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Perception of White for Stimuli with Luminance Beyond the Diffuse White

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Abstract. *The appearance of color stimuli with luminance levels beyond the diffuse white is gaining importance due to the popularity of high dynamic range (HDR) displays. Past work on color appearance of stimuli, color appearance models, and uniform color spaces mainly focused on the stimuli with luminance levels below the diffuse white, which were produced using surface color samples or conventional standard dynamic range (SDR) displays. In this study, we focused on the perception of white appearance for stimuli with luminance beyond the diffuse white. Human observers adjusted the color appearance of a stimulus to the whitest under different adapting conditions, including a dark condition and 12 illuminated conditions. It was found that the chromaticities for producing the white appearance under the dark condition were generally similar to those under the 6500 K conditions, regardless of the adapting luminance levels. In comparison to a recent study focusing on the stimuli with luminance below the diffuse white, the perception of white under the conditions with the adapting CCT levels of 2700, 3500, and 5000 K was significantly affected by the lightness level of the stimulus, which cannot be accurately characterized by CAM02-UCS. The results can be used for reproducing white appearance for highlights in HDR scenes. Further investigations on uniform color spaces for characterizing stimuli with luminance beyond the diffuse white are urgently needed for processing and displaying HDR images.* © *2021 Society for Imaging Science and Technology.*
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1. INTRODUCTION

Perception of white is an important concept in color science and has been investigated from various perspectives. For instance, Priest found the average chromaticities for producing a white light under dark surround conditions should be around 5100 K [1], while Helson and Michels found the chromaticities should be around 15000 K [2]. Smet and his colleagues investigated the chromaticities for producing white appearance in object [3] and illumination modes [4] under a dark-adapted condition, and derived models to predict the degree of neutrality. Rea and Freyssinier investigated the D_{uv} level for producing a white illumination in an empty cube at six different correlated color temperature (CCT) levels [5]. Wei and his colleagues carried out a series of experiments to understand how to characterize the whiteness appearance of surface colors, including those containing fluorescent whitening agents, under different lighting conditions [6–8]. Several recent studies also investigated the chromaticities for producing a white appearance on display under different adapting conditions [9–11]. Moreover, the perception of white also plays an important role in color appearance models (CAMs), chromatic adaptation transforms (CATs), and uniform color spaces (UCSs). For example, the chromaticities of a perfect diffuse white are always adopted as the white point in CAMs, CATs, and UCSs for processing and displaying images, the color of a diffuse white in an illuminated scene is commonly adopted as the white point for performing white balance, and the white point of a display is commonly used to perform characterizations and color manipulations of the images [12, 13]. Most of these studies mainly focused on the color stimuli with the luminance below the white point (i.e., the perfect diffuse white). Specifically, surface color samples typically have luminance below the perfect diffuse white in the same scene, and stimuli on displays typically have luminance below the luminance of the display white point, both of which were the sources for developing CAMs and UCSs [14–16].

In real scenes, highlights with luminance beyond the perfect diffuse white commonly exist. For instance, a neon sign or the filament of an incandescent lamp would have much higher luminance than the perfect diffuse white in a scene. Since the luminance ranges of real scenes are commonly larger than those of displays, tone mapping is needed for reproducing images from real scenes to displays, which is commonly performed in uniform color spaces. Therefore, it is critically important to understand how the human beings perceive color stimuli with luminance beyond the diffuse white and to investigate how the uniform color spaces characterize such color stimuli. This is especially important these days due to the popularity of high dynamic range (HDR) displays. In comparison to conventional standard dynamic range (SDR) displays, HDR displays not only have the conventional white point, known as the *diffuse white level*, but also a *peak luminance level*, so that stimuli with luminance beyond the perfect diffuse white can also be rendered on HDR displays [17].

