Academy Spectral Similarity Index (SSI): Overview

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INTRODUCTION

Since its inception, color cinematography has used and evolved around natural light sources: daylight and tungsten. These sources are characterized by broad, smooth spectral power distributions (SPDs), which describe the distribution of light energy across the visible spectrum. Film stocks, and later digital sensors, were expressly designed to work with daylight and tungsten. New lighting technologies such as light-emitting diodes, however, differ from these sources in fundamental respects. They also differ from each other. When these new lighting technologies are introduced into photography environments that have traditionally used natural light sources, undesirable color rendering is often the result.

A number of existing color metrics have been used in an attempt to quantify the color-rendering quality to be expected with such new light sources. However, the existing metrics were developed to measure rendering quality as seen by human observers or television cameras; due to the particular characteristics of cinema cameras, these metrics are inadequate for motion picture photography.

The Academy of Motion Pictures Arts and Sciences developed the Academy Spectral Similarity Index (SSI) in response to this problem. SSI quantifies the similarity of one light source's SPD to another's. For example, if the reference source is daylight, the SSI value for the test source would indicate the extent to which its color-rendering capability would be a match for daylight.

SSI has been adopted and published by the Society of Motion Picture and Television Engineers as a SMPTE standard, ST 2122:2020 – Spectral Similarity Index (SSI).[1] That document is the definitive description of the index.

This paper describes some basic lighting and color principles, lighting metrics currently used in motion picture production, and the need for a metric that better addresses the color-rendering issues confronting motion picture professionals today. It then introduces SSI and explains how it is calculated.

BACKGROUND

Color is fundamentally a function of the SPD of a light source, the per-wavelength reflectance and/or transmittance of an object, and the per-wavelength sensitivity of a detector. As the SPD of a light source or the sensitivity of a detector changes, so does the perceived color of the object. This can create problems if an object is photographed under different light sources and specific, consistent color rendering is desired.

Historically, two types of light sources have been used in motion picture production: daylight and tungsten incandescent luminaires. Likewise, there was one type of detector: photographic film, whose spectral sensitivity is relatively consistent from manufacturer to manufacturer. Over time, other types of light sources such as fluorescent gas-discharge and "hydrargyrum medium-arc iodide" (HMI) lamps came into use to mimic these traditional sources, but their SPDs were significantly different. With a keen awareness of how these differences affected color, lighting manufacturers extensively tested their products in combination with photographic films so cinematographers on set could obtain reasonably predictable results.

As new technologies in both lighting and cameras were introduced, the number of variables affecting color grew exponentially. Solid-state lighting sources such as light-emitting diodes (LEDs) not only differ substantially from traditional sources, but also from each other. Likewise, digital cameras have spectral sensitivities that are not only very different from photographic film, but also different from one digital camera to the next. Even two cameras from the same manufacturer can have dramatically different spectral sensitivities. These factors can lead to unpredictable and often undesirable results which cannot be fixed using standard color-correction tools. It's also no longer practical for manufacturers to test their products in a comprehensive range of scenarios, as the combinations of luminaires and cameras are virtually limitless. Nonetheless, manufacturers have begun to measure and promote, using various metrics, the color-rendering capability of their lighting products. These metrics include CCT, CRI, CQS, IES TM-30, and TLCI. For reasons that will be outlined in this paper, these metrics are either inadequate or incapable of predicting color-rendering results for motion picture production. In response, the Academy of Motion Picture Arts and Sciences has developed the Spectral Similarity Index, which quantitatively compares the spectral power distribution of two different light sources.

