https://doi.org/10.2352/ISSN.2169-2629.2017.32.278

Designing Spectral Power Distribution of Illumination with Color Chart to Enhance Color Saturation

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Abstract

We propose a method to enhance color saturation while keeping the color appearance of white by controlling the spectral power distribution (SPD) of illumination. A color chart is used to design the SPD of illumination, which enables us to enhance several colors at the same time. In experiments, a sixteen-color LED lighting system was used as a light source. The intensity of each colored light can be modulated and is determined using three color patches of the X-Rite ColorChecker^{TM}. The color checker and multicolor wood-block prints were used to evaluate the results of color enhancement. The color distributions of these objects before and after changing the SPD of illumination were compared on a chromaticity diagram. Results show that the selected three colors are well enhanced while keeping metameric white and the color balance under daylight.

Introduction

Ukiyo-e, a genre of art featuring multicolor wood-block prints, flourished in the eighteenth century in Japan. The old ukiyo-e used natural pigments, which suffer from discoloration and degradation of color saturation with exposure to sunlight. Reproducing the original colors will help us to better understand the culture at the time and will make the prints more attractive for display in museums and galleries. For the reproduction of original colors, images of ukiyo-e are normally captured by a digital camera followed by photo retouching on a computer. The resultant image is then displayed on a monitor. However, the quality of material appearance of the original object is often degraded during the image capture and display processes.

Techniques for mixed-reality (MR), such as projection mapping, are effective in making up for the loss of quality of material appearance. Additional visual information is provided on real objects directly using a video projector, or as an image on an optical see-through display. In adding visual effects properly, there are mainly two issues: an image corresponding to the visual effect have to be generated and position gaps between the generated image and the real object have to be corrected. This makes the calculation cost large.

On the other hand, colors of an object can be enhanced by controlling the spectral power distribution (SPD) of illumination. This approach does not require any image processing. Nakauchi et al. designed the SPD of illumination to discriminate the colors of blueberry jam and foreign substances and implemented it using a tunable multi-wavelength light source [1]. Ito et al. enhanced the color differences between the skin and blood vessels using three types of LEDs to emphasize the color differences [2]. The tunable multi-wavelength light source can control light intensities of all wavelengths and generate light with various SPDs. However, the total output of the lighting system is currently relatively weak and is not suitable for practical use. On the other hand, although the output of LEDs has been becoming stronger recently, the color rendering properties of light synthesized using three types of LEDs are not sufficient for accurate color reproduction of object like ukiyo-e. This is because the half bandwidth of an LED is narrow and it has little energy in some parts of the visible wavelength spectrum. Moreover, the combination of LEDs has to be optimized every time the target color for enhancement is changed [1, 2].

In this paper, we propose enhancing several colors at the same time by changing the SPD of illumination. The SPD of illumination is designed using the spectral reflectance of color patches on a color chart. The proposed method was applied to observing the color chart and wood-block prints in experiments. Observed colors of these objects before and after changing SPD of illumination were compared on a chromaticity diagram.

Designing SPD of illumination to enhance color saturation

Formulation of SPD of illumination

The SPD of an illumination can be represented as linear combination of SPDs of a monochrome LED. Let us consider a lighting system consisting of N -colored LEDs. The SPD of objective illuminant $I_{obj}(\lambda)$ is described as

$$I_{obj}(\lambda) = \sum_{i=1}^{N} w_i e_i(\lambda), \quad (1)$$

where λ is wavelength and w_i and $e_i(\lambda)$ are the weight and SPD of the i th color LED of the lighting system. An object's color is enhanced by changing the values of $\mathbf{w} = [w_1, \cdots, w_N]$. To maintain the color balance under an illumination before changing the SPD of illumination, let us consider the constraint conditions where objective illumination satisfies metameric white, which means that chromatistic values of standard white and its luminance are maintained after the SPD of illumination is changed. These conditions are described as

$$\{f_a(I_0(\lambda),1) - f_a(I_{obj}(\lambda),1)\}^2 + \{f_b(I_0(\lambda),1) - f_b(I_{obj}(\lambda),1)\}^2 = 0\ , \qquad (2)$$

$$f_L(I_{obj}(\lambda),1) = f_L(I_0(\lambda),1)\ , \qquad (3)$$

where $I_0(\lambda)$ is the SPD of original illumination. The $f_L(I(\lambda), r(\lambda))$, $f_a(I(\lambda), r(\lambda))$, and $f_b(I(\lambda), r(\lambda))$ are functions for calculating CIE-Lab values, where $I(\lambda)$ is the SPD of illuminant and $r(\lambda)$ is the spectral reflectance of an object's surface.

