Critical spectra in the color reproduction process of digital motion picture cameras

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Abstract

Most cameras resolve a color stimulus by three spectral sensitivity responses. Commonly, these do not satisfy the Luther-Ives condition. Hence, there is no linear mapping between the camera's RGB values and the CIE XYZ tristimulus values. Although more complex methods for camera characterization have been proposed, none can solve the issues caused by camera metamerism: While being different to the human eyes, certain stimuli will induce the same RGB response in the camera. To investigate color reproduction errors and the effects of device metamerism, metameric spectra must be found. Previously proposed methods generate metameric pairs artificially. We present a method for finding metameric pairs within a database of real-world measured spectra, which we believe has more practical utility than methods employing synthesized metameric pairs. By using measured camera sensitivities and reflectances from the SOCS database we can identify metamers with a real-world occurrence possibility. We characterize critical spectra by type of object and by hue, considering both CIE illuminants and real-world LED fixtures.

Introduction

Commonly a linear color correction is used to map the camera's RGB values to the CIE XYZ tristimulus values. Since most digital cameras do not satisfy the Luther-Ives condition, conspicuous residual errors remain. Non-linear methods have been proposed to address some color reproduction problems [1][2], but none of these methods can solve the issues caused by camera metamerism: While different to the human eyes, certain stimuli will induce indistinguishable RGB values in the camera. Therefore, even a complex color correction algorithm can not distinguish between two metameric stimuli, and accurate color correction can only be done for one of them. Hence, such spectra are termed *critical*.

Some methods have been suggested to build metameric or rather *parameric* sets (see below). Tajima *et al.* defined representative sets within the SOCS database (called 'typical sets') [3]. Metamers are then found by selecting spectra within a range of 5 CIELAB unit values based on structural difference. However, their method does only account for a human observer and not for another observer, *e.g.* a camera.

Urban *et al.* proposed a density distribution of metamers [4]. A set of metameric spectra is constructed by using the Monte-Carlo method. Transformed into a perceptual color space, the center of gravity is used as a target value for the color correction. However, there is just a possibility but no proof for the real-world occurrence of artificial generated spectra.

In this paper we will show how one can use a large set of spectral measurements of real-world objects to investigate color reproduction errors and the occurrence of metamers for a digital motion picture camera. Even though most spectra—such as those we used—were not measured *in situ*, one can assume that measurements of real-world objects are closer to a real-world observed scene than the artificially-created ones, proposed in the abovementioned related work.

We used the SOCS database [6] and applied a measured spectral sensitivity response of the ARRI ALEXA, a field-proven camera widely used in film and TV production. A general description of the camera can be found at [5]. To calculate tristimulus values, we used the CIE 1931 2° standard observer. The illumination spectra were either calculated using CIE standards or measured spectral power distributions of light sources typically used in film and TV. In this paper we will focus on an ARRI L7-C LED-fixture in comparison with the blackbody radiation at 3200K denoted as A_{32} and CIE daylight with a correlated color temperature of 5600K, denoted as D_{56} .

First we will show the determination of the camera sensitivity functions and evince their accuracy by comparing calculated RGB values with actual RGB values captured in a controlled testing environment. Next we will present our method for finding critical pairs within a database of reflectance spectra. Finally, we will examine the characteristics of critical spectra set by way of example.

Color Camera Model

The spectral sensitivities used to model the response of the ARRI ALEXA are based on measurements of five cameras. Response was measured in the range from 380 to 780nm in steps of 5nm using a double monochromator. While entering an image sensor, light crosses a stack of materials used to make the sensor. At each boundary a part of the light will be reflected back and interfere with the original ray causing a ripple in the measured spectral sensitivity. Since this ripple is highly specific for an individual sensor and the thickness of the color dyes in the color mosaic may vary slightly, the results of several measurements were averaged.

