Unique Hue Data for Colour Appearance Models. Part I: Loci of Unique Hues and Hue Uniformity

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Abstract: Psychophysical experiments were conducted to assess unique hues on a CRT display for a large sample of colour-normal observers (n = 185). These data were then used to evaluate the most commonly used colour appearance model, CIECAM02, by transforming the CIEXYZ tristimulus values of the unique hues to the CIECAM02 colour appearance attributes, lightness, chroma and hue angle. We report two findings: (1) the hue angles derived from our unique hue data are inconsistent with the commonly used Natural Color System hues that are incorporated in the CIECAM02 model. We argue that our predicted unique hue angles (derived from our large dataset) provide a more reliable standard for colour management applications when the precise specification of these salient colours is important. (2) We test hue uniformity for CIECAM02 in all four unique hues and show significant disagreements for all hues, except for unique red which seems to be invariant under lightness changes. Our dataset is useful to improve the CIECAM02 model as it provides reliable data for benchmarking. © 2010 Wiley Periodicals, Inc. Col Res Appl, 00, 000–000, 2010; Published online in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/col.20637

Key words: unique hues; colour appearance models; CIECAM02; hue uniformity

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INTRODUCTION

Recently, interest in colour appearance models has grown because of the increased need of cross-media colour reproduction. CIE TC8-01 recommended the use of the CIECAM02 colour appearance model for colour management,[1,2] which is capable of accurately predicting the appearance of colours under a wide range of viewing conditions. Generally, colour appearance models consist of three stages: a chromatic adaptation transform, a dynamic response function and the transformation into a uniform colour space.[3]

Unique hues were originally defined by Hering[4] as the hues of four fundamental chromatic percepts regardless of saturation and lightness: unique red (UR) and unique green (UG) are defined as colours for which the yellow-blue opponent channel is at equilibrium; unique yellow (UY) and unique blue (UB) are defined as colours where the red-green opponent channel is at equilibrium. Experimentally, UR is obtained by asking observers to select the reddish stimulus that contains neither yellow nor blue; similarly, a greenish light is called 'UG' if it contains neither yellow nor blue. A stimulus is called 'UY' or 'UB' if it contains neither red nor green. Most colour appearance models include the loci of unique hues; in CIECAM02, four system unique hues are defined based on unique hues in the Natural Color System.[5]

The first goal of our study is to investigate whether the four system unique hues adopted in CIECAM02 are accurate. Second, we will test whether hue uniformity holds in CIECAM02; hue uniformity is important as it affects performance of image reproduction and enhancement.

A number of studies have been performed to identify the loci of unique hues and the intra- and inter-observer variability for a range of different stimuli: monochromatic lights,[6–8] stimuli displayed on CRTs or Munsell Chips.[9–13] However, none of these datasets was appropriate to test the validity of colour appearance models. The primary focus of this article is to define the loci of the unique hues in a widely used colour appearance model, namely CIECAM02, and to evaluate the validity of CIECAM02 itself, in particular its hue invariance properties under different lightness and chroma settings.

EXPERIMENTS

CRT Characterisation

A 21-inch Sony GDM-F520 CRT driven by a ViSaGe system and a Dell computer was used for stimulus presentation. The CRT was calibrated and characterized by using the ColourCal calibration device (Cambridge Research System, Kent, UK). The CRT monitor had a correlated colour temperature of about 9300 K with a peak luminance of 120 cd/m^2. The CIE chromaticity coordinates (x, y, luminance) of the phosphors at peak output were as follows: red = 0.627, 0.342, 28.12; green = 0.287, 0.608, 80.96; blue = 0.151, 0.074, 14.16, respectively. As there was some initial monitor drift, the monitor was switched on at least 1 h before the start of the experiment.

Experimental Interface

A GUI interface was designed to fully control the display of the colour patches on the CRT by using Matlab 7.4 and the CRS Matlab toolbox by Cambridge Research Systems. As shown in Fig. 1(a), 10 colour patches arranged along an annulus at constant eccentricity are displayed on the screen. Each patch had a diameter of 2° of visual angle and was presented at an eccentricity of 4°. The background was always set to a mid-grey with a lightness (L^*) of 50,[14] that is, at a luminance of 23.9 cd/m^2 corresponding to 20% of the peak white.

