20 Years of Colour Appearance Research at CIC

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Abstract

The CIC has been an important platform to disseminate research results in colour science since its first conference in 1993. This paper reviews the colour appearance research at CIC over the last two decades. It is divided into three stages: before 1997, between 1997 and 2002, and after 2002. Before 1997, some colour appearance models were developed and the psychophysical data were accumulated to develop and verify the models. In 1997, CIECAM97s was recommended by the CIE. In 2002, its refined version, CIECAM02, was recommended. After the 2002, new experiments were conducted to extend the functions of CIECAM02.

INTRODUCTION

Colour appearance research can be divided into two directions. One is to consider colour aspect of objects and images. The other is the extension of colour aspect to the spatial domain. Fairchild (Pattanaik *et al*, 1998) introduced the concept of 'spatial vision and colour appearance' and he then proposed image colour appearance model, ICAM (Fairchild, 2002) predict the appearance of images. He will review the progress on spatial based colour appearance modelling in a separate talk at CIC20.

COLOUR APPEARANCE RESDEARCH BEFORE 1997

Since Wright (1934) started colour appearance research in his famous colour matching experiment, many researchers had developed visual colorimeters to produce colour matches under two sets of viewing conditions. An example is given in Figure 1, in which an observer viewed from an eyepiece and saw the left field by one eye and the right field by the other eye. After allowing time to adapt, one eye is adapted to illuminant D65 and the other to illuminant A. The observer is then asked to adjust the stimulus, *C2*, seen by one eye to match *C1* seen by the other eye by altering amounts of red, green and blue lights. The aim is to produce 'corresponding colours' (CC), i.e. two sets of XYZ values match when viewed under two specific backgrounds.

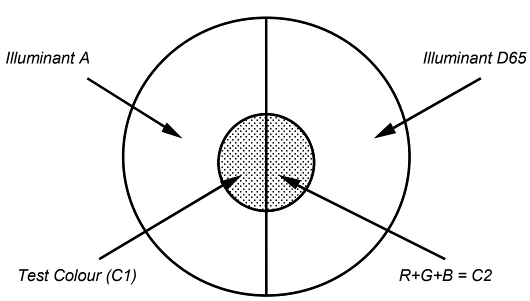


Figure 1*. A typical viewing condition used in the haploscopic matching experiment.*

The technique is considered to be unpleasing because of constrained eye movement and two eyes in competition with each other due to binocular rivalry.

After 70s, magnitude estimation method became more widely used to avoid the problems of the above haploscopic method. The team led by Luo carried out the work to accumulate data, named LUTCHI, and the data were described by Luo and Rhodes (1998) including over 10,000 estimations in terms of the visual attributes of lightness, colourfulness and hue under about 20 sets of viewing conditions. The data were also used to test the colour appearance models at that time such as CIELAB (CIE, 2004a), RLAB (Fairchild, 1996a) and LLAB (Luo *et al*, 1996), Hunt (1994), and Nayatani (1997). Hunt (2003) introduced his model in the first CIC as a keynote speaker. Since then, colour appearance has become a hot topic at CIC. In this paper, the author intents to refer to mainly the CIC papers to reflect the contribution of colour appearance research.

Before 1997, some papers were given at CIC to introduce the model testing using pictorial images. This is mainly contributed from the Fairchild's group. Kim *et al* (1993) proposed the successful-Ganzfeld technique to overcome the problem of haploscopic matching. Observer's one eye will look one field at a time, while the other eye was adapted in a neutral background of the other illuminant. Hence, more complete adaptation can be achieved. Fairchild (1994 and 1996b) and Braun and Fairchild (1995 and 1996) assessed colour appearance of images by devising different experimental methods and their results were used to evaluate the performance of colour appearance models. These papers generated large interests from imaging field for assessing the colour reproduction quality.

