Locating Unique Hues under mixed illumination conditions in CIECAM02

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Abstract

Unique hue settings of 185 observers under two room lighting conditions were used to evaluate the accuracy of mixed chromatic adaptation transform models of CIECAM02 in terms of unique hue reproduction. The current CIE recommendation for mixed chromatic adaptation ratio produced unsatisfying performance in terms of perceptual hue shifts in CIECAM02. Using our large data set of unique hue data as a benchmark, an optimised parameter is suggested for chromatic adaptation under mixed illumination conditions that produces more accurate results in unique hue reproduction.

Introduction

Colour appearance modeling is an active research area with the aim to extend basic colorimetry to predict how observers perceive, describe and match colours in a wide range of viewing conditions. Interest in colour appearance models has been stimulated by the increased need of industrial applications, such as the prediction of colour inconstancy, the evaluation of colour rendering properties of light sources and gamut mapping based on perceptual attribute correlates. The work presented in this paper focuses on the prediction of colour appearance changes in terms of hue perceptual correlates for consumer applications, where soft images are viewed on displays in rooms with sufficient ambient light, by determining the state of chromatic adaptation of the observers.

In the most common form, colour appearance models consist of three stages: a chromatic adaptation transform, a dynamic response function and a transformation into a uniform colour space [1]. Chromatic adaptation transforms (CATs) allow the prediction of corresponding colours under different illumination conditions; the single most important computation towards modelling colour appearance [2]. CIECAM02 [5] adopted a modified version of the CMCCAT2000 chromatic adaptation transform model [3], which was developed based on 8 different corresponding-colour datasets [4]. To produce more accurate predictions, it is commonly recommended to assume that observers are fully adapted to a single, not highly chromatic illumination and use a complete chromatic adaptation transform. This requirement is not representative for real world settings because of the time-course of adaptation [2] and of the concurrent adaptation of the observers to multiple light sources.

In CIECAM02, incomplete chromatic adaptation is determined by the D factor, a ratio that linearly scales between the defined adapted light source and the equal energy illuminant [5]. For mixed illumination conditions, CIE TC 8-04 recommended an extension of CIECAM02 [6], which compensates in the first stage for the incomplete chromatic adaptation and then compensates for the adaptation of the observers to light from sources of different chromaticities. The technical committee suggested an adaptation ratio (R_{adp}) of 0.6 between a given white point of a monitor and an ambient light source based on the findings of a series of experiments, which were conducted to determine the adaptation state when observers compared soft to hard copy images viewed under various lighting conditions.

To test colour appearance models that incorporate the effect of adaptation, it is necessary to assess the appearance of a coloured patch under different adaptation conditions. A widely used assessment method is asymmetric matching where a test patch seen under a particular chromatic adaptation is matched to a reference patch viewed under a different adaptation; this requires to fully adapt different parts of the retina to different adapting lights (e.g. [7]). An alternative method is to ask observers to provide unique hue settings on a computer controlled monitor viewed under various illumination conditions, the advantage being that no reference is necessary. Unique hues (e.g. [8]) are defined as pure colours, such that either a putative red-green channel is at equilibrium, yielding unique yellow and blue; or a putative yellow-blue channel is at equilibrium, yielding unique red and green. These four unique hues can be obtained using hue cancellation [9] or a hue selection task [10]. In the present paper we use unique hue settings measured on a CRT under two ambient illumination conditions; thereby extending previous experiments that obtained achromatic settings under different illumination conditions [16]. The unique hues in each illumination condition are then predicted by using the mixed chromatic adaptation transform embodied in CIECAM02. The performance of each chromatic adaptation transform is evaluated by measuring perceptual hue differences between predicted and observed unique hue settings. Two optimised adaptation parameters are proposed for mixed chromatic adaptation under mixed illumination conditions that produce more accurate colour appearance predictions.

Experiments

Methods

The experimental setup and the assessment of the unique hues under a dark room had been described in previous papers [11, 12]. Stimuli were presented on a 21 inch SONY CRT display driven by a ViSaGe system (Cambridge Research Systems, Ltd, Kent). Unique hue settings were obtained from 185 colour normal observers (screened with the Cambridge Colour Test, Cambridge Research Systems, Ltd. Kent) under two ambient illumination conditions; under a day light simulator and CWF room lighting conditions.

