Incomplete Chromatic Adaptation under Mixed Illuminations

Suchitra Sueeprasan and Ronnier Luo
Colour & Imaging Institute, University of Derby
Derby, United Kingdom

Abstract

A set of psychophysical experiments was conducted to investigate the state of adaptation between hardcopy and softcopy images when viewed under mixed illuminations. The experimental procedures closely followed the guidelines of the CIE Technical Committee TC8-04 *Adaptation under Mixed Illumination Conditions*. Three chromatic adaptation transforms (CMCCAT97, CMCCAT2000 and CIECAT94) and the S-LMS mixed adaptation model were evaluated. Each chromatic adaptation transform includes an adaptation ratio. This experiment was intended to find the best ratio for each model. Paired comparison technique was used to determine the degree of colour match between the print originals and softcopy reproductions viewed under different illuminants (or white points). The simultaneous binocular matching method was employed. The experiment was divided into nine phases in accordance with a change of illuminants and luminance levels of the ambient light. Fifteen observers took part in each experimental phase. The results reveal that the state of adaptation of human visual system is about 40-60%, and this is independent of illumination conditions. Reliable CATs with a proper incomplete adaptation ratio are capable of producing appearance colour matches under mixed adaptation. Overall results show that CMCCAT2000 and CMCCAT97 gave better performance than CIECAT94 and S-LMS mixed adaptation model.

Introduction

The use of colour management systems to reproduce colour images is commonplace in colour imaging industries. For example, in the pre-press industry hardcopy images are often reproduced and viewed on a computer monitor as a soft proof prior to making a final print. Due to the fact that colours appear differently when viewed under different viewing conditions, and viewing configurations of various media differ from one another, the reproduction of the image on the monitor does not generally match the original hardcopy print. In this case, to achieve an accurate cross-media colour reproduction, one needs a colour appearance model (CAM) which is capable of predicting the corresponding colours from one set of viewing conditions to another. In general, CAMs comprise 3 parts: a chromatic adaptation, perceptual correlates, and a uniform colour space. However, only the chromatic adaptation plays a vital role for accommodating between two different illuminations in two media viewing conditions.

In 1997, CIE recommended the CIECAM97s model[1] as a colour appearance model for general use. The model was derived based on the assumption that a colour was viewed under a steady state of adaptation. However, in many colour-imaging applications, softcopy and hardcopy images are viewed simultaneously. In such cases, the state of adaptation for the human visual system is not complete. The Internet shopping where one looks at coloured goods on the web and makes an order is an example. Not only do the differences in colour temperature of the office lighting and the computer display alter the colour appearance of the goods, but also the differences in luminance levels. One may then find the colours of the actual goods much different from what one sees on the web when comparing them side-by-side. This is because the human visual system partially adapts to the colour of the ambient light and partially to the monitor's white. Hence CIECAM97s which attempts to predict colours under complete adaptation would fail to produce the perceived colour matches. In order to achieve the accurate matches, the use of incomplete adaptation in CIECAM97s must be well understood.

In recent years, a number of experiments[2-5] were carried out to establish the state of mixed chromatic adaptation. The S-LMS mixed adaptation model[5] proposed by Katoh et al was specifically developed for such applications. They also found that an image of a 60% of adaptation to the monitor's white point was most preferred for hardcopy and softcopy comparisons. Nevertheless, an understanding of applying CIECAM97s in mixed adaptation is of great interest. Recently, a study by Henley and Fairchild[6] showed promising results for the use of CIECAM97s in predicting cross-media colour reproduction under mixed illuminations. Their results showed that the model's performance could be improved by changing the incomplete adaptation factor. However, they did not report the ratio and the experimental data were not sufficient to suggest the best value. In addition, only simple colour patches rather than complex images were used in the experiments.

This study aimed to gather more data for further improvement of the performance of CIECAM97s for cross-media reproduction under mixed illuminations. Appearance matches between the two most commonly used media, i.e. hardcopy prints and CRT displays, were investigated using complex images. The performance of CMCCAT97[7] together with CMCCAT2000[8] was investigated because the former is a chromatic adaptation transform (CAT) used in CIECAM97s and the latter is its simplified version. The performance of CIECAT94[9] was also investigated. This transform was originally recommended for field trial by CIE in 1994. At a later stage, Nayatani et al[9] modified the original model by adding a new equation for the degree of incomplete adaptation. This latest transform named CIECAT94 was used in this study. The performance of these CATs was compared with the Katoh's mixed adaptation model[5]. The experiments were conducted under the guidelines of the CIE TC8-04 *Adaptation under Mixed Illumination Conditions*[10].