With the above in mind, this study was intenionally designed to understand how human beings perceive and define white appearance for stimuli with luminance levels beyond the diffuse white. By comparing with a recent study on stimuli with luminance below the diffuse white [18], we

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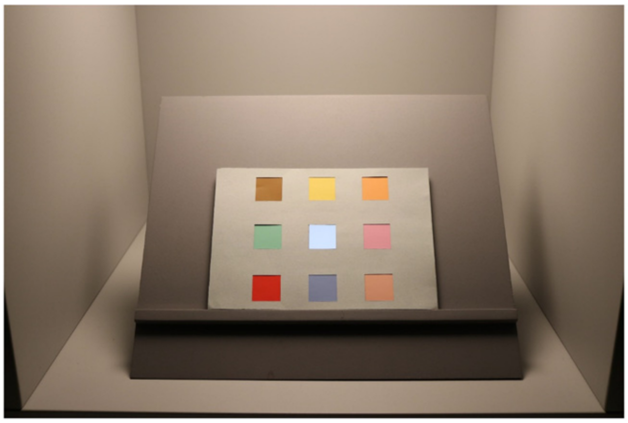

Figure 1. Photograph of the experiment setup. The center color patch was produced by an iPad display, which was placed on the viewing table and covered by a Munsell sheet. The eight surrounding patches were NCS color samples, which were used to help the observers for chromatic adaptation.

Table I. Colorimetric and photometric characteristics of the adapting conditions.

Nominal L_w (cd/m^2)	CCT (K)	D_{uv}	(u'_{10}, v'_{10})	$L_{w,10}$ (cd/m^2)	CRI R_a
Dark	—		—	—	—
10	2679	0.000	(0.268,0.528)	12.13	94.8
	3411	-0.001	(0.244,0.511)	13.45	92.1
	5011	0.000	(0.213,0.486)	13.31	88.4
	6547	+0.003	(0.200,0.469)	11.18	94.4
50	2680	-0.005	(0.269,0.52)	54.18	93.4
	3508	-0.006	(0.243,0.503)	55.51	92.0
	4986	-0.006	(0.217,0.479)	55.93	87.7
	6518	-0.005	(0.206,0.463)	56.56	93.8
115	2704	-0.001	(0.267,0.525)	121.74	97.2
	3516	+0.003	(0.237,0.516)	123.86	97.2
	4997	+0.008	(0.208,0.494)	127.02	97.8
	6515	+0.005	(0.196,0.471)	128.25	97.7

can understand whether these two types of stimuli need to be characterized in different ways.

2. METHODS

The experiment protocols and procedures were approved by the Hong Kong Polytechnic University Institutional Review Board. The experiment was carried out in the Color and Illumination Laboratory.

2.1 *Apparatus*

The experiment was carried out using a viewing booth, with dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height) and the interiors were painted using Munsell N7 spectrally neutral paint. Above the viewing booth, a 14 channel spectrally tunable LED device was placed to produce a uniform illumination to the booth floor. A 45° viewing table painted using Munsell N7 spectrally neutral paint was placed at the center of the viewing booth, with an iPad Air 2 placed on the viewing table. A Munsell N7 sheet, with a 3 cm ×3 cm opening cut at the center, was used to cover the iPad display, so that a 3 cm × 3 cm stimulus was produced by the display. Eight Natural Color System (NCS) color samples (i.e., S0530-Y90R, S1040-R80B, S0580-Y90R, S0550-Y50R, S0550-Y10R, S4040-Y30R, S1030-G, S0540-R30B), with a size of 3 cm × 3 cm, were carefully selected to cover different hues and placed around the opening, which was used for creating a chromatic background to help chromatic adaptation. A chin rest was mounted just outside the front opening of the viewing booth, allowing the stimulus produced by the display to occupy a field of view (FOV) around 4° for all the observers during the experiment. Figure 1 shows the photograph of the setup.

2.2 *Experimental Design*

The adapting luminance, as characterized using L_w (i.e., the luminance of a perfect white diffuser), adapting CCT, and stimulus luminance (L) were the three independent variables, which were organized as a 3 × 4 × 2 factorial design, comprising three levels of L_w (i.e., 10, 50 and 115 cd/m^2), four levels of CCT (i.e., 2700, 3500, 5000, and 6500 K), and two levels of L (i.e., 200 and 350 cd/m^2). In addition, a dark condition was also included, with a total of 13 adapting conditions. It can be observed that the L values were designed to be greater than L_w, the luminance of a perfect diffuse white, with the ratio of L to L_w between 35 and 1.74. Under the 12 non-dark adapting conditions, the average Y values of the eight NCS samples were 61.5, 41.4, 24.1, 52.2, 21.3, 55.3, and 53.9, with the standard deviation of 2.7, 1.4, 3.5, 3.7, 1.3, 1.4, and 2.0, respectively. These NCS samples covered a range of lightness levels, which did not significantly change with the adapting conditions.