In the CIE 1996 Expert Symposium (1996), there was a strong demand from industry to recommend a model of colour vision for image applications. There were heated discussions on the major principles to be included in the new CIE model. These were:

- To predict well the basic visual phenomena in order for the model to be used in a variety of applications.
- To adopt a function to cover a wide range of stimulus intensities by setting a maximum in the dynamic range.
- To cover a wide range of viewing conditions including backgrounds of different luminance factors, and simplified media (surround) viewing conditions: average (such as prints, coatings, textiles, etc), dim (such as broadcast television) and dark (projected images).
- The spectral sensitivities of the cones should be a linear transform of the CIE 1931 or 1964 standard colorimetric observers, and the $V'(\lambda)$ curve should be used to approximate rod vision.
- The model should include an incomplete adaptation factor, which allows for adaptation between complete adaptation and none adaptation.

- The model should predict a wide range of percepts: hue angle, hue composition, brightness, lightness, colourfulness, chroma and saturation. All these percepts are important in certain applications.
- The model must be able to be reversed. This is particular important in colour management systems for imaging applications.
- The model should be no more complicated than is necessary to meet the above requirement.
- To include all the best features of all existing models to form new models.
- The model should perform better than or equal to the existing best colour appearance models in predicting the selected experimental data sets.
- It is necessary to have two models for dealing with all possible (comprehensive) and limited (but most frequent) applications respectively.
- To be able to switch on and off the rod vision for stimuli viewed under very low scotopic levels.
- The comprehensive model should be available for application to unrelated colours such as those seen in dark surrounds in isolation from other colours.
- The comprehensive model should be able to predict the simultaneous colour contrast effect.

In 1997, only a 'simple' model, CIECAM97s was recommended (Luo and Hunt, 1998a). The model gave an overall best performance for predicting the LUTCHI dataset, i.e. best to predict lightness and hue, and ranked second for predicting the colourfulness results (close to the best Hunt model). The performance of CIECAM97s is considered to be highly satisfactory and it was agreed by CIE TC1-34 members in 1997 to recommend the CIECAM97s model for general industrial applications (CIE, 1998).

BETWEEN 1997 AND 2002

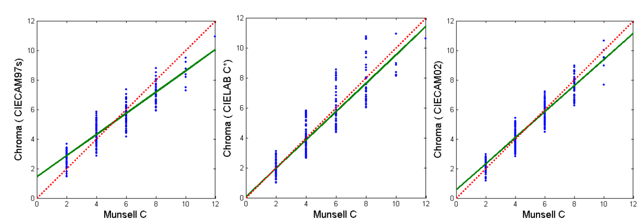
Since the recommendation of CIECAM97s, a new TC8-01, *Colour Appearance Modelling for Colour Management Systems*, was formed to evaluate CIECAM97s for its predictions of colour appearance, and its appropriateness for engineering and implementation requirements for open colour management systems.

One topic closely associated with colour appearance research is chromatic adaptation transform (CAT). The one imbedded in CIECAM97s is CMCCAT97 (Luo and Hunt, 1998b). It had a power function in the blue channel and make an analytical reverse mode to be impossible. The workers in International Color Consortium (ICC) use a simplified CAT by removing the power factor and call it 'Simple BFD' CAT. Li *et al* (1999) then developed an iterative method to make CNCCAT97 reversible. Li *et al* (2000) further developed CMCCAT2000 to simplify the model and give more accurate prediction to the visual corresponding data. Later, they devised a new CAT by fitting the CC data without the McCann dataset which were generated under unnatural illuminant, i.e. highly saturated low luminance level. The McCann data behave quite different as the other datasets. This CAT was known as CAT02 as part of CIECAM02. Finlayson and Susstrunk (2000) also developed a new CAT, called 'sharpened sensors'. Calabria and Fairchild (2001) compared various CATs. They found that the results from different CATs are not very largely different.