Experimental Set-up

The experiments were performed to evaluate relative performance between the most promising CATs (CMCCAT97, CMCCAT2000 and CIECAT94) and S-LMS mixed chromatic adaptation model under mixed illuminations. Additionally, it was intended to quantify the degree of adaptation so as to gain a better understanding of how to model such psychophysical effects. Thus, the incomplete adaptation factors for each CAT were varied to define the state of adaptation from one illuminant to the other. In the case of S-LMS model, the adaptation ratio, R_{adp}, was varied whilst the incomplete adaptation was left to be determined by the model itself. The values were altered from 0.2 to 0.8 at 0.2 intervals. The extreme points (0 and 1) indicating complete adaptation either to hardcopy or to softcopy were not included as it was considered not to be an issue in this experiment. Note that the CATs tested are the original models with no incorporation of mixed adaptation. This was done for simplicity and to examine whether simply changing incomplete adaptation factors is sufficient to achieve successful appearance matches under mixed illuminations.

Four different complex images were used in the study: party, picnic, pier and bottle. Party is an image of a lady shot indoors with a greyish background. Picnic consists of three different race ladies sitting on a green field under a blue sky. These two images are provided by the CIE/TC8-04 at: http://www.colour.org/tc8-04/test_images/Sony. Pier is an outdoor scene containing buildings and a blue sky. Bottle is a picture of metallic objects with lustrous appearance shot indoor against a neutral background. The latter two images were selected from the SHIPP[11] standard images.

Hardcopy images were used as originals. They were printed on glossy papers using a Kodak Color Proofer 9000A at a resolution of 200 dpi. The hardcopies were captured using an Agfa StudioCam digital camera at 300 dpi in order to convert the images to digital form and transform to obtain softcopy reproductions. The digital camera was characterised by means of a polynomial regression technique[12] with an accuracy of 2.82 ± 1.59 (an average ΔE^*_{ab} ± standard deviation) units based on 144 random colours. Softcopy images were displayed on a Calibrated Barco monitor at 72 dpi with the same physical size as that of the hardcopy. The monitor was characterised using the GOG model[13], and its accuracy was 0.23 ± 0.13 ΔE^*_{ab} units based on 27 test colours.

The experimental conditions were designed with two main variables (illuminant and luminance level) which are considered to have a strong impact on colour appearance. Three alternative illuminants were used to illuminate the experimental room: a CIE Illuminant D50 simulator (CCT = 4964K), an Illuminant A (CCT=2478K) and a typical office lighting (Cool-white Fluorescence with a CCT of 3867K). These are referred to as D50, A and CW, respectively, throughout the paper. The paper white was chosen as the reference white for the hardcopy. Its luminance levels were set up either at high level, approximately 60 cd/m^2, or at low level, approximately 10 cd/m^2. The monitor's white point was set to a CCT of 9300K (referred to as D93). Its luminance levels were also varied in the same way, i.e. high level at approximately 60 cd/m^2 and low level at approximately 10 cd/m^2. A summary of the experimental conditions is given in Table 1.

Table 1. Experimental conditions.

Phase	Illuminant		Luminance Level	
	Print	CRT	Print	CRT
1	D50	D93	High	High
2	D50	D93	Low	High
3	D50	D93	Low	Low
4	CW	D93	High	High
5	CW	D93	Low	High
6	CW	D93	Low	Low
7	A	D93	High	High
8	A	D93	Low	High
9	A	D93	Low	Low

The print original having a 5-mm white border was presented on a uniform grey cardboard with 20% of the luminance of the reference white (paper white). The cardboard had the same physical size as that of the CRT's screen and was placed next to the monitor in a way that the hardcopy and softcopy were viewed at the same plane. A pair of softcopy reproductions was displayed on a uniform grey background with 20% of the luminance of the monitor's white point and was surrounded by 100% white border 5 mm wide. The experimental set-up is illustrated in Figure 1.