The adapting conditions were calibrated using a JETI Specbos 1411UV spectroradiometer and a Labsphere reflectance standard placed at the center of the viewing table. The intensities of the LED channels were carefully adjusted, so that the CIE General Color Rendering Index CRI R_a values were as high as possible. Table I summarizes the colorimetric and photometric characteristics of the adapting conditions. The iPad display was calibrated using a gain-offset-gamma (GOG) model [13] using the CIE 1964 10° Color Matching Functions (CMFs). A customized program was then developed to adjust the chromaticities of the display along the two axes u'_{10} and v'_{10} in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram, with an interval of 0.001 unit, using the four arrow keys on a keyboard (i.e., right: $+u'_{10}$; left: $-u'_{10}$; up: $+v'_{10}$; down: $-v'_{10}$) while holding the luminance constant. The adjustments towards these four directions corresponded to red, green, yellow, and blue, which was found easy to understand to human observers [18].

The dependent variable was the chromaticities adjusted by the observers to make the stimulus produced by the iPad display appear the whitest.

2.3 *Experimental Procedure*

Upon arrival, the experimenter explained the general task and procedure of the experiment, and the observer completed the general information survey and the Ishihara Color Vision Test. The observer was then escorted to the viewing booth, with his or her chin fixed on the chin rest. The general illumination in the laboratory was switched off. The observer was asked to look into the viewing booth for two minutes, which was believed to allow a relative stable degree of chromatic adaptation [19]. The experimenter placed the iPad and the covering sheet on the viewing table, with the display chromaticities randomly adjusted to make the stimulus appear obviously chromatic. The observer then used the four arrow keys to adjust the color appearance of the stimulus to the whitest to him or her without any time limitation. After he or she was satisfied with the adjusted color appearance, the experimenter helped to verify the decision by adjusting one step along each of the four directions. If the observer confirmed the stimulus adjusted by himself or herself, the experimenter recorded the RGB values. The same procedure was repeated for all the conditions, with the conditions with a lower adapting luminance conducted first and the two stimulus luminance levels randomized. For characterizing the intra-observer variations, the adjustments were repeated under four conditions (i.e., L of 200 and 350 cd/m^2 under L_w of 10 and 50 cd/m^2 with a CCT of 6500 K).

In total, 14 observers (12 males and 2 females) between 22 and 28 years of age (mean = 24.3, std. dev. = 2.2) participated in the experiment. All the observers had normal color vision, as tested using the Ishihara Color Vision Test.

3. RESULTS AND DISCUSSION

In order to accurately characterize the stimuli adjusted by the observers, the recorded RGB values were used to reproduce the stimuli under the corresponding adapting conditions, with the spectroradiometer used to measure the spectral power distributions (SPDs) from the observer's eye position. Since the color of the stimulus was adjusted by changing the RGB values but holding the luminance constant, these RGB values were predicted based on the GOG model. Therefore, the actual luminance and chromaticities would not be identical as the predicted ones. The differences between the measured and target stimulus luminance levels ranged from −4.09% to +0.70%, with an average of −1.98%, suggesting the reliability of the control program. The chromaticities of all the adjusted stimuli were far from the display gamut boundary. Thus, all the analyses were based on the measured SPDs.

3.1 *Intra- and Inter-observer Variations*

Both the intra- and inter-observer variations were characterized using the mean color difference from the mean (MCDM) in the CIE 1976 $u'_{10}v'_{10}$ units. The intra-observer variations were characterized based on the average chromaticity difference between the chromaticities that were repeatedly adjusted by each observer under the four conditions. The MCDM values were between 0.001 and 0.005 units with an average of 0.003 units. The inter-observer variations were characterized based on the average chromaticity difference between the average chromaticities that were adjusted by all the observers (i.e., an average observer) and the chromaticities adjusted by each observer under the same condition. The MCDM values were between 0.008 and 0.014 units, with an average of 0.010 units. The intra- and inter-observer variations were generally comparable to several recent studies using similar experiment methods [18, 20–23].

3.2 *Average chromaticities in the CIE 1976 $u'_{10}v'_{10}$ Chromaticity Diagram and in CAM02-UCS*

The chromaticities adjusted by the observers, together with the one-standard-deviation ellipses, under each adapting condition are shown in Figure 2, with the average adjusted chromaticities shown in Figure 3. Figure 4 shows the chromaticity difference $\Delta u'_{10}v'_{10}$ between the adapting chromaticities and the average chromaticities adjusted under the corresponding adapting condition. Specifically, the adapting luminance had little effect when the adapting CCT was 5000 or 6500 K. In contrast, when the adapting CCT was 2700 or 3500 K, the adapting luminance played a significant role, with the adjusted chromaticities being closer to the adapting chromaticities under a higher adapting luminance. In addition, when the adapting luminance was 50 or 115 cd/m^2, the stimuli with the lower luminance level (i.e., 200 cd/m^2) were always adjusted closer to the adapting chromaticities.

