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Investigating unique hues at different chroma levels with a smaller hue angle step

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Unique hue plays a critical role in color appearance models and uniform colors spaces. Past studies investigating unique hues commonly used 40 Munsell samples with the same chroma and lightness levels to produce color stimuli, with a hue angle step of 9°. These 40 samples were always simultaneously presented to the observers. Both the larger hue angle step and the simultaneously presentation of the samples may help to reduce the variations. In this study, we reduced the hue angle step to 5° and each stimulus was individually presented to the observer, which resulted in larger inter- and intra-observer variations. The results suggested that the hue angles of the unique hues in both CIECAM02 and CIELAB should be revised, but both CIECAM02 and CIELAB had good hue uniformity at the hue angles of the four unique hues.

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1. INTRODUCTION

Unique hue is an important concept in color vision. The investigations on unique hue can trace their roots to the work by Aubert and Mach in 1865, in which the concept of unique hue was expressed as "principal colors" and "basic color sensations". There are two pairs of hues—red versus green and blue versus yellow. No color can simultaneously contain the two hues in a pair. For example, red and green can never simultaneously appear in a color. Therefore, unique hue is defined as a hue that cannot be further described by the use of hues other than its own. In other words, a color with a unique hue does not contain any of the two hues in the other pair. Great efforts have been made to understand the underlying mechanism or the variabilities of the unique hues, trying to correlate the unique hue with the wavelength of a stimulus or the responses of cones [1-9].

On the other hand, the concept of unique hue plays an important role in color specification and color management. The Swedish Natural Color System (NCS) implemented the concept, adopting hue as one of the three variables for color specification. Based on the results of a series of psychophysical experiments, the four unique hues were identified and were specified with an interval of 90° in the hue circle [10, 11]. Color appearance models (e.g., CIECAM02) and uniform color spaces (e.g., CIELAB) were developed to specify colors in three-dimensional spaces, with the hue of a color being specified through Cartesian representations. For example, the two axes in CIECAM02 were defined based on unique hues, with the hue angle h being specified using $\tan^{-1}(b/a)$; CIELAB specifies the hue angle h through $\tan^{-1}(b^*/a^*)$. Colors with a same hue angle, lying on a same line through the origin of the chromatic diagram of CIECAM02 or CIELAB, are considered to have a same hue. Colors with hue angles of 20.14°, 90°, 164.25°, and 237.53° in CIECAM02 are considered to have unique red, yellow, green, and blue respectively [12], while those with hue angles of 25°, 92°, 163°, and 253° in CIELAB are considered to have unique red, yellow, green, and blue [13].

These hue angles of unique hues, however, were derived in different color spaces or color appearance models based on the data used to develop NCS [12-14]. Studies have been carried out to investigate whether these defined hue angles in different color appearance models and uniform color spaces correlate to human perception under different viewing conditions. The reader is referred to two review articles, which were published in 2004 [5] and 2014 [15], and the references for the six new studies since 2014 [16-21]. In these studies, a series of color stimuli, with the same chroma and lightness levels but different hues, were presented to human observers and the observers were instructed to select the ones that appeared to have the four unique hues. These stimuli were commonly produced using either surface color samples (i.e., NCS or Munsell samples) or computer displays. Computer displays generally allowed more accurate controls of the stimuli, but the stimuli only had lower luminance levels. In contrast, surface color samples allowed higher luminance levels, but the stimuli cannot be accurately controlled. Xiao et al presented 10 color patches with a mid-grey gray background on a CRT, with the hue angles of the 10 color patches covering the possible range of the unique hues. It was found the experiment results did not corroborate the hue angles of the unique hues defined in CIECAM02, and CIECAM02 did not have a good performance in hue uniformity [22]. Later Xiao et al used NCS hue data to test the performance of CIECAM02 and found significant differences in terms of hue angles and hue uniformity. An effect of medium was also found, with the hue angles derived using surface color samples and displays being significantly different [18]. Huang et al investigated unique hue under six lighting conditions, comprising two levels of CCT—2700 and 3500 K—and three levels of D_{uv}—0, -0.02, and -0.04—using two sets of 40 Munsell samples, with one containing 40 saturated samples (i.e., Munsell Value 6 Chroma 8) and one containing 40 desaturated samples (i.e., Munsell Value 8 Chroma 4). It was found that the hue angles of the unique hues were significantly different between the two chroma levels, suggesting that CIECAM02 had a bad hue uniformity. In addition, the hue angles of unique blue and yellow in CIECAM02 were significantly different from the experiment results [19]. Shamey et al then performed a similar experiment under four lighting conditions using the two sets of 40 Munsell samples. The hue angles of the unique hues were significantly different from those defined in CIELAB [20].

It can be observed that in these studies, a series of color samples were always simultaneously presented to the observers, which may affect the selections of the samples with unique hues, as found in past studies. For example, Shamey et al used two experimental methods to investigate unique hues. In one experiment, the 40 Munsell samples were simultaneously presented to the observers and the observers were asked to select the ones with the unique hues; in the other experiment, these 40 samples were individually presented to the observers and the observers were asked to scale the hue of each sample [8]. Such a difference may also be due to the relatively large hue angle step between adjacent samples, with 40 samples resulting in a hue angle step of 9°.

In this study, we aimed to investigate the unique hues, in terms of hue angles and hue uniformity, with a smaller hue angle step of 5°. In order to produce such a small hue angle step, the stimuli were produced using a spectrally tunable LED device. However, the viewing condition was carefully designed based on two recent studies [23, 24] by carefully adjusting the photometric and colorimetric characteristics of the adapting field, so that the stimuli appeared to be produced using surface colors. In addition, instead of presenting a series of color stimuli simultaneously to the observers, the observers used a keyboard to switch among 72 stimuli, with one stimuli being presented at a time.

