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RESEARCH ARTICLE

Unique hue judgments using saturated and desaturated Munsell samples under different light sources

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Abstract

Past studies investigating the unique hues only used samples with a relatively high saturation levels under standard illuminants. In this study, 10 observers selected the four samples with unique hues from 40 V6C8 (Value 6 Chroma 8) and 40 V8C4 (Value 8 Chroma 4) Munsell samples under six light sources, comprising three levels of D_{uv} (i.e., 0, −0.02, and −0.04) and two levels of correlated color temperature (i.e., 2700 and 3500 K). Significant differences were found between the two chroma levels for unique blue and yellow, with the hue angles of unique yellow and blue judged using the desaturated samples being significantly different from those defined in CIECAM02. The iso-lines of unique yellow, blue, and green did not always go through the origin of the a^*-b^* or a'-b' planes in CIELAB and CAM02-UCS. Thus, the problems of CIECAM02, CIELAB, and CAM02-UCS identified in this study need further investigations.

KEYWORDS

color appearance model, uniform color space, unique hues

1 | INTRODUCTION

Unique hue, an important concept in color science, has a long history. Early in 1865, Aubert and Mach used "Principle colors" and "basic color sensations" to describe the concept of four unique hues—red, green, blue, and yellow. These four hues were later divided into two pairs—red versus green and blue versus yellow, which represented the two chromatic channels in the opponent-process mechanism in the human visual system. Since no color can simultaneously contain the two hues in a pair (e.g., no color can contain red and green at the same time), a unique hue is defined as the hue of a color that does not contain any of the neighboring two major hues (e.g., a color with a unique red is neither yellowish or bluish).

The concept of unique hue was implemented in the Natural Color System (NCS), which uses hue as one of the three variables to specify a color and arranges the four unique hues with an interval of 90° in the hue circle. The concept of unique hue is also an important consideration in developing color appearance models and uniform color spaces. For instance, the unique hues are used to define the *a* and *b* axes in CIECAM02, with the hue angle *h* of the four unique hues being defined as 20.14° (unique red), 90° (unique yellow), 164.25° (unique green), and 237.53° (unique blue).[1] In CIELAB or CAM02-UCS, colors with chromaticities lying on a line (i.e., iso-hue line) through the origin of the a^*-b^* or a'-b' planes are judged to have an identical hue irrespective of lightness and chroma.[1,2] Both the hue angles in the color appearance models and the iso-hue lines in the uniform color spaces play important roles in various color-related applications, such as light source color rendition,[3,4] cross media color reproduction[5], and gamut mapping.[6–8]

Great efforts have been made to determine the unique hues through psychophysical experiments, in which observers selected the samples with the four unique hues from a series of color samples under standard illuminants. For example, the observers were asked to select from 40 V6C8 (Value 6 and Chroma 8) Munsell samples under a D65 simulator in Hinks et al.[9] and Shamey et al.[10] Kuehni[11] asked the observers to

TABLE 1 Colorimetric characteristics of the light sources and the white tile under each light source

	Light source						White tile				
	CCT	D_{uv}	CRI-R_a	X	Y	Z	CCT	D_{uv}	X	Y	Z
1	2674	0	97.8	368.9	328.4	100.8	2693	0.001	328.7	293.9	89.8
2	2692	−0.019	92.3	392.0	324.5	195.4	2711	−0.019	348.4	289.9	172.6
3	2673	−0.04	90.8	427.3	325.7	304.7	2703	−0.039	378.9	290.9	268.7
4	3459	+0.001	94.9	344.5	333.2	164.4	3469	+0.002	305.7	296.6	144.7
5	3519	−0.019	92.0	377.3	332.9	267.3	3524	−0.018	334.2	296.5	233.8
6	3436	−0.039	89.6	416.0	334.2	365.2	3447	−0.037	368.0	297.8	318.7

select from 32 Munsell samples with the highest chroma level under a D75 simulator. Shamey et al.[12] asked the observers to select from 40 highly chromatic NCS samples under four illuminants (i.e., D65, A, F2, and F11). It can be observed that the illuminants used in these studies generally had chromaticities on or around the blackbody locus. Although illumination was suspected to have an impact,[13] little effort has been made to investigate the effect of illumination chromaticities on unique hue judgments. In addition, these studies only used samples with a relatively high chroma level and applied the results to other lightness and chroma levels. A recent study using a display to produce color stimuli, however, found that chroma level affected the selections of unique hues.[2]

