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The Necessity of a Whiteness Scale for FWA-enhanced Whites

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Abstract

Two scales (i.e., Cho's whiteness scale and Berns' depth scale) were investigated to see whether they can accurately predict the whiteness of surface colors (e.g., textile and paper), both scales were found to be highly correlated to the NCS samples in past studies. The results indicated that the whiteness of samples without FWA-enhancement was highly correlated to both scales, but neither of them can predict the whiteness of FWA-enhanced white samples. These FWA-enhanced samples did not follow the concept that higher lightness and lower chroma produce whiter appearance. The study suggests the necessity to have a unique model to characterize the whiteness of FWA-enhanced whites, especially given the wide use of FWAs around human beings.

Introduction

White is one of the most familiar colors for human perception. Numerous objects around us are in white, some are natural objects and some are man-made objects. When characterizing surface property, white is often defined as a non-selective and high spectral reflection [1]. In colorimetry, white is the attribute of a visual sensation according to which a given stimulus appears to be void of any hue and grayness [2]. However, human beings have found ways to create whiter than white effect by adding a little bit blue dye or fluorescent whitening agents (FWAs) to objects. The latter absorb ultraviolet or violet radiations from the illumination and re-emit blue radiation. Both methods create a slight blue tint and lightness enhancement. Most man-made white objects and some natural objects (e.g., teeth) contain FWAs; manufacturers modulate the amount of FWAs to achieve the desired whiteness appearance. Thus, both the spectral content of the illumination and the FWAs included in an object are important for whiteness enhancement, as suggested by past studies [3, 4].

With the increase of LED adoption for general lighting, numerous efforts have been made by LED manufactures and scientists on how to characterize and improve the color rendition ability of LED sources [5-7]. In comparison, the ability of LED sources to render white objects receives little attention, though white is one of the most familiar colors for human's visual experience. A recent study suggested that typical blue-pumped white LED products in the market fail to render white objects with FWAs due to the lack of ultraviolet and violet emission in LED products [8]. A measure characterizing the ability of a light source to render whiteness, which is similar to the CIE General Color Rendering Index (CIE R_a) characterizing the ability to render colors, is necessary [9].

A scale or a metric which can characterize whiteness of object colors is critical in characterizing the ability of a light source to render whiteness. Such a scale or a metric should be highly correlated to how humans perceive whiteness of object colors. The most familiar whiteness scale in colorimetry is the one included in the Natural Color System (NCS). It has been widely used by designers as color specifier. Each of the 1950 NCS samples can be described using three metrics—whiteness, blackness, and chromaticness; the sum of these three metrics equals to 100 [10]. Before 2015, no simple models that can transform the three metrics of the NCS samples into CIE color space existed, except a large look-up table developed by Rhodes and Luo in 1996 [11]. In 2015, Cho developed a whiteness scale which was highly correlated to the whiteness values of the NCS samples; this model can compute the whiteness of an object color using its chromaticities in a color space (i.e., CIELAB, CIECAM02, or CAM02-UCS) [12]. In addition, the depth scale D^*_{ab} developed by Berns in 2014 also had a strong negative correlation to whiteness; it characterizes the degree of departure of a color from a neutral white color [13].

This study aims to investigate whether these two scales—Cho's whiteness scale and Berns' depth scale—can predict the whiteness of FWA-enhanced white objects.

Methods

Two psychophysical experiments were conducted in this study. Observers evaluated nominally white samples under various lighting conditions in a viewing booth, with dimensions of 70 cm (width) × 66.5 cm (depth) × 55 cm (height). The first experiment included 50 samples and 12 lighting conditions that were comprised of three levels of UV radiation (i.e., zero, medium, and high) for each of the four levels of CCT (i.e., 3000K, 4000K, 5000K, and 6500K); the second experiment included 55 samples and six lighting conditions that were comprised of two levels of UV radiation (i.e., zero and high) for each of the three levels of CCT (i.e., 3000K, 4000K, and 6500K). For each sample under each lighting condition, the observers were asked to rate the percentage of white using a 0%-100% rating scale, with 0% for "no trace of white" and 100% for "pure white". Detailed procedures and descriptions of the experiment can be found in Ma et al [3].