2. METHODS

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

A. Apparatus

The experiment was carried out using a viewing booth, with dimensions of 60 cm (width) × 60 cm (depth) × 60 cm (height). The interiors of the viewing booth were painted using Munsell N7 spectrally neutral paint. A spectrally tunable LED device (i.e., LEDCube) was placed above the viewing booth to provide a uniform illumination to the booth. A 4.5 cm × 4.5 cm opening was cut at the center of the back panel, with a diffuser being attached to the back of the wall. A spectrally tunable LED projector light was fixed on a tripod and placed behind the viewing booth, with the light uniformly illuminating the opening on the back wall, so that a uniform color stimulus can be perceived from the front side of the viewing booth, as shown in Fig 1. The projector light was controlled through a computer using a Digital Multiplex (DMX) controller, so that the intensities of the RGB channels can be individually adjusted with a resolution of 16-bit. A chin rest was mounted in front of the viewing booth, centered on the front opening, so that the stimulus subtended a 4.3° × 4.3° field of view (FOV). The top part of the front opening was partially covered using black felt to prevent the observer from seeing the LEDCube directly.

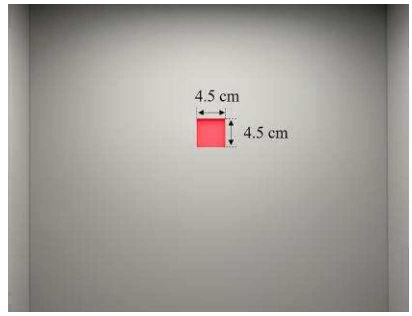

Fig. 1. Photograph of the experiment setup, captured at the observer's eye position. A spectrally tunable LED projector light was placed behind the wall to uniformly illuminate the opening, with the light being diffused by the diffuser, to produce the stimulus, shown as the red square in the figure.

B. Adapting conditions and stimuli

The intensities of the 11 channels in LEDCube were carefully adjusted to produce two adapting conditions with a CCT of 3000 and 6500 K and a luminance (i.e., L_w) of 500 cd/m^2. This luminance level was specifically selected, so that the degree of chromatic adaptation factor D in CIECAM02 (also in CAT02) was around 0.99. These two adapting conditions were calibrated at the opening on the back wall using a calibrated JETI Specbos 1211UV spectroradiometer and a reflectance standard being attached at the opening. The colorimetric characteristics of the adapting conditions were derived using the measured spectral power distribution (SPD), as summarized in Table 1. In addition, a dark adapting condition was included in the experiment, with a total of three adapting conditions.

Table 1. Colorimetric Characteristics of the Adapting Conditions

Nominal CCT (K)	Measured CCT (K)	D_{uv}	$L_{w,10}$ (cd/m^2)	CRI Ra
3000	2982	0	538.0	98.2
6500	6457	+0.004	548.5	98.8

Under each adapting condition, three groups of stimuli were designed to have a same lightness level but three chroma levels C (i.e., C = 10, 20, and 30) in CIECAM02 $a_{c,10}$-$b_{c,10}$, with J around 65. There were 72 stimuli, with a nominal hue angle step of 5°, for each chroma level. All the stimuli were calibrated using the spectroradiometer, considering the light produced by the projector light and the reflection of the adapting condition. The chromaticities of the stimuli calculated using the measured spectra, the corresponding adapting condition, and the CIE 1964 10° color matching functions (CMFs) are shown in Fig 2(a)-(c). For the dark condition, the 6500 K adapting condition was used in the calculation. Due to the limited gamut that can be achieved by the LED device, the chroma levels of some stimuli under the 3000 K adapting condition were a little different from the designed chroma of 30, as shown in Fig 2(b).

To better illustrate the distribution the stimuli under the adapting conditions. The chromaticities were also calculated in CIELAB, with the L^* values being around 75. Though the chroma levels were not always constant in CIELAB, the variations were generally small, as shown in Fig 2(d).

Though the stimuli were produced using a spectrally tunable LED device, such a setup, including the two non-dark adapting conditions and the lightness levels of the stimuli, made the stimuli appeared to be produced by surface colors based on two recent studies [23, 24]. Specifically speaking, whether a stimulus appears self-luminous or reflective does not completely depend on whether the stimulus is produced using a self-luminous source or a reflective surface colors. The stimulus would appear self-luminous when its luminance is lower than a perfect reflector at the same viewing condition (i.e., L_W), but it would appear as a reflective surface color when its luminance is higher than a perfect reflector at the same viewing condition. To the authors, the stimuli under the 3000 and 6500 K conditions did not appear as self-luminous.

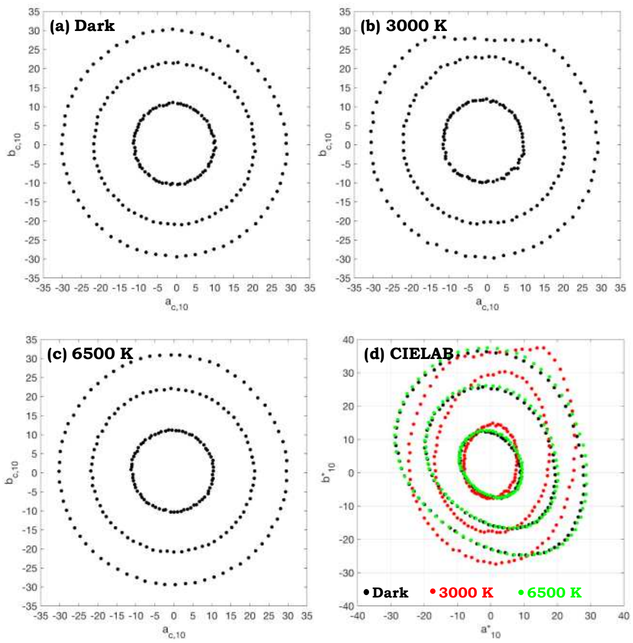

Fig. 2. Chromaticities of the stimuli in CIECAM02 and CIELAB. (a) – (c) are the chromaticities in the $a_{c,10}$-$b_{c,10}$ plane of CIECAM02, (d) shows the chromaticities in the a^*_{10}-b^*_{10} plane of CIELAB.