The average chromaticities of the adjusted stimuli were also calculated in CAM02-UCS, which is more uniform than the CIE 1976 $u'v'$ chromaticity diagram and also embeds a chromatic adaptation transform (i.e., CAT02). The degree of chromatic adaptation factor D was always set to 1, assuming a complete chromatic adaptation. Figure 5 shows the average chromaticities of the adjusted stimuli in the $a'_{10} - b'_{10}$ plane of CAM02-UCS. It can be observed that the adjusted chromaticities were generally stable when the adapting CCT was 6500 K, regardless of the adapting luminance and stimulus luminance levels. When the adapting CCT was different from 6500 K, larger differences can be found under lower CCT and lower adapting luminance.

3.3 *Perception of White for Related and Unrelated Color Stimuli*

The stimuli in this study included both related and unrelated colors. Related colors refer to the stimuli that are viewed in relation to other color stimuli; while unrelated colors refer to those that are viewed completely in isolation [12]. In this experiment, the stimuli viewed under the dark condition were the unrelated colors, since it was the only stimulus viewed by the observers. In contrast, the stimuli viewed under other conditions were the related colors, as the stimuli were viewed with others. As shown in Figs. 2 and 3, the adjusted chromaticities under the 6500 K conditions at the three luminance levels were generally similar to those adjusted under the dark condition. Interestingly, the

