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Illumination source metrics and color difference – selecting sources for cinematography

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Abstract

This paper uses calculated ΔE^*_{ab} values for 730 spectral reflectances, two reference illumination sources, 88 candidate illumination sources, five camera spectral sensitivities and the CIE 1931 observer to determine the degree to which the illumination source metrics CCT, CRI Ra, TM-30 Rf, TLCI and SSI can be used to reliably select candidate sources to avoid color differences with reference sources. The ISO 7589 spectral distribution index and digital camera scene analysis errors are used to determine excellent and very good ΔE^*_{ab} criteria. Correlations between the illumination source metrics and color differences are generally poor, but metric values close to 100 predict the small color differences required for cinematography.

Introduction

As energy efficient lighting sources are more widely used for cinematography, object color differences resulting from different source spectra are becoming something of a problem. Clothing changes colors as actors move around the set, objects that were one color become another, and colorists have to deal with skin colors that are unpredictably slightly off. To some extent cinematographers are used to dealing with such problems. HMI lights have been used for some time to supplement or replace daylight, and location lighting can present a variety of challenges. Nevertheless, more accessible information on light source color difference possibilities could better inform source selection thereby reducing associated production and post-production difficulties.

Already, correlated color temperature (CCT)[1] and color rendering index (CRI Ra)[2] metric values are often available and considered. Since many people feel that CCT and CRI Ra are insufficient, new metrics such as the TM-30 Rf[3], television lighting consistency index (TLCI)[4], and spectral similarity index (SSI)[5] have been developed. In some cases the newer metrics have not yet had much use, but it also seems that they are not fully addressing the problem. In some cases sources with what might be considered good metric values produce noticeable color differences and in other cases sources that might be expected to cause a problem are used successfully. This paper presents an exploration of color differences resulting from illumination source spectral differences and how they relate to the different illumination source metrics.

Approach

Several decisions were required concerning the calculation and evaluation of color differences. The first was the practical use case to be addressed. This analysis is focused on the use case where the candidate source will be interspersed with the reference source, and therefore the reference source white balance and scene analysis transform are used. Another use case of possible interest is the case where only the candidate source is used so the camera can be white balanced to it, but the reference source scene analysis transform is used. However, this use case is only applicable if only the candidate source will be used, in which case it would be better to also use a scene analysis transform optimized for the candidate source. A third use case is where both the white balance and scene analysis transform are optimized for the candidate source, but in this case the candidate source is effectively the reference source and there will be no color differences.

The next decision was the choice of the color difference metric. In this paper, all delta Es are CIELAB 1976 ΔE^*_{ab}[1]. This color difference metric is used because it is familiar and widely used, and is relatively simple to calculate. Also, the perceptual importance of color differences in neutrals and skin colors is addressed with color space region-specific tolerances as opposed to using the same tolerances for all delta Es. The development of color difference metrics is ongoing. For example, the IC_TC_P based color difference metric[7] has been shown to have a better correlation to perception than CIE DE2000, with a complexity comparable to CIELAB 1976 ΔE^*_{ab}.

The next decision was which reference sources to use for the investigation. A single "tungsten" and a single "daylight" reference source were chosen – daylight (CIE illuminant D55) and Studio Tungsten as specified in ISO 7589[8]. These reference sources were used because of decades of experience proving that they do indeed represent average or common daylight and studio tungsten as used for photographic capture. An additional benefit of these reference sources is their use allows comparison to historical illumination qualification metrics, such as the ISO spectral distribution index (ISO/SDI), which is specified in ISO 7589. However, it is worth noting that other reference sources could be used. For example, if one used a 3200K blackbody radiator for "tungsten" and D56 for daylight, there would be very little effect on the results.

The next decision was which candidate sources to investigate. We selected 86 sources that appeared to be the better sources from a database of sources maintained by the Academy of Motion Picture Arts and Sciences. We then added two other theoretical sources – a 5000K blackbody and a 5500K blackbody. The theoretical sources were added to help with investigation of the effects of the transitions from blackbody to D illuminant reference sources used by the CRI Ra and TM-30 Rf.