The obtained spectral response curve was validated by filming a Macbeth ColorChecker test chart with a randomly selected ARRI ALEXA camera (not among the measured cameras) and comparing the actual RGB values thus obtained with the predicted ones. The average difference in the RGB chromaticity among the 24 patches is 0.004 in g and 0.007 in r .

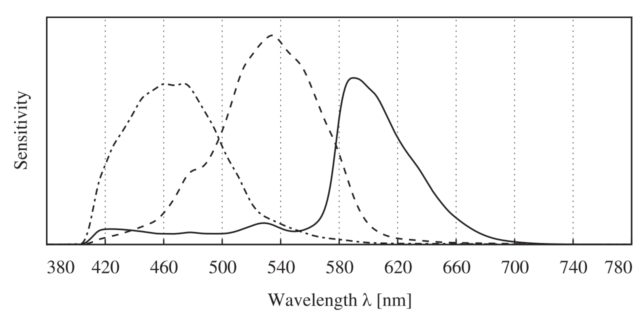

Figure 1. Modelled spectral sensitivity functions of the ARRI ALEXA.

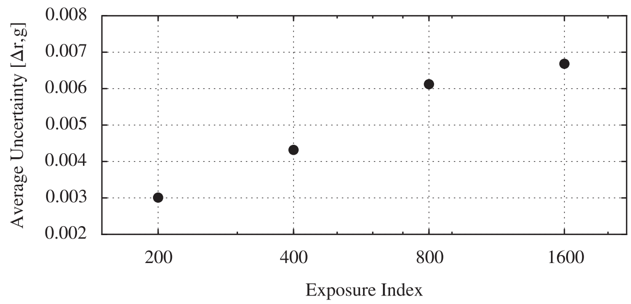

Figure 2. Average uncertainty of camera chromaticity values based on the exposure index. Higher exposure index means lower signal level.

Figure 3. Two spectral samples that are device parameric under tungsten light are shown. The inner rectangle shows the reproduced color of the camera after a linear color correction. The outer rectangle shows the color as seen by the CIE 1931 2° standard observer.

Finding Critical Spectra

We want to investigate the occurrence and structure of metameric samples in database $\mathbb{D}$. Two samples are called device metameric if their RGB tristimulus values are the same. Because of photon noise and sensor noise, two stimuli will almost never produce exactly the same RGB values. For this reason, other authors use the term *parameric* for reflectance samples that are "either indistinguishable or only slightly different" (in [7], see also [8]).

Our basic idea is to calculate the chromaticity coordinates in the camera RGB color space and compare the CIE 1976 UCS coordinates of samples that are close to each other in camera chromaticity space. Since neither brightness nor lightness of a stimulus in a scene is known *a priori*, we will only compare chromaticity points (CPs).

The definition of a general threshold for the distance of CPs in camera chromaticity space might be regarded as a complicated problem for several reasons: First, the space is not perceptually uniform. Second, a tolerable threshold is application dependent. Finally, the noise in the camera tristimulus values (and consequently in the CPs) is signal-dependent.

With these limitations in mind, we define two samples $x_{1,2} \in \mathbb{D}$ as parameric when the distance between the two CPs is smaller than a threshold φ_C

$$f \mapsto \left\| c\left(Q_T^{\mathrm{T}} x_1\right) - c\left(Q_T^{\mathrm{T}} x_2\right) \right\| \leq \varphi_C \tag{1}$$

where c denotes the chromaticity function defined as

$$r = \frac{R}{R+G+B}, \quad g = \frac{G}{R+G+B}, \quad \left(b = 1 - r - g\right) \tag{2}$$

where R, G, B are the sensor tristimulus values. The matrix product of the sensor sensitivities C and the illuminant L_T of type T equals the lighting matrix $Q_T = CL_T$.