Hue Selection Task

A modified hue selection task[15,16] was used in this study to obtain unique hue data. On a particular trial, the colour patches [Fig. 1(a)] always had the same lightness and chroma but different hue angles. The task of the observer was to select, by using a button box, the patch that was neither yellow nor blue (to obtain UR and UG). UY (blue) was obtained by selecting from a selection of yellowish (bluish) patches that contained neither red nor green.

In this particular implementation, the colour patches appear in an ordered fashion as shown in Fig. 1(a). With a subset of participants (30 observers), we performed the same experiment using a random arrangement of colours within the annulus to make sure that the orderly arrangement of the colours does not introduce any bias in the selection (e.g., the automatic assumption that the final unique hue setting cannot be the near either end of the sequence). The mean hue angles derived from the random arrangement did not differ from the angles derived from the orderly arranged colours, but the variability of the hue settings was higher in the random arrangement. Observers perceived the task for the random arrangement as more difficult and took more time to respond. Therefore, we decided to use the ordered annulus for the experiment described here.

In addition, the subjects were allowed to skip over a particular hue judgment (by pressing a button labeled 'NONE OF THESE') if they do not consider that any of the colours displayed are representative of a true unique

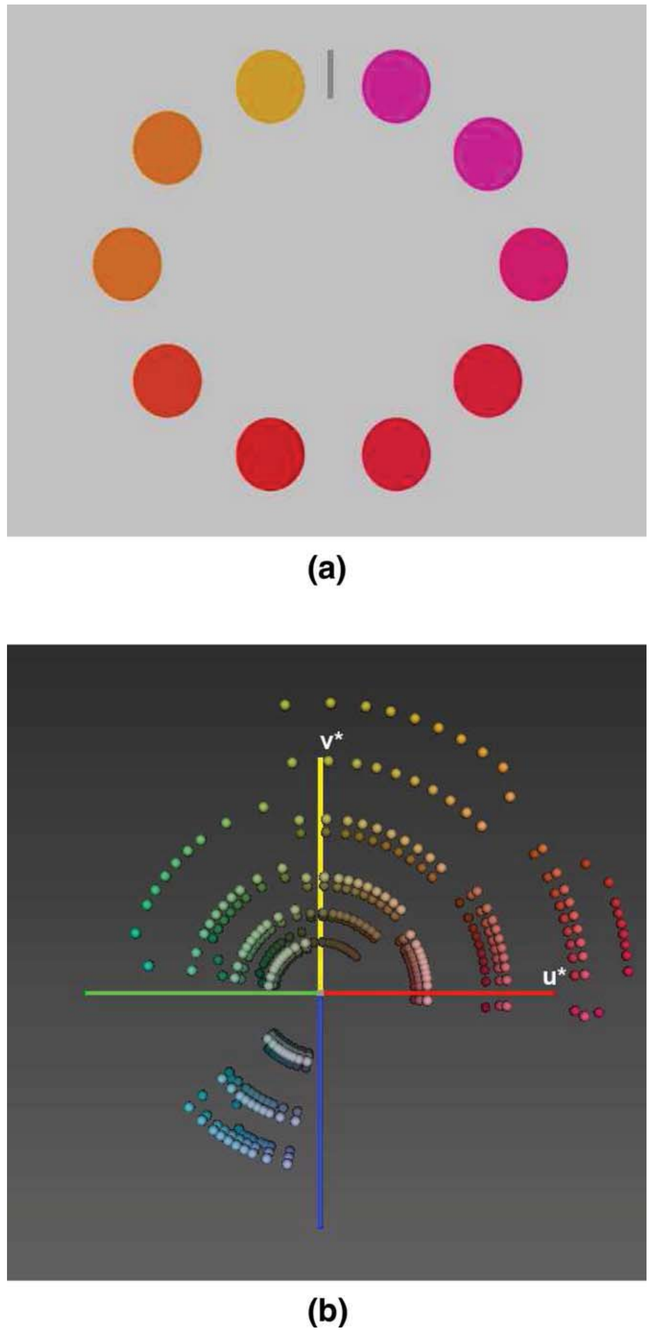

FIG. 1. (a) Viewing patterns used in the experiment. (b) The 360 colours selected to investigate unique hue data in the CIELUV space, u^* versus v^*.

TABLE I. Lightness and chroma of testing samples for each unique hue.