A customized program was developed to switch the stimuli at a same chroma level by calling the corresponding RGB signals that were stored in the computer. Two arrow keys ←→ on the keyboard were used to switch to the next stimulus by adjusting the hue angle of ±5°.

C. Observers

Twenty-nine observers (20 males and 9 females) between 20 and 31 years of age (mean = 22.9, std. dev. = 2.79) participated in the experiment. All the observers had a normal color vision, as tested using the 24 Plate Ishihara Color Vision Test.

D. Experimental procedures

Upon arrival, the observer completed a general information survey and the Ishihara Color Vision Test. Then the experimenter explained the general procedure of the experiment, and specifically explained the concept of 'unique hue' to the observer. The observer was then escorted to the viewing booth and the general illumination of the space was switched off. The observer was asked to fix his or her chin on the rest throughout the experiment.

The LEDCube was then switched to the first setting to produce an adapting condition to the viewing booth. The observer looked into the viewing booth for two minutes for chromatically adapt to the condition. A color stimulus with a preset hue angle (45° for unique red and yellow, and 225° for unique blue and green) was then appeared at the opening, and the observer used the two keys to switch the stimulus, either increasing or decreasing the hue angle of 5°, until the stimulus appeared to have a unique hue to him or her. The observer was allowed to spend as much time as he or she needed. After pressing the 'enter' key to confirm that the current stimulus had a unique hue, the observer was asked to estimate the confidence in the unique hue selection between 0 to 100%. 100% meant the selected stimulus had an identical hue as the unique hue in his or her memory, and 0% meant the selected stimulus had a completely different hue from the unique hue in his or her memory.

The order of the three chroma levels under each adapting condition was randomized; the order of the three adapting conditions was also randomized. The adjustments of unique green were repeated for evaluating the intra-observer variations. It took around 45 minutes for each observer to complete 45 selections—3 adapting conditions × 3 chroma levels × (4 unique hues + 1 repeated unique green).

3. RESULTS

A. Intra- and inter-observer variations

The intra-observer variations were characterized using the repeated selections on unique green made by each observer for each chroma level under each adapting condition, with a total of nine hue angle differences for each observer. The average hue angle difference of the nine pairs of repeated selections made by each observer ranged between 4.57° and 21.74°, with an average of 11.65°. The inter-observer variations were characterized using the hue angle differences between average hue angles of the stimuli selected by the observers (i.e., an average observer) and the hue angles of the stimuli selected by each observer. The average hue angle difference for each observer ranged between 7.80° and 20.02°, with an average of 12.99°. Table 2 summarizes the intra- and inter-observer variations for each unique hue at each chroma level under each adapting condition.

Table 2 Summary of intra- and inter-observer variations in terms of CIECAM02 hue angles. The hue angle difference between two adjacent stimuli was around 5°.

Adapting Condition	Chroma	Intra-(UG)	Inter-			
			UR	UG	UB	UY
Dark	10	22.73	15.02	24.65	18.53	15.76
	20	11.79	12.06	16.67	11.55	11.05
	30	7.88	16.34	13.74	10.73	9.24
3000 K	10	15.96	24.63	12.90	10.85	10.55
	20	9.78	12.88	13.17	10.24	9.82
	30	9.92	16.41	11.93	7.84	9.30
6500 K	10	14.1	15.27	14.21	12.53	11.17
	20	9.88	10.00	11.97	8.17	7.95
	30	9.02	8.96	11.40	8.55	7.73
Mean		12.35	14.62	14.51	11.00	10.28

It can be observed that higher chroma levels resulted in smaller intra- and inter-observer variations under all the three adapting conditions, which was similar to past studies [19, 20]. Both the intra- and inter-observer variations, especially to those at the chroma level of 10, were a little larger than those in the past work using Munsell samples [19, 20]. The comparable inter- and intra-observer variations, however, were not found in past studies [7, 8, 16, 17, 19, 20, 22].

B. Observers' confidence in unique hue selections

When selecting the stimuli with the unique hues, the observers were asked to indicate their confidence in the unique hues of the selected stimuli. Fig 3 shows the average confidence in the hue selections versus the inter-observer variation for the four unique hues at three chroma levels under three adapting conditions. It can be clearly observed that a lower confidence always came with a larger inter-observer variation. The observers always had the lowest confidence when selecting the stimuli at the chroma level of 10.