With the above in mind, this study was purposely designed to (1) evaluate the effect of the illumination chromaticities, in terms of correlated color temperature (CCT) and D_{uv} (distance from the chromaticities to Planckian locus in the CIE 1960 UCS),[14] on unique hue judgments, (2) evaluate the effect of sample chroma level on unique hue judgments, and (3) evaluate the performance of CIECAM02,

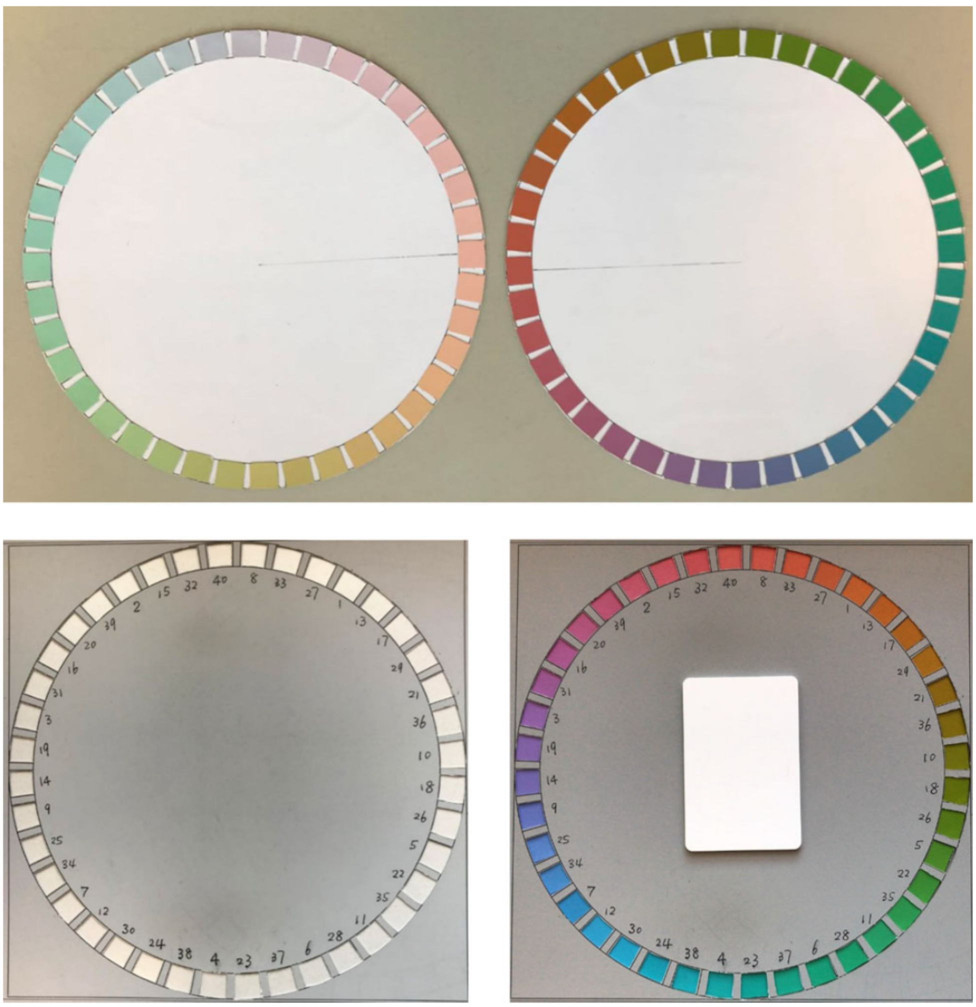

FIGURE 1 Photographs of the color disks used in the experiment. (A) Two circular color disks, with the left one containing 40 V6C8 Munsell samples and the right one containing 40 V8C4 Munsell samples; (B) a Munsell N7 paper containing 40 holes being labeled in a random order; (C) a color disk that was randomly rotated and placed below the Munsell N7 paper, with a white tile being placed above the Munsell paper for chromatic adaptation, so that each sample had a corresponding number for recording observers' unique hue selections

CIELAB, and CAM02-UCS in predicting unique hues, especially when a chromatic adaptation transform is included in CIECAM02 and CAM02-UCS.

2 | METHODS

2.1 | Apparatus, illuminants, and color samples

A viewing booth, with dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height) and interiors being painted using Munsell N7 spectrally neutral paint with the reflectance of 43% ($\rho \approx 43\%$), was used in this study. The floor of the booth was uniformly illuminated by a 14-channel spectrally tunable LED lighting device, with the peak wavelengths of the 14 channels covering from 350 to 700 nm. The intensity of each channel can be individually adjusted to produce different spectral power distributions (SPDs). A chin-rest was mounted just outside the booth to form a 0°:45° viewing geometry for all the observers to observe the color samples that were placed in the booth. The top front of the viewing booth was partially covered, so that the observers cannot see the LED device during the experiment.