	Red		Yellow		Green		Blue	
	L^*	C_{uv}	L^*	C_{uv}	L^*	C_{uv}	L^*	C_{uv}
1	32	37	32	20	32	18	32	24
2	32	65	32	30	32	25	32	29
3	50	37	50	30	50	18	50	24
4	50	67	50	40	50	30	50	45
5	50	95	50	60	50	45	50	50
6	50	115	76	40	76	18	63	60
7	63	67	76	60	76	30	76	24
8	63	95	76	80	76	45	76	45
9	76	37	76	100	76	67	76	60

hue. Previously, we have experimented with different ways of obtaining the unique hue settings,[15] such as going from a coarse scale (an annulus that covers a wide hue range) to a 'zoomed-in' version of the annulus (that covers a smaller hue range derived from the previous response). In our experience, the particular range of hues presented in the annulus on a particular trial did not induce a significant bias in the final unique hue settings.

Test Colour Samples

The test colour patches were equally spaced in terms of CIELUV hue angles [Fig. 1(b)].[14] The range of hue angles used in the main experiment was based on the results obtained in previous experiments.[15] To test hue uniformity, we assessed all four unique hues at different lightness and chroma levels. The nine particular chroma and lightness levels were chosen for each unique hue in CIELUV uniform colour space to maximize the available gamut as listed in Table I. For each level, pilot studies ensured that the chosen hue differences between patches were small enough to determine the intra- and inter-observer variability. In total, 360 test colours (4 unique hues × 9 combinations of different chroma–lightness levels × 10 colour patches per test) were selected, which are all inside of the CRT colour gamut. They are transformed to CIE XYZ tristimulus values and relative RGB luminance for the CRT.

Subjects

One hundred eighty-five paid subjects (82 males and 103 females; mean age: 32 years; age range: 18–75 years) participated in the experiment. Except for the authors, all subjects were naïve in regard to the aim of the experiment. The experiments were approved by the Ethics Committee of the School of Psychology, University of Liverpool. All observers had normal or corrected-to-normal acuity and normal colour vision (assessed with the Cambridge Colour Test[17]).

Experimental Procedures

The data reported here are part of a more extensive series of experiments including the effect of ambient illumination on unique hue settings. In this article, we report the experimental procedures and data obtained under dark viewing conditions. Observers were seated in a dark, sound-attenuated room; the only source of light in the room was the CRT monitor used to display the stimuli. At the beginning of the experiment, observers adapted to the grey CRT background for 5 min. Ten colour patches [as in Fig. 1(a)] were shown on the CRT until the observer responded (hue selection task; see above). Responses were collected using a button box (CT6, Cambridge Research System). Once the button was pressed, the next trial started automatically. Each observer made 36 different hue judgments (4 unique hues × 9 different lightness–chroma levels), and the set of 36 judgments was repeated three times in a single session. Each session lasted ~20 min.

RESULTS AND DISCUSSION

After each experiment, the colour patches selected as unique hues, were re-displayed on the CRT and measured with a Photo Research PR-650 tele-spectroradiometer, under identical illumination conditions. Note that the TSR was placed in the same position of observer when they conducted visual assessment. Subsequently, each observer's selected unique hue stimulus was recorded in CIE XYZ tristimulus values under the unit of cd/m^2 based on a 2° standard observer. Based on these measurements, observer variability was calculated in terms CIEDE2000 colour difference units.[18] To relate unique hue data to colour appearance models, their colour appearance attributes were calculated by using CIECAM02.

Observer Variability

In the course of this experiment, 19,980 unique hue settings were obtained (185 subjects × 9 lightness–chroma levels × 4 unique hues × 3 repetitions). We first evaluate how reliable the settings are by calculating the inter- and the intra-observer variability. Inter-observer variability indicates the extent to which individual observers agree with the average observer, whereas intra-observer variability indicates how consistent the individual observer is across different trials. The CIEDE2000 colour difference formula was used to calculate the mean colour difference to the mean value,[19] for both inter- and intra-observer variability for each of the four unique hues. The mean value for inter-observer variability is calculated by averaging results of the 185 observers; the mean value used to calculate intra-observer variability is the average across the three repetitions for each individual observer. The inter- and intra-observer variability results are listed in Table II. Note that although the observer variability is expressed in CIEDE2000 (ΔE_{00}) colour difference units, it should be really interpreted as a pure hue difference (ΔH) as the lightness and chroma parameters of all colour patches displayed on the screen for any particular unique hue judgement are always the same in CIELUV colour space.