Figure 1 shows the color shifts in a'-b' plane of CAM02-UCS from the samples under 6500K-zero to those under 6500K-high in the two experiments. The samples having large shifts contained FWAs which were excited by the UV radiation, and the samples having slight shifts did not contain FWAs. It can be observed that the excitation of the FWAs through the UV radiation shifted the color towards the negative direction of b', corresponding to a blue tint.

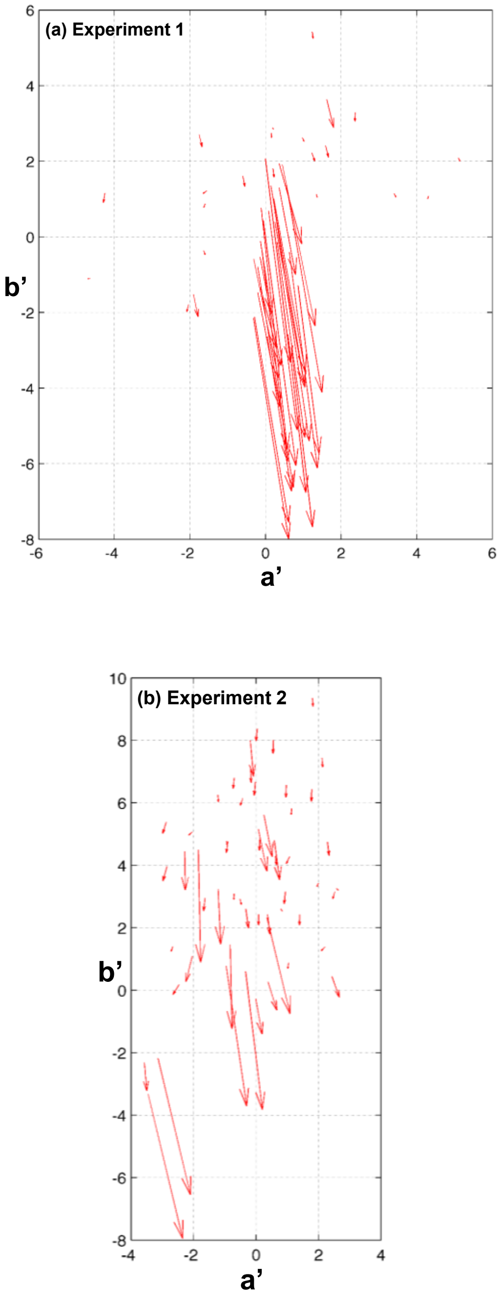


__Figure 1__ The color shifts in a’-b’ plane of CAM02-UCS from the samples under 6500K-zero to those under 6500K-high. Large shifts indicate the samples contained FWAs, which were excited by the UV radiation included in the 6500K-high illumination.

Performance of Whiteness Scales

The correlations were investigated between the visual assessments made by the observers and the two scales—Cho’s whiteness scale and Berns’ depth scale. Figure 2 shows the correlation between the visual assessments and Cho’s whiteness scale; Figure 3 shows the correlation between the visual assessments and Berns’ depth scale. It can be observed that both scales were correlated to the visual assessments when there was no FWA-enhancement, either the color sample did not contain FWAs or the illumination did not contain UV radiation to excite the FWAs. The FWA-enhanced white samples were generally rated to have a higher rating, but the ratings were not correlated to either scales.