Six light sources, comprising three levels of D_{uv} (i.e., 0, −0.02, and −0.04) and two levels of CCT (i.e., 2700 and 3500 K), were created to produce a horizontal illuminance of 1000 lx at the center of the booth floor. All the sources were designed to have a high CIE general color rendering index (CRI-R_a).[15] The colorimetric characteristics of the sources, which were derived from the SPDs measured using a calibrated JETI specbos 1211 UV spectroradiometer and a standard reflectance, are summarized in Table 1.

Two circular color disks, with a diameter of 20 cm, were made. One disk contained 40 V6C8 (Value 6 Chroma 8) Munsell samples and the other contained 40 V8C4 (Value 8 Chroma 4) Munsell samples. On each disk, the 40 samples of identical size (1 cm × 1 cm, subtended around 2° to the observers during the experiment) were pasted along the perimeter according to hue, as shown in Figure 1A. On top of the disk, a Munsell N7 paper containing 40 holes (1 cm × 1 cm) was used, with the holes being randomly numbered from 1 to 40, as shown in Figure 1B. During the experiment, a diffuse white tile (6 cm × 8 cm) was placed on top of the Munsell N7 paper for chromatic adaptation, as shown in Figure 1C. As summarized in Table 1, there were very small differences in colorimetric characteristics between each light source and the white tile under the light source.

2.2 | Observers

As Since no past studies have investigated whether light sources with a same CCT but different chromaticities would significantly affect unique hue judgments, a small panel of 10 Asian observers (eight males and two females) between 20 and 23 years of age (mean = 21.0, SD = 1.0) with normal color vision, as tested using the Ishihara Color Vision Test, participated in this experiment. In addition, we purposely limited the age and cultural background of the observers, because they may affect the unique hue selections.