TABLE II. Observer variability.

CIEDE2000	UR	UY	UG	UB	Mean
Inter-observer	2.30	1.92	1.17	1.97	1.84
Intra-observer	0.97	1.07	0.66	1.06	0.94

Table II shows that the largest inter-observer variability occurs for red (2.30 ΔE_{00}), whereas the maximum intra-observer variability is 1.07 ΔE_{00}. This variability is in line with our previously reported results[15] but lower than estimates reported by other groups (for a review see Ref. 12). In our dataset, the intra-observer variability is roughly 50% of the inter-observer variability, which is higher than that reported for the unique hue data of Hinks *et al.*,[12] in which the percentage of intra- to inter-observer variability is about 15%. Using the CIEDE2000 as a distance metric, we find the lowest observer variability for UG; for the other three unique hues, the observer variability is similar. In terms of wavelength, it is known that the largest spread occurs for UG, ranging from about 487 to 567 (Kuehni's dataset[11]), that is, a range of about 60 nm; the wavelength range for UY is rather small, about 20 nm, and the wavelength range for UB is larger than for UY, about 40 nm. It is not meaningful to compare directly the wavelength range with the variability based on the CIEDE2000 distance metric (see also Ref. 15). As we are interested in the variability of unique hue settings in relation to perceived colour differences, we chose units that are approximately perceptually uniform.

To provide a baseline for unique hue predictions in the CIECAM02 colour space, the inter-observer variability is also calculated by using the CIECAM02 colour difference formula as described in Eq. (1).

$$\Delta E_{\mathrm{CAM02}} = \sqrt{(J_1 - J_2)^2 + (a_{c1} - a_{c2})^2 + (b_{c1} - b_{c2})^2} \quad (1)$$

The inter-observer variability in $\Delta E_{\mathrm{CAM02}}$ units is 4.73, 2.61, 2.55 and 2.74 for UR, UY, UG and UB, respectively. These values will be used in the next section to evaluate the performance of the unique hue predictions assuming the CIECAM02 model.

Unique Hue Data

In the following analysis, we first averaged over the three repetitions for each of the 36 hue judgments for each observer; then the grand mean over all 185 subjects was calculated, obtaining a single set of 36 judgments for the entire sample. These data will be referred to as the unique hue data in the following analysis.

Unique Hues in the CIECAM02 Colour Appearance Model

The loci of the unique hues constitute a good test for colour appearance models as they provide a direct estimate of the perceived hue. Colour appearance models are important for colour management to ensure good colour reproduction across different media. Hue uniformity, that is, the extent to which perceived hue is independent of lightness and chroma, is an important feature of colour appearance models due to its importance in colour image reproduction and enhancement. Typical gamut mapping algorithms[20] tend to preserve the perceptual attribute of hue while altering chroma and lightness if necessary. In the next sections, we will use the experimentally obtained unique hue data to examine the uniformity of hue representation in the CIECAM02 colour appearance model.

To identify unique hues in CIECAM02, the unique hue data are transformed to the three CIECAM02 colour appearance attributes, lightness (J), chroma (C) and hue angle (h). The input parameters used for CIECAM02 are listed in Table III. They reflect the viewing conditions during the experiment. L_w refers to the absolute luminance of the reference white in cd/m^2, whereas Y_b is the relative luminance of the background. The "Dim" surrounding setting is defined to be used for conditions similar to "viewing television," which match the conditions of our experiment (dark room, with the only source of light being the CRT monitor).

Loci of Unique Hues in CIECAM02. First, we plot the loci of the unique hues in the CIECAM02 $a_c b_c$ chromatic diagram [Fig. 2(a)]. Each point in the diagram represents the grand mean obtained for a particular unique hue judgment (under specific lightness and chroma settings) across all 185 subjects and three repetitions per observer, calculated as explained before. As each hue was assessed at nine lightness–chroma levels, each unique hue line is defined by the best-fit line of nine points by using Eq. (2); the best-fit line was derived by a linear least-squares fitting [dashed line in Fig. 2(a)]. The coefficients K and C for each unique hue line are listed in Table IV. The scatter (S) for each unique hue line is defined as the average distance between the line and the individual data points as defined in Eq. (3) and indicates the goodness of the model fitting.

$$b_c = K a_c + C \quad (2)$$

$$S = \sum_{i=1}^{9} \frac{|K a_{ci} - b_{ci} + C|}{9\sqrt{K^2 + 1}} \quad (3)$$

While comparing scatters with the inter-observer variability expressed in $\Delta E_{\mathrm{CAM02}}$ [see Eq. (1)] for each unique hue, it can be seen that the fitting performance is much better than the error due to inter-observer variability,

TABLE III. Viewing parameters of CIECAM02 for unique hue prediction.