SOLID-STATE LIGHTING (SSL)

In a previous report, the Solid State Lighting Project Committee of the Academy's Science and Technology Council examined color-rendering errors that arose from the differences in the spectral characteristics of LED versus incandescent light sources in motion picture production.[2] At their core is a fundamental difference in SPDs. The spectral sensitivities of film emulsions, and of most digital cameras, are designed using the relatively smooth, unimodal SPDs of "photographic daylight" and "studio tungsten" as described and standardized in ISO 7589.[3] In contrast, many solid-state sources are characterized by peaky, multimodal, or narrow-band SPDs. Since film and digital cameras are designed to work with – and are indeed optimized for – daylight and tungsten, undesirable color rendering is often the result with LED sources.

MEASURING RENDERING QUALITY

The Color Rendering Index (CRI)[4] and correlated color temperature (CCT) are two metrics used to describe the degree to which a non-incandescent light source can mimic the color rendering of daylight and tungsten. However, an object lit with two sources with the exact same CCT but different SPDs may appear very different to a particular detector (such as a camera sensor). CRI was not designed to evaluate color as seen by cameras; rather, it is based on the spectral sensitivity of the human eye (the "CIE 1931 Standard Observer"[5]). Film and digital sensors have spectral sensitivities different than those of the human visual system. And, as there is no standard for the spectral sensitivity curves of the component red, green and blue filters in single-chip digital cameras, the "peakiness" of LED spectra in particular affects different cameras differently, which can result in unexpected color rendition. In short, a high CRI score cannot guarantee a faithful rendering of skin, costumes, and other visual elements that have precise color relationships in a scene.

In 2007 the CIE (Commission Internationale de l'Éclairage, or International Commission on Illumination) proposed that an alternate index for color rendering should be established to address the incompatibility of CRI values and SSL sources. Two CIE workgroups have spent years on the challenge, but a new index has yet to be published. The National Institute of Standards and Technology (NIST) published a proposed index called the Color Quality Scale (CQS),[6] but it, as with CRI, is based on human perception. The British Broadcasting Corporation (BBC) and European Broadcasting Union (EBU) have published Recommendation R 137,[7] the Television Lighting Consistency Index (TLCI). This metric, however, is primarily based on the spectral sensitivity of an idealized three-chip television camera capturing images to be displayed on devices with a specific color gamut (described in ITU-R

Recommendation BT.709[8]). It does not adequately account for the more-varied spectral sensitivities of single-chip digital cinema or still cameras. The Illuminating Engineering Society (IES) has published TM-30,[9] “IES Method for Evaluating Light Source Color Rendition,” but this metric, like CRI, is based on the human visual system, and does not account for the variances in spectral sensitivities among digital cameras.