The value $\varphi_C = 0.005$ was chosen based on numerical simulations using the actual noise characteristics of the camera [9]. A range of RGB signal combinations was generated where the dominant channel had a signal level corresponding to a perfect reflecting diffuser captured at the selected exposure index (EI) (see [10]). The relative signal levels in the RGB channels were varied from neutral (all channels balanced) to a maximum ratio of 8:1 (a difference of 3 stops). After converting the RGB signal combinations to chromaticity coordinates the resulting uncertainties were averaged.

The chosen value for φ_C lies between the average uncertainty for EI400 and EI800 (see Figure 2). It has the same magnitude as the average difference between the predicted and the actual CPs found in the verification of the camera's spectral response curve.

We build an adjacency matrix F, which holds the truth values that satisfy function f. For each spectrum the CP in the CIE 1976 UCS is calculated. In the same manner as F we build an adjacency matrix G, that holds the truth values satisfying function g

$$g \mapsto \left\| h\left(P_T^{\mathrm{T}} x_1\right) - h\left(P_T^{\mathrm{T}} x_2\right) \right\| \geq \varphi_H \tag{3}$$

where h denotes the function that determines the CPs in CIE 1976 UCS. Again, the matrix product of the CIE CMFs H and the illuminant L_T equals the lighting matrix $P_T = HL_T$.

As opposed to f we are not looking for spectra pairs that are parameric, but clearly distinguishable by a human observer. Therefore, a value of $\varphi_H = 0.011$ is chosen, which corresponds to a 10-step MacAdam ellipse [11]. Camera-parameric pairs having a $\Delta u', v'$ distance larger than φ_H are further referred as *critical*.

It can be shown that the chromaticity differences of most of the camera-parameric pairs are below the φ_H threshold. Figure 4 shows an example. The samples in (a)—whereas (a) represents the camera chromaticity space—that are surrounded by the circle representing φ_C can be considered parameric for the camera under the given light, whereas the crosses lying outside are not parameric for the selected CP.

In Figure 2 (b) the same samples are depicted in the 1976 UCS diagram. Samples that fall within φ_H are shown as dots. The critical samples are depicted as squared dots in both plots in Figure 4.

Using F and G these can be identified by logical conjunction

$$Z = F \wedge G \tag{4}$$

The fact that in this example the critical CPs are closer to other CPs (crosses) than to their own counterparts (dots), shows their criticalness towards a complex color correction.

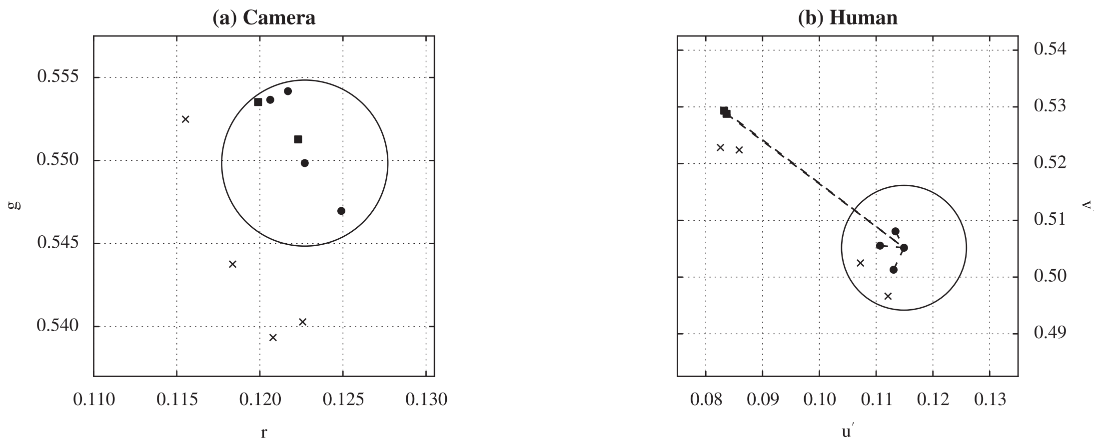

Figure 4. Exemplarily depiction of our method for some greenish-bluish CPs under incandescent light at 3200K. Please, see description below.