Parameters	X_w	Y_w	Z_w	L_w	Y_b	Surrounding
CIECAM02	98.0	100.0	139.7	114.6	20	Dim

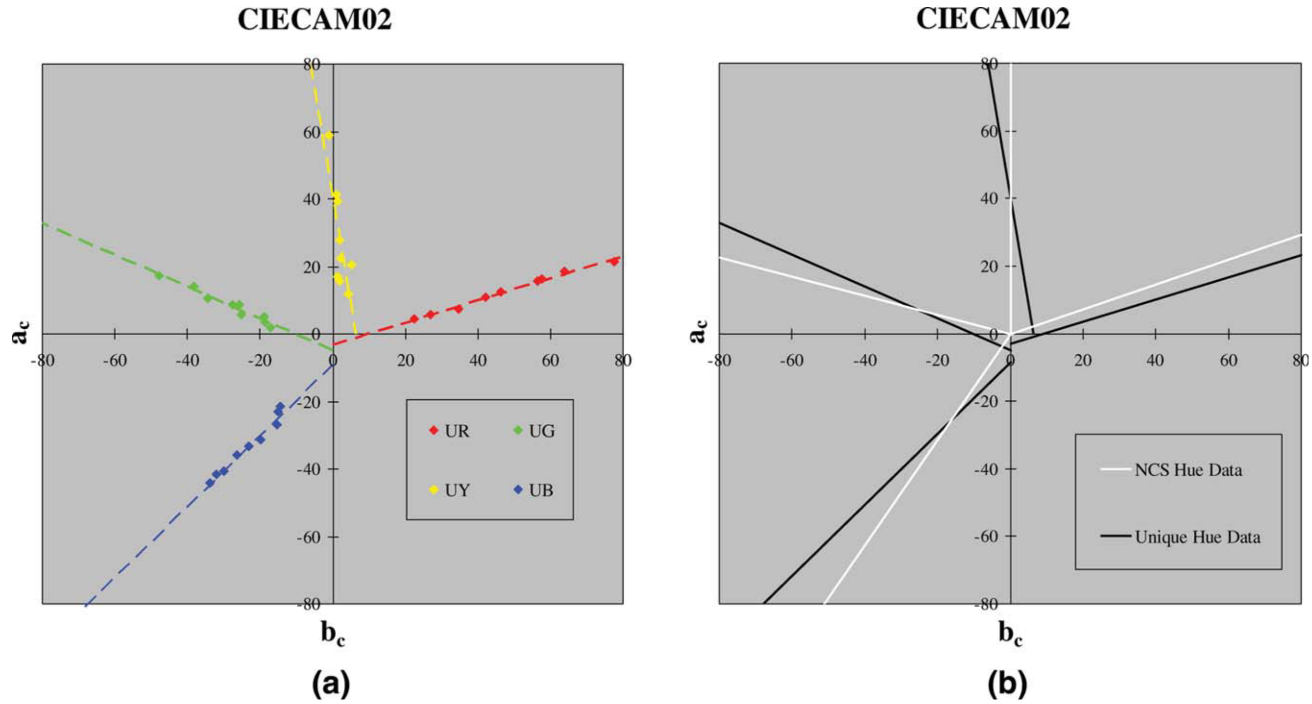

FIG. 2. (a) Unique hues in the chromatic diagram for CIECAM02. (b) Unique hue lines and NCS hue lines in CIECAM02.

which indicates each unique hue lines fit the data well. The largest scatter is obtained for UY (1.3); this scatter does not reflect inter-observer variability (as the grand mean over all observers was used to fit the line) but reflects the lack of hue uniformity. If UY settings were independent of chroma and lightness, all UY settings would lie on a single line (see discussion below). Furthermore, the four unique hue lines do not converge to the same neutral point, which is mainly due to the yellow settings.