The next decision concerned the spectral reflectances for which the delta Es were calculated. We used two sets, the first being a set of 190 spectral reflectances (190 sr) that were used in the ACES Project Committee for the determination of Input Device Transforms[9]. These spectral reflectances were collected from actual objects and represent a wide distribution of colors and spectral characteristics. The left image in figure 1 shows the colors of the 190 sr as illuminated using CIE D55, chromatically adapted to D65 and converted to sRGB. The second set of spectral reflectances used was a set culled from the Image Engineering in-situ spectral radiance measurement database[10]. Only spectra identified as being skin spectra were selected, and each spectrum used was checked to ensure that it looked like a skin color, and that the lighting of the skin measured was appropriate compared to the white reference tile measured (to avoid reflectances greater than 1). The right image in figure 1 shows the colors of the 540 skin spectral reflectances (skin sr) used, as illuminated using CIE D55, chromatically adapted to D65 and converted to sRGB.

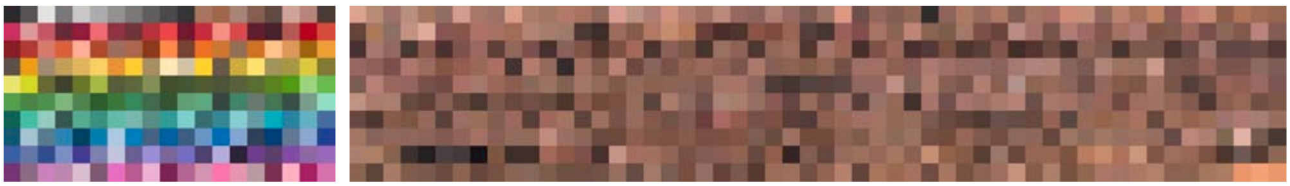

Figure 1. The colors of the 190 sr (left); the colors of the skin sr (right)

The next decision was which capture spectral sensitivities to use. We chose the human visual sensitivities (HVS) as represented by the CIE 1931 2° color matching functions and five digital camera spectral sensitivities – those of three commonly used professional motion picture cameras and two digital SLR cameras that are used in the production of motion pictures (cameras A, C, E, B and D).

The last decision was for which image state to calculate the delta Es – should they be those of the scene captured (scene-referred) or the reproduction to be produced (output-referred)? For this study we chose the scene-referred color differences to avoid the question of how the color differences would be affected by color rendering, which is often variable. ACES values were calculated for each test spectral reflectance using each candidate source and the appropriate reference source. CIELAB values were then calculated from the ACES values and the delta Es between the candidate and reference sources determined.[1,2]

Determining what are "very good" and "excellent" delta Es

One of the fundamental questions in this work is how much color difference can be tolerated and still considered "very good" and "excellent". There are several approaches to answering this question. One can simply use rules of thumb for color matching, e.g. a one delta E color difference can be seen by an expert colorist, but the color difference may have to be two to three delta Es to be noticed by an average person. Unfortunately, color differences in complex images do not necessarily follow these rules of thumb. How a specific color difference of an element relates to the rest of the image can affect the degree to which the color difference is objectionable. We decided that, to be safe, we should look at color difference criteria that have been used in practice with complex images.

The historical standard for selecting light sources for photography is ISO 7589[8] which specifies the ISO/SDI. At the time this standard was developed, the vast majority of sources used were either incandescent tungsten or natural daylight. While filters were sometimes used for artistic purposes or to balance a source different from the source for which the film stock was designed, spectral power distributions were smooth and free from peaks or dips. So when the ISO/SDI tolerances were developed, the primary concern was that the candidate sources produce the same neutrals as the reference source. Eleven of our 88 candidate sources pass the ISO/SDI tolerances: nine "tungsten" sources and two "daylight" sources. However, if only the incandescent tungsten sources that pass the ISO/SDI tolerances are considered, *they all have gray delta Es of less than three for all five cameras and the HVS.* Also, the 5000K and 5500K blackbodies have gray delta Es around 3.5 and 2.5 respectively. The 5500K blackbody just fails the ISO/SDI tolerances because these tolerances are based on typical film spectral sensitivities, which are higher in the far red than those of most digital cameras and the HVS.