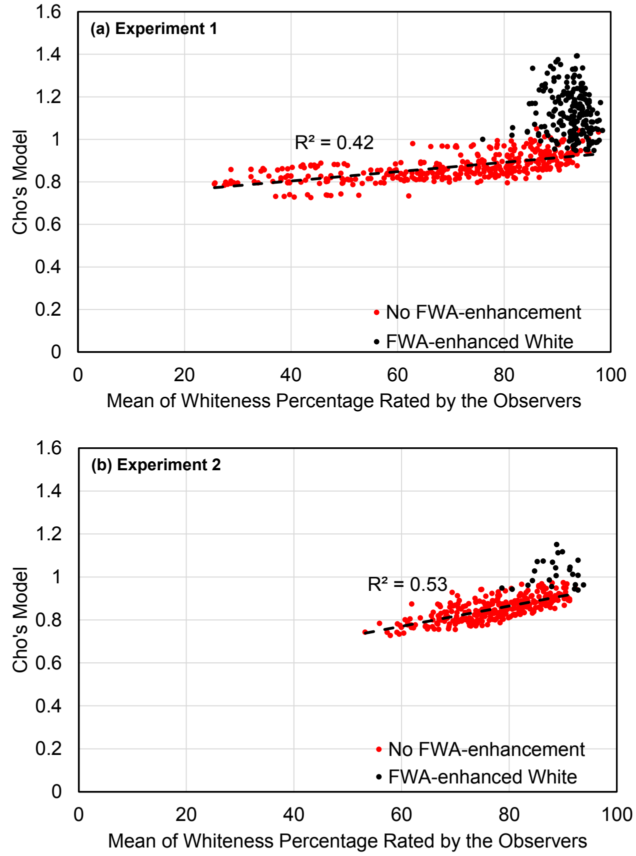
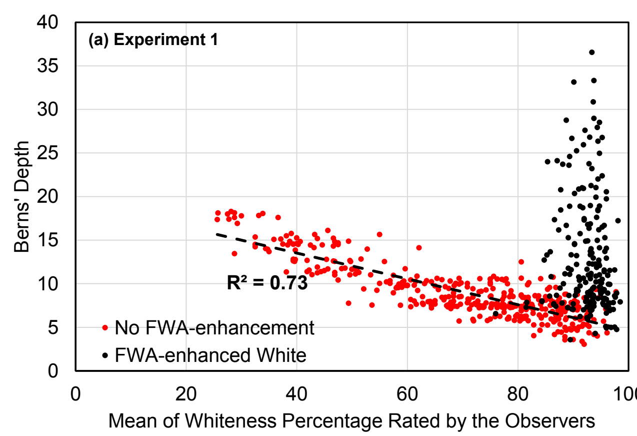


__Figure 2__ Scatter plot of Cho’s whiteness model versus the mean whiteness percentage rated by the observers for each sample under each lighting condition.



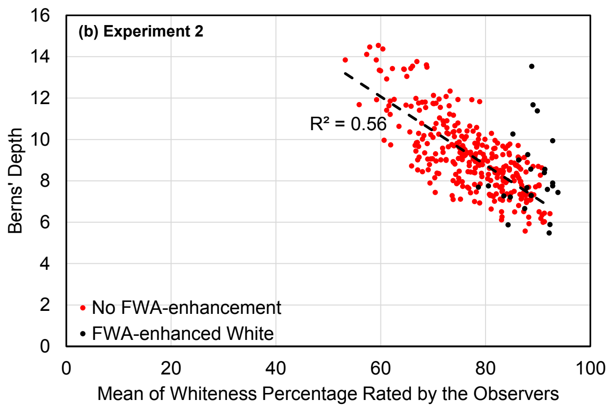


Figure 3 *Scatter plot of Berns' Depth scale versus the mean whiteness percentage rated by the observers for each sample under each lighting condition.*

Whiteness, Lightness, and Chroma

For whiteness, it generally follows the concept that sample with higher lightness and lower chroma is whiter [2]. A scatter plot of lightness versus chroma for the 1950 NCS samples with its whiteness scale is shown in Figure 4. Berns' depth scale tries to model an attribute which is opposite to whiteness; Figure 5 shows the 1950 NCS samples with its Berns' depth scale [13].

The visual assessments, however, indicated that only those samples without FWA-enhancement required higher lightness and lower chroma for higher whiteness, as shown in Figure 6 (a). The FWA-enhanced whites generally had high lightness levels, which were roughly around or higher than 90. The higher chroma levels for these FWA-enhanced whites did not reduce the whiteness appearance, as shown in Figure 6 (b).