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Stimuli and Task

A hue selection task was used to find the coordinates of the four unique hues (Figure 1). For example, to obtain unique red, 10 reddish patches were displayed on an annulus (eccentricity: 10^o) and the task of the observer was to indicate via a mouse press which of these patches contained neither yellow nor blue. Unique green was assessed in an analogous way. To obtain unique yellow and unique blue, observers chose that patch that contained neither red nor green. The coloured patches presented on a particular trial were always of the same luminance and saturation to facilitate the task. During the experiments, each observer first assessed unique hue stimuli under D65 and then under CWF. For each lighting condition, 108 unique hue stimuli (4 unique hues x 9 different lightness-chroma levels x 3 repetitions) assessed by 185 subjects and 19980 assessments were made in total. The experiment lasted approximately 50 minutes for each subject.

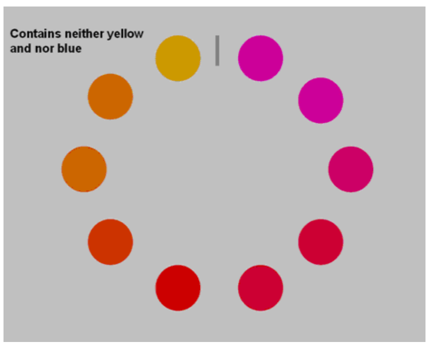


***Figure 1**. Viewing patterns used in the experiment.*

Ambient Illumination

A GTI ColorMatcher GLE M5/25 installed in the centre of a sound-attenuated room was used to provide two lighting conditions, a D65 simulator for day-light and a cool white fluorescent for typical office light. A white tile was placed underneath the light sources and measured by a PhotoResearch PR-650 tele-spectroradiometer (TSR). Their specifications (luminance, CIE xy chromaticity and Correlated Colour Temperature) are listed in Table 1.

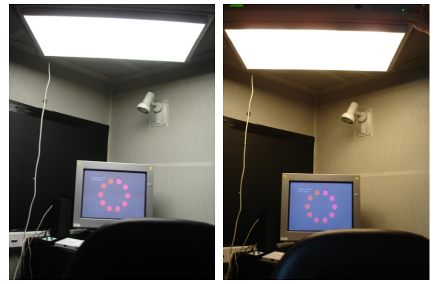
Table 1: Specification of ambient illumination (room lighting)

Room Lighting	*Lum*	*x*	*y*	*CCT*
CWF	136.8	0.3890	0.3887	3866
D65	41.3	0.3229	0.3453	5917

Before the experiment started, the light sources were allowed to equilibrate for at least 15 minutes and each observer was adapted to the viewing field for at least 5 minutes. Stimuli were displayed on a CRT under either a D65 simulator or a CWF room lighting (Figure 2).

Unique Hue Data

After each experiment, the colour patches selected as unique hues, were re-displayed on the CRT and measured with the TSR, under identical illumination conditions, respectively. The unique hue settings were recorded in CIE XYZ tristimulus values in the units of cd/m2 based on a 2-deg standard observer [13].



(a) *(b)*

***Figure 2**. Experimental setup under different room lightings. (a) D65 simulator (b) CWF*

Observer Variability

Both inter- and intra- observer variability were evaluated to measure the reliability of the unique hue data. 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 sessions. The CIEDE2000 colour difference formula [14] was used to calculate MCDM [15]; the mean colour difference to the mean value, for both inter- and intra- observer variability for each group of experimental data. It is noted that the mean value for inter-observer variability represents the mean results between 185 observers, whereas the mean results of three assessments in a different time are used to calculate intra-observer variability. The inter-and intra- observer variability results for each unique hue and the overall mean are listed in Tables 2 and Table 3, respectively.

