalization methods performed during the calculation of the CCMRI metric [8]. If the reference source is not provided, one is generated based on the CCT of the test source. For test sources with a CCT less than 4,000K, a blackbody reference illuminant of the same CCT is generated. For test sources with a CCT greater than or equal to 4,000K up to 25,000K, a reference illuminant is generated that is CIE daylight of the same CCT. The normalized spectral sensitivities are then used to compute the OCS for the reference illuminant and the MMB for the test illuminant.

The CLMI is calculated by first determining the metamer mismatch body (MMB) for the camera when viewing objects under the two different light sources: the test and the reference. The MMB represents the set of color stimuli that match under one light source but may not match under the other. To characterize this MMB, an equivalent ellipsoid is computed, which shares the same principal moments of inertia as the MMB[8]. This ellipsoid provides a simplified representation of the MMB's shape, capturing the extent of metamerism between the two light sources for the camera. The dimensions of this ellipsoid are then used to determine the mean of its three principal radii. The CLMI is obtained by normalizing the MMB relative to the object color solid (OCS) and calculating this mean. The mean provides a quantitative measure of the metamerism potential between the two light sources, reflecting the robustness of color matching under different lighting conditions as viewed by the camera.

Testing

To test CLMI, we first conducted a correlation analysis between the SSI and CLMI. The SSI and CLMI values for 318 SPDs were calculated, with the SPDs obtained from the IES Spectral Calculator Example Library. As shown in Figure 1, the correlation coefficient was 0.95 ($p = 1.48 \times 10^{-162}$), indicating a very strong positive linear relationship between CLMI and SSI. This correlation is highly statistically significant, suggesting that the likelihood of this relationship being due to random chance is extremely low. Note, SSI sometimes produces out-of-range negative values, whereas CLMI values are always greater than 0. Negative SSI values were observed for 4 of the 318 SPDs from the IES TM-30 Calculator Example Library[3].

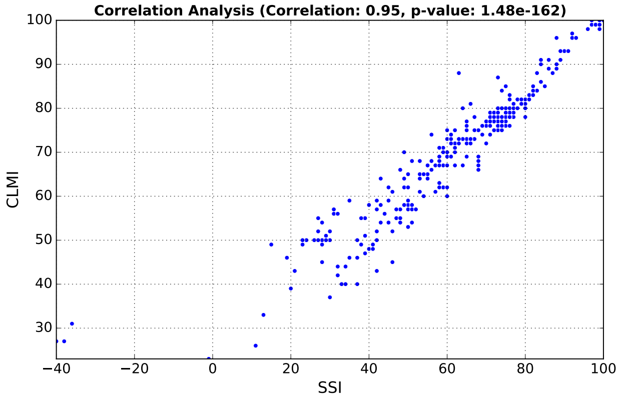

Figure 1. *Correlation analysis of the SSI and CLMI values of 318 Spectral Power Distributions from the IES Example Library*

While the SSI does not claim to directly predict a camera's response to a test source compared to a reference source, it is often used in that manner. As previously mentioned, the Camera Lighting Metamer Index (CLMI) has the potential to relax the requirement for the spectral power distribution (SPD) of the test source to closely match that of the reference source for the camera to produce a similar response.

An example of this can be seen in Figure 2, where each of the spectral power distributions (SPDs) has an SSI value of 63. However, CLMI values vary, as reported in Table 1, where the CLMI values were calculated for three cameras with different spectral sensitivities. The spectral sensitivities of the three cameras are shown in Figure 3.

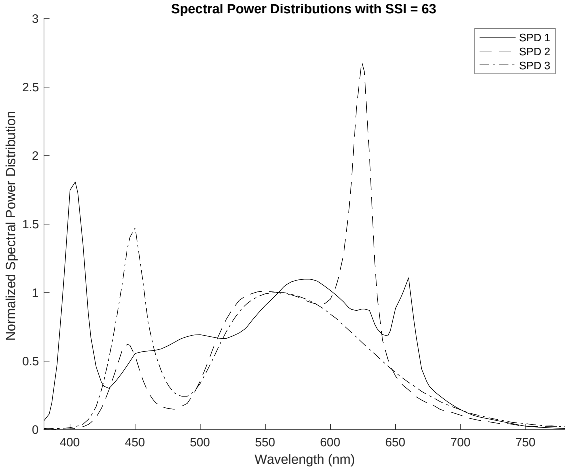

Figure 2. *Normalized spectral power distributions with an SSI of 63*

Given the known spectral sensitivities of the cameras, it is possible to calculate a synthetic image using the spectral reflectance values for a set of test patches and determine the change in the RGB values of each patch under the test source compared to the reference source. The RGB values of a Macbeth Color Checker were calculated for each of the SPDs in Figure 2.