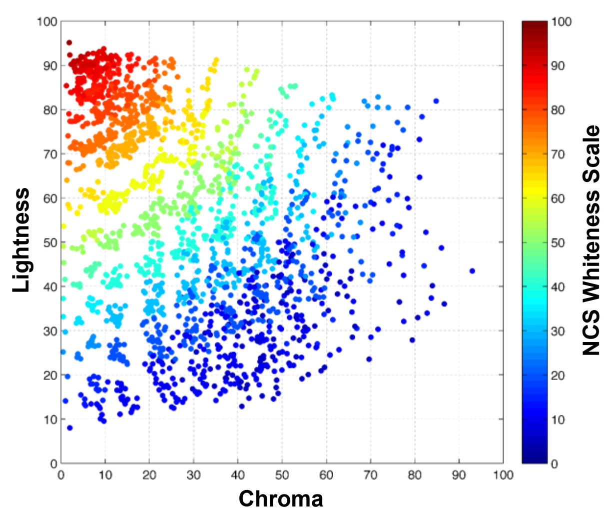


Figure 4 *The relationship between NCS whiteness scale and sample's lightness and chroma*

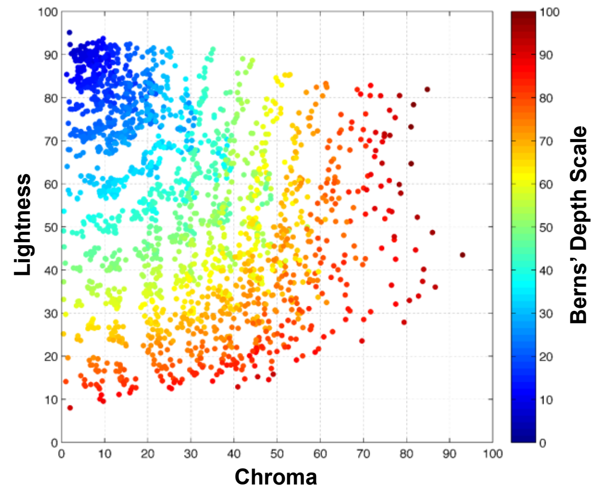


Figure 5 *The relationship between Berns' Depth scale and sample's lightness and chroma*

Hue Composition for FWA-enhanced Whites

The FWA-enhanced whites, which included FWAs and were excited by the UV radiation from the illumination, had a small range of hue composition between 300 and 330, as shown in Figure 7. Thus, the higher lightness levels (shown in Figure 6) together with such a specific hue composition made these FWA-enhanced whites have higher whiteness.

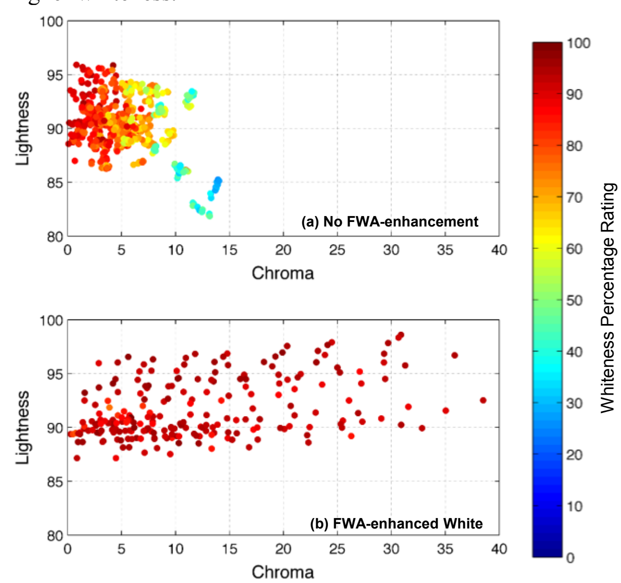


Figure 6 *Plot of mean rating of whiteness percentage of white samples and lightness and chorma values. a) with no FWA-enhancement; (b) FWA-enhanced white samples.*