Another topic was also involving chromatic adaptation under mixed adaptation conditions, which consider the chromaticity of peak white of displays is different from that of the illuminant used. Hence observers adapted under two competed adaptation. Henley and Fairchild (2000) found that by optimising the best ratio between the two adapting illuminants, all chromatic adaptation transforms greatly improve their performance in predicting visual results. CIECAM97s already equipped with a factor D (incomplete adaptation factor) can do the job very well. Sueeprasan and Luo (2001) found that to set the D factor with a percentage of 40-60% between the monitor white and illuminated white can predict the effect of incomplete adaptation quite well. This was agreed with the finding of. CIE TC8-04 Chromatic adaptation under mixed illumination conditions (CIE, 2004b) adopted a mixed chromatic adaptation model for real applications.

Hunt (2001) gave a keynote speech on 'Saturation, Superfluous or Superior? described the difference between percepts of colourfulness, chroma and saturation and introduced the psychophysical method devised by Juan and Luo (2002) for assessing saturation by the painted cubes. Their results were used to modify the saturation scale (s) in the CIECAM97s.

In 2004, CIE TC8-01 recommended a new model: CIECAM02 (Morony *et al*, 2002; CIE, 2004c). It is not only a refinement of CIECAM97s, removing many shortcomings, but also an improvement giving equivalent or better predictions of colour appearance dataset. A typical example is given here to show the anomalies of the predictions the chroma scale of CIECAM97s. Figure 2 plots the Munsell chroma data against the chroma predictions from (a) CIECAM97s, (b) CIELAB, and (c) CIECAM02. The results show that the CIELAB C_{ab}* scale gave the largest scatter comparing with the other two models, but it goes through the origi CIECAM02 model outperforms the other two models, i.e., it gives the smallest scattering of the data and converging to zero for neutral colours.



(a) (b) (c)

***Figure 2**. The predictions from (a) CIECAM97s, (b) CIELAB, and (c) CIECAM02 are plotted against the Munsell Chroma data. Both the 45^o line and the best-fit line are plotted.*

The followings summarise the difference between CIECAM97s and CIECAM02.

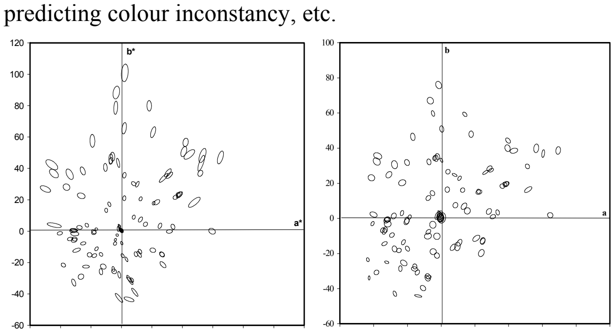
- To simplify and improve CMCCAT97 transform by adopting CAT02,
- To correct the error that the lightness (*J*) was not equal to zero for a stimulus having a *Y* tristimulus value of zero,

- To ensure that the sizes of the gamut volumes from the colour appearance model rank from the largest to smallest in the order of average, dim, and dark surround conditions,
- To improve the prediction of chroma for near neutral colours: it was reported that CIECAM97s predicts colourfulness and chroma too high for colours close to the neutral axis.
- To improve the fit to the saturation results accumulated by Juan and Luo (2002), which are the only available saturation data to test the colour appearance model.

AFTER 2002

After 2002, CIECAM02 has been rapidly spread. In some companies, it becomes a norm in their routine practice and they have implemented it to be part of their colour management system. In the research field, this period has been focused on the consolidate the model, the extension of the model and the derivation of new scales for applications.

Li *et al* (2003) extended CIECAM02 to become uniform colour space by fitting available datasets which were divided into large and small colour-difference groups for mean ΔE^*_{ab} smaller than 5 and larger than 10 respectively. The spaces developed were named CAM02-SCD and CAM02-LCD respectively. Also, a space called CAM02-UCS was fitted to the combined large and small data. After various testing, the results showed that the CAM02-UCS space dealing with colour differences with different ranges quite well. Figures 3a and 3b show the experimental ellipses accumulated for assessing colour-differences of homogeneous colour patches for CIELAB and CAM02-UCS respectively. It can be seen that all ellipses in the latter are more or less close to a constant radius circle and the sizes of the former ranged from smallest close to neutral axis to very large size ellipses for very saturated colours. It has also been used in colour rendering, predicting colour inconstancy, etc.