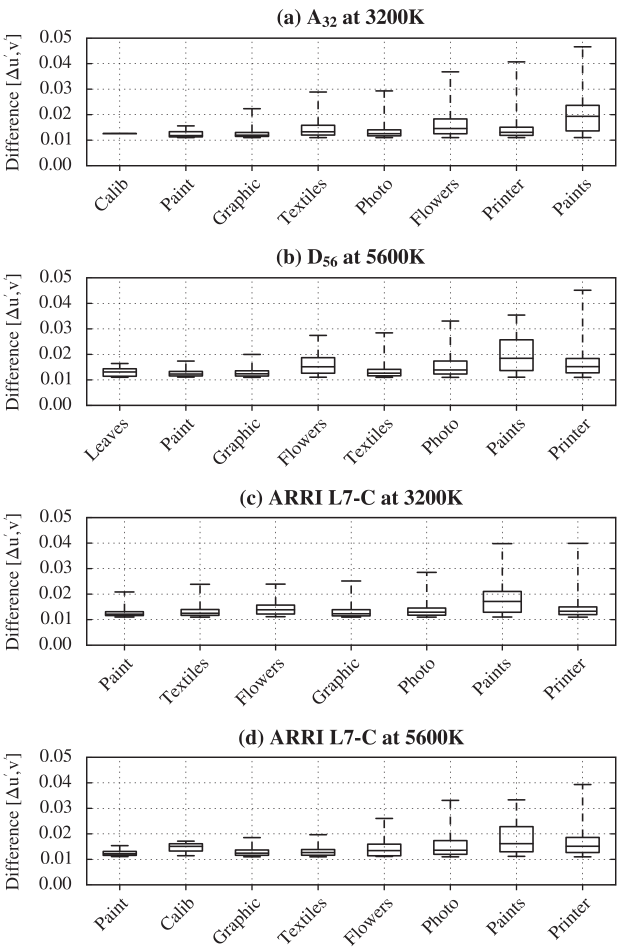

Figure 5. Difference distribution for the sets, where critical spectra where found. The whiskers indicate the 1% respectively 99% percentiles.

Table 1. Stats for the database under the indicated light source.

	Parameric Spectra	Critical Spectra
A_{32} at 3200K	52819 (99.42%)	10215 (19.23%)
D_{56} at 5600K	52821 (99.42%)	15433 (29.05%)
L7-C at 3200K	52831 (99.44%)	10747 (20.23%)
L7-C at 5600K	52822 (99.43%)	15026 (28.28%)

Experimental Results and Discussion

As mentioned in the introduction, metameric sets can be used to evaluate the non-correctable errors in color reproduction caused by sensors that do not satisfy the Luther-Ives condition.

Almost all spectra in the database are camera-parameric to at least another spectrum. Between 19% and 29% of the spectra are part of a critical pair, with notable differences between tungsten and daylight, as seen in Table 1.

Origin

Since all spectra in the database are object-related, one may ask which subsets of the SOCS database are most critical, in terms of their spectra producing the greatest difference for a human observer, while being parameric to the camera. Therefore, we looked at the distribution of the $\Delta u', v'$ chromaticity difference in each subset.

Figure 5 depicts the differences in the sets. Sets which do not contain critical spectra are excluded. As the boxplot shows, most critical spectra have a moderate median chromaticity difference between 0.01 and 0.02 $\Delta u', v'$. Sets of artificial reflectances like the photo, paints and printer sets from SOCS contain the most critical spectra, which produce a difference up to 0.04. The flower set is critical especially under tungsten light. Under LED light with the same CCT the maximum difference is about 0.015 lower.

Also noteworthy is that under a daylight illuminant some of the leaves spectra are considered critical, whereas no critical spectra are found in the leaves set under LED light tuned to daylight. Nearly all other sets have a slightly lower maximum error under LED light than under the corresponding reference light.