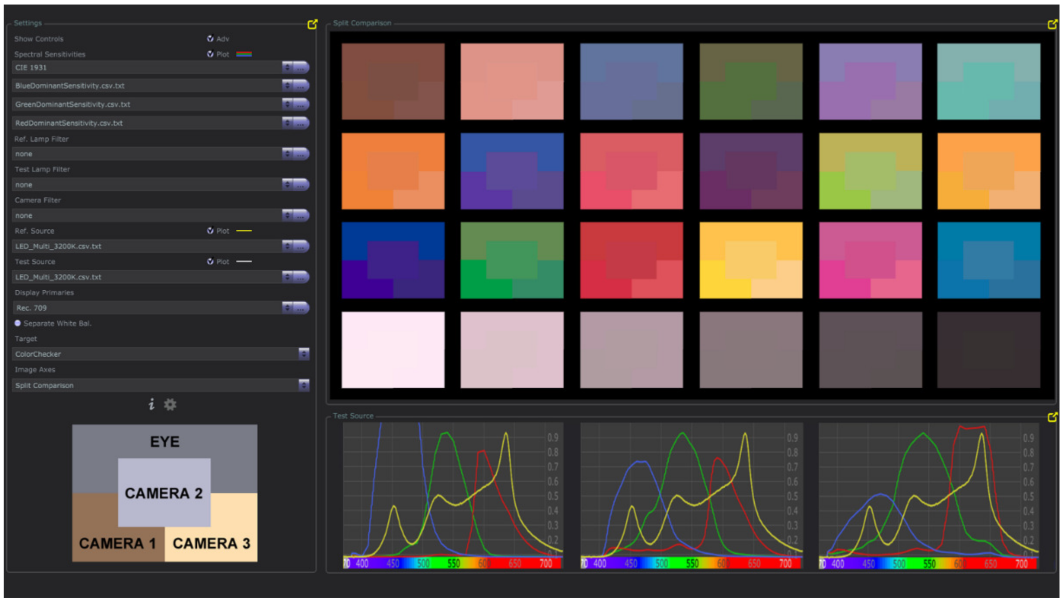

FIGURE 1. Segmented Macbeth chart demonstrating color-rendering differences among three different cameras (single light source).

Figure 1 is a graphic simulation of how the human eye and three digital cameras with different spectral sensitivities “see” color. The yellow curve represents an actual LED source commonly used in cinematography. The red, green and blue curves represent the spectral sensitivities of the three cameras. Each of the color patches, from a Macbeth Color Checker chart, is rendered in distinct sections that correspond to the human eye and cameras 1, 2 and 3 (the key is located at the lower left of the figure). As Figure 1 illustrates, a light source’s CRI – in this case, a relatively high value of 92 – is not a reliable predictor of color-rendering accuracy.

For additional discussion about these existing metrics, see the Appendix.

<u>SSI</u>

The Academy’s Science and Technology Council, working with cinematographers, manufacturers, scientists, engineers, and other experts, developed the Academy Spectral Similarity Index (SSI) to fill the need for greater predictability in the color rendering of a photographed scene. SSI does not directly describe color rendering itself. Instead, it quantitatively compares the SPD of a test luminaire with that of a reference light source. In a given spectral region, if the SPD of a test luminaire matches that of a reference source, the user can expect a color-rendering match, regardless of the spectral sensitivities of the camera or the number and variety of devices in the color-processing pipeline. Thus the SSI offers a “confidence factor” with regard to color-rendering accuracy. Its goal is to provide motion picture professionals with a metric to compare various light sources with color rendering as the primary concern.

The SSI uses values on a 100-point scale, where 100 indicates a perfect match. Any value greater than 90 means there will likely be no unexpected color-rendering results; the lower the score, the greater the likelihood of color-rendering errors. However, it is important to note that even low scores can still produce acceptably similar color-rendering results with a particular camera.

Although the SSI can be applied to most sources of visible light, it is primarily intended for use with "white" sources of various color temperatures in cinematography, television, still photography and human-vision scenarios. The SSI value is always denoted with the reference light source shown in [brackets]. For example, an SSI[P3200] value uses a 3200K blackbody ("Planckian") illuminant (such as tungsten incandescent), an SSI[CIE D55] value uses the CIE D55 standard daylight illuminant, and an SSI[Xenon*] value uses the xenon spectrum for comparison. Typically, the reference light source selected will be the blackbody illuminant with the correlated color temperature of the test luminaire (under 4000K) or the CIE standard daylight of the same CCT (over 4000K). However, SSI allows for any test and reference sources to be compared.

Figure 2 illustrates the SPD variance between a typical tungsten incandescent source (represented by the yellow curve) and a typical white LED source of the same correlated color temperature (represented by the white curve). In each case, relative power has been graphed as a function of wavelength across the visible spectrum. The cyan-shaded area shows the variance. SSI essentially scales this variance: the smaller the area between the two curves, the higher the SSI value, and the better the match. The simplicity of this approach makes it relatively easy to compare sources for a desired color-rendering result.