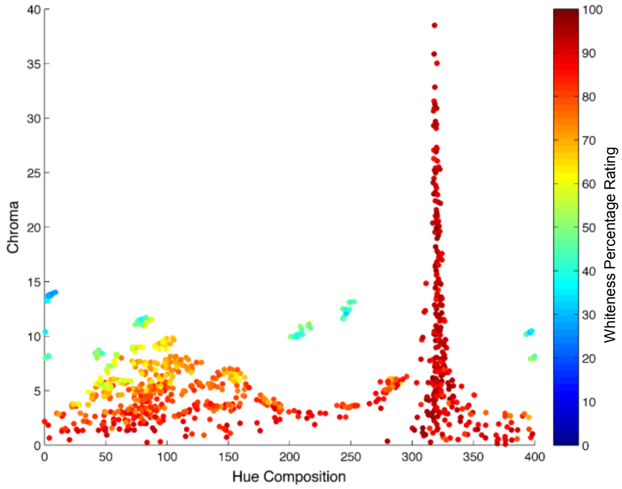


Figure 7 *The mean rating of whiteness percentage of each white sample under each lighting condition and its hue composition and chroma.*

FWA-enhanced White versus NCS Samples

The failure of both Cho's whiteness scale and Berns' depth scale in predicting whiteness of the FWA-enhanced whites is likely due to the distribution of NCS samples, as both scales are well correlated to the NCS whiteness scales derived from visual assessments. Figure 8 shows the distributions of the NCS samples and samples included in our experiments in a'-b' plane of CAM02-UCS. It can be seen that NCS samples do not cover the specific hue introduced by the FWA-enhancement. Meanwhile, the comparison of Figure 6 (b) and Figure 5 illustrates that the FWA-enhanced whites simultaneously had higher lightness and chorma levels. However, this trend cannot be found in the NCS samples. Thus, the scales that were derived using NCS samples cannot characterize the whiteness of FWA-enhanced whites.

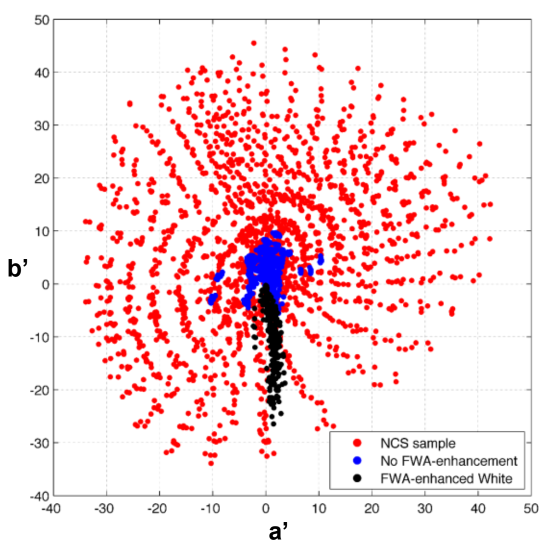


Figure 8 *The distributions of the NCS samples and white samples included in the experiments plotted in a'-b' plane of CAM02-UCS.*

Conclusions

A whiteness metric or scale which can predict the whiteness appearance of white objects is critical for the development of a measure to characterize the ability of a light source to render white objects. Two psychophysical experiments were conducted to investigate the effect of FWAs and UV radiation in illumination on whiteness enhancement. Two scales (i.e., Cho's whiteness scale and Berns' depth scale) that were highly correlated to the NCS whiteness were investigated to see whether it can be used to predict the whiteness of these FWA-enhanced whites. The failure of the two scales is due to the specific hue shift introduced by FWA excitation, which does not exist among the NCS color samples. This study addressed a need to develop a new whiteness scale, as the ones proposed by Ma et al [14], to characterize the whiteness for FWA-enhanced whites, especially given the wide use of FWAs in white objects around us.

Funding

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Author Biography

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