Looking at only the incandescent sources that pass the ISO/SDI tolerances, the delta Es for other spectral reflectances are as follows:

190 sr – mean < 3, max < 5
skin sr – mean < 3, max < 4

We will use these delta E tolerances, combined with the gray delta E tolerance of < 3, as the limits for "excellent" sources, as they correspond to the tolerances for historical sources that meet the ISO/SDI tolerances.

[1] The ACES values for the HVS color differences were calculated by determining CIE XYZ tristimulus values for each spectral reflectance illuminated using both the candidate and reference sources, chromatically adapting the XYZ values from the reference source chromaticity to the ACES neutral chromaticity (D60) using CAT02, and then converting the chromatically adapted XYZ values to ACES. The reference source chromatic adaptation was used with the candidate sources even though some candidate sources had different chromaticities than the reference sources in keeping with the use case being evaluated.

[2] The ACES values for the five cameras were calculated by first determining an IDT for each reference source for each camera using AMPAS Procedure P-2013-001, *Recommended Procedures for the Creation and Use of Digital Camera System Input Device Transforms (IDTs)* [9], with the 190 sr illuminated by the reference source as the training spectral radiances, CAT02 for the chromatic adaptation, CIELAB as the error minimization color space and the matrix regression constrained to preserve neutrals. Linear raw camera RGB values were then calculated for each spectral reflectance with each candidate source and the appropriate reference source using measured camera spectral sensitivities. The linear raw camera RGB values were then converted to ACES values using the IDTs for the reference source. Both the white balance and matrix of the IDT for the appropriate reference source were used with the candidate sources in keeping with the use case being evaluated.

Table 1: Digital camera scene analysis color errors for the 190 sr and skin sr spectral reflectance sets

Illumination – spectral reflectances	Camera A	Camera B	Camera C	Camera D	Camera E
D55 190 sr mean ΔE^*_{ab}	2.06	2.57	3.43	2.40	3.08
D55 190 sr max ΔE^*_{ab}	12.27	13.54	13.49	19.73	12.3
D55 skin sr mean ΔE^*_{ab}	1.36	2.37	3.12	1.66	2.68
D55 skin sr max ΔE^*_{ab}	2.36	3.85	5.39	2.73	4.55
Studio Tungsten 190 sr mean ΔE^*_{ab}	2.49	2.85	3.98	3.14	2.84
Studio Tungsten 190 sr max ΔE^*_{ab}	15.71	17.96	17.23	18.17	10.19
Studio Tungsten skin sr mean ΔE^*_{ab}	1.7	2.4	3.11	2.33	2.12
Studio Tungsten skin sr max ΔE^*_{ab}	2.89	3.88	5.3	3.77	3.62

Another way to obtain a practical estimate of what people will accept for color differences in complex images is to look at digital camera scene analysis color errors, as shown in table 1. Using these delta E values as guides, we will consider the following delta E tolerances to be the limits for "very good" sources:

gray < 3

190 sr – mean < 4, max < 20

skin sr – mean < 4, max < 6

The gray limit is unchanged because white balance is critical and is set exactly in digital cameras – there is no gray scene analysis color error for a spectral neutral with the reference source if the camera is white balanced correctly, so the "excellent" limit based on the ISO/SDI tolerances is used.

