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SHORT COMMUNICATION

COLOR RESEARCH AND APPLICATION WILEY

Short communication: White balance for self-luminous highlights in images

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Abstract
An image is commonly white balanced using a white point that is considered to accurately characterize the scene illumination color (e.g., the white point estimated by the main camera on a smartphone, or the white point estimated by an ambient light sensor). Two recent studies, however, suggest that the perceived color appearance of self-luminous highlights is less affected by the ambient illumination color in a scene, with the color appearance judged using a white point between 5000 and 7000 K, especially when the stimulus luminance is much higher than the diffuse white luminance. Based on this, we hypothesized to use a D65 white point for white balancing the self-luminous highlights in images, regardless of the estimated white points. We captured a series of images containing self-luminous highlights, and processed them with three different white points (i.e., the white point estimated by the main camera, D50, and D65). The hypothesis was supported by the survey results collected from 73 observers, together with our observations, and believed to introduce better image color appearance, especially for images shown on high dynamic range displays.

KEYWORDS
chromatic adaptation, white balance

1 | CHROMATIC ADAPTATION AND WHITE BALANCE

Human beings perceive the color appearance of stimuli relatively constant under a wide range of illumination. This is mainly due to the chromatic adaptation mechanism in the human visual system. It automatically adjusts the sensitivities of the three types of cones in the retina based on the color of the ambient illumination, so that the color cast of the illumination on the objects can be removed.[1] In digital cameras, white balance is implemented to adjust the gains for the red, green, and blue values of each pixel, which aims to simulate the chromatic adaptation mechanism and make the colors in images similar to what we perceive.[2] The gains can be set either manually (i.e., manual white balance) by selecting the light source that matches the scene illumination or automatically (i.e., auto white balance) by estimating the scene illumination using a certain algorithm. Typically, white balance is commonly performed globally on an image, with the same set of gain values applied to all the pixels in the image.

In recent years, cameras, especially those on smartphones, are using advanced white balance algorithms, to better consider the chromatic adaptation to the ambient conditions. For example, some smartphones use advanced algorithms to estimate multiple white points in a scene, which can be used to apply local color tuning through masking. Some algorithms have been proposed to apply local white balance.[3,4] Furthermore, an image captured by a telephoto camera with a high value of zoom factor can be white balanced based on the white point estimated by the main camera, since it has a larger field of view to better estimate the illumination in the scene.[5]

2 | CHROMATIC ADAPTATION WHEN VIEWING SELF-LUMINOUS HIGHLIGHTS

The mechanism of chromatic adaptation has been investigated through psychophysical studies. In these studies, observers viewed color stimuli produced using surface color samples (e.g., Munsell samples) which reflected the ambient illumination or conventional standard dynamic range (SDR) displays.[6–8] Therefore, the luminance of the stimuli were always below the diffuse white point luminance, and the ambient illumination color was found to significantly affect the color appearance of the stimuli due to the chromatic adaptation.

Real scenes, however, commonly contain highlights, especially self-luminous stimuli (e.g., light sources), with luminance beyond the diffuse white. Also, recent high dynamic range (HDR) displays are able to show images containing pixels with luminance beyond the diffuse white point. For example, a new HDR image format embeds a gain map image storing the luminance data of the image into an SDR image,[9] as shown in Figure 1, which allows the recovery when showing on an HDR display.

In two recent studies,[10,11] we purposely investigated how chromatic adaptation affects the color appearance of a stimulus with a luminance beyond the diffuse white point. The observers were asked to adjust the chromaticities of the stimulus having a field of view around 4° at a certain luminance level under different ambient illumination conditions, so that the stimulus appeared the whitest. It was found that all the adjusted chromaticities were shifted towards a region around the daylight locus with a Correlated Color Temperature (CCT) between 5000 and 7000 K, when the stimulus luminance was more than four times of the diffuse white luminance. In particular, when the luminance difference between the white point and stimulus was larger, the adjusted

FIGURE 1 Example of new high dynamic range image format, with the gain map (right) embedded in the standard dynamic range image (left).

chromaticities were closer to the above region and the ambient illumination color had a smaller effect. When the ambient condition was dark, the chromaticities were adjusted to around the D70 chromaticities and the stimulus can be considered as an unrelated color. Such results suggest that the ambient illumination color has a much smaller effect on the color appearance of stimuli with luminance beyond the diffuse white, and the color appearance of these stimuli is judged with a white point having the CCT between 5000 and 7000 K. Such a finding was also supported by another study.[12]