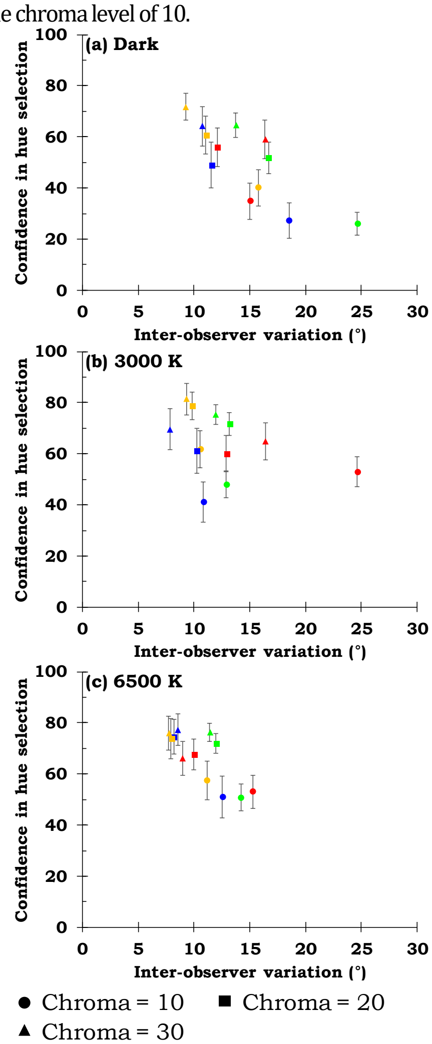

Fig. 3. Average confidence in hue selections indicating how similar the hue of the selected stimuli in comparison to the unique hue in the observers' memory versus inter-observer variation. (a) Dark; (b) 3000 K; (c) 6500 K.

C. Unique hue angles in CIECAM02

Since the stimuli were designed to have similar chroma and lightness levels in CIECAM02, the average hue angles of the stimuli selected by the observers can be directly compared to the hue angles of the unique hues defined in CIECAM02. Fig 4 shows the average hue angles of the stimuli selected by the observers, the 95% confidence intervals, and the unique hue angles defined in CIECAM02, with the values being summarized in Table 3. The average hue angles of the unique hues under the dark and 6500 K adapting conditions were similar, though the color stimuli were perceived as unrelated and related colors under the dark and 6500 K adapting conditions respectively. In contrast, the average hue angles under the 3000 K conditions were a little different.

Table 3 Summary of the average hue angles for the unique hues at different chroma levels under different adapting conditions.

Adapting Condition	Chroma	UR	UG	UB	UY
Dark	10	12.13	160.04	216.56	94.89
	20	18.37	158.36	218.71	92.27
	30	13.43	159.29	219.60	94.33
	Mean	14.64	159.23	218.29	93.83
3000 K	10	11.82	165.08	223.60	99.39
	20	9.68	163.55	225.38	99.84
	30	9.26	166.19	225.04	98.91
	Mean	10.25	164.94	224.67	99.38
6500 K	10	15.43	158.64	213.74	93.15
	20	13.91	157.70	221.81	95.07
	30	10.86	157.17	219.51	94.46
	Mean	13.40	157.84	218.35	94.23

Table 4 Summary of the average perceptual hue differences $(\overline{\Delta H})$ of each hue under each adapting

Adapting Condition	Chroma	UR	UG	UB	UY
Dark	10	-0.44	0.14	-0.30	0.19
	20	1.30	-0.30	0.15	-0.54
	30	-0.64	0.03	0.69	0.26
	Mean	0.08	-0.04	0.18	-0.03
3000 K	10	0.273	0.02	-0.19	0.00
	20	-0.20	-0.49	0.25	0.16
	30	-0.52	0.65	0.19	-0.25
	Mean	-0.15	0.06	0.08	-0.03
6500 K	10	0.35	0.14	-0.81	-0.19
	20	0.18	-0.05	1.21	0.29
	30	-1.33	-0.35	0.61	0.12
	Mean	-0.27	-0.09	0.34	0.08

It can be observed that the selections at the chroma level of 10 generally had larger variations than those at the chroma levels of 20 and 30, which was also found in the past studies [19, 20], but the chroma level did not significantly affect the hue angles of the four unique hues under each adapting condition. For each unique hue, the hue angles were generally the same under the three adapting conditions, but discrepancies between the experiment results and the unique hue angles defined in CIECAM02, especially for the unique blue, can be clearly observed, which was also found in previous studies [19]. In addition, though the fitted line of the average chromaticities of the selected stimuli at the three chroma levels did not strictly coverage to the origin of the $a_{c,10}$-$b_{c,10}$ plane in CIECAM02, as shown in Fig 5, the intercepts were much smaller than those in several past studies [19, 22]. The average perceptual hue differences $\overline{\Delta H}$, reflecting the deviations of the individual hue angles at a chroma level form the grand mean, are summarized in Table 4. A larger value of $\overline{\Delta H}$ indicates a poorer hue uniformity. In comparison to those found in [18], the results here suggested a much better hue uniformity of CIECAM02.