The requirement that the gray delta E be less than 3 also leads to a way to preselect sources based on CCT. Of the 88 candidate sources, all sources for which the Studio Tungsten reference was used (sources with CCTs < 4000K) that had gray delta Es less than 3 had CCTs between 2960K and 3250K (mired 338 to 308). Likewise, all sources for which the D55 reference was used (sources with CCTs > 4000K) that had gray delta Es less than 3 had CCTs between 5100K and 6000K (mired 196 to 167). So, one can conclude that for a candidate source to be considered, its mired value needs to be within about 15 of the reference source mired value. It turns out that this prequalification based on CCT is necessary for the elimination of unsuitable sources using the CRI Ra, TM-30 Rf or TLCI metrics.

However, in further qualifying sources it remains important to consider the gray delta E limit. Figure 2 is a plot of the five camera gray delta Es vs. the HVS gray delta E for the 88 sources. This plot illustrates the variability of the gray delta E with the candidate sources resulting from different capture spectral sensitivities.

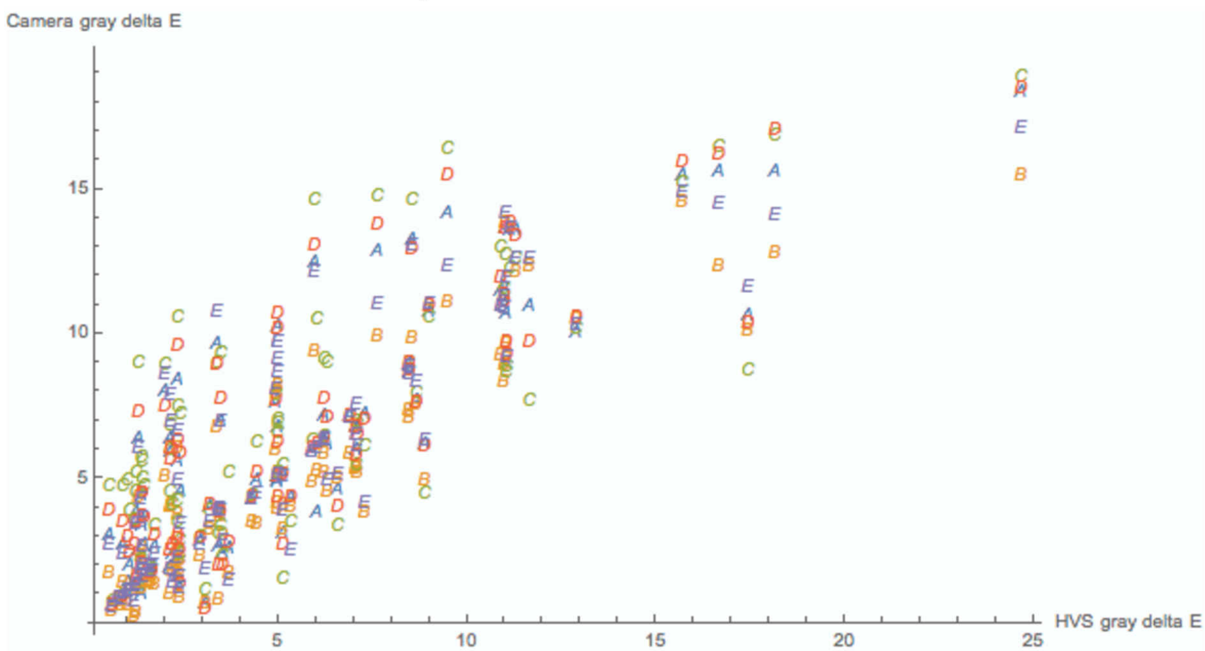

Figure 2. The five camera gray delta Es plotted vs. the HVS delta Es

A final note concerns the difference between scene analysis color errors and illumination source dependent color differences. They are both expressed here in terms of delta E, and when a source different from the reference source is used they may both occur, but as they are vectors how they add is highly variable. In some cases, a relatively small scene color analysis error might combine with a relatively small illumination source error to produce an objectionably larger total color difference. In other cases, the error and difference might cancel. As we will discuss below, one of the main findings of this work was that the color differences that can result from different scene reflectances, cameras and sources are extremely difficult to predict without actually performing somewhat complex spectral calculations.