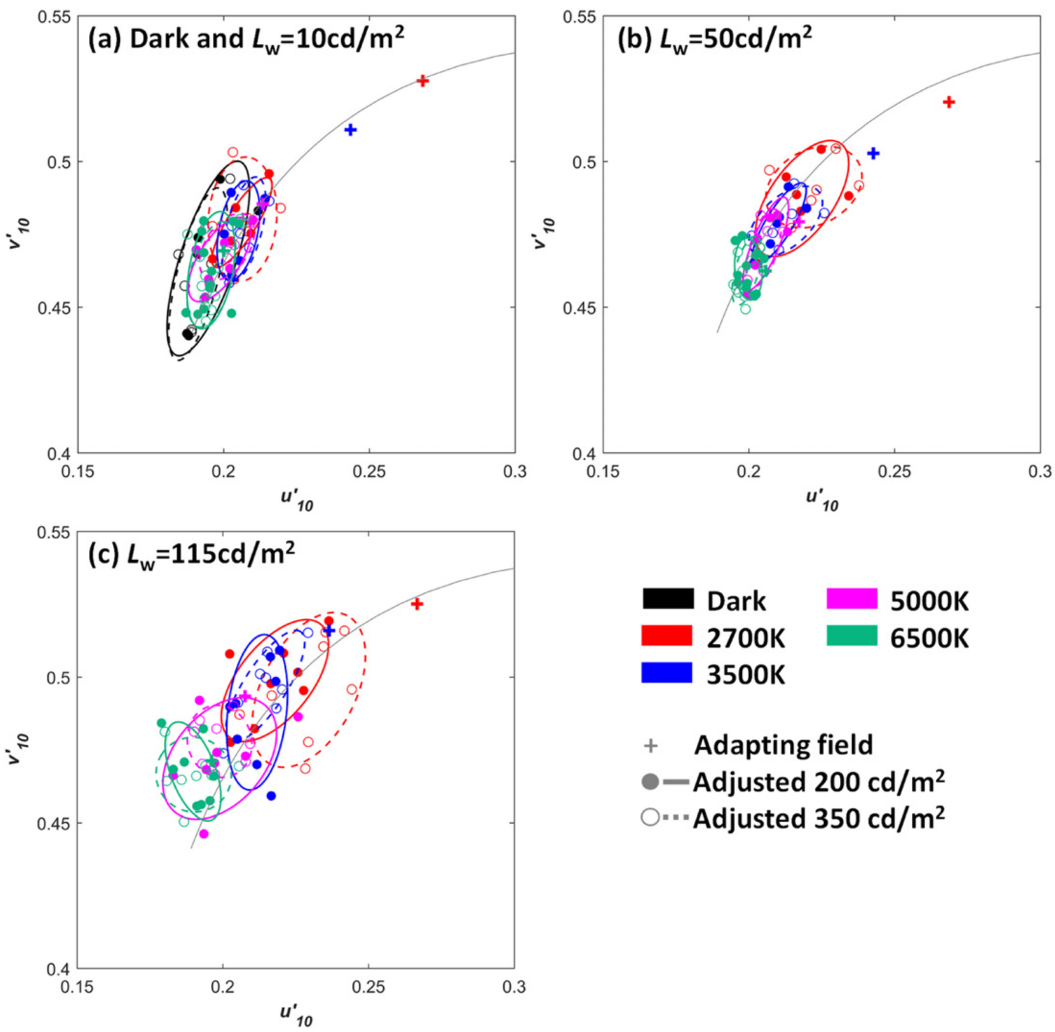

Figure 2. Chromaticities, together with the one-standard-deviation ellipses, of the stimuli adjusted by the observers for producing the whitest appearance under the different adapting conditions in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram.

similarity between the dark and the 6500 K condition was also found in a recent study, in which the observers judged the four unique hues (i.e., red, green, blue, and yellow) under the dark and 6500 K condition [24]. This suggested that the definition and perception of hues were generally the same for unrelated colors and related colors under the 6500 K conditions. For related colors, the definition and perception of hues were significantly affected by the adapted CCT, with a smaller difference among the high CCT levels.

3.4 *Perception of White for Related Colors at Different Lightness Levels*

Since the human perception is related to both the stimulus luminance (i.e., L) and the adapting luminance (i.e., L_w), we used the lightness dimension in CAM02-UCS (i.e., J') to better illustrate the perception of different stimuli. It is worthwhile to mention that lightness is defined as "the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white" in CIE S 017:2020 ILV [25]. It is typically used for characterizing colors with luminance below the diffuse white (i.e., J' below 100). Here, we simply extended this concept to all the stimuli under the non-dark conditions, resulting in the stimuli to have J' values beyond 100. Figure 6 shows the chromaticity distance $\Delta a'_{10}b'_{10}$ between the adjusted stimulus and the origin of the a'_{10}–b'_{10} plane in CAM02-UCS—the chromaticities of a perfect diffuse white under the same adapting condition (i.e., the adopted white point). Since all the stimulus luminance levels were purposely designed to be greater than the adapting condition, the J'_{10} values were all greater than 100. It can be observed that the chromaticity distances were generally the same when the adapting CCT was 6500 K. For the other three adapting CCT levels, a higher stimulus lightness introduced a larger chromaticity distance. This, together with Fig. 2, suggested that the definition and perception of white became more similar, in terms of chromaticities (u'_{10}, v'_{10}) in the CIE 1976 $u'v'$ chromaticity diagram, with an increase of stimulus lightness. In other words, the effect of the adapting condition became smaller when the luminance ratio between the stimulus and adapting

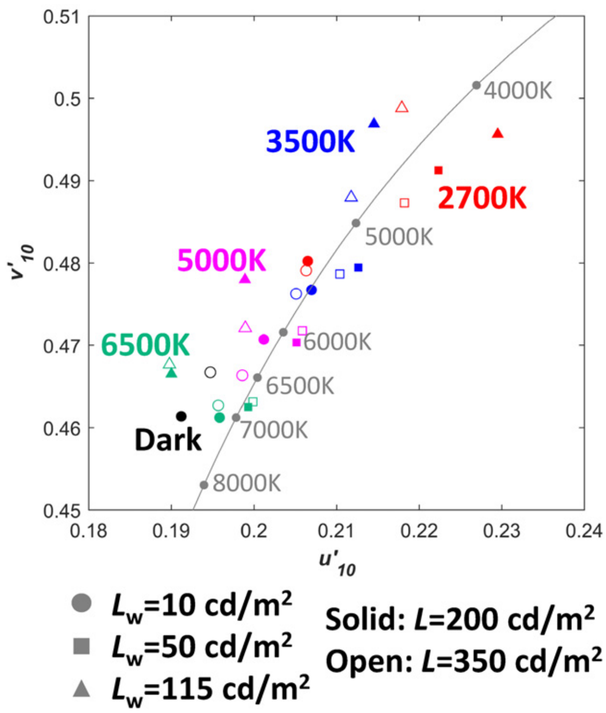

Figure 3. Average chromaticities of the stimuli adjusted by the observers for producing the whitest appearance under the different adapting conditions in the CIE 1976 $u'_{10}v'_{10}$ chromaticity diagram.