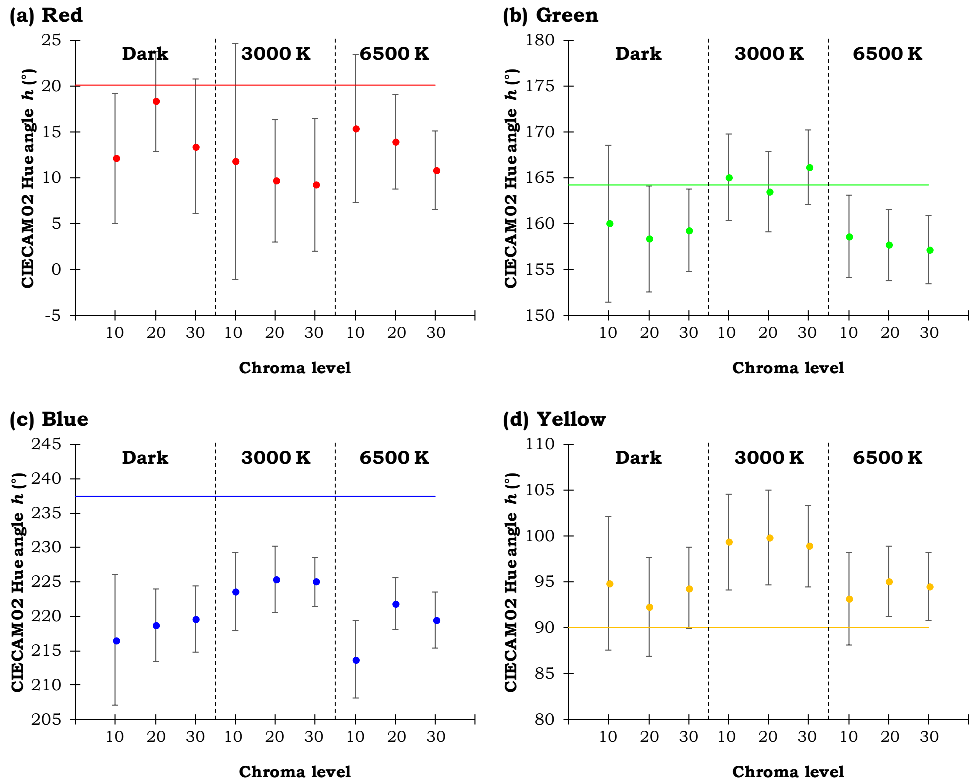

Fig. 4. Average hue angles of the selected stimuli with unique hues, together with the 95% confidence interval, and the hue angles of the unique hues defined in CIECAM02 (labeled in solid horizontal lines) [12].

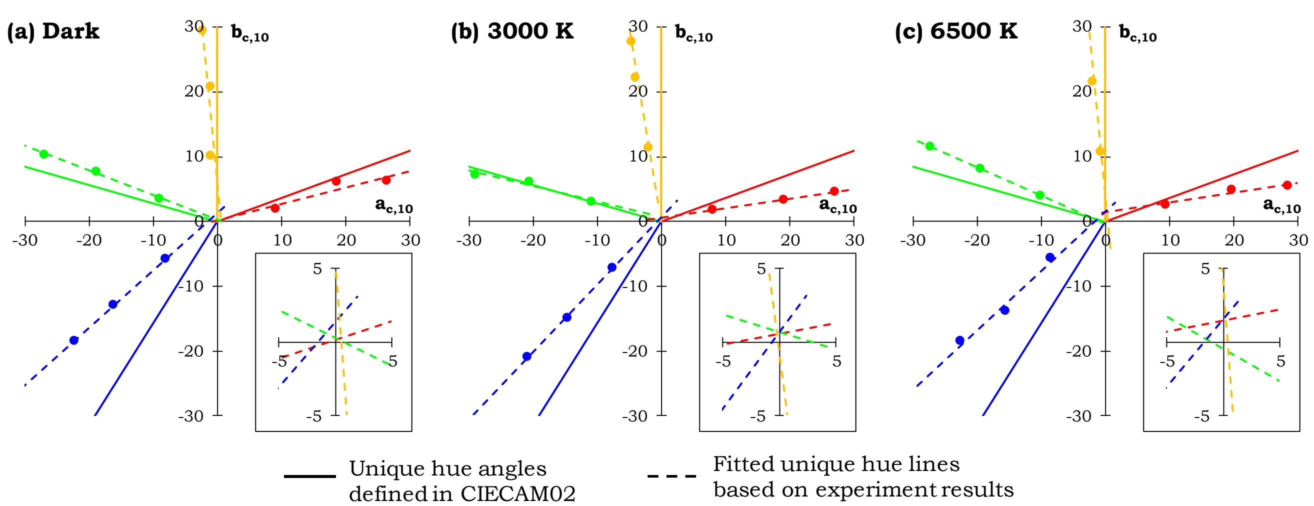

Fig. 5. Average chromaticities of the selected stimuli with the unique hues, together with the fitted lines, and the hue angles of the unique hues defined in the a_{c10}-b_{c10} plane of CIECAM02 [12]. Right bottom area of each figure is the close-up of area near the origin of the a_{c10}-b_{c10} plane of CIECAM02. (a) Dark; (b) 3000 K; (c) 6500 K.

4. DISCUSSIONS

A. Unique hue angles in CIELAB

Though the stimuli were not designed and calibrated in CIELAB, as illustrated in Fig 2(d), a post-hoc analysis was performed to evaluate the unique hue angles in CIELAB. As shown in Fig 6, discrepancies between the experiment results and the unique hue angles defined in CIELAB also existed, which was consistent to the past study [19]. Similar to the results in CIECAM02, though the unique hue lines did not strictly coverage to the origin of the a^*_{10}-b^*_{10} plane in CIELAB, the intercepts were much smaller.

B. Unique hues under the dark condition

For all the CIECAM02 and CIELAB calculations for the dark condition, the parameters of the 6500 K adapting condition was used. Though the stimuli under the dark and 6500 K adapting conditions resulted in completely different perception, with unrelated colors under the dark and related colors under the 6500 K condition, the average hue angles of the unique hues, either in CIECAM02 or CIELAB, were similar.

In past studies, the unique hues for unrelated colors (e.g., spectral lights) were typically specified using dominant or complementary wavelengths. Figure 7 shows the chromaticities of these stimuli ($L \approx 235$ cd/m²) at the three chroma levels and the average chromaticities of the selected ones with the unique hues in the CIE 1931 chromaticity diagram. Though the stimuli were not designed in this diagram, they seemed to have a uniform distribution at the three chroma levels. The shifts of the dominant and complementary wavelengths for the unique hues with the chroma level, especially the directions of the shift, as summarized in Table 5, were expected according to the Abney effect. Though the dominant and complementary wavelengths were not completely identical to those reported in the past studies [1, 2, 6], which was likely due to the different luminance levels (known as the Bezold-Brucke effect) [12], the discrepancies were generally small.