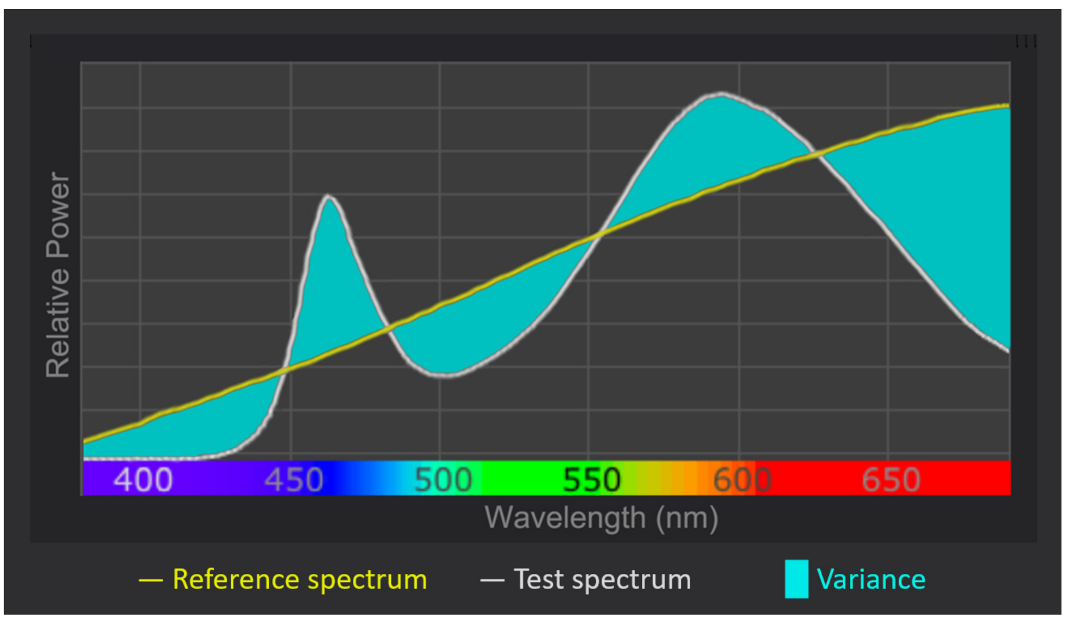

FIGURE 2. A graph of the spectral power distributions of both studio tungsten light ("Reference spectrum") and a white LED source ("Test spectrum"), and the variance between them.

As an example, the SPD of the LED source illustrated in Figure 1 has a CRI value of 92, but it has an SSI[P3200] value of 76 because of its peaks and troughs. The lower SSI value more clearly warns of the potential for color-rendering errors. It does not, however, indicate what errors are likely to occur. As previously mentioned, cameras with different spectral sensitivities can yield significantly different color-rendering results.

CALCULATION OF SSI

In designing SSI, the range of wavelengths to be included in its calculation was determined by the range of sensitivity of photographic film and multiple digital cinema and still cameras. The SPD data are "binned" into 10-nm samples to accommodate small irregularities and measurement tolerances. The binned values are then weighted so that less emphasis is placed on the lower and upper wavelengths, where variances have less overall effect on color-rendering results. The values are smoothed using an additional weighting factor to reduce the effect of minor deviations. These mathematical adjustments were optimized using Fourier analysis and simplified using convolution for calculation purposes.

A test luminaire's SSI value is computed as follows:

1) Specify test and reference source SPDs (at intervals not exceeding 5 nm).
2) Interpolate spectra to 1-nm increments from 375 nm to 675 nm (padding with zeroes if the test luminaire is not specified fully across that range).
3) Integrate spectra in 10-nm intervals from 380 to 670 nm.
4) Normalize to unity total power of test and reference sources by dividing each 10-nm sample by sum of all 10-nm samples for each source.
5) Calculate relative difference vector = (normalized test source vector – normalized reference source vector) / (normalized reference source vector + 1/30).
6) Calculate weighted relative difference vector = relative difference vector * spectral weighting vector
{4/15, 22/45, 32/45, 8/9, 44/45, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 11/15, 3/15}.
7) Add zero to each end of weighted relative difference vector to have 32 values.
8) Convolve with {0.22, 0.56, 0.22} to create 30-element smoothed weighted relative difference vector.
9) Calculate vector magnitude = square root of sum of squares of elements of smoothed weighted relative difference vector.
10) SSI value = round (100 – 32 * vector magnitude).