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Illumination source metrics

It is worth noting some differences between the illumination source metrics investigated. CCT depends only on the chromaticity of the illumination as projected onto the blackbody chromaticity curve. However, there are slightly different methods used to do the projection and consequently the same source measurements will not always result in exactly the same CCT value. The CCT predicts gray color differences along the blackbody curve but does not predict color differences perpendicular to the blackbody curve.

The SSI depends only on the selected reference and candidate source spectral power distributions. It is therefore independent of any scene/object spectral reflectance or capture spectral sensitivity assumptions. It also performs well without the need for pre-selection based on CCT and can be used with any reference source.

The other three metrics, the CRI Ra, TM-30 Rf and TLCI share some common characteristics different from those of the CCT and SSI, namely:

1. The reference source is not selectable but is determined using the CCT of the candidate source. For the CRI Ra the reference source is a blackbody radiator with the same CCT as the candidate source for CCTs below 5000K, and the D illuminant with the same CCT as the candidate source for CCTs equal to or above 5000K. For the TM-30 Rf the reference source is a blackbody radiator with the same CCT as the candidate source for CCTs less than or equal to 5000K, a blend of the corresponding blackbody radiator and D illuminant for sources between 5000K and 5500K, and the D illuminant with the same CCT as the candidate source for CCTs equal to or above 5500K. For the TLCI the reference source is a blackbody radiator with the same CCT as the candidate source for CCTs less than or equal to 3400K, a blend of the corresponding blackbody radiator and D illuminant for sources between 3400K and 5000K, and the D illuminant with the same CCT as the candidate source for CCTs equal to or above 5000K.
2. Specific capture spectral sensitivities are used for the metric value calculations, with a single set of sensitivities specified for each metric. The CRI Ra and TM-30 Rf use HVS spectral sensitivities and the TLCI uses a set of RGB spectral sensitivities defined in that specification.
3. Specific scene-object spectral reflectances are defined for each metric and used for calculating the metric value.

Each of these three metrics has some shortcomings for cinematographic applications. The reference sources should be fixed and selectable and need not be either a blackbody or a D illuminant. For source mixing the reference is already decided and for other cases cameras can be white balanced to chromaticities not on the blackbody or D illuminant curves. The fact that the references change with the candidate source CCT for these three metrics is what makes the pre-selection based on CCT necessary. For determining a default reference source, the TLCI formula is most appropriate, coming closest to describing the most probable reference source given some candidate CCT. Likewise, the capture spectral sensitivities would ideally be selectable. The camera-to-camera variability does not support the use of "average" camera sensitivities. The HVS sensitivities are probably as good a default as anything as cameras are gradually moving toward them as technology improves. Finally, the scene-object spectral reflectances should be as varied as possible. Of the three metrics, the TM-30 Rf has the most varied scene-object spectral reflectances, which probably results in its relatively good performance, but as can be seen from the results presented below even more variability would be desirable.

Table 2 provides R^2 values, which indicate the fraction of the variation explained by linear regression of the different metrics as applied to the sources that fall within the CCT limits specified above.

Table 2: R^2 values between different illumination source metrics

x-coordinate	y-coordinate	R^2
CRI Ra	TM-30 Rf	0.772147
CRI Ra	TLCI	0.318940
CRI Ra	SSI	0.329250
TM-30 Rf	TLCI	0.422844
TM-30 Rf	SSI	0.641420
TLCI	SSI	0.529869

Comparing delta E values and illumination source metrics for the 88 sources

The main part of this work is the selection of the very good and excellent sources based on the color differences, and investigation of the possibilities to use one or more of the metrics to select sources for cinematographic use without having to perform the color difference calculations. 385,440 delta E values were calculated (88 candidate sources x 730 spectral reflectances x 6 spectral sensitivities). Unfortunately, summary plots of the mean and maximum delta Es vs. the different metrics requires more space than is available here. Example plots are shown in figure 3 and R^2 correlation values are provided in table 3. Highlights and final results are provided in the next section.