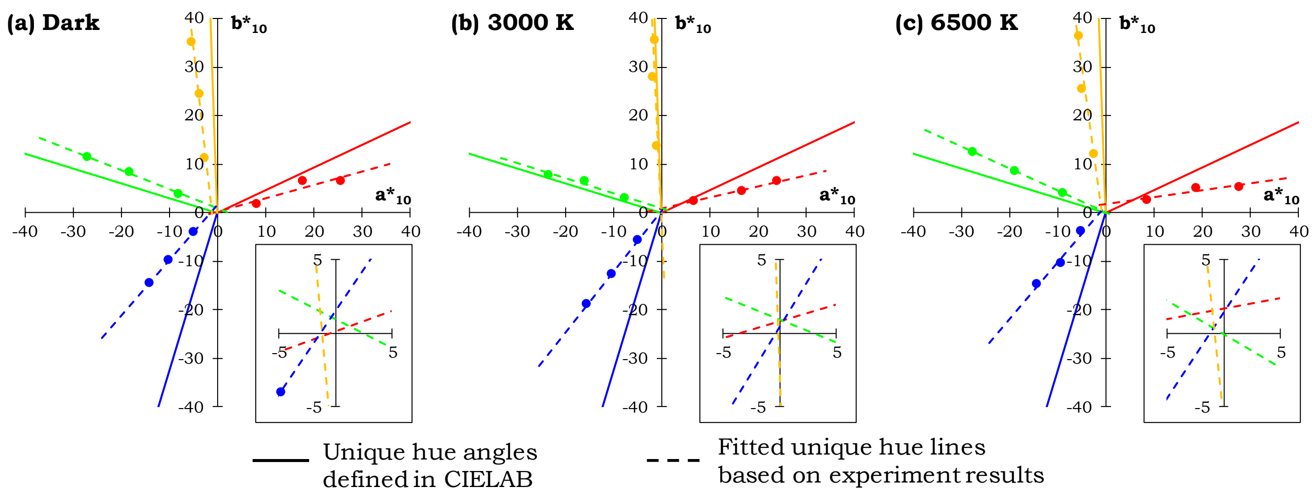

Fig. 6. Average chromaticities of the selected stimuli with unique hues, together with the fitted lines, and the hue angles of the unique hues defined in the a^*_{10}-b^*_{10} plane of CIELAB [13]. Right bottom area of each figure is the close-up of area near the origin of the a^*_{10}-b^*_{10} plane of CIELAB. (a) Dark; (b) 3000 K; (c) 6500 K.

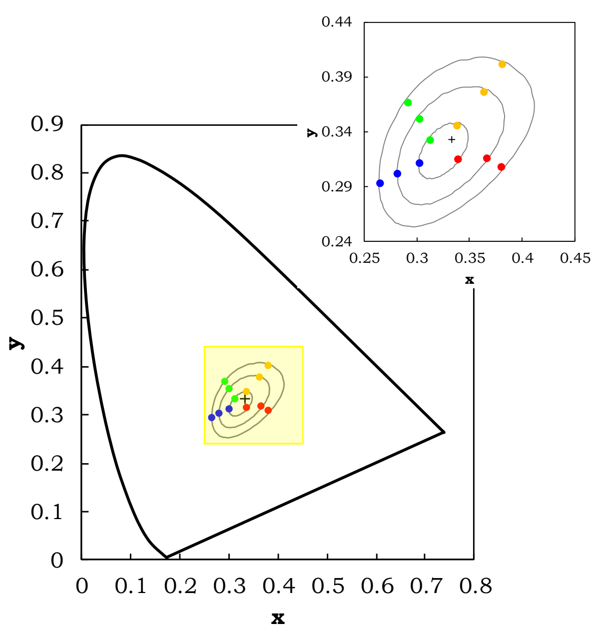

Fig 7 Chromaticities of the stimuli at the three chroma levels (grey contours) and the chromaticities of the selected stimuli having unique hues in the CIE 1931 chromaticity diagram. + shows the chromaticities of the equal-energy illuminant. Top right is the close-up of area near the chromaticities of the equal-energy illuminant.

Table 5 Dominant or complementary wavelengths of the average chromaticities of the selected stimuli with the unique hues under the dark condition (+complementary wavelength)

	Chroma = 10	Chroma = 20	Chroma = 30
UR+	537.1 nm	498.5 nm	498.7 nm
RG	491.2 nm	499.6 nm	502.6 nm
UB	481.9 nm	483.3 nm	483.7 nm
UY	568.6 nm	573.7 nm	573.7 nm

C. Selected unique hues and variations

When the adapting conditions were 3000 and 6500 K, the stimulus was expected to appear as reflective surface colors. The hue angles of the unique hues, however, were not identical to those found in the past studies using real surface colors samples (i.e., Munsell or NCS color samples). In contrast, the unique hues under the dark condition were similar to those in the past studies using spectral lights, as described in Section 4. B. Therefore, the differences under the non-dark conditions were likely due to the experimental setups (i.e., smaller hue angle step and presentation of individual stimulus), especially the presentation of individual stimuli would make it more difficult to estimate the illumination.