Since Hunt and Pointer's colour appearance model,[21] four pre-defined system unique hues derived from the Natural Color System (NCS) are used to provide predictions for unique hues as well as for intermediate hues. The unique hue angles derived from the NCS system are 20.1, 90.0, 164.3 and 237.5 for UR, UY, UG and UB, respectively, and are shown as white lines in the CIECAM02 $a_c b_c$ chromatic diagram in Fig. 2(b). The comparison of unique hue data obtained in our experiments [replotted as solid black lines in Fig. 2(b)] with the NCS-derived unique hue lines [white lines in Fig. 2(b)] reveals a clear discrepancy, and we conclude that the current use of the NCS-derived hue angles in the CIECAM02 appearance model is not a good representation of these perceptually salient hue mechanisms. Therefore, either the NCS hue angles or the transformation mapping CIE XYZ values into a uniform colour space (CIECAM02 model) need to be modified to represent accurately the colour appearance data (unique hues).

TABLE IV. Coefficients and scatters for unique hue lines in CIECAM02.

CIECAM02	UR	UG	UY	UB
K	0.33	−0.47	−6.35	1.05
C	−3.05	−4.89	41.18	−8.60
S	0.37	0.81	1.28	0.79

Hue Uniformity. Hue uniformity represents the extent to which perceived hue is independent from the other two perceptual attributes, lightness and chroma. As we obtained unique hue data at nine different lightness–chroma levels, we can test whether the hue data depend on the levels of these two other attributes. First, the mean hue value over all nine lightness and chroma settings and the associated standard deviation for each of the four unique hues is calculated (Table V) in terms of hue angle in CIECAM02. If hue was uniform across different settings, then all the obtained hue angles should almost be identical for all chroma–lightness levels, and hence resulting in small standard deviations. Table V shows that UR yields the smallest standard deviation, whereas UY yields the largest one. Even in the best case, the standard deviation calculated indicates nonuniform hue behavior across different lightness and chroma settings.

If hue uniformity holds, then the hue angle should be the same for the nine different lightness–chroma levels, and hence all data point should lie on a single line through the origin.

TABLE V. Unique hues in CIECAM02.

Hue (CIECAM02)	UR	UY	UG	UB
Grand mean	14.19	83.64	164.56	235.41
Standard deviation	1.89	6.63	4.53	2.70