3 | WHITE BALANCE FOR SELF-LUMINOUS HIGHLIGHTS

Given the results and analyses above, it can be hypothesized that the color of ambient illumination may not be appropriate for white balancing self-luminous highlights in an image, and a white point between 5000 and 7000 K may be more appropriate for adjusting the colors of these highlights. To test such a hypothesis, we used a Huawei Mate XS2 to capture a RAW image of a scene illuminated by a candle using the telephoto camera, with the candle flame covering the most areas of the image. Such a RAW image was white balanced with four different white points, followed by the color correction matrix (i.e., applying a matrix that is interpolated based on the CCT of the white point with the two color matrices extracted from the image DNG header file[13]) and gamma correction (note: since the flame covered the most area of the image and the rest pixels were mainly black, we performed the global white balance instead of local white balance on the flame). These four white points were carefully selected, including the white point estimated by the main camera—2630 K (this was derived based on the

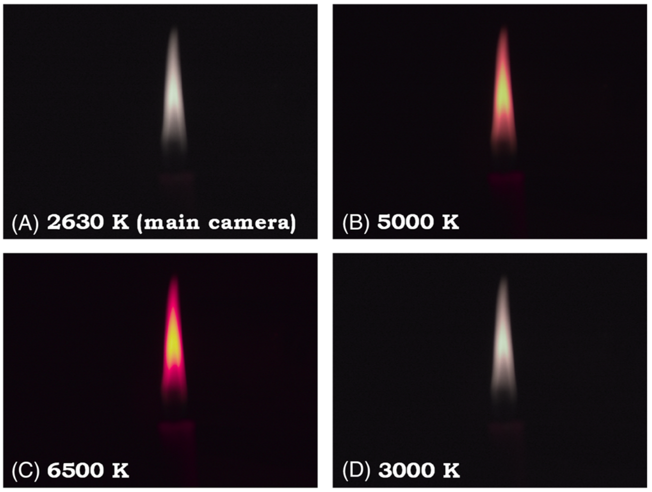

FIGURE 2 Illustration of how white point affects the color appearance of a self-luminous highlight. (a) 2630 K as estimated by the main camera; (b) 5000 K; (c) 6500 K; (d) 3000 K as found in a pervious study.[14]

RGB values of the white point recorded in the header file and the two color matrices in the header file through an iteration process[13]), the white point of D50, the white point of D65, and the white point of 3000 K (note: this was selected based on our past work investigating the white balance for scene illumination[14]), with Figure 2 showing the processed images. It can be found that the white point derived from the main camera makes the flame appear neutral, which should not be the appearance when viewed in person. The white point of D50 seems to make the color appearance more similar to what we would expect, than that of D65. The same comparison was made on the images of a high-pressure sodium lamp used for road lighting, which led to the same observation.

Based on the trial described above, we captured RAW images of a series of scenes containing self-luminous highlights, which were generally signs and billboards of different logos. In order to let observers have an idea of the color appearance of the stimulus without even seeing the scene, we purposely selected the logos that are familiar to the observers. When capturing the images using the main camera, we let the camera to automatically adjust the exposure settings (i.e., exposure time and ISO) to capture the overall appearance of the scene; when capturing the images using the telephoto camera (i.e., the image of the highlights), we adjusted the settings to have a shorter exposure for avoid any color clipping (note: the color shifts of the highlights we experience sometimes are due to the color clipping).

The RAW images were processed into 8-bit sRGB images in the same way as described above, using three white points (i.e., the white point automatically estimated by the main camera, D50, and D65). Since the scenes we captured were not corner cases, the white points estimated through the auto white balance algorithm of the main camera were considered accurate enough. The experiment only included 20 scenes with the white point derived from the main camera being very different from D50 and D65, which introduced an obvious color appearance difference with the three white points. In the experiment, the observer viewed a gray scale image of a scene captured by the main camera (i.e., a wide-FOV image), which allowed him or her to have an idea about the context of the scene, and the three telephoto images processed with the three white points (i.e., the images captured by the telephoto camera, as shown in Figure 3), and was asked to select the one with the color appearance of the logo closer to his or her memory. Again, since the logos covered most area of the telephoto images, we simply performed the white balance on the entire image, instead of local white balance on the pixels of the logos. The order of the 20 scenes was randomized among the observers, and there were 73 observers in total. All the observers were junior-year students, and had self-reported normal color vision. During the experiment, the observer was asked to view the display in a dark environment with the display white point set to D65.

Figure 3 shows the images of the 20 scenes that were white balanced using the three white points. Figure 4 summarizes the percentage for selecting the image with each white point. It can be observed that the white point estimated by the main camera was never selected by the greatest number of observers for each scene, while D50 and D65 were selected by the greatest number of the observers for seven and 13 scenes respectively. On average, the white point estimated by the main camera, D50, and D65 were selected by 19.2%, 34.8%, and 46.0%. And there seemed to be no relationship between the selections and the white points estimated by the main camera. Such results clearly supported our hypothesis that the color of the ambient light condition is not appropriate to be used as the white point for white balancing the self-luminous highlights in an image, while a white point between 5000 and 6500 K is more appropriate. This was likely due to that the chromatic adaptation mechanism has a smaller effect on the color appearance of self-luminous stimuli. And the results derived from these 20 scenes specifically support the adoption of the D65 white point.