Designing SPD of illumination using color chart

Let us consider the case where a target color for enhancement is a color patch whose spectral reflectance is $r_{obj}(\lambda)$. The SPD of the objective illumination $I_{obj}(\lambda)$ is obtained by determining weight $\mathbf{w} = [w_1, \cdots, w_N]$, which fulfills eqs. (2) and (3) and maximizes ε.

$$\varepsilon = f_a(I_{obj}(\lambda), r_{obj}(\lambda))^2 + f_b(I_{obj}(\lambda), r_{obj}(\lambda))^2\ , \qquad (4)$$

Let the number of the target colors C. Then ε is rewritten as

$$\varepsilon = \sum_{j=1}^{C} \varepsilon_j\ , \qquad (5)$$

$$\varepsilon_j = f_a(I_j(\lambda), r_j(\lambda))^2 + f_b(I_j(\lambda), r_j(\lambda))^2\ . \qquad (6)$$

When target colors are blue, green, and red, ε is represented as

$$\varepsilon = \varepsilon_{blue} + \varepsilon_{green} + \varepsilon_{red}\ . \qquad (7)$$

Experiments

Experimental setup

A sixteen-color LED lighting system (Telelumen Light Replicator, TeleLumen LCC) was used as the light source in experiments. Figure 1 shows SPDs of each LED light. The intensity of each color light can be modulated. For designing the SPD of illumination, three color patches of the X-Rite ColorChecker™ (no. 13 for blue, no. 14 for green, and no.15 for red) were used. Their spectral reflectance is

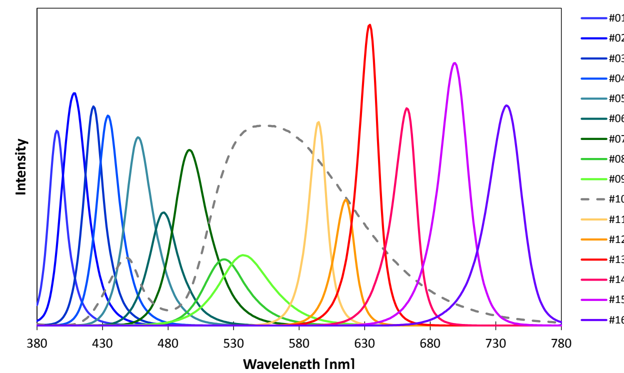

Fig.1. Spectral power distributions of each LED on the sixteen-color LED lighting system

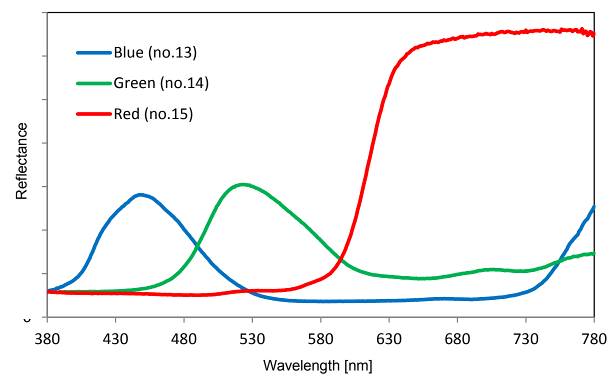

Fig.2. Spectral reflectance of blue, green, and red patches.