Fifteen normal-colour vision observers took part in each experimental phase. Observers sat in the middle between the monitor and the cardboard at a distance of 50-60 cm from the target images. Before carrying out the experiment, they were given approximately a minute to adapt to the environment of the room. They were then asked to identify a closer colour-match image to the print original from a given pair of softcopy reproductions. The simultaneous binocular (SMB) matching technique[14] was used. Note that the hardcopy was placed in the middle of the cardboard, so there was space between the hardcopy and softcopies. This necessitated each observer moving his eyes at some distances for image comparisons. No time restriction was placed on the observers.

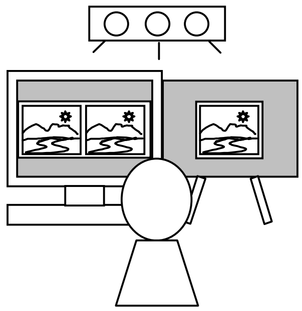

Figure 1. Experimental set-up

The experimental raw data were converted to an interval psychophysical scale using Thurstone's law of comparative judgement.[15] A 95% confident interval was calculated to indicate significant differences in performance between the models.

Results and Discussions

An inter-observer variance is presented in terms of a percentage of wrong decision[16] (%WD), the percentage of times that an observer made the wrong decision. The results are summarised in Table 2.

Table 2. Observer variance (% WD).

Phase	Party	Picnic	Pier	Bottle	Mean
1	26	24	27	24	25
2	15	9	12	13	12
3	18	25	21	20	21
4	19	25	18	16	20
5	18	17	19	17	18
6	19	18	15	17	17
7	15	8	17	19	15
8	13	17	18	14	16
9	20	22	24	20	17
Mean	18	18	19	18	18

The highest variation was found in Phase 1. This reveals that the differences between images generated by different models were small and observers found it difficult to make a confident judgement over some pairs. The results also show that the agreement between observers' results tend to increase when the differences between two adapting fields were large. Hence, the models performed more distinctly in these experimental phases. For example, the change in colour temperature in Phase 4, from CW to D93, was smaller than that in Phase 7, from A to D93, and the %WD clearly show the better agreement in Phase 7 over Phase 4. Not much variation was found between different images in each phase.

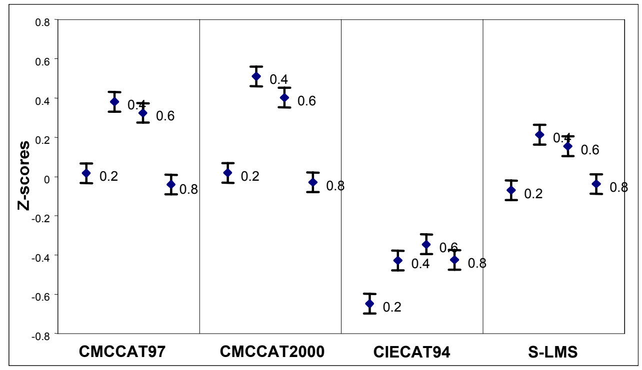

Figure 2. Models' performance combined from nine phases.

The overall results combined from nine phases are summarised in Figure 2. The results show the similar trends between the models in terms of the state of adaptation. This reveals that human visual system is between 40% and 60% adapted to the monitor's white point under mixed illumination conditions. This agrees with the results from the previous studies by Berns and Choh[2] and Katoh et al[5]. Additionally, it was found that CMCCAT2000 gave the best performance, followed closely by CMCCAT97. It is expected that the performance of these two models is very similar as the result of their similar structure. CMCCAT2000 not only has a simpler structure but also predicts more accurate to all available corresponding-colour datasets than CMCCAT97, which was derived to fit only one dataset. Thus, it is encouraging that CMCCAT2000 performed slightly better. Note that CMCCAT97 is the chromatic adaptation transform used in the CIECAM97s colour appearance model. Hence, a replacement of the CAT in CIECAM97s could further improve and simplify the model. It is also worthy to note that the S-LMS model, which was specifically designed for mixed adaptation conditions, did not outperform the CATs in all cases. This indicates that the CATs, which were derived under single-state adaptation, are also capable of predicting colour reproductions under mixed illuminations. However, the incomplete adaptation factor must be chosen carefully so as to enable the colour matches.