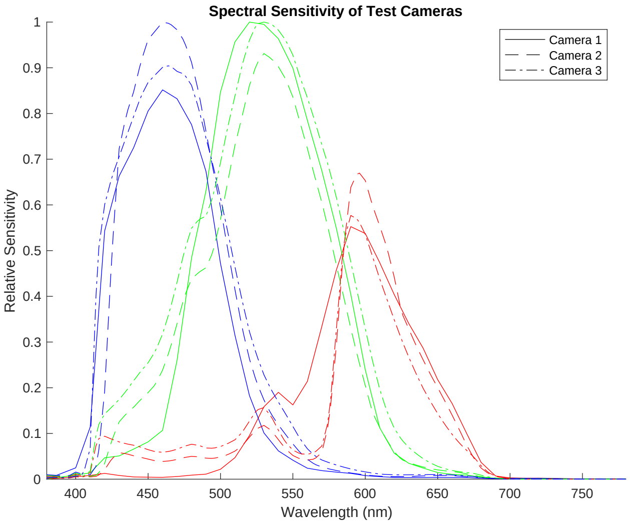

Figure 3. *The red, green and blue spectral sensitivities of the three test cameras*

	SSI	CLMI Camera 1	CLMI Camera 2	CLMI Camera 3
SPD 1	63	88	90	88
SPD 2	63	72	72	74
SPD 3	63	73	75	75

Table 1. *SSI and CLMI values for three cameras with different spectral sensitivities.*

Figure 4 shows three synthetically generated Macbeth Color Checker targets, where each patch is split in half. The top half of each patch represents the color of the spectral reflectance illuminated by the reference source and captured by the spectral sensitivities of Camera 1. The bottom half represents the color of the spectral reflectance illuminated by the test source and captured by the same camera. This visual representation highlights the color difference on the patches caused by the change in the light source, as captured by Camera 1. A single set of white balance factors was used for both the reference and test source. This was intended to mimic the use of both lights on a single set where the camera could only be white-balanced to one source. Due to the difference in spectral power distribution of the test and reference sources, slight white balance shifts can be observed. It is important to note that the RGB values used to generate the chart are linear RGB values from the camera and have not been processed for display or printing. The intention is to directly illustrate the impact of the light source on the camera's response to the patch reflectances. Table 2 shows the mean, min and max delta values between the reference-source-lit RGB values and the test-source-lit RGB values of the MacBeth patches.

	SPD 1	SPD 2	SPD 3
Mean RGB Delta	0.135	0.535	0.329
Min RGB Delta	0.003	0.068	0.026
Max RGB Delta	0.443	1.728	0.693

Table 2. *Mean, Min, and Max Delta RGB values between the test and reference source for the MacBeth Color Checker Chart for Cameras 1.*

Figure 4. *Synthetic Macbeth color checker where the top half of each patch represents the Macbeth patch lit by the reference source, and the bottom by each of the three test sources with an SSI of 63. From top to bottom, the test sources used were SPD1, SPD2, and SPD3. The camera spectral sensitives used in this illustration were those of Camera 1. These images are not processed for display or printing and are intended to be an illustration of the difference in linear camera response to the test sources vs. the reference source.*

Conclusions

The paper has presented a new metric, the Camera Lighting Metamer Index (CLMI), for predicting color-rendering in photography and cinematography. The advantage of CLMI over existing metrics such as CRI and TM-30 is that it uses a camera's spectral sensitivities in its calculation rather than human cone sensitivities. Additionally, it provides the advantage of considering the sensor spectral sensitivities, when known, to provide a more nuanced understanding of the impact of lighting on camera response as compared to SSI which only compares the similarity of two spectral power distributions across a weighted wavelength range. Consequently, CLMI provides a comparison of the color-rendering effects of a test light source as compared to a reference light source that is more targeted to photographic applications.

Correlation analysis shows CLMI has a strong positive relationship with the SSI. However, by leveraging the camera's spectral sensitivities and the concept of Metamer Mismatch Bodies (MMBs), CLMI quantifies the potential of metamer mismatching and color discrepancies more directly than comparing spectral power distributions. SSI was engineered to provide a good indicator of the color differences that might arise when using one illuminant versus another. In comparison, CLMI is based on a theory of metamer mismatching. The high correlation between CLMI and SSI shows that CLMI, based as it is on theory, provides further support for SSI. The correlation also shows that CLMI works in practice and provides a promising direction for further research.

In summary, the Camera Lighting Metamer Index (CLMI) is a camera-specific color-rendering metric developed for use in photography and cinematography. Unlike traditional color-rendering metrics such as TM-30 and CRI, which are designed for human visual perception, CLMI accounts for the unique spectral sensitivity of a camera. This provides a more detailed analysis of how different light sources impact color-rendering in photographic applications. While CLMI correlates with the Spectral Similarity Index (SSI), it offers additional insights into the effects of light sources, particularly in cases where metamer mismatching affects color accuracy in a camera-specific manner.

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