SMPTE ST 2122:2020[1] provides the complete and definitive specification for the calculation of SSI values.

SSI REPORTING FORMAT

SSI values must be reported with the reference SPD denoted in brackets, as:

SSI[spd_r] *s*

where *s* is the computed SSI value and spd_r is as follows according to the type of reference SPD:

Type of reference SPD	spd_r	**Examples**
Blackbody (Planckian)	P*temp*	SSI[P2705] 93
Tabulated CIE illuminant or smoothed illuminant (A, C, D50, D55, D65, sD50, sD55, sD60, sD65, sD70, sD75, sID50, sID65, or E)	CIE *name*	SSI[CIE A] 85 SSI[CIE D50] 89 SSI[CIE sID65] 91

CIE D illuminant of arbitrary CCT, calculated per CIE 015 or CIE 204 Table 1	CIE D*temp*	SSI[CIE D5035] 87
CIE D smoothed illuminant of arbitrary CCT, calculated per CIE 204 Table 3	CIE sD*temp*	SSI[CIE sD5140] 90
CIE source, per ISO 11664-2 or CIE 015	CIE *name*	SSI[CIE Source B] 83
ISO 7589 illuminant	*For details, refer to SMPTE ST 2122*	
Other	*For details, refer to SMPTE ST 2122*	

In the spd_r notations above, *temp* is the temperature or correlated color temperature (CCT) in kelvins, truncated to an integer value; and *name* is the name of the CIE illuminant or source.

SSI HIGHLIGHTS

- Provides a quantitative means to evaluate luminaires used for motion picture production, but is also applicable to television, still photography and human vision
- Uses a 100-point scale to indicate the similarity of a test luminaire's SPD to that of a reference light source (typically daylight or tungsten), denoted in brackets (for example, "SSI[P3400] 83", or "SSI[CIE D55] 87")
- Index values offer a "confidence factor" that scene colors will be rendered predictably
- A value of 100 indicates a perfect match to the reference source SPD; values above 90 should be a very good match; values below 60 will probably result in color-rendering errors
- Considers wavelengths from 375 to 675 nm, with less impact from wavelengths at the low and high ends of the visible spectrum
- Smooths out low-energy spikes and noise

ADDITIONAL INFORMATION

As mentioned earlier, the official definition of SSI is SMPTE standard ST 2122:2020.[1]

SSI was introduced and more fully described in a paper presented at the 2016 Society of Motion Picture and Television Engineers (SMPTE) Technical Conference.[10] (Note: In that presentation, the only reference illuminants postulated were ISO daylight and studio tungsten. SSI was later revised to add the ability to use other reference sources such as blackbody illuminants of arbitrary color temperature and CIE standard illuminants.)

Additional information, including an SSI calculator, is available at http://oscars.org/SSI.

Questions and comments should be sent to SSI@oscars.org.

APPENDIX: REVIEW OF EXISTING METRICS

Manufacturers of devices used in motion picture production often provide lighting metrics to both assist and attract customers. This section outlines some of the more popular metrics that users may find on a specification sheet.

Correlated Color Temperature (CCT)

Correlated Color Temperature is a basic measurement of the color of a light source. It describes the temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus, at the same brightness and under specified viewing conditions. In simpler terms, it uses light emitted from an element heated to a specific temperature as a reference to describe a light source's perceived color. CCT does not address the source's SPD or its total color-rendering effect – only the warmth or coolness of the light.