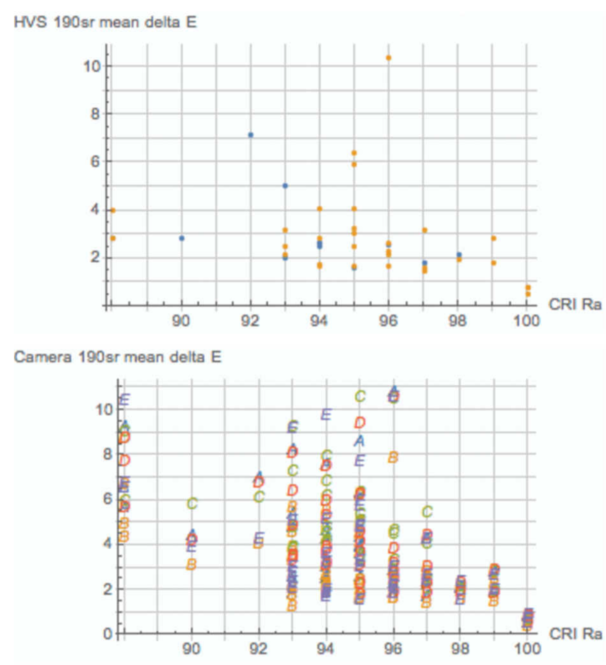

Figure 3. Plot of HVS 190 sr mean delta E (top) and camera 190 sr mean delta Es (bottom) vs. CRI Ra

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Table 3: R^2 values for ΔE^*_{ab} and illumination source metrics

x-coordinate	y-coordinate	R^2
CRI Ra	HVS 190 sr mean ΔE^*_{ab}	0.076439
CRI Ra	Camera 190 sr mean ΔE^*_{ab}	0.340425
CRI Ra	HVS 190 sr max ΔE^*_{ab}	0.206122
CRI Ra	Camera 190 sr max ΔE^*_{ab}	0.448260
CRI Ra	HVS skin sr mean ΔE^*_{ab}	0.046539
CRI Ra	Camera skin sr mean ΔE^*_{ab}	0.314537
CRI Ra	HVS skin sr max ΔE^*_{ab}	0.064316
CRI Ra	Camera skin sr max ΔE^*_{ab}	0.326509
TM-30 Rf	HVS 190 sr mean ΔE^*_{ab}	0.097296
TM-30 Rf	Camera 190 sr mean ΔE^*_{ab}	0.362407
TM-30 Rf	HVS 190 sr max ΔE^*_{ab}	0.358139
TM-30 Rf	Camera 190 sr max ΔE^*_{ab}	0.534134
TM-30 Rf	HVS skin sr mean ΔE^*_{ab}	0.032078
TM-30 Rf	Camera skin sr mean ΔE^*_{ab}	0.251262
TM-30 Rf	HVS skin sr max ΔE^*_{ab}	0.057991
TM-30 Rf	Camera skin sr max ΔE^*_{ab}	0.259371
TLCI	HVS 190 sr mean ΔE^*_{ab}	0.022512
TLCI	Camera 190 sr mean ΔE^*_{ab}	0.227334
TLCI	HVS 190 sr max ΔE^*_{ab}	0.227020
TLCI	Camera 190 sr max ΔE^*_{ab}	0.474901
TLCI	HVS skin sr mean ΔE^*_{ab}	0.000099
TLCI	Camera skin sr mean ΔE^*_{ab}	0.171919
TLCI	HVS skin sr max ΔE^*_{ab}	0.003642
TLCI	Camera skin sr max ΔE^*_{ab}	0.161605
SSI	HVS 190 sr mean ΔE^*_{ab}	0.036127
SSI	Camera 190 sr mean ΔE^*_{ab}	0.218911
SSI	HVS 190 sr max ΔE^*_{ab}	0.321291
SSI	Camera 190 sr max ΔE^*_{ab}	0.427687
SSI	HVS skin sr mean ΔE^*_{ab}	0.001673
SSI	Camera skin sr mean ΔE^*_{ab}	0.108027
SSI	HVS skin sr max ΔE^*_{ab}	0.015338
SSI	Camera skin sr max ΔE^*_{ab}	0.102183