In addition, the the inter-observer variations were generally comparable among the four unique hues, which was different from other past studies [16, 19, 20, 22]. To better present the variations, the selections made by the observers were plotted in histograms, as shown in Fig. 8. It can be observed that the selected stimuli covered smaller ranges of hue angles with the increase of the chroma level. For the stimuli at the chroma level of 10, the observers seemed to have difficulties to distinguish unique green, yellow, and blue, regardless of the adapting conditions. This was expected, since a hue angle step of 5° corresponded to a color difference $\Delta E_{ac,10\text{-}bc,10}$ of 0.87 at the chroma level of 10, which was much smaller than the just-perceptible color difference. Moreover, the selections of different unique hues at different chroma levels under different adapting conditions generally had a normal distribution, though bimodal distributions of unique green selections were found in several past studies [7, 25].

The ranges and variations of the unique hue judgements in this study, as shown in Fig 8, were much larger than those in the past work [19, 22]. For example, Fig 9 shows the histograms of the unique hue selections in [19]. The inter-observer variations in ΔE_{CAM02} units was 3.15 in [22], but it is 4.87 in this study. Such a larger variation was likely due to two reasons. Firstly, surface color samples (e.g., Munsell samples and NCS samples) were commonly used in the past studies to produce color stimuli when investigating unique hues under the adapting conditions that were not dark. The observers simultaneously viewed an array of samples with same chroma and lightness levels and selected the samples that appeared to have unique hues to them. With 40 Munsell [4, 8, 19, 20, 26] or NCS [17] samples being used to cover the hue cycle, the hue angle step between two adjacent samples was 9°, which was larger than the step of 5° in this experiment. Thus, the color differences between adjacent samples were larger. Secondly, presenting 40 samples simultaneously was likely to help the observers to judge the unique hue from the adjacent hues. As found in Shamey et al [8], the variations and ranges of the unique hues were larger when the observers only saw individual samples, in comparison to when they viewed a series of ordered samples. At the same time, these two protocols were also likely to increase the intra-observer variations, which caused comparable inter- and inter-observer variations in this study.

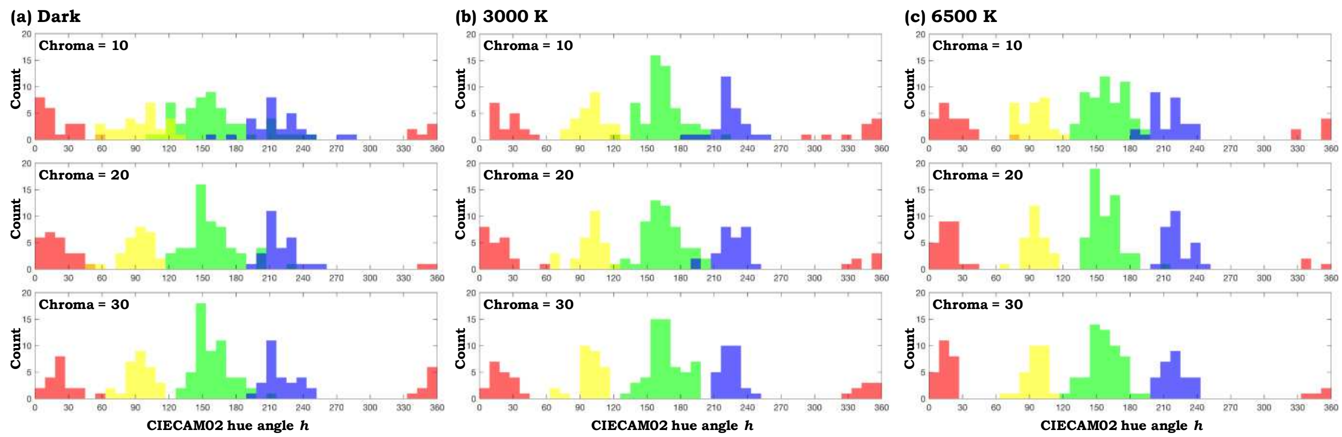

Fig. 8. Hue angle distributions of the selected stimuli with the unique hues under the three adapting conditions in this study. (a) Dark; (b) 3000 K; (c) 6500 K.

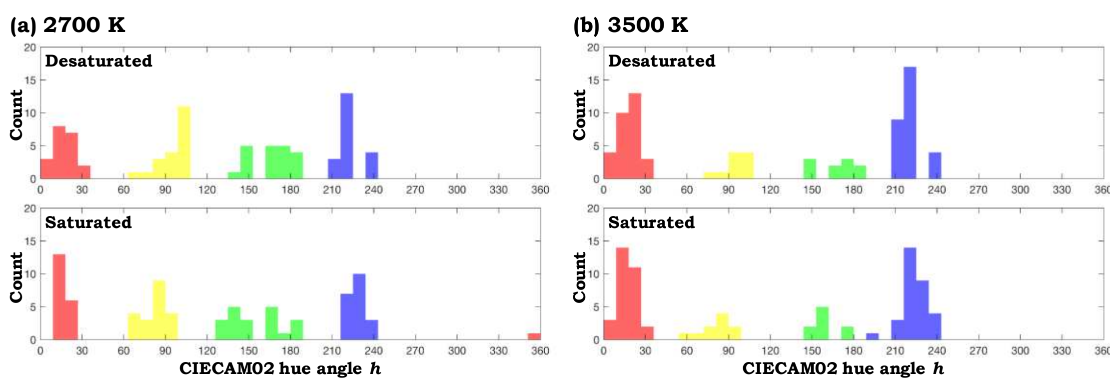

Fig. 9. Hue angle distributions of the selected stimuli with unique hues under the two adapting conditions in a recent study [19], in which the human observers viewed 40 Munsell samples simultaneously and selected the ones with unique hues. (a) 2700 K; (b) 3500 K.