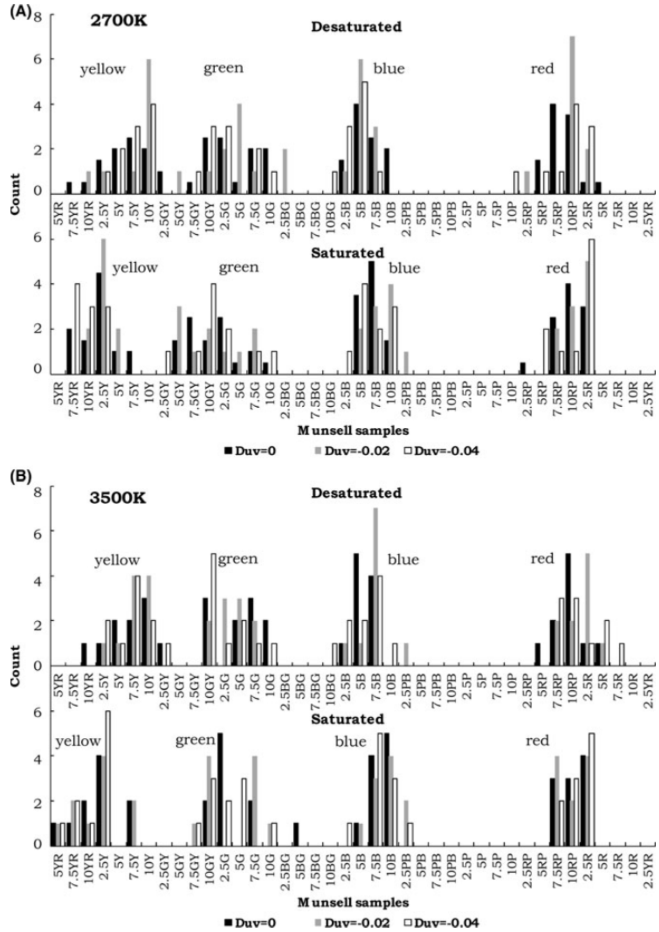

FIGURE 2 Frequencies of the samples being selected to have a unique hue under each light source (a) 2700 K sources; (B) 3500 K sources

2.3 | Experimental procedures

Under each light source, the white tile was first placed in the booth. The observer was asked to look at the white tile

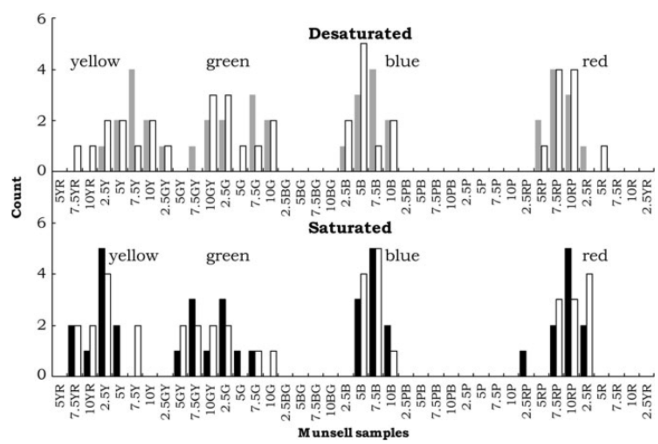

FIGURE 3 Frequencies of the samples being selected under the 2700 K light source with a D_{uv} of 0, which was performed twice for evaluating the intra-observer variations

TABLE 2 Munsell hue range of the samples that were selected by the observers to have a unique hue under the light sources