Results and Conclusions

The CCT pre-screening eliminated 46 of the 88 sources. Using the ΔE^*_{ab} criteria, 7 of the remaining 42 sources were selected as "excellent" and 4 other sources were selected as "very good." These 11 sources included 5 sources that did not pass ISO 7589. With the CRI Ra, TM-30 Rf and TLCI metrics it is necessary to pre-screen candidate sources based on their CCT, with only sources having a mired value within 15 of that of the reference source being further considered. Pre-screening is not necessary with candidate sources that have an SSI value greater than 95.

None of the illumination source metrics reliably predicted candidate source capture color differences from the reference source, except for the case where the metrics have values close to 100. There are differences in how close the metric values have to be to 100 to reliably predict small color differences. For the CRI Ra the value had to be greater than 97, for the TM-30 Rf the value had to be greater than 95, for the TLCI the value had to round to 100, and for the SSI the value had to be greater than 95. However, this does not mean these metrics are useless for the purpose of estimating candidate source color differences, because historical metrics and available experience indicates that critical and average color differences have to be quite small in order to be acceptable. So, while the metrics may not predict color differences reliably outside a very limited range close to 100, that very limited range is the range of acceptability and therefore the range of interest.

Specifically:

- All sources that meet the excellent and very good delta E criteria fall within the CCT limits of ± 15 Mired.
- Many sources outside the CCT limits have very high CRI Ra, TM-30 Rf, or TLCI values, so the CCT limits alone are insufficient for qualification.
- The sources that fall within the CCT limits AND have CRI Ra > 97 match the sources selected using the excellent delta E criteria.
- The sources that fall within the CCT limits AND have a TM-30 Rf > 95 match the sources selected using the excellent delta E criteria.
- The sources that fall within the CCT limits AND have a TLCI > 99 match the sources selected using the excellent delta E criteria.
- It is not possible to exactly match the sources selected using the excellent delta E criteria using only the SSI. Only excellent sources will have an SSI > 95, even if not pre-screened using the CCT, but one excellent source is unnecessarily eliminated. SSI values above 91 include all excellent sources but also one source that narrowly misses being excellent and one that is not even very good.
- It is not possible to exactly match the sources selected as very good according to the delta E criteria using any of the metrics (CRI Ra, TM-30 Rf, TLCI or SSI).

For the mixing sources use case, the gray color differences are critical, but not so for the cases where only the candidate source is used and the camera is white balanced to it. However, it should be noted that when sources are used with chromaticities that are similar in CCT but different in chromaticity from the reference source for some metric, that metric might be misleading. This is one case where adaptation of the metric to use specific reference sources or the use of the SSI (which already has this capability) would be more appropriate.

There is room for further improvement in the metrics. With the CRI Ra, the 14 samples should be greatly expanded and it should be possible to specify a reference source other than those prescribed. With the TM-30 Rf, the 99 samples are a noticeable improvement but their spectral variability still seems to be to limited. The TM-30 Rf especially would benefit from the ability to specify a reference source other than those prescribed because of the large percentage of daylight captures between D45 and D55. The three metrics that use a UCS should consider new work. The CAM02-UCS used by the TM-30 Rf and the DE2000 metric used by the TLCI may be slight improvements perceptually over the 1964 UCS used by the CRI Ra, but the increase in complexity is undesirable. Newer UCSs such as IC_TC_P may be a better choice. It is not apparent that the TLCI "average" camera spectral sensitivities provide any advantage when used for estimating candidate source color differences with camera capture. Different real camera spectral sensitivities produce quite different results, so the use of "average" spectral sensitivities does not improve camera predictions. The coarseness of the TLCI scaling is also a disadvantage. The SSI metric is fundamentally different from the other metrics in that it is a measure of spectral similarity and is not designed to measure color difference. It is independent of any sample spectral reflectances, capture spectral sensitivities, or UCS. It is therefore much simpler to calculate and can be used with any reference source. All of the 88 sources with SSI values greater than 95 were excellent in terms of color difference, but one excellent

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source had an SSI value of 92. Of the 9 pre-screened sources with SSI values greater than 90, three sources meeting the excellent or very good criteria were excluded and one source that did not meet these criteria was included.