In motion picture production, CCT is an important metric for balancing image-capture color channels. For film photography it helps in choosing an appropriate stock for use with the light source, and for digital cameras it helps in choosing the proper white-balance values. While the CCT of a light source is an important characteristic, it does not tell motion picture professionals how faithfully scene colors will be rendered. Two luminaires can have the same CCT but significantly different SPDs, and using the luminaires interchangeably can lead to undesirable results. For this reason, CCT is inadequate as a sole descriptor of a light source's color-rendering capabilities.

Color Rendering Index (CRI)

The Color Rendering Index measures a light source's ability to reveal the colors of various objects faithfully in comparison with an ideal or natural light source. Unlike CCT, the CRI of a light source does not indicate the apparent color of the light source but rather how it makes objects appear in comparison to a reference source.

At first glance, this metric seems to focus on the lighting qualities that are important in motion picture production. But CRI (in its several variants, such as CRI Ra and CRI R96a) was designed for use in general interior and exterior environments, and the detector in its algorithm is representative of the human visual system. Motion picture cameras and photographic film have spectral sensitivities that differ significantly from those of the human visual system, so CRI is not representative of how cameras see color.

Color Quality Scale (CQS)

The Color Quality Scale was designed by the National Institute of Standards and Technology (NIST) to address the shortcomings of CRI Ra and CRI R96a – issues related to the color samples used, color difference metrics, chromatic adaptation, scaling, color appearance models, and more. However, like CRI Ra and CRI R96a, CQS uses in its algorithm the CIE 1931 2° Standard Observer, representative of the human visual system. So CQS, too, is an inadequate tool for motion picture production.

IES TM-30

IES TM-30 also was developed as an alternate color-rendering index. Unfortunately, as with CRI and CQS, it presumes a detector representative of the human visual system, making it an inadequate tool for motion picture production.

Television Lighting Consistency Index (TLCI)

The Television Lighting Consistency Index was developed by the European Broadcasting Union in recognition of many of the same color-rendering issues confronting broadcast-television production.

The EBU's solution was to use a standard set of camera sensitivities in its metric. Simulations of test color samples captured by the standard camera are processed using a typical broadcast-television color-processing pipeline and compared in a color gamut representative of a broadcast-television monitor. This methodology works well within the typical constraints of broadcast television, but translates poorly to motion picture production, where spectral sensitivities can vary significantly between cameras, and motion picture color-processing pipelines are not nearly as consistent.

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[1] SMPTE ST 2122:2020, "Spectral Similarity Index (SSI)," Society of Motion Picture and Television Engineers, 2020. ISBN 978-1-68303-220-5 (http://doi.org/10.5594/SMPTE.ST2122.2020).
[2] Academy of Motion Picture Arts and Sciences, "Solid State Lighting Project," oscars.org/ssl.
[3] ISO 7589:2002, "Photography – Illuminants for sensitometry – Specifications for daylight, incandescent tungsten and printer," International Organization for Standardization, Geneva, January 02, 2002.
[4] CIE 13.3-1995, "Method of Measuring and Specifying Color Rendering Properties of Light Sources" (3rd edition), Commission Internationale de l'Eclairage, Paris, 1995.
[5] CIE S 014-1/E:2006 (ISO 11664-1:2007), "CIE Standard Colorimetric Observers," Commission Internationale de l'Eclairage, Paris, December 1, 2008.
[6] W. Davis et al, "Development of a Color Quality Scale," *Optical Engineering*, March 2010.
[7] EBU 137, "Television Lighting Consistency Index-2012 and Television Luminaire Matching Factor-2013," European Broadcasting Union, Geneva, August 2016.
[8] ITU-R BT.709-6, "Parameter values for the HDTV standards for production and international programme exchange," International Telecommunication Union, Geneva, June 2015.
[9] IES TM-30-18, "IES Method for Evaluating Light Source Color Rendition," Illuminating Engineering Society, New York, 2018.
[10] J. Holm et al., "A Cinematographic Spectral Similarity Index," SMPTE 2016 Annual Technical Conference and Exhibition (http://ieeexplore.ieee.org/abstract/document/7819442).