Table 2: Inter-observer variability

Inter-Observer	*UR*	*UG*	*UY*	*UB*	*Mean*
CRT (D65)	1.44	0.95	1.76	1.76	1.48
CRT (CWF)	1.58	0.91	1.51	1.63	1.41

Table 3: Intra-observer variability

Intra-Observer	*UR*	*UG*	*UY*	*UB*	*Mean*
CRT (D65)	0.77	0.53	0.90	0.91	0.78
CRT (CWF)	0.73	0.46	0.74	0.85	0.69

Comparing the intra-observer variability (Table 3) between the two mixed illumination conditions revealed that observers were overall slightly more consistent under CWF than under D65. Equally, variability across observers (Table 2) is also lower under CWF compared to the D65 condition. The lowest observer variability was found for unique green while for the other three unique hues variability was similar. The intra-observer variability is roughly 50% of the inter-observer variability.

Results

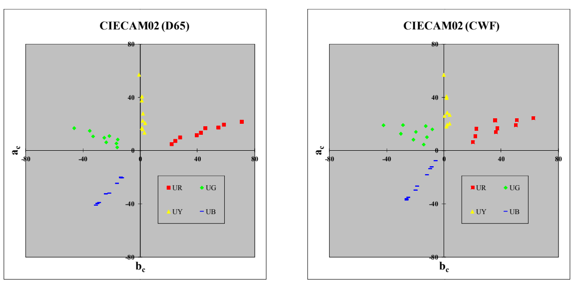
Using the obtained unique hues settings under different illuminations as reference, we tested CIECAM02 for incomplete and mixed chromatic adaptation by predicting the loci of the unique hues. In the forward model, it was assumed that subjects were adapted to both, the white point of the CRT display and to each of the ambient room illumination (Table 1). The measured peak white of the screen was used as the adopted white point and the measured room lighting was used to represent ambient light (Table 4). The mixed chromatic adaptation model using the recommended R_{adp} value of 0.6 [6] was adopted to transform unique hue stimuli from the test mixed illumination condition to the standard equal-energy white condition and CIECAM02 was used to predict their colour appearance attributes.

Table 4. Input parameters for CIECAM02 for mixed adaptation

CIECAM02	X_n	Y_n	Z_n	X_a	Y_a	Z_a	R_{adp}
D65 (D65)	117.6	120.0	167.6	38.6	41.3	39.7	0.6
CWF(CWF)	117.6	120.0	167.6	136.9	136.8	78.2	0.6

Unique Hue Loci in CIECAM02

CIECAM02 was used to predict colour appearance attributes for each unique hue stimuli under each corresponding mixed illumination condition. Figure 3 illustrates unique hue data plotted in the CIECAM02 ac bc chromaticity diagram. Each point in the diagram represents a grand mean of unique hue settings across 185 subjects in three experimental sessions.



(a) (b)

Figure 3. Unique hue loci in CIECAM02 chromatic diagram. (a) Predicted Unique hue stimuli under D65 (b) Predicted unique hue stimuli under CWF. Each diagram includes 36 points (9 lightness-chroma levels x 4 unique hues) plotted in four different colours and symbols (red, green, yellow and blue) corresponding to the four unique hues. For unique green and unique red the distribution was found narrower under the D65 room lighting than under the CWF room lighting. The mean of the 9 unique hue settings across different lightness-chroma levels and repetitions are listed in Table 5.

Table 5. Mean unique hue angles in CIECAM02

Mean Hue	*UR*	*UG*	*UY*	*UB*
CRT (D65)	14.4	165.7	83.3	239.0
CRT (CWF)	13.2	170.1	92.5	241.1

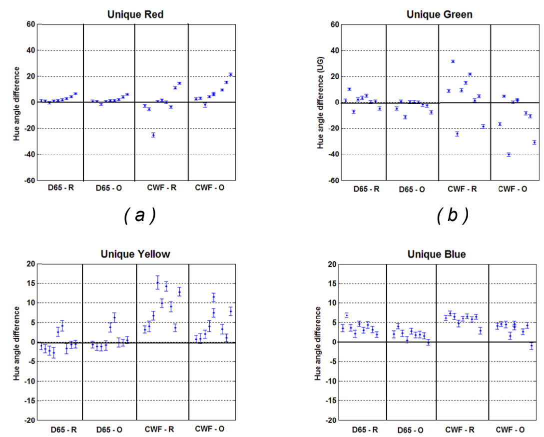
If the CIECAM02 is a correct model of colour appearance, the hue angles of the unique hue stimuli under different mixed illumination conditions should be identical. However, as shown in Table 5 and Figure 3, there are systematic hue differences between pairs of unique hue stimuli under different illuminants. This implies that the current form of chromatic adaptation transform models do not compensate well for unique hue constancy when colour patches are viewed in different room lighting conditions.