The results from the same illuminants but different luminance levels conditions were combined to investigate luminance level dependency. The results are summarised in Figure 3. It was found that the best ratios for each model were between 0.4 and 0.6 regardless of the luminance conditions. This reveals that the adaptation ratios are not affected by the luminance changes. There were large differences between models' performance in Low-High condition. CIECAT94 with the proper adaptation ratio produced similar colour matches to S-LMS with the best ratio under High-High but very much worse under Low-

High condition. Whilst S-LMS performed equally to CMCCAT2000 under Low-High, it gave rather different results under Low-Low. This indicates that some models do not perform well under some luminance levels.

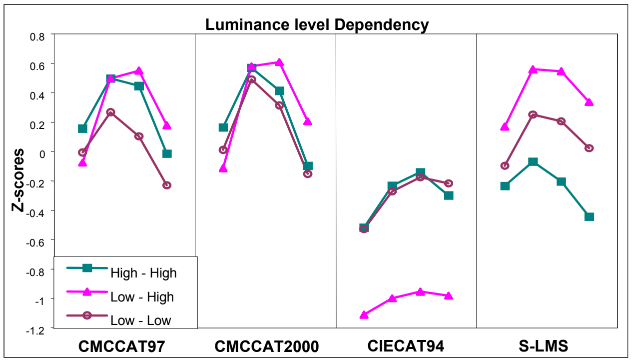

Figure 3. Models' performance of various luminances conditions

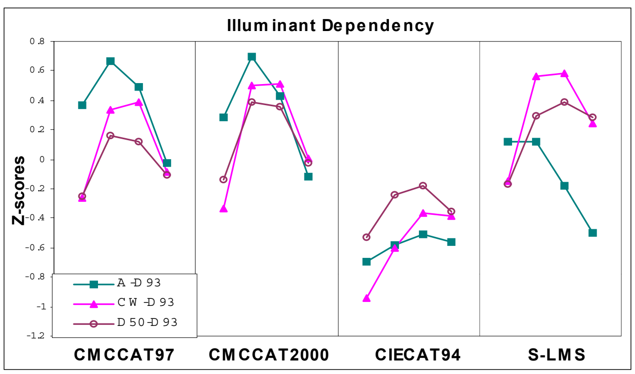

Figure 4. Models' performance of various illuminants conditions.

Figure 4 shows the results combined from the same luminance levels conditions to investigate the effect of illuminants. It shows that the state of adaptation is independent of the illuminant changes. However, the variation of models' performance under different illuminants was found. CIECAT94 performed much worse than the other models under A-D93 condition but not much differently under D50-D93. S-LMS gave very similar performance to CMCCAT2000 under CW-D93 but not A-D93. It can therefore be concluded that some models' performance is dependent upon the illuminant conditions.

Image dependency was also investigated by combining all results from nine phases for each image and can be seen in Figure 5. The results were highly consistent. It shows that models' performance is not affected by image content. This confirms the observer variation (%WD) results that there is not much variation between different images.

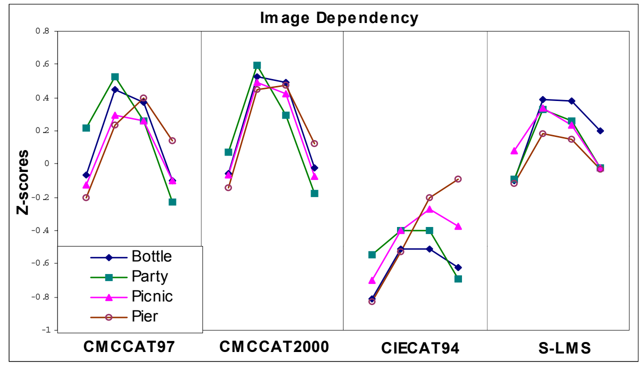

Figure 5. Models' performance of different images.