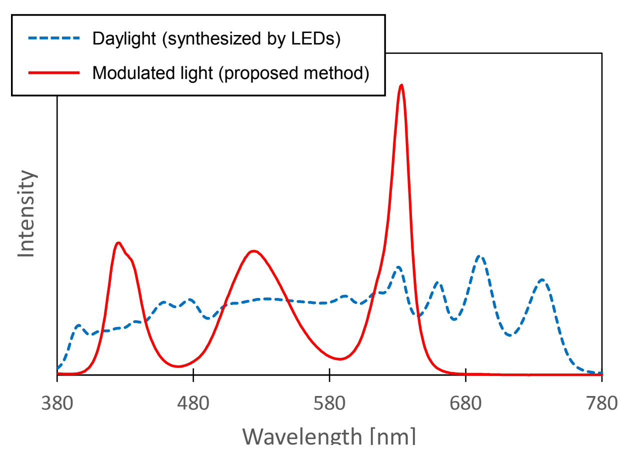

Fig.3. Spectral power distributions of illumination designed for color enhancement.

shown in Fig. 2. Daylight synthesized by the lighting system was used as the reference illumination in experiments.

First, the SPD of the designed illumination for enhancing blue, green, and red at the same time was designed using the color chart. Weights of each LED were determined using

Fig. 4. Captured images of color chart under daylight (left) and designed illumination (right).

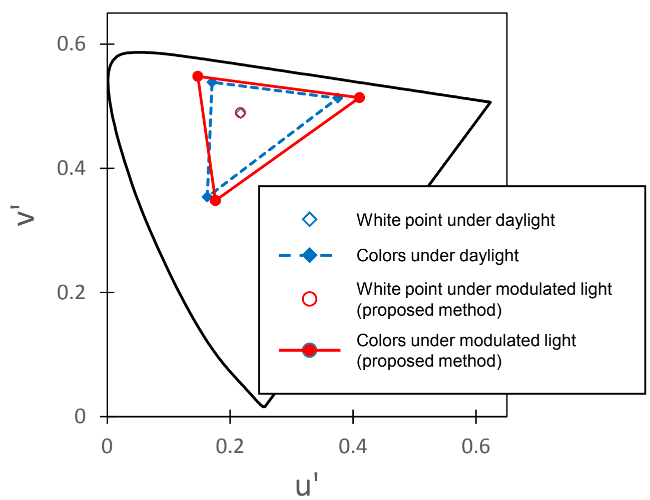

Fig.5. Color distribution of white, blue, green and red patches plotted on CIE-u'v' chromaticity diagram.

the generalized reduced gradient method (GRG). Next, color enhancement results were evaluated on chromaticity diagram. The color chart and several wood-block prints were used for the evaluation. Finally, SPDs of illumination for enhancing blue, green, or red respectively were designed and color enhancement results were evaluated on a chromaticity diagram.

Result of desiging SPD of illumination

Figure.3 shows SPDs of daylight (blue dashed line) and the designed illumination (red solid line). The SPD of the designed illumination has three peaks whose center wavelengths are 435, 530, and 634 nm. Their center wavelengths are correspond to the peak wavelength of the spectral reflectance of blue and green patches and to the rising wavelength of the spectral reflectance of the red patch.

Results of color enhancement

Images of the color chart captured under daylight and the designed illumination are shown in Fig. 4. Comparing color patches of the bottom row, one sees that neutral colors corresponding to white and gray stared the same before and after changing the illumination. On the other hand, saturations of other color patches were enhanced after the illumination was changed, especially for blue, green, pink,