An optimised adaptation ratio

Using our unique hue data as a benchmark, an optimisation routine was performed to identify the best parameter for R_{adp}, which produces least mean perceptual hue difference between unique hue stimuli obtained in a dark room [11] and under mixed illumination conditions by using Equation 1:

$$\overline{\Delta H} = \frac{\sum_{i=1}^{9}|\Delta H_i|}{9} \quad \text{where} \quad \Delta H_i = 2\sqrt{C_{Ri}C_{Ti}}\sin\left(\frac{h_{Ri}-h_{Ti}}{2}\right) \qquad (1)$$

C_R and C_T represent chroma for reference and test hue stimuli and h_R and h_T denotes the hue angle of reference and test hue stimuli. Note that, as recommended by Li et al. [3] , instead of using root mean square (RMS) of perceptual hue difference, the mean perceptual hue difference is used to measure overall the predictive hue error.



(a) (b) (c) (d)

***Figure 4**. Hue angle differences between predicted hue attributes and observed unique hue stimuli under different illuminants for red (a), green (b), blue (c) and yellow (d).*

The optimal parameter R_{adp} is equal to 0.75 and 0.80 for D65 and CWF room lightings, respectively. In Table 6, the performance of recommended (R) [6] and optimised (O) adaptation ratios for CAT in CIECAM02 are evaluated by calculating mean perceptual hue differences (ΔH) between the reference hue stimuli and test stimuli predicted by the proposed CAT method. The hue shift for each of 9 stimuli with different lightness-chroma levels is also illustrated in Figure 4.

Table 6. Mean perceptual hue difference in CIECAM02 for unique hue stimuli under two illuminants

$\overline{\Delta H}$	*UR*	*UG*	*UY*	*UB*	*Mean*
Dark vs. D65-(R)	1.0	1.6	0.8	2.4	1.4
Dark vs. D65-(O)	1.7	1.2	0.6	0.9	1.1
Dark vs. CWF-(R)	3.8	6.4	3.0	4.1	4.3
Dark vs. CWF-(O)	5.3	4.7	1.5	1.5	3.3

Overall the optimised ratios achieved better performance than the recommended ratio for both D65 and CWF ambient lighting conditions. Specifically, the ratio suggested by this study can

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achieve as good results as the recommended for UR and UG but to provide a sound improvement for UY (CWF only) and UB (D65 and CWF).

Conclusions

Unique hue judgments from a large number of colour-normal observers (n=185) were obtained under two different room lighting conditions using a CRT display. These unique hue data were used to evaluate the performance of a mixed [6] chromatic adaptation transform of CIECAM02 for two lighting conditions by measuring least perceptual hue differences between predicted and observed pairs of unique hues stimuli. The evaluation of the performance resulted in large predictive errors particularly when the light source of the room had large deviation from the white point of the monitor.

In most respects, the current CIE recommendation ($R_{adp} = 0.6$) for the mixed chromatic adaptation model produced an unsatisfactory performance in terms of perceptual hue shifts indicating that the current form of chromatic adaptation transform needs to be modified to accurately reflect the hue shift for mixed illumination conditions. Using optimised ratios for D65 (R_{adp} =0.75) and for CWF room lightings (R_{adp} =0.80), the mixed chromatic adaptation outperformed the recommended chromatic adaptation model for both mixed lighting conditions. Our experiments reflect fairly common viewing conditions, where observers look at displays with sufficient ambient illumination to allow comfortable viewing.

This study complements existing research on CAM for mixed and full chromatic adaptation transform by proposing (1) a new method to evaluate the performance of CAT for colours on CRTs without the need of an external reference, and (2) two optimised adaptation ratios which predict more accurately hues attributes on display devices viewed in two different ambient illumination conditions.

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