Conclusions

The performance of three chromatic adaptation transforms was investigated in comparison with that of the mixed adaptation model. The experiments were designed to evaluate the best adaptation ratio for hardcopy/softcopy image comparisons under mixed illumination conditions. Illuminants and luminance levels of the ambient light were varied. The results show that the state of adaptation of human visual system is approximately 40 to 60% adapted to the monitor's white point and independent of the illuminants and luminance levels used. On the other hand, models' performance depends upon the ambient lighting conditions. When the differences between the hardcopy and softcopies' adapting fields were small, all models performed similarly. But when the differences were large, some models would badly fail to produce good matches and show relatively worse performance. Models' performance was not affected by image content. Overall, the better transforms such as CMCCAT97 and CMCCAT2000 gave most accurate predictions regardless of the illuminants, luminance levels and images used.

The results show that the incomplete adaptation ratio is crucial in producing a matching colour image. By applying the proper ratio, CMCCAT97 could perform at least equal to or better than the S-LMS mixed adaptation model. The CATs investigated here were the original models without incorporation of mixed adaptation. This indicates that a reliable CAT is sufficient for the mixed-illuminant applications. As CMCCAT97 is the CAT used in the CIECAM97s model, this implies that CIECAM97s with a 50% of adaptation ratio should give accurate prediction in cross-media colour reproduction under mixed adaptation. CMCCAT2000 gave very similar performance to that of CMCCAT97, yet slightly better and always the best. It is a simplification and further improvement of CMCCAT97. This suggests that the performance of CIECAM97s could be improved with a replacement of the simpler chromatic adaptation transform.

Acknowledgements

The authors thank Dr Peter Rhodes and Professor Tony Johnson for technical advice. Time and patience of observers who took part in the experiments is highly appreciated.

References

1. M.R. Luo and R.W.G. Hunt, The structures of CIE1997 colour appearance model (CIECAM97s), *Color Res. Appl*. **23**, 138-146 (1998).
2. R.S. Berns, and K.H. Choh, Cathode-ray-tube to reflection-print matching under mixed chromatic adaptation using RLAB, *J. Elec. Imaging* **4**, 347-359 (1995).
3. N. Katoh, Practical method for appearance match between soft copy and hard copy, *Proc. SPIE* **2170**, 170-181 (1994).
4. N. Katoh, Appearance match between hard copy and soft copy under mixed chromatic adaptation, *Proc. IS&T/SID Color Imaging Conference* **3**, 22-25 (1995).
5. N. Katoh, K. Nakabayashi, and M. Ito, Effect of ambient light on the color appearance of softcopy images: Mixed chromatic adaptation for self-luminous displays, *J. Elec. Imaging* **7**, 794-806 (1998).
6. S. A. Henley and M.D. Fairchild, Quantifying mixed adaptation in cross-media color reproduction, *Proc. IS&T/SID Color Imaging Conference* **8**, 305-310 (2000).
7. M.R. Luo and R.W.G. Hunt, A chromatic adaptation transform and a colour inconstancy index, *Color Res. Appl*. **23**, 154-158 (1998).
8. C. Li, M.R. Luo, and B. Rigg, Simplification of the CMCCAT97, *Proc. IS&T Color Imaging Conference* **8**, 56-60 (2000).
9. Y. Nayatani, T. Yano, K. Hashimoto, and H. Sobagaki, Proposal of an abridged color appearance model CIECAT94LAB and its field trials, *Color Res. Appl.* **24**, 422-438 (1999).
10. http://www.colour.org/tc8-04/Experiment-guideline.html, Dec., 2000.
11. K. Sakamoto, and H. Urabe, Standard High Precision Pictures: SHIPP, *Proc. Color Imaging Conference* **5**, 240-244 (1997).
12. G. Hong, M.R. Luo, and P.A. Rhodes, Colorimetric characterisation for digital cameras, *Proc. ICPS'98 International Congress on Imaging Science* **2**, 354-357 (1998).
13. R.S. Berns, Methods for characterizing CRT displays, *Display* **6**, 173-182 (1996).
14. K.M. Braun, M.D. Fairchild, and P.J. Alessi, Viewing techniques for cross-media image comparisons, *Color Res. Appl*. **21**, 6-17 (1996).
15. L.L. Thurstone, A law of comparative judgement, *Psycholog. Rev*. **34**, 273-286 (1927).
16. R. McDonald, Industrail pass/fail colour matching part I-Preparation of visual colour-matching data, *J. Soc. Dyers Col*. **96**, 372-376 (1980).