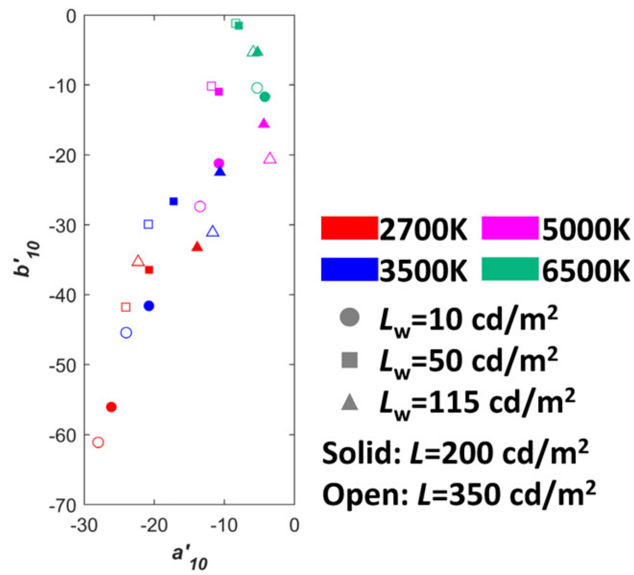

Figure 5. Average chromaticities of the stimuli adjusted by the observers for producing the whitest appearance under the different adapting conditions in the a'_{10}-b'_{10} plane of CAM02-UCS (note: the origin is the chromaticities of the adapting field).

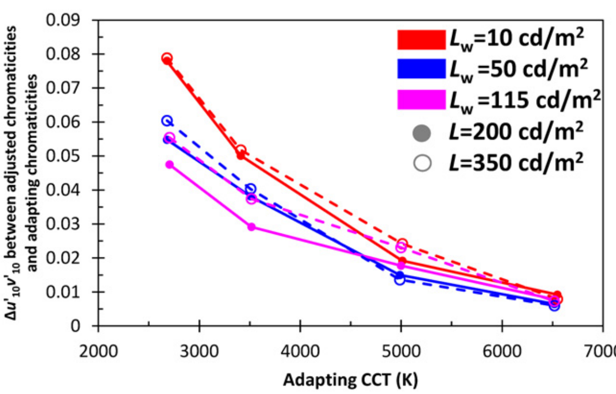

Figure 4. Chromaticity distance $\Delta u'_{10}v'_{10}$ between the average chromaticities of the stimuli adjusted by the observers and the chromaticities of the adapting field.

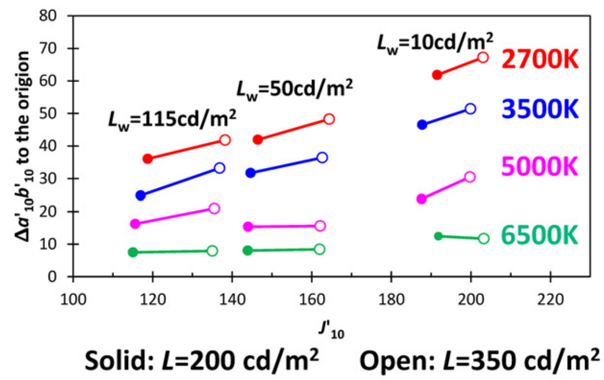

Figure 6. Chromaticity distance $\Delta a'_{10}b'_{10}$ between the average chromaticities of the stimuli adjusted by the observers and the origin (i.e., the chromaticities of the adapting field).

condition was larger. When the ratio is infinity (i.e., a dark condition), the stimulus becomes unrelated color.

To more comprehensively investigate the effect of lightness, we combined the data with those collected in our recent study [18], with a total of six adapting luminance and four adapting CCT levels, as shown in Figure 7. Consistent differences among the four adapting CCT levels can be observed, with larger distances under lower CCT levels. When the adapting CCT was 6500 K, the chromaticity distances were consistently small, indicating the effectiveness of CAM02-UCS in predicting the perception of white under the 6500 K adapting conditions. For the other three adapting CCT levels, the chromaticity distances were smaller when the lightness levels were below 100. This suggests that CAM02-UCS has better performance for characterizing the stimuli with lightness below 100, but has much worse performance for characterizing those with lightness beyond 100.