	Light source		Range of selection (steps)			
	CCT	D_{uv}	Red	Green	Blue	Yellow
(a) Saturated samples (i.e., V6C8)						
1	2700	0	2.5RP-2.5R (four steps)	5GY-10G (six steps)	7.5YR-7.5Y (four steps)	5B-10B (two steps)
2	2700	−0.02	7.5RP-2.5R (two steps)	5GY-7.5G (five steps)	10YR-5Y (two steps)	5B-2.5 PB (three steps)
3	2700	−0.04	5RP-2.5R (three steps)	2.5GY-10G (seven steps)	5YR-2.5Y (two steps)	2.5B-10B (three steps)
4	3500	0	7.5RP-2.5R (two steps)	10GY-5BG (six steps)	7.5YR-2.5Y (five steps)	5B-10B (two steps)
5	3500	−0.02	7.5RP-2.5R (two steps)	7.5GY-10G (five steps)	5YR-7.5Y (five steps)	5B-2.5 PB (three steps)
6	3500	−0.04	7.5RP-2.5R (two steps)	7.5GY-10G (five steps)	5YR-2.5Y (three steps)	2.5B-2.5 PB (four steps)
(b) Desaturated samples (i.e., V8C4)						
1	2700	0	5RP-5R (three steps)	7.5GY-10G (five steps)	7.5YR-2.5GY (six steps)	2.5B-10B (three steps)
2	2700	−0.02	2.5RP-2.5R (four steps)	10GY-2.5BG (five steps)	10YR-5GY (six steps)	2.5B-7.5B (two steps)
3	2700	−0.04	10P-2.5R (five steps)	7.5GY-10G (five steps)	2.5Y-10Y (three steps)	7.5BG-7.5B (three steps)
4	3500	0	5RP-5R (four steps)	10GY-10G (four steps)	10YR-2.5GY (five steps)	2.5B-7.5B (two steps)
5	3500	−0.02	7.5RP-5R (three steps)	10GY-7.5G (three steps)	2.5Y-10Y (three steps)	2.5B-2.5 PB (four steps)
6	3500	−0.04	7.5RP-7.5R (four steps)	10GY-10G (four steps)	2.5Y-2.5GY (four steps)	10BG-10B (four steps)

TABLE 3 Parameters used in the CIECAM02 calculations

	Light source		CIECAM02 parameters					
	CCT	D_{uv}	X_W	Y_W	Z_W	L_A	Y_b	Surround
1	2674	0	112.3	100.0	30.7	141.2	43	Average
2	2692	−0.019	120.8	100.0	60.2	139.5	43	Average
3	2673	−0.04	131.2	100.0	93.6	140.1	43	Average
4	3459	+0.001	103.4	100.0	49.3	143.3	43	Average
5	3519	−0.019	113.3	100.0	80.3	143.1	43	Average
6	3436	−0.039	124.5	100.0	109.3	143.7	43	Average

for 2 minutes for chromatic adaptation. Then, a color disk, together with the Munsell N7 paper, was placed below the white tile, as shown in Figure 2C, with the color disk randomly rotated. The observer was asked to look at the 40 samples on the disk and tell the experimenter which four samples had the four unique hues. The definitions of the four unique hues were clearly explained to the observers before the experiment. Each observer judged the four unique hues on each color disk under each light source and repeated the judgments under one light source (i.e., light source 1) for evaluating the intra-observer variation. The sequence of the two color disks under each light source and the sequence of the seven light sources were randomized. The entire experiment took around 35 minutes for each observer.

3 | RESULTS AND DISCUSSIONS

3.1 | Selections of unique hues

The frequencies that each sample was selected to have a unique hue are summarized in Figure 2. The frequencies of the selections that were repeated under the same light source (i.e., 2700 K and D_{uv} of 0) are averaged in Figure 2, but are individually shown in Figure 3. The ranges of the unique hues, in terms of Munsell hues, are summarized in Table 2.

TABLE 4 Intra- and inter-observer variations in terms of CIECAM02 hue angles

		Saturated (V6C8)				Desaturated (V8C4)			
	Light source	Red	Green	Blue	Yellow	Red	Green	Blue	Yellow
Intra-	2700 K (0)	2.33	5.02	2.14	3.64	3.08	3.75	3.10	5.19
Inter-	2700 K (0)	4.95	15.51	3.24	7.26	5.68	13.00	5.82	5.60
	2700 K (−0.02)	4.46	16.97	7.13	3.19	5.02	7.83	3.83	7.71
	2700 K (−0.04)	7.43	12.54	8.05	6.65	10.35	11.01	5.72	5.19
	3500 K (0)	3.92	11.21	4.30	8.95	5.24	12.43	3.72	8.14
	3500 K (−0.02)	4.84	16.69	6.87	9.88	5.17	7.68	4.77	4.08
	3500 K (−0.04)	4.80	10.65	8.73	7.83	8.78	11.19	10.47	5.51
	Overall	5.07	13.93	6.39	7.29	6.71	10.52	5.72	6.04

TABLE 5 Average CIECAM02 hue angles of the unique hues judged by the observers under each light source

	Light source		Average hue angles in CIECAM02 (°)			
	CCT	D_{uv}	Red	Green	Blue	Yellow
(a) Saturated samples (i.e., V6C8)						
1	2700	0	16.53	154.65	228.41	80.95
2	2700	−0.02	19.75	150.11	237.81	90.15
3	2700	−0.04	17.16	151.60	234.81	85.96
4	3500	0	17.04	165.02	229.01	78.64
5	3500	−0.02	16.38	159.20	235.83	83.08
6	3500	−0.04	18.18	155.41	238.29	87.37
(b) Desaturated samples (i.e., V8C4)						
1	2700	0	17.56	167.95	222.55	96.06
2	2700	−0.02	22.19	169.54	222.57	105.82
3	2700	−0.04	20.20	157.65	215.45	110.76
4	3500	0	18.97	165.97	217.99	94.50
5	3500	−0.02	22.89	161.62	225.97	102.13
6	3500	−0.04	23.80	155.44	223.37	107.72

3.2 | Intra- and inter-observer variations

The intra-observer variation was evaluated by comparing the two repeated judgments that were made by each observer under the same light source. The inter-observer variation was evaluated by comparing the selections made by each observer and the average selections of all the observers (i.e., an average observer) under different light sources. In order to derive numerical values and to compare with the previous studies, the CIECAM02 hue angle (h) was calculated for each sample under each light source with the parameters being summarized in Table 3, which was used as the dependent variable.

Table 4 summarizes the intra- and inter-observer variations variations, as characterized using the hue angle, for each unique hue. It can be observed that the inter-observer variations were generally twice of the intra-observer variations irrespective the unique hues, which was similar to the findings of Xiao et al.[2,16] The inter-observer variations of unique red and blue were larger under the sources with a larger D_{uv} (i.e., chromaticities further away from the blackbody locus), especially under the 2700 K sources. No systematic changes were found to the other unique hues.

The largest inter-observer variation of the unique green selections was consistent to those found in Hinks et al.[17] and Shamey et al.[10] which also used the saturated samples (i.e., V6C8 Munsell samples) but under the light sources with higher CCT levels. In contrast, the inter-observer variations of the unique red and yellow selections were smaller.

3.3 | Unique hues in the CIECAM02 color appearance model

The average CIECAM02 hue angles of the unique hues for both the saturated and desaturated samples are summarized in Table 5, with the corresponding Munsell hues being summarized in Table 6. Tables 5 and 6, together with Figure 2, illustrate that D_{uv} had little impact on the unique hue selections and the Munsell hues being selected as the unique hues generally shifted either zero or one step under different D_{uv} levels. The four unique hues of the saturated samples, in terms of Munsell hues, under the 2700 and 3500 K sources were similar to those under the 6500 K sources in Hinks et al. and Shamey et al.[10,17]

Moreover, Figure 4 shows the average CIECAM02 hue angles and the 95% confidence intervals for the four unique hues judged by the observers under the six light sources, in comparison to those defined in CIECAM02. The hue angles defined in CIECAM02 were similar to the unique red and green judgments made by the observers, but not to the unique blue and yellow judgments. For unique blue, the observers' judgments generally shifted toward green, as shown in Figure 4C, while the observers' judgments on unique yellow varied with

TABLE 6 Average Munsell hues of the unique hues judged by the observers under each light source

	Light source		Unique hue samples			
	CCT	D_{uv}	Red	Green	Blue	Yellow
(a) Saturated samples (i.e., V6C8)						
1	2700	0	7.5RP/10RP	10GY/2.5G	7.5B/10B	10YR/2.5Y
2	2700	−0.02	10RP/2.5R	10GY/2.5G	7.5B/10B	2.5Y/5Y
3	2700	−0.04	10RP/2.5R	10GY/2.5G	5B/7.5B	7.5YR/10YR
4	3500	0	10RP/2.5R	2.5G/5G	7.5B/10B	10YR/2.5Y
5	3500	−0.02	10RP/2.5R	2.5G/5G	7.5B/10B	10YR/2.5Y
6	3500	−0.04	10RP/2.5R	10GY/2.5G	7.5B/10B	10YR/2.5Y
(b) Desaturated samples (i.e., V8C4)						
1	2700	0	7.5RP/10RP	2.5G/5G	5B/7.5B	5Y/7.5Y
2	2700	−0.02	7.5RP/10RP	5G/7.5G	5B/7.5B	7.5Y/10Y
3	2700	−0.04	10RP/2.5R	10GY/2.5G	10BG/2.5B	7.5Y/10Y
4	3500	0	7.5RP/10RP	2.5G/5G	5B/7.5B	5Y/7.5Y
5	3500	−0.02	10RP/2.5R	2.5G/5G	7.5B/10B	5Y/7.5Y
6	3500	−0.04	10RP/2.5R	10GY/2.5G	5B/7.5B	5Y/7.5Y

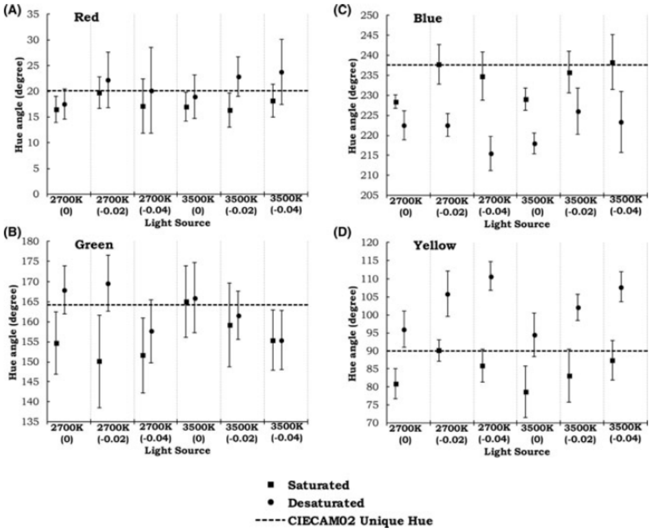

FIGURE 4 Average CIECAM02 hue angles, together with the 95% confidence intervals, of the unique hue judgments using the saturated and desaturated samples under each light source (A) unique red; (B) unique green; (C) unique blue; (D) unique yellow (note: the dotted lines are the hue angles of the four unique hues defined in CIECAM02)

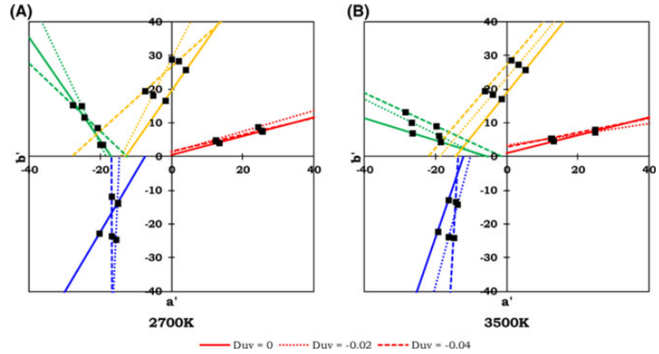

FIGURE 6 Average chromaticities of the samples that were selected by the observers to have the four unique hues and the fitted iso-hue lines under each light source in the a'-b' plane in the CAM02-UCS color space (A) 2700 K light sources; (B) 3500 K light sources

the saturation levels of the samples and the D_{uv} levels of the light sources. The unique yellow defined in CIECAM02 agreed with the observers' judgments using the saturated samples under the sources with a D_{uv} of 0 or those using the desaturated samples under the sources with a D_{uv} of −0.02 and −0.04. The discrepancies for unique yellow and blue between the observers' judgments and color appearance models corroborated the findings in Shamey et al.[12] that large differences existed for the unique yellow and blue judgments under the source simulating CIE Illuminant A. This may be due to the lower CCT level and merits further investigations.

3.4 | Unique hues in uniform color spaces

In a uniform color space, the perceived hue is expected to be independent of lightness and chroma. Thus, under each light source, the samples with a same hue designation should have the same hue angle for different lightness and chroma levels, with the chromaticities lying on a single line going through the origin. This should be applicable to different light sources, if the embedded chromatic adaptation transforms perform well.

The average chromaticities of the samples that were selected to have the unique hues under each light source, together with the fitted iso-hue lines, in CIELAB and CAM02-UCS are shown in Figures 5 and 6, respectively. It can be observed that the iso-hue lines of unique red generally passed through the origins, while those of unique yellow and blue did not pass through the origins, regardless of the light sources and uniform color spaces. For unique green, the lines passed through the origins under the 3500 K light sources, but not 2700 K light sources.

Furthermore, the unique red, green, and yellow judgments using the desaturated samples under the light sources with a D_{uv} of 0 were consistent to those defined in the CIELAB space.[18] The discrepancy for unique blue could be caused by the relatively low CCT levels used in the experiment. On the contrary, the unique hues that were judged using the saturated samples were much different from those defined in the CIELAB space.

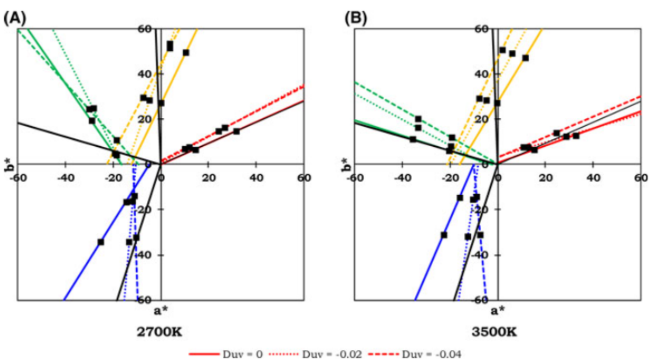

FIGURE 5 Average chromaticities of the samples that were selected by the observers to have the four unique hues and the fitted iso-hue lines under each light source in the a^*-b^* plane in the CIELAB color space (A) 2700 K light sources; (B) 3500 K light sources (note: the black lines represent the unique hue angles defined in the CIELAB color space)

4 | CONCLUSION

A psychophysical experiment was carried out to ask 10 observers to select the four unique hues from Munsell samples under six light sources with different CCT and D_{uv} levels. CCT was not found to significantly affect the observers' judgments, but D_{uv} was found to significantly affect the judgments on unique yellow. Furthermore, the observers' judgments on unique blue and yellow using the desaturated Munsell samples (i.e., V8C4) were found significantly different from those when using the saturated Munsell samples (i.e., V6C8), which revealed serious problems in CIECAM02, CIELAB, and CAM02-UCS and suggests potential problems in using these color appearance models and uniform color spaces for color reproduction. The hue angles of the unique yellow and blue judgments using the desaturated samples were significantly different from those defined in CIECAM02. The iso-lines of the unique yellow, blue, and green judgments did not always go through the origin of the a^*-b^* or a'-b' planes in CIELAB and CAM02-UCS. Thus, future work is needed to further investigate the unique hues at different lightness and chroma levels under different light sources to revise the color appearance models and uniform color spaces.

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