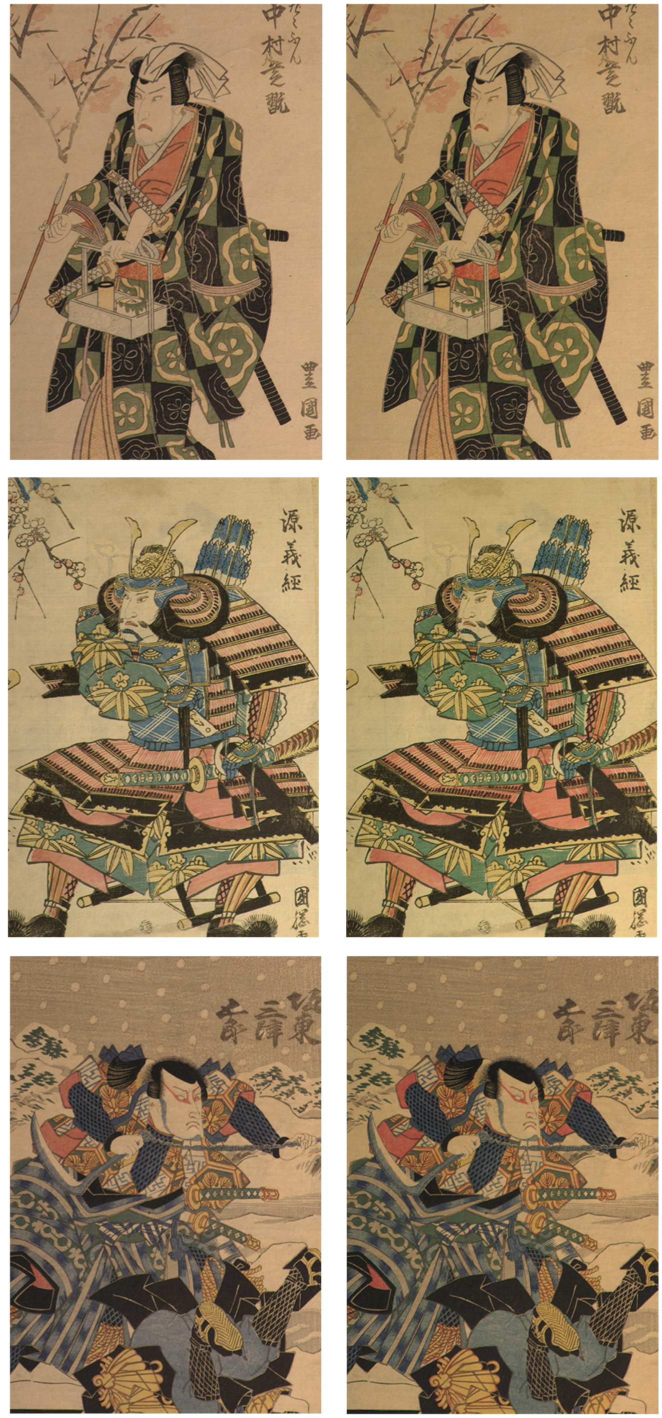

Fig. 6. Observed images under daylight (left) and designed illumination (right).

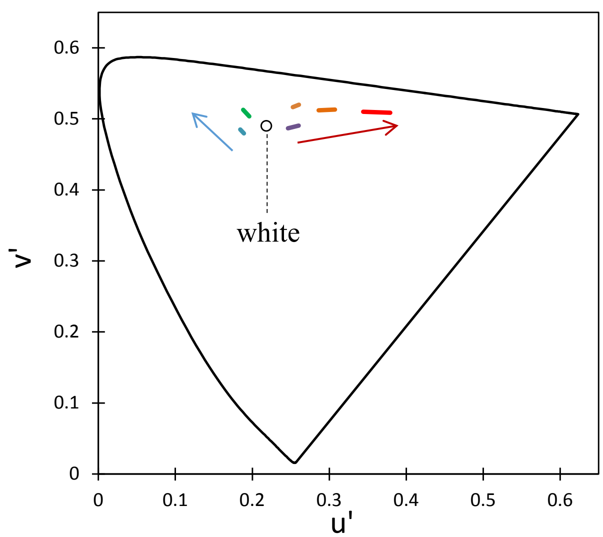

Fig.7. Color shift on CIE-u'v' chromaticity diagram.

orange, and red patches. The color balance of the color chart was also maintained after changing the illumination was changed. Figure 5 shows chromatistic values of white, blue, green, and red patches plotted on the CIE-u'v' chromaticity diagram. Blue diamonds and the dashed line represent colors under the illumination before the SPD was changed and red circles and solid line represent colors after the illumination was changed. This diagram shows that u'v' values of white under each illumination are the same and color saturation of other three color patches is enhanced.

Figure 6 shows images of wood-block print captured under daylight (left) and the designed illumination (right). Within the upper images, reddish and green parts on the clothes under the designed illumination look more vivid than those under daylight. Pink blossoms also look more reddish and it becomes easier to distinguish their shape. Likewise, reddish and blue-green parts of the center and bottom prints look more vivid under the designed illumination. Note that total color balance of these prints is maintained, although the SPD of illumination was changed and color saturation of some parts on prints was enhanced. Figure 7 shows the colors of blue, green, and reddish parts on these prints plotted on the CIE-u'v' chromaticity diagram plotted. The circle represents white point and red and blue arrows represent directions of color shifts caused by changing the SPD of illumination. This diagram shows how much the colors in wood-block prints were enhanced.