It needs to be pointed out the distances among the different lightness levels could also be due to the degree of chromatic adaptation caused by the adapting luminance levels [12]. The degree of chromatic adaptation factor D in CAT02, however, ranged from 0.831 to 0.997 under these six adapting luminance levels. Thus, we consider the lightness level of the stimulus, instead of the degree of chromatic adaptation, as the main reason to affect the perception and

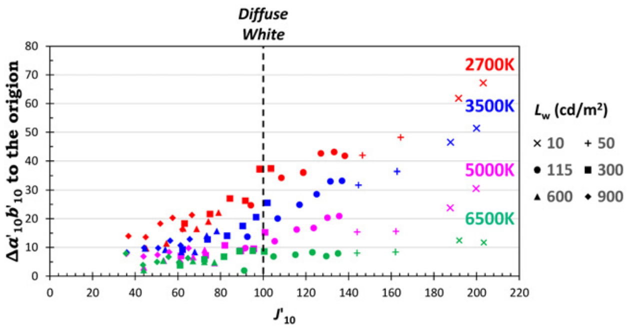

Figure 7. Chromaticity distance $\Delta a'_{10}b'_{10}$ between the average chromaticities of the stimuli adjusted by the observers and the origin (i.e., the chromaticities of the adapting field) (note: the data collected from a recent study was included).

definition of white and the performance of CAM02-UCS. It will be worthwhile to further verify this by fixing the lightness level under different adapting luminance levels.

The results suggest that the human beings generally interpret the color appearance of unrelated colors or those of related colors under 6500K conditions as the color of the stimuli. When the luminance of the adapting condition increases, the human beings start to interpret that the perceived color appearance is affected by the illumination, with a greater effect under a higher luminance condition.

3.5 *Uniform Color Space and HDR*

Several studies have clearly suggested the necessity to revise the chromatic adaptation transform under lower adapting CCT levels to improve the performance of uniform color spaces. The results and analyses presented above further suggested that CAM02-UCS needs to be revised to better characterize the color appearance of stimuli at different lightness levels below 100 under the 2700 and 3500 K. In addition, greater efforts need to be made on better characterizing the color appearance of stimuli at different lightness levels beyond 100. This is especially critical for processing and displaying highlights in HDR images (e.g., tone mapping), especially when the white point is different from 6500 K. For example, a real scene contains a highlight which has a lightness of 200 and is perceived as white. In order to show it on an HDR display with the peak lightness of 140, a uniform color space, instead of CAM02-UCS, is needed to perform tone mapping to maintain its white appearance.

4. CONCLUSION

Uniform color spaces are important for characterizing and processing color stimuli under different conditions. Most uniform color spaces are designed for stimuli with luminance below the diffuse white, with the stimuli appearing reflective and viewed in the surface mode. In this study, the human observers were asked to adjust the color appearance of a stimulus with luminance beyond the diffuse white. The experiment included two stimuli luminance (200 and 350 cd/m^2) and 13 adapting conditions, including 12 comprising 3 adapting luminance levels (i.e., 10, 50 and 115 cd/m^2) and 4 adapting CCT levels (i.e., 2700, 3500, 5000, and 6500 K) and a dark condition. It was found that the chromaticities of the adjusted stimuli under the dark condition were generally similar to those under the 6500 K conditions, though the former were unrelated colors and the latter were related colors. In addition, when the adapting CCT was 6500 K, the adjusted chromaticities were generally stable and around the adapting chromaticities regardless of the adapting luminance. In contrast, larger differences between the adjusted chromaticities and the adapting chromaticities were observed under lower adapting CCT and adapting luminance. When comparing to the data collected in our previous study, it was found that CAM02-UCS has a good performance when characterizing the white appearance for the stimuli with luminance below the diffuse white (i.e., lightness below 100), except the overestimation of the degree of chromatic adaptation under the low adapting CCT levels. However, it has a much poor performance when characterizing the white appearance for the stimuli with luminance beyond the diffuse white (i.e., lightness beyond 100). This needs to be carefully investigated to develop better uniform color spaces, especially when these spaces are used for processing and displaying HDR images, so that tone mapping along the lightness axis only changes the lightness without affecting the hue and chroma, and color adjustment in the a'–b' plane does not affect the lightness appearance.

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