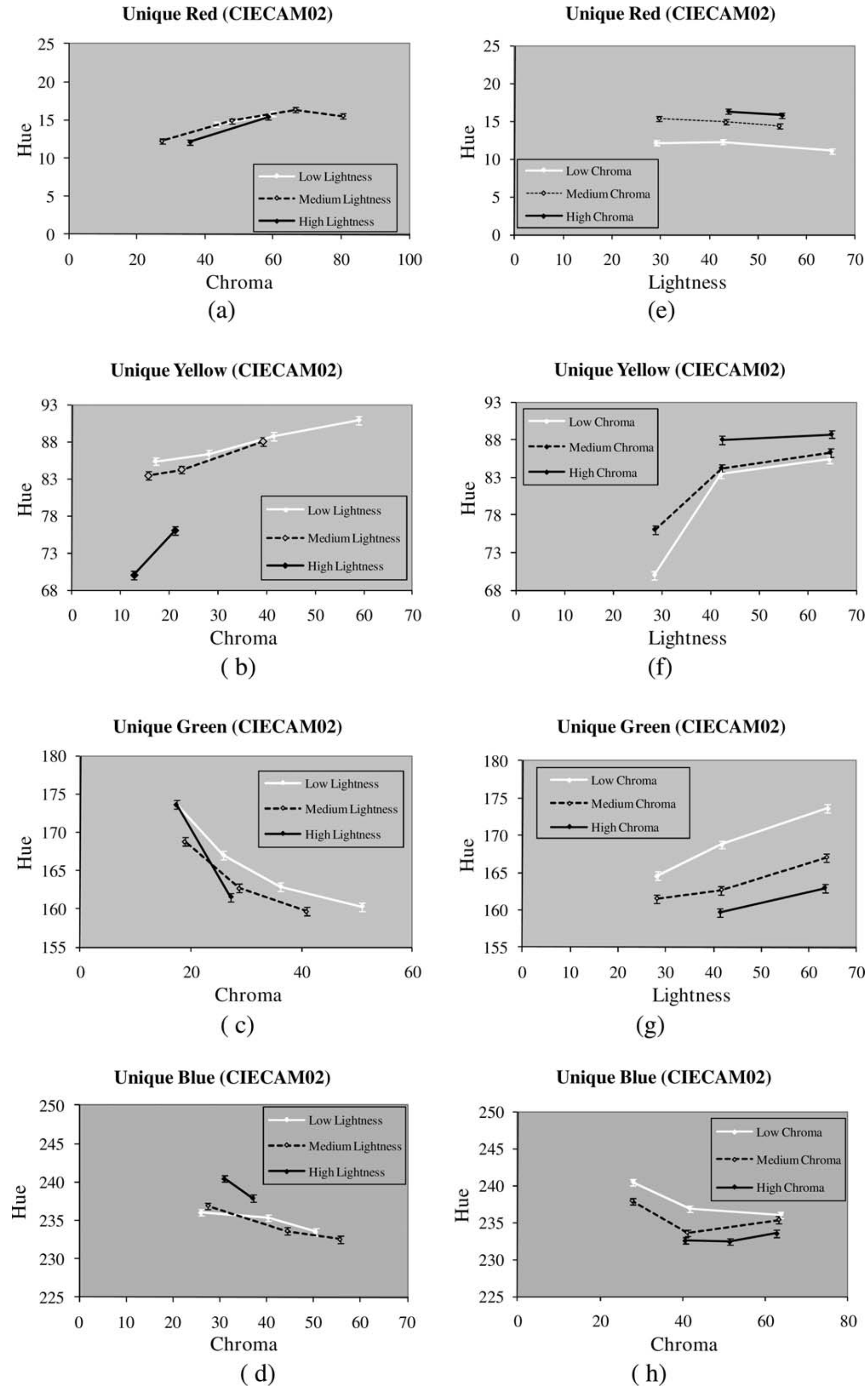

FIG. 3. Hue angles as a function of chroma (a–d) and lightness (e–h).

To investigate how unique hues are affected by lightness and chroma in CIECAM02, we calculate the observed hue shifts as a function of changes in chroma (Table AI) with a fixed lightness and as a function of changes in lightness (Table AII) with a fixed chroma. To that end, we first divided stimuli into three lightness categories (low, medium and high lightness; Table AI) and into three different chroma categories (low, medium, high; Table AII). We then calculated the hue difference as a function of chroma changes for the three different lightness ranges (Table AI, columns 7–9). Similarly, Table AII (columns 6–7) shows the calculated hue differences as function of a change in lightness for the three different chroma levels. For each unique hue (UR, UG, UY, UB), we performed a one-way ANOVA to test whether hue angles are different for the nine lightness–chroma levels. For all four unique hues, the ANOVA revealed significant differences in hue angle ($P < 0.05$). Then, we used posthoc comparisons ($P < 0.05$) to test which lightness or chroma changes lead to violations of hue uniformity. The significant hue changes are specified by a '*' sign in Tables AI and AII. In summary, chroma changes induce changes in hue angles for all four colours (Table AI); a change in lightness leads to significant hue changes for all hues except red (Table AII).

To visualize the effects of chroma and lightness on hue, hue angles are plotted as a function of chroma for different lightness levels [Figs. 3(a)–3(d), left panel] and as a function of lightness for different chroma levels [Figs. 3(e)–3(h); right panel]. Perfect hue invariance predicts that all lines should be horizontal, and the lines associated with different parameters (lightness or chroma levels) should lie on top of each other; if there is an interaction between lightness and chroma in the way they affect hue, the lines should cross over, or at least, not be parallel. In Figs. 3(a)–3(d), hue angles for three different lightness levels are plotted (white solid line: higher lightness level; dashed line: medium lightness level; black solid line: lower lightness level) as a function of chroma. For UR [Fig. 3(a)], hue angles are increasing with chroma, and these effects are significant at the lower lightness level (cf. Table AI). A similar hue change is seen for UY [Fig. 3(b); Table AI]; hue uniformity is violated at all lightness levels. For UG [Fig. 3(c)], an increase in chroma leads to a decrease in hue angle, which is significant at both higher lightness levels (Table AI). The hue angle for UB [Fig. 3(d)] also changes with an increase in chroma, and these effects are significant at several lightness levels (Table AI). Similar hue changes are observed when the hue angles are plotted as a function of lightness [Figs. 3(e)–3(h)] at different chroma levels. White solid lines represent colours with a high chroma level; dashed lines represent colours with a medium chroma level and black solid lines represent colours with a lower chroma level. It can be seen that significant violations of hue uniformity are found for all hues (Table AII), except for UR which seems to be invariant under changes in lightness.