The results suggest that the non-correctable color reproduction errors of the camera are smaller under LED light than under the

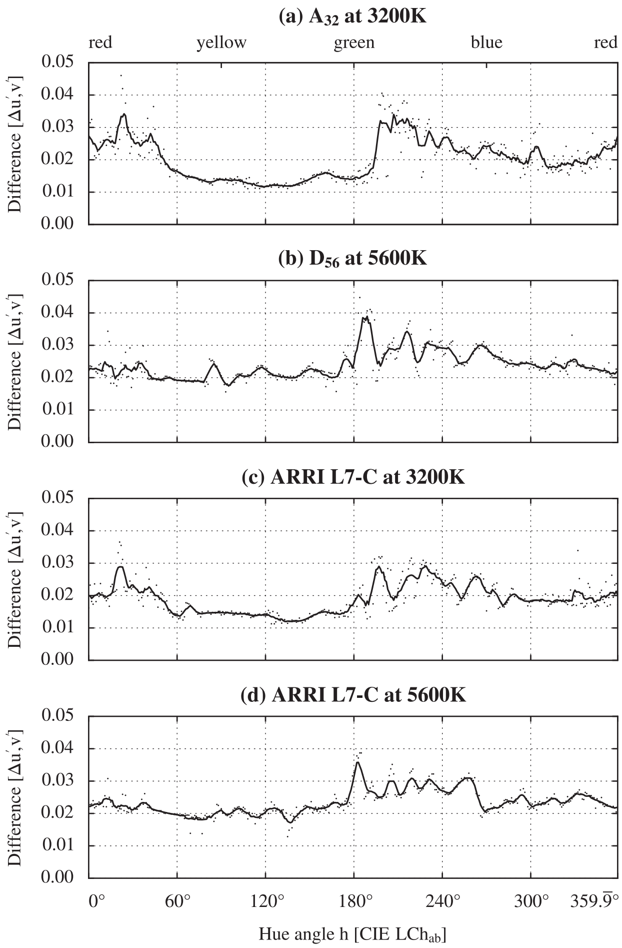

Figure 6. Difference Distribution among hue angle h. Dots indicate true values. A Savitzky-Golay filter with a window size of 7 and a polyorder of 1 was applied to plot the smoother line.

corresponding reference light. This, however, is most likely caused by a worse color rendering for the human observer under LED light.

Hue Dependence

Next to origin of critical spectra, their hue is crucial. Again, we select the critical pairings in Z and calculate their distance in relation to each other. The distances are plotted against the hue measured in CIE LCh$_{ab}$. Figure 6 shows the relative hue distribution of critical CPs under the indicated light source. As one may see, for all light sources most critical hues can be found between 180° and 240° (green-bluish hues); additionally, for tungsten balanced light sources critical hues can be found between 0° and 50°, which are respectively orange tones. For all light sources, but especially for tungsten-balanced ones, hues between yellow and green are relatively less critical.

Apart from that, the result for every light source, especially of the same correlated color temperature, is roughly the same, *i.e.* the spectral distribution of the light source does not have a large effect on the error distribution based on hues.

Conclusion

Considering, that spectra that are parameric for a camera, but not for a human observer, are critical in the color reproduction process we have shown how those can be found in a large database. We have also shown how one can use these to investigate the quality of the sensor and its behavior to different objects and light sources.

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Author Biography

Manuel Leonhardt received both his BSc and MSc in Computer Science in Media at the Hochschule Furtwangen University in 2013 and 2015 respectively. Since then he has worked in the Image Science Group at Arnold & Richter Cine Technik. His work focuses on color correction and camera characterization.

Harald Brendel received his diploma degree in Biology at the LMU Munich in 1992. After working in medical information technology he went into post-production for motion pictures. Since 2010 he is a Principal Engineer and Head of the Image Science Group at Arnold & Richter Cine Technik and mostly involved in color engineering and software development.