Summary

Using ISO 7589 as a historical baseline, "excellent" sources should result in the following CIELAB 1976 ΔE^*_{ab} color differences using the 190 sr and skin sr:

Gray < 3
190 sr – mean < 3, max < 5
skin sr – mean < 3, max < 4

Using current typical digital camera scene analysis errors as a baseline, "very good" sources should result in the following CIELAB 1976 ΔE^*_{ab} color differences using the 190 sr and skin sr:

Gray < 3
190 sr – mean < 4, max < 20
skin sr – mean < 4, max < 6

While there is room for improvement in illumination source metrics as noted above, current shortcomings do not preclude the metrics being used as long as the target metric values are sufficiently high. Specifically, if the SSI > 95, the source should be fine, although this criterion may unnecessarily eliminate some sources. Likewise, if only sources with Mired values within 15 of the reference source are considered, sources with CRI Ra > 97, Tm-30 Rf > 95 or TLCI = 100 (rounded) should result in color differences that meet the "excellent" criteria. The two-step selection using both the CCT Mired value and the CRI Ra or TM-30 Rf metric value may be somewhat less likely to unnecessarily eliminate sources.

Concerning improving illumination source metrics, some opportunities are:

- Allow for specification of the reference source, and for the default case use the TLCI reference.
- Greatly expand the spectral variability of the test spectra. Even the TM-30 99 spectra do not have sufficient dimensionality. Uncommon spectra are often of interest.
- Use of the IC_TC_P UCS should be considered, especially for the scene-referred case where the color rendering and viewer adaptation may not be known.

Concerning the variability of camera spectral sensitivities, this variability significantly affects candidate and reference source color differences, including white balance differences. However, the use of the TLCI "average" camera spectral sensitivities did not improve the color error prediction with the cameras tested. The spectral sensitivities of these cameras are quite different from each other and from the TLCI "average" sensitivities. As cameras have improved, their sensitivities have moved closer to the HVS sensitivities, so it is the HVS sensitivities that are probably the best default sensitivities, even with camera capture.

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Author Biography

Jack Holm became interested in imaging while living near the Johnson Space Center in the late 60's and early 70's, leading to work at the University of Texas McDonald Observatory. While teaching photographic technology at the Rochester Institute of Technology, he became interested in "electronic" imaging. Following that he worked at Hewlett Packard Company, first on the development of digital camera technology, and later as a principal color scientist in the Office of Strategy & Technology. He has many publications and several patents relating to pictorial digital image processing, including developing the first camera raw processing application with variable color rendering. He was a primary contributor in the development of ICC color management and the Emmy-winning Academy Color Encoding System. He participates in standards organizations including ISO, IEC and ITU-R.

Scott Dyer is Senior Imaging Engineer for the Science and Technology Council of the Academy of Motion Picture Arts and Sciences. He was the first graduate from the BS Motion Picture Science program at Rochester Institute of Technology in 2010. A key contributor to the development of the Academy Color Encoding System (ACES), he continues to support ACES adoption and other Science and Technology Council projects.

Dan Sherlock is Senior Project Engineer for the Science and Technology Council of the Academy of Motion Picture Arts and Sciences. He has been on the Council staff for the last 13 years, and is the project lead for the Council's Solid State Lighting project. He has spent over 30 years involved with industrial and military displays and simulators, as well as video and motion picture technology. He has several patents for in-flight entertainment systems, and has written numerous articles on motion picture technology. He has a Bachelor's degree in Electrical Engineering from California State University at Long Beach.

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