Discussion

The SPD of illumination was designed to enhance blue, green, and red at the same time. Here let us consider the case of enhancing one color. SPDs of illumination for enhancing blue, green, and red separately were designed

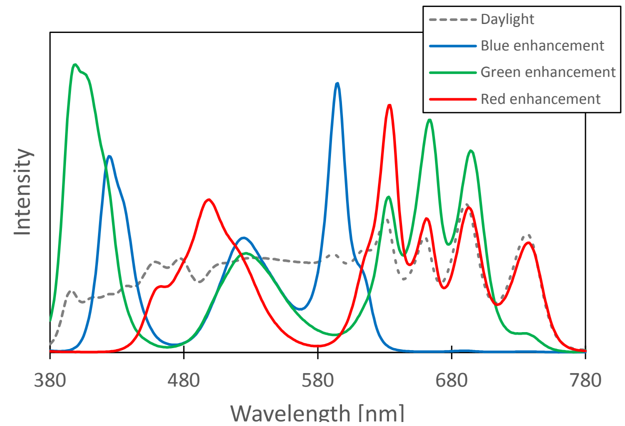

Fig. 8. Spectral power distributions for enhancing blue, green, and red respectively.

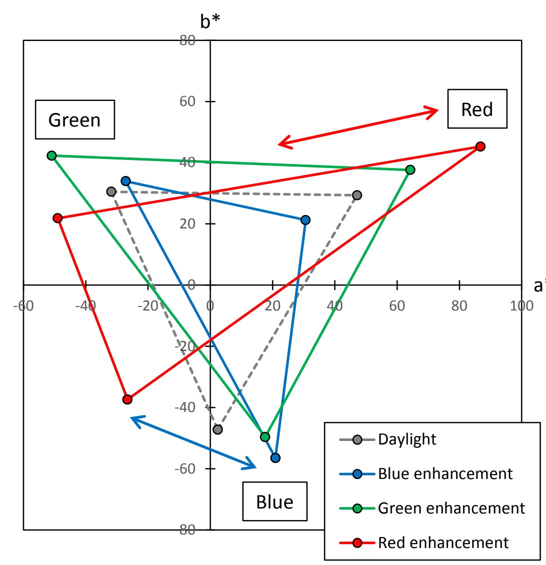

Fig. 9. Color shift on CIE-a*b* color space.

using the spectral reflectance of a color patch on the color chart used in the previous experiments and eqs. (2), (3), and (4).

Figure 8 shows three SPDs of the designed illumination. For the blue enhancement illumination, little energy longer than 630 nm exists in the SPD. On the other hand, for the red enhancement illumination, little energy shorter than 450 nm exists in the SPD. These results indicate that the saturation of reddish colors degrades when enhancing blue and the saturation of bluish colors degrades when enhancing reddish colors. To confirm this, chromatistic values of blue, green, and red patches in the color chart were measured and plotted on a CIE-a*b* color space (see Fig. 9). Tendencies in the color shift of bluish and reddish colors can be found from Fig. 9.

Conclusion

We propose a method for enhancing several colors at the same time by changing the SPD of illumination. In experiments, blue, green and red patches of the X-Rite ColorCheker^{TM} were used for designing the illumination and the designed illumination was synthesized using a sixteen-color LED lighting system. Old wood-block paints, which were discolored with degraded color saturation, were illuminated by the designed light. Experimental results showed the designed illumination could enhance colors on wood-block prints with maintaining metameric white and the color balance under daylight. In addition, illuminations for enhancing blue, green and red separately were designed and relationship between one enhanced color and the others was shown.

Reference

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Author Biography

Masaru Tsuchida received the B.E., M.E. and Ph.D. degrees from the Tokyo Institute of Technology, Tokyo, in 1997, 1999, 2002, respectively. In 2002, he joined NTT Communication Science Laboratories, where his research areas included color science, three-dimensional image processing, and computer vision. His specialty is color measurement and multiband image processing. From 2003 to 2006, he worked as a researcher at the National Institute of Information and Communication Technology (NICT) for the "Natural Vision" project.