(a) (b)

***Figure 3**. The experimental ellipses plotted in (a) CIELAB and (b) CAM02-UCS.*

There are many viewing parameters in CIECAM02 such as background, surround and size effect. These were not precisely defined. Fu *et al* (2005, 2006) conducted experiments based on patches to verify the definition of Y value of the background and the change of viewing distance and field size between background and surround. Park *et al* (2006, 2007, 2008) intended to develop a colour management system for mobile-phone applications. After slight modifications to CIECAM02, the model predicts well to the visual results under a variety of the surround conditions facing mobile phone users.

Choi *et al* (2007, 2008, 2009) carried out the work for assessing image quality. They developed image quality percepts such as of naturalness, colourfulness, local contrast, based on CIECAM02. Jun *et al* (2010) developed the emotion scales of exciting and pleasantness for the pictorial images.

More recently, works were focused on new scales which are all based upon CIECAM02. Cho *et al* (2011) believed that the definition of the third colour percepts including 'colourfulness', 'chroma', 'saturation' are difficult to understand, which seem to have very similar meanings. In their study, they found that 'saturation' and 'vividness' seem to receive well by none colour science background users involving British and Korean observers. In addition, they are also studying NCS attributes such as 'blackness' and 'whiteness'. The above attributes based on CIECAM02

Although there have been many successful application of CIECAM02, some problems (Li *et al*, 2009) still remain such as failed for calculation of certain colours, CIECAM02 gamut is smaller than that of ICC, the HPE matrix and the brightness function. CIE TC8-11 *CIECAM02 mathematics* was established to tackle these problems. Good progress has been made and some problems will be resolved in the near future.

Hunt gave two keynote papers on 'The challenge of our known unknown' (Hunt, 2010) and 'The challenge of our unkown known' (Hutnt, 2011). In the former, it addressed some research (unknown) areas: the difference between Maxwell- and Saturation- colour matching methods, why sharpening helps the chromatic adaptation transform?, why unique hues different between different colour spaces?, why rods in hibited at high level of illumination? Why bluer white appear to be whiter, and black becomes blacker? How to improve the prediction of the colour rendering of white LEDs. For the latter, how the important knowledge of colour appearance to be applied. The typical onces include: to use u'v' rather than xy chromaticity diagram, to describe colour constancy, to explore the feature of colourfulness, satutation and chroma.

Finally, the author introduces CIE TC1-75 chaired by him (*A comprehensive colour appearance model*). It was established with an aim to extend the functions of CIECAM02. Again, many recent experimental datasets reported at CIC were included. Xiao *et al* (2003) reported the change of colour appearance between field sizes of 2^o to 50^o in real room. Later, they generated more experimental data for stimuli to cover a large size range and the models were developed to predict visual data accurately. Fu *et al* (2007) and Kwak (2003) conducted experiments to look into the unrelated colours under from phtopic to mesopic vision. In addition, the CAM02-UCS (see Figure 3b) will be included.

CONCLUSIONS

This paper reviews most of the papers in the field of colour appearance research published at CIC in the last 20 years. The CIC has proven to be one of the most prestigious conferences to present the research results of colour science. The milestones of colour appearance research are represented by the recommendation of the CIE on CIECAM97s, CIECAM02 and possibly the comprehensive colour appearnce model.

The future colour appearance areas still require new psychophysical experiments to extend more user friendly attributes such as saturation, vividness, whiteness, blackness. These new scales could be developed to apply for enhancing image quality. Also, with the increase attention on the LED lighting, there is a need to evaluate the lighting percepts such as spatial brightness and spatial uniformity in a lit environment

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