CONCLUSIONS

Unique hue judgments from a large set of colour-normal observers ($n = 185$) were obtained under dark viewing conditions using a CRT display. We used these data to test the validity of a commonly used colour appearance model, CIECAM02. We first plotted the loci of our unique hue data in the CIECAM02 chromaticity diagram and compared the unique-hue lines derived from our dataset with the built-in NCS hues. We find a large discrepancy between these two sets of hue lines; we argue that our unique hue lines provide a more reliable representation of the perceptually salient and unique hue mechanisms than the built-in NCS hue lines. We then evaluated hue uniformity for CIECAM02 by comparing hue angles at different lightness and chroma levels. Overall, we find significant deviations for all hues with the exception of UR, which is invariant under changes in lightness. We conclude that the CIECAM02 model needs to be modified to reflect accurately the hue data of colour-normal observers.

ACKNOWLEDGMENT

The unique hue data (CIE XYZ) will be made available at the website of the Colour Group (Great Britain).

APPENDIX

TABLE AI. Specification of chroma in different lightness ranges in CIECAM02 and the corresponding observed hue shift.

	Col. 1	Col. 2	Col. 3	Col. 4	$\Delta h_{1,2}$	$\Delta h_{2,3}$	$\Delta h_{3,4}$
UR							
Low lightness	$C = 35.6$	$C = 58.5$			−3.3*		
Medium lightness	$C = 27.5$	$C = 48.0$	$C = 66.6$	$C = 80.6$	−2.6*	−1.4	0.8
High lightness	$C = 43.5$	$C = 60.0$			−1.4		
UY							
Low lightness	$C = 12.8$	$C = 21.2$			−6.0*		
Medium lightness	$C = 15.7$	$C = 22.5$	$C = 39.3$		−0.8	−3.8*	
High lightness	$C = 17.1$	$C = 28.1$	$C = 41.3$	$C = 58.9$	−1.0	−2.4*	−2.2
UG							
Low lightness	$C = 19.7$	$C = 27.2$			3.0		
Medium lightness	$C = 18.9$	$C = 28.7$	$C = 40.9$		6.1*	3.0	
High lightness	$C = 17.3$	$C = 25.9$	$C = 36.1$	$C = 50.9$	6.6*	4.1*	2.7
UB							
Low lightness	$C = 31.0$	$C = 37.1$			2.6*		
Medium lightness	$C = 27.4$	$C = 44.4$	$C = 55.6$		3.3*	1.1	
High lightness	$C = 26.0$	$C = 40.4$	$C = 50.5$		0.7	1.9*	

TABLE AII. Specification of lightness in different chroma ranges in CIECAM02 and the corresponding observed hue shift.

	Col. 1	Col. 2	Col. 3	$\Delta h_{1,2}$	$\Delta h_{2,3}$
UR					
Low chroma	$J = 29.1$	$J = 42.8$	$J = 65.2$	−0.2	1.2
Medium chroma		$J = 43.4$	$J = 54.4$		0.5
High chroma	$J = 29.6$	$J = 43.9$	$J = 55.0$	−0.9	0.6
UY					
Low chroma	$J = 28.6$	$J = 42.3$	$J = 64.6$	−13.4*	−2.0
Medium chroma	$J = 28.7$	$J = 42.4$	$J = 64.8$	−8.2*	−2.1
High chroma		$J = 42.5$	$J = 64.9$		−0.7
UG					
Low chroma	$J = 28.2$	$J = 41.8$	$J = 63.9$	−4.2*	−4.9*
Medium chroma	$J = 28.1$	$J = 41.6$	$J = 63.6$	−1.2	−4.4*
High chroma		$J = 41.3$	$J = 63.4$		−3.3
UB					
Low chroma	$J = 27.9$	$J = 41.6$	$J = 63.7$	3.6*	0.9
Medium chroma	$J = 27.8$	$J = 41.0$	$J = 63.2$	4.3*	−1.7
High chroma		$J = 40.6$	$J = 62.7$		−1.0

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