It is worthwhile to point out that the hypothesis and the experiment were designed to investigate the white point for white balancing (i.e., in the early stage of ISP pipeline), so the experiment was carried out with the display white point set to D65 as past studies.[12,13,15] When the images or displays are not viewed under a D65 condition, it is necessary to adjust the display white point for producing a better viewing experience as suggested by other studies.[16,17]

FIGURE 3 Images of the 20 scenes that were white balanced using the three white points: The white point estimated by the main camera, D50, and D65. The CCT values shown on the left are the white point estimated by the main camera and by the telephoto camera (in parentheses).

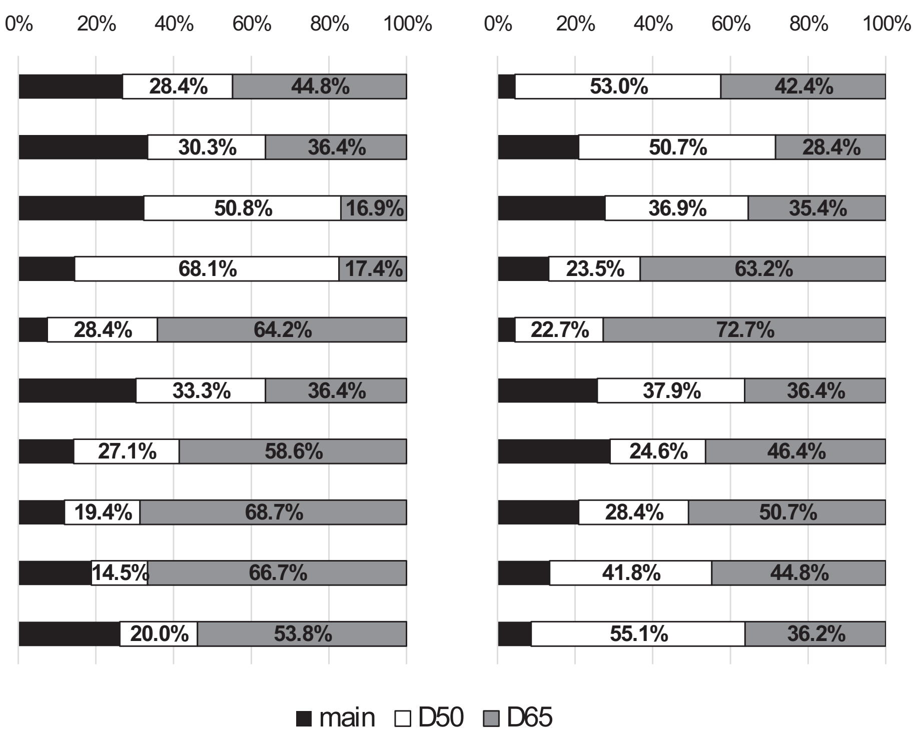

FIGURE 4 Summary of the selections made by the observers, with the orders the same as Figure 3.

FIGURE 5 Examples comparing the appearance between the image with the self-luminous highlight using the white point estimated by the main camera and that using the D65 white point (only one self-luminous highlight is adjusted in each image, which was done by creating a mask using Photoshop).

It is reasonable to wonder whether using such a proposed white point only for the self-luminous highlights in an image would cause any perceptual artifacts. Figure 5 compares the appearance between the image with the pixels of the self-luminous highlight using the white point estimated by the main camera and that using the D65 white point, with the rest regions in the image using the white point estimated by the main camera. It seems that the proposed white point for the self-luminous highlights generally makes the appearance look similar to what we would see in real life. Such an effect would be more obvious when viewing the images on an HDR display.

In short, this short study was developed based on the findings of our two recent studies that the perceived color appearance of self-luminous highlights in a scene was less affected by the ambient illumination color, and was judged with a white point of D65. The hypothesis that the pixels of the self-luminous highlights in an image should be white balanced with a white point of D65 was supported by a survey results in which 73 observers compared the color appearance of self-luminous highlights that were white balanced using three white points (i.e., the white point in the scene that was estimated by the main camera, D50, and D65). Showing the images with self-luminous highlights white balanced using a D65 white point on an HDR display is likely to produce better perceptual experience.

AUTHOR CONTRIBUTIONS

Conceptualization: Yuyang Liu, Shuwei Yue and Minchen Wei. Data collection and data analysis: Yuyang Liu. Manuscript preparation and revision: Minchen Wei.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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