Comparison of Colour Harmony Models: Visual Experiment with Reflecting Samples Simulated on a Colour CRT Monitor

Ferenc Szabó, Peter Bodrogi, János Schanda
Virtual Environment and Imaging Technologies Laboratory, Department of Image Processing and Neurocomputing, Faculty of Information Technology, Pannon University, Veszprém, Hungary

Abstract

Colour harmony was investigated using direct visual observations of computer simulated displays and compared with predictions of different colour harmony theories. Ou and Luo [1] constructed a model of colour harmony (CH formula) based on a harmony pair comparison experiment. The present paper compares our results with harmony predictions of the CH formula, and of colour harmony models based on Munsell's[6] and Nemcsics's[8] work.
The visual impression of colour harmony is subject to changes when the light source illuminating the samples is changed from a reference source (e.g. D65) to e.g. an RGB LED based light source. Colour rendering quality of a light source might be characterized by the extent of the distortion of the perceived harmony of certain sets of test colour samples that are harmonious under the reference illuminant. This would yield a "colour harmony rendering index" which might supplement the current CIE colour rendering index.

Keywords: colour rendering, colour harmony, CRT simulation, LED light sources, CH formula

Introduction

The concept of colour harmony has been used for a long time in many fields of life (e.g. art, architecture, etc.). One possibility of a definition of colour harmony is as suggested by Judd and Wyszecki[2]: "when two or more colours seen in neighbouring areas produce a pleasing effect, they are said to produce a colour harmony". The observer's impression of "harmony" among the perceived colours of a set of reflecting colour samples under a given light source depends very