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Preservation of spectral color information under different light sources

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ABSTRACT

Preservation of spectral color information of a set of surface colors under 36 different light sources are evaluated. Two measures of information are used, the energy and relative entropy. The energy is assessed by the eigendecomposition method. It is found that while 9 eigenvectors are necessary for full presentation of the spectral reflectances of surface colors, 5–8 eigenvectors are adequate to fully characterize the total variances of radiance spectrum, depending on light sources. Results also show that, the derived eigenvectors are sparse in some wavelengths mostly for the sources with limited numbers of emission bands. It is found that a significant spectral information loss occurs due to the illumination of surface colors. The Kullback- Leibler divergence measure is used to compare the relative entropy between reflectance spectra of objects and the corresponding radiance spectra of samples under each light source. Results show that there are big differences between the light sources in relative entropy between the reflectance spectra and the radiance spectra of objects. Based on energy and relative entropy considerations, the tri-band mixed-color white light LEDs generally have the highest loss of spectral information before the projection of radiance data over the reciver.

1. Introduction

Color is simply a reciprocal interaction between the spectral power distribution of light source, the reflectance spectra of object and the spectral sensitivity of the receiver, mostly human visual system. While the alteration of perceived color with the changes of the reflectance spectra of objects is logically anticipated, the tolerance of variations in the color of objects for the light sources is generally quite limited. In the current standards, the impact of light sources on the perceived object color should be small as possible compare to the reference illuminant. Ideally the light sources should not change the appearance of object color [1].

Evaluation of the effects of light sources on the perceived color has been a continuous practical and research interest in color science as well as illumination engineering [2–10]. Introducing of the new generation of light sources like LEDs, has made the issue more challenging than ever [5]. There are several color quality metrics for light sources [2–10]. In spite of serious weaknesses, in particular for new generation of light sources, the CIE color rendering index (CRI), is still

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the only universally accepted method for numerical evaluation of color appearance under light sources. Similar to most color rendering indices, the CIE CRI evaluates the light sources by degree of color deviation in a set of defined test color samples (TCS) [2]. The samples are seen under the test light source in comparison to reference illuminant. Other metrics, like color quality scale (CQS) [8], rank order color rendering index (RCRI) [9], feeling of contrast color rendering index (FCI) [7] and gamut area index (GAI) [6,10] are still under evaluation and/or improvement and have not been universally accepted. Majority of these indices are basically established on the basis of colorimetric aspects of a given collection of surface colors under desired light source. Most indices are defined in terms of reference light source and provides the psychophysical colorimetric comparative performance analysis rather than a fundamental physical property.

Although different studies have compared and/or criticized the existing rendering indices and tried to present the new metrics with better correlation to psychophysical tests [5,11], the fundamental principles of light sources in color formation has not been extensively studied. For instance, less attention has been paid to the effect of a light source to the preservation of the spectral color information, i.e. the spectral behaviors of objects under particular illumination. The effect of a limited number of light sources to the quality of the reconstructed spectrum has been reported and the effect of light sources on the dimension reduction of spectral data has been examined [12]. However, the role of light sources and their potential to provide different levels of spectral color information has not been extensively studied or reported.

Two extreme examples probably make the issue more clear. A narrow band light source seriously bounds the amount of spectral information to a limited range of spectrum and yields very sparse information over the visible region. On the other hand, a broad band illuminant, like a virtual equal energy light source (EE), would provide detailed and informative data that ideally duplicates the spectral pattern of reflectance spectra of objects. So, the preservation of spectral color information by light sources would be a key characteristic to demonstrate the level of color data under such illumination. In fact, during the transformation from the spectral data to colorimetric coordinates of objects, the employed light source plays a crucial role. This study deals with the capacity of light sources in term of preserved spectral color information. In this concept, the spectral information transferred by 36 different light sources were analyzed by means of accumulated residual energy of subspace defined by principal component analysis and the concept of relative entropy, i.e. the Kullback-Leibler divergences between the reflectance and radiance spectra.

2. Background

2.1. Intermediate spectral data in color formation

The colorimetric tristimulus values may be viewed as a compressed representation of spectral color data. Color is simply created by the projection of the reflected light spectrum from the object onto the tri-dimensional subspace spanned by the color matching functions of standard observer. Obviously, the reflected light, i.e. the product of light source and object, plays a significant role in such process. The information amount of created intermediate spectral data during the calculation of color as well as the final corresponding colors, depends on the employed vectors and matrices that specify the object, the light source and the observer.

Let $\mathbf{s}\left(\lambda\right)$ be the reflectance of a colored object, $\mathbf{e}\left(\lambda\right)$ the illuminance of the light source and $\mathbf{o}_i\left(\lambda\right)$ the observer sensitivity, where i varies between 1 to 3. The color of the object is then defined through tristimulus values

$$\begin{aligned} X &= k\int \mathbf{s}\left(\lambda\right)\mathbf{e}\left(\lambda\right)\mathbf{o}_1\left(\lambda\right)d\lambda \\ Y &= k\int \boldsymbol{s}(\lambda)\boldsymbol{e}(\lambda)\boldsymbol{o}_2(\lambda)d\lambda \\ Z &= k\int \boldsymbol{s}(\lambda)\boldsymbol{e}(\lambda)\boldsymbol{o}_3(\lambda)d\lambda \end{aligned} \tag{1}$$

where $k = 100/\int \mathbf{e}\left(\lambda\right)\mathbf{o}_2\left(\lambda\right)d\lambda$. If we ignore k, the normalization factor, Eq. (1) can be expressed in the matrix form as follows

$$\mathbf{C} = (\mathbf{E}S)^{\mathbf{T}}\mathbf{O} \tag{2}$$

where $\mathbf{S}$ is a $N \times 1$ column vector of object reflectance, $\mathbf{E}$ is a $N \times N$ diagonal matrix with illuminance values on the diagonal and $\mathbf{O}$ is a $N \times 3$ matrix, with observer sensitivities as columns. If we have P objects (reflectance vectors) the matrix $\mathbf{S}$ is $N \times P$ matrix. For calculating the tristimulus values of P objects from Eq. (2), the first intermediate step is to calculate the matrix

$$\mathbf{R} = \mathbf{ES} \tag{3}$$

a $N \times P$ matrix, where the columns are actually the radiances of objects $\mathbf{r}_i\left(\lambda\right)$, i = 1,. . .,P under illumination $\mathbf{e}\left(\lambda\right)$.

Now, the matrix $\mathbf{S}$ contains the original spectral information of objects and matrix $\mathbf{R}$ contains the spectral information transferred under the illumination $\mathbf{e}\left(\lambda\right)$ and reaching the observer. Hence, when we compare the information content of lateral matrix, i.e. matrix $\mathbf{R}$, we can predict the effect of illumination to the objects' color and use it for evaluating the quality of light in the view of ability to transfer spectral color information.