Comparison of Object-Color and Illuminant Metamerism for Digital Image Color Correction

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ABSTRACT

Metamerism is the phenomenon that two object colors, which are colorimetrically indistinguishable under one lighting and viewing condition, become distinguishable under another condition. Since the number of channels of an RGB camera is less than that required to represent the spectral information, the variation of either the captured object or the illuminant may introduce color reproduction errors when transforming device-dependent RGB values to device-independent stimuli. In this study, we collected and utilized a large spectral reflectance database to investigate the color reproduction errors corresponding to the object-color metamerism, and employed a spectrally tunable LED light source to generate spectral power distributions (SPDs) that were metameric to a specific illuminant to analyze the reproduction errors corresponding to the illuminant metamerism. The image quality assessment (IQA) metric was adopted to evaluate the degree of image distortion caused by the two types of metamerism. The IQA results indicate that, compared with the illuminant metamerism, the object-color metamerism has little impact on the accuracy of color correction, and consequently the acquisition of the SPD of the illuminant is the critical factor for high-fidelity color reproduction.

KEYWORDS: object-color metamerism, illuminant metamerism, digital image color correction

INTRODUCTION

As the demand for accurate color reproduction grows, various color correction methods have been proposed to reduce the color distortion between the output digital images and the ground truths [1]. However, few studies concerned about the metamerism for the digital image color correction. Since the independent channel numbers of cameras are less than the number of bands required to represent the spectral information of the objects, the metamerism is an inherent uncertainty for the color correction [2]. The color correction module in the digital camera usually uses a transformation matrix to convert the device-dependent color signals to the device-independent color tristimulus values. Because of the failure to meet the Luther-Ives condition by the camera spectral sensitivity, two objects with the same perceptive color by the human visual system (HVS) under one condition may appear different in the output image after color correction, thus reducing the fidelity of color reproduction of the imaging system [3].

In this study, we employed a large set of spectral reflectance data and a spectrally tunable LED light source to evaluate image distortion caused by the metamerism during color correction. Two metamer-distorted images for each test scene of the object-color metamerism were reconstructed and compared with the ground truth by the image quality assessment (IQA) metric to investigate the color distortion caused by the object-color metamerism. Similarly, another two images for each test scene were reconstructed and compared to discuss the illuminant metamerism.

METHODS

In a typical 3-channel digital imaging system, the raw responses at pixel $\mathbf{x}$ can be simply written as

$$p_c(R,E,\mathbf{x}) = \int_\Omega R(\lambda,\mathbf{X})E(\lambda)S_c(\lambda)\mathrm{d}\lambda, \quad c \in \{r,g,b\} \tag{1}$$

where $R(\lambda, \mathbf{X})$ is the spectral reflectance of $\mathbf{X}$, $E(\lambda)$ is the spectral power distribution (SPD) of the illuminant, $S_c(\lambda)$ is the camera spectral sensitivity of c channel [4], and $\mathbf{X}$ is the point in space corresponding to $\mathbf{x}$. In this study, we denote the metamerism of R, i.e., the same response p_c from different reflectance spectra under a certain illuminant, as the object-color metamerism, and the set of all reflectance spectra being metameric to R under the test illuminant E (here not standing for equal-energy illuminant) as the *object-color metamers set* (*OCMS*), $\mathcal{O}_E(R)$. Analogously, the metamerism of E will be denoted as the illuminant metamerism, and the set of all illuminants that have the same chromaticity but different SPDs with E as the *illuminant metamers set* (*IMS*), $\mathcal{I}(E)$.

In the digital signal processing pipeline, color correction is usually accomplished by pixel-wise multiplying RGB triplets by a color correction matrix (CCM). In this study, we used 3×3 matrix to transform the camera RGBs to the CIE tristimulus values XYZs. Given the SPD of a test illuminant E, 273 reflectance spectra (from ColorChecker DC and ColorChecker Digital SG, of which the peripheral neutral patches were excluded) are utilized as the training samples to calculate the camera responses matrix $\mathbf{P}(E) = [\mathbf{p}(R_1, E); \mathbf{p}(R_2, E); \ldots; \mathbf{p}(R_{273}, E)]$ by Eq. (1), where $\mathbf{p}(R_i, E) = [p_r(R_i, E), p_g(R_i, E), p_b(R_i, E)]$.

The color correction matrix $\mathbf{M}(E)$ is calculated by minimizing the average CIEDE2000 color difference between the color corrected responses and the ground truth:

$$\mathbf{M}(E) = \arg\min \sum_{i=1}^{273} \Delta E_{00}\left[\hat{\mathbf{q}}(R_i, E), \mathbf{q}(R_i, E_c)\right], \tag{2}$$

where $\hat{\mathbf{q}}(R_i, E) = \mathbf{p}(R_i, E) \cdot \mathbf{M}(E)$ is the estimated XYZ triplet of *i*th sample, and $\mathbf{q}(R_i, E_c)$ is the XYZ ground truth when lit by the canonical illuminant E_c.

Because of the object-color metamerism, the color difference between the color corrected responses of spectrum R_0 and its OCMS $\mathcal{O}_E(R_0)$ may be no longer below the threshold ΔE^{th} when the illuminant E is replaced by the canonical illuminant E_c. For each reflectance spectrum R_0, we retrieve its median and the 95% worst degrees of the object-color metamerism by searching for its 50th and 95th percentiles metameric spectra from $\mathcal{O}_E(R_0)$. Specifically, the *k*-percentiles metameric spectrum of R_0 is defined as

$$R_0^k \in \mathcal{O}_E(R_0) \left| \Delta E_{00}\left[\hat{\mathbf{q}}(R_0, E), \hat{\mathbf{q}}(R_0^k, E_c)\right] \simeq \frac{kM}{100} \right., \tag{3}$$

where M is the maximum color difference caused by the object-color metamerism corresponding to R_0 under illuminant E, i.e., $M = \max_{R \in \mathcal{O}_E(R_0)} \Delta E_{00}\left[\hat{\mathbf{q}}(R_0, E), \hat{\mathbf{q}}(R, E_c)\right]$. Fig. 1 illustrates the schematic diagram of the reconstruction of the images with and without the object-color metamerism.

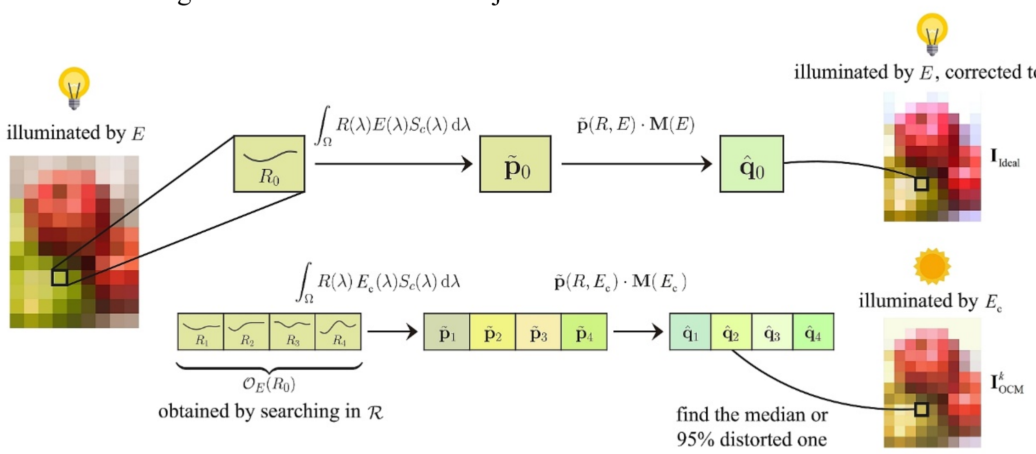

Figure 1: Schematic diagram of the reconstruction of the color corrected images $\mathbf{I}_{\text{Ideal}}$ *as well as the distorted image* $\mathbf{I}^k_{\text{OCM}}$ *by the object-color metamerism.*

EXPERIMENTS

The reflectance spectra database was constructed by combining several hyperspectral image databases and individual spectral reflectance databases. After some filtration and refinement, 7,326,497 reflectance spectra were finally collected to cover most of the objects in daily photography.

In this study, 8 frequently used illuminants were employed to investigate the object-color metamerism for the color correction, among which D65 was fixed as the canonical illuminant. In other words, the ground truth that a metamer-distorted image being compared to is the image with the same appearance as HVS perceives for the same scene illuminated by D65.

As seen in Fig. 1, the distorted images of metamerism were reconstructed pixel-wise. To reduce the computational cost, the hyperspectral imgaes (HSIs) with lengths more than 1000px were spatially downsampled to 25% pixels but without the modification of the spectra. Among all the HSI databases, 106 HSIs in total were selected as the test samples.

To evaluate the image distortion caused by the illuminant metamerism, we used the spectra of daylight series E_{Day} and spectrally tunable LED light source E_{LED} to generate a simplified IMS $\mathcal{I}(E)$ corresponding to each test illuminant E [5]. Fig. 2 shows the SPDs of 8 test illuminants as well as their corresponding IMSs, in which all illuminants are normalized so that the luminance Y = 1 for the ideal reflector.

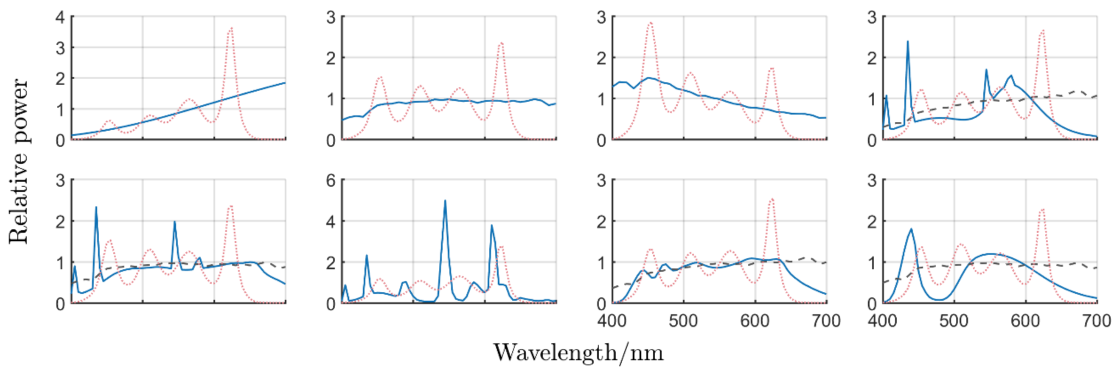

Figure 2: The SPDs of the 8 test illuminants (blue solid line) with the daylight metamers (black dashed line) and 4-channel LED metamers (red dotted line). From left to right, top to bottom: CIE-A, D50, D100, CWF, F8, TL84, LED, and iPhone Flash. Note that CIE-A and TL84 have no daylight metamer since their CCT are below 4000K.

RESULTS AND DISCUSSION

To evaluate the degree of image distortion caused by the metamerism, a full-reference image quality assessment (IQA) metric, directional statistics based color similarity index (DSCSI) [6], was adopted to compare the images with and without metamer-distortion, which has been proven to be successful in quantifying the perceptual quality of color images consistently with subjective evaluations. Given a reference image (the ground truth $\mathbf{I}$ in this study) and a distorted image ($\mathbf{I}^k_{\text{OCM}}$, k-percentiles distorted image of the object-color metamerism, or $\mathbf{I}_{\text{IM}}$, the distorted image of the illuminant metamerism), the "matching scores" of the image pair can be calculated by the DSCSI, of which the higher values stand for the better similarity.

The DSCSI results of two degrees (the median and 95% worst) of object-color metamerism as well as two types of illuminant metamerism (LED and daylight series illuminant metamer) are demonstrated in Fig. 3, in which the box-and-whisker plots show the medians, lower and upper quartiles, 2$^{\text{nd}}$ and 98$^{\text{th}}$ percentiles of the data. To provide a benchmark for the DSCSI scores, the images $\mathbf{I}_{\text{Ideal}}$ corrected with the correct CCMs, which represent the best achievable color correction results (labeled with "Ideal"), were also compared with the ground truths in Fig. 3.

The DSCSI scores in Fig. 3 indicate that the image distortion caused by the object-color metamerism is relatively milder compared to the distortion by the illuminant metamerism, and only has inconsiderable impact on the image quality during the color correction. Besides, the poor DSCSI scores of the illuminant metamerism, especially that from the daylight series, suggest that the color mismatching between the cameras and the HVS is mainly originated from the improperly selected color correction matrices. Thereby, even the chromaticities of the illuminants have been accurately estimated, the illuminant metamerism makes the color corrected image deviate from the appearance that HVS perceives. Unfortunately, most of the color correction module in cameras use a set of pre-built color correction matrices, obtained by training under several common illuminants, to correct the color of raw images. In the manual white balancing mode provided by most of the high-end digital cameras, the users are requested to photograph a flat neutral field to obtain the chromaticities of the light sources so as to provide the ground upon which an “appropriate” matrix is to be selected. The chromaticity based color correction strategies may lead to the difficulty of achieving the high-fidelity color reproduction, since the illuminant metamerism is inevitable when the spectral information is unavailable.

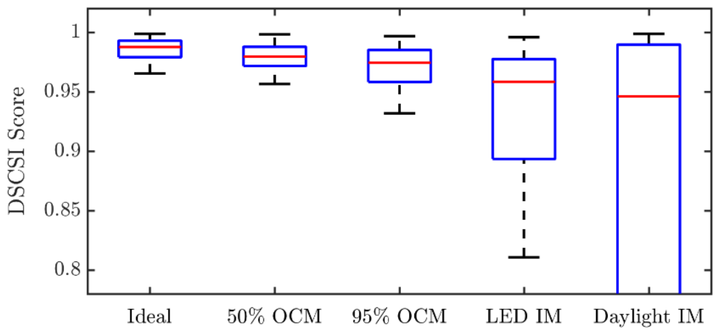

Figure 3: The DCSCI scores of two degrees of the object-color metamerism and two types of the illuminant metamerism.

CONCLUSION

Because of the lack of the spectral information, the metamerism is an inherent uncertainty in the digital signal processing of cameras that obstructs the perfect color reproduction. In this study, the image distortions caused by the object-color and the illuminant metamerism were quantitatively analyzed using DSCSI image quality assessment metric. It is indicated that, compared to the illuminant metamerism, the object-color metamerism is more tolerable during the color correction, whereas the frequently occurring illuminant metamerism causes more distortion to the images, even if the chromaticities of the illuminants have been accurately estimated.

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