5. CONCLUSIONS

A psychophysical study was carried out to investigate unique hues at three different chroma levels under three different adapting conditions. For each chroma level under each adapting condition, 72 stimuli were carefully designed and calibrated to have the same lightness and chroma levels but different hues with a hue angle step of 5° in CIECAM02, which was much smaller than those used in the past studies. Instead of viewing all the stimuli simultaneously, each stimulus was individually presented. The observers used a keyboard to switch between adjacent stimuli by adjusting the hue angles of ±5°. The inter- and intra-observer variations reduced with the increase of chroma level. The hue angles of the unique hues were not always identical to those defined in CIECAM02. Specifically, large discrepancies were observed for unique blue under the three adapting conditions and the unique yellow under the 3000 K adapting conditions. The results suggested a better hue uniformity in CIECAM02, compared to those reported in the past studies. Last but not the least, the experimental methods were believed to have significant impacts on observers' unique hue judgments. The larger inter- and intra-observer variations found in this study were speculated due to the fact that the hue angle step was much smaller and each stimulus was individually presented.

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References

1. M. Ayama, T. Nakatsue, and P. K. Kaiser, "Constant hue loci of unique and binary balanced hues at 10, 100, and 1000 Td," JOSA A **4**, 1136-1144 (1987).
2. J. L. Nerger, V. J. Volbrecht, and C. J. Ayde, "Unique hue judgments as a function of test size in the fovea and at 20-deg temporal eccentricity," JOSA A **12**, 1225-1232 (1995).
3. M. A. Webster, E. Miyahara, G. Malkoc, and V. E. Raker, "Variations in normal color vision. II. Unique hues," JOSA A **17**, 1545-1555 (2000).
4. R. G. Kuehni, "Determination of unique hues using Munsell color chips," Color Research & Application **26**, 61-66 (2001).
5. K. Rolf G., "Variability in Unique Hue Selection: A Surprising Phenomenon," Color Research & Application **29**, 158-162 (2004).
6. I. Abramov and J. Gordon, "Seeing unique hues," JOSA A **22**, 2143-2153 (2005).
7. D. Hinks, L. M. Cárdenas, R. G. Kuehni, and R. Shamey, "Unique-hue stimulus selection using Munsell color chips," JOSA A **24**, 3371-3378 (2007).
8. R. Shamey, M. G. Sedito, and R. G. Kuehni, "Comparison of unique hue stimuli determined by two different methods using Munsell color chips," Color Research & Application **35**, 419-424 (2010).
9. J. Bosten and A. Lawrance-Owen, "No difference in variability of unique hue selections and binary hue selections," JOSA A **31**, A357-A364 (2014).
10. A. Hård, L. Sivik, and G. Tonnquist, "NCS, natural color system—From concept to research and applications. Part I," Color Research & Application **21**, 180-205 (1996).
11. A. Hård and L. Sivik, "NCS—Natural Color System: A Swedish standard for coloer notation," Color Research & Application **6**, 129-138 (1981).
12. M. Fairchild, *Color appearance models, 3rd edition* (The Wiley-IS&T Series in Imaging and Technology, 2013).
13. G. Derefeldt and C. Sahlin, "Transformation of NCS data into CIELAB colour space," Color Research & Application **11**, 146-152 (1986).
14. G. Derefeldt, C.-E. Hedin, and C. Sahlin, "Transformation of NCS data into CIELUV colour space," Displays **8**, 183-192 (1987).
15. R. G. Kuehni, "Unique hues and their stimuli—state of the art," Color Research & Application **39**, 279-287 (2014).
16. K. Xiao, C. Fu, D. Mylonas, D. Karatzas, and S. Wuerger, "Unique hue data for colour appearance models. Part II: chromatic adaptation transform," Color Research & Application **38**, 22-29 (2013).
17. R. Shamey, M. Zubair, and H. Cheema, "Effect of field view size and lighting on unique-hue selection using Natural Color System object colors," Vision Research **113**, 22-32 (2015).
18. K. Xiao, M. Pointer, G. Cui, T. Chauhan, and S. Wuerger, "Unique hue data for colour appearance models. Part III: Comparison with NCS unique hues," Color Research & Application **40**, 256-263 (2015).
19. H. P. Huang, M. Wei, K. Xiao, and L. C. Ou, "Unique hue judgments using saturated and desaturated Munsell samples under different light sources," Color Research & Application **44**, 419-425 (2019).
20. R. Shamey, M. Zubair, and H. Cheema, "Unique hue stimulus selection using Munsell color chips under different chroma levels and illumination conditions," JOSA A **36**, 983-993 (2019).
21. T. Chauhan, E. Perales, K. Xiao, E. Hird, D. Karatzas, and S. Wuerger, "The achromatic locus: Effect of navigation direction in color space," Journal of vision **14**, 25-25 (2014).
22. K. Xiao, S. Wuerger, C. Fu, and D. Karatzas, "Unique hue data for colour appearance models. Part I: Loci of unique hues and hue uniformity," Color Research & Application **36**, 316-323 (2011).
23. S. Chen and M. Wei, "Chromaticities for producing white stimuli depend on viewing mode rather than viewing medium: a pilot study," LEUKOS (2019).
24. M. Wei and S. Chen, "Effects of Adapting Luminance and CCT on Appearance of White and Degree of Chromatic Adaptation," Optics Express (2019).
25. S. R. Cobb, "The unique green phenomenon and colour vision," Clinical Genetics **7**, 274-279 (1975).
26. M. A. Webster, S. M. Webster, S. Bharadwaj, R. Verma, J. Jaikumar, G. Madan, and E. Vaithilingham, "Variations in normal color vision. III. Unique hues in Indian and United States observers," JOSA A **19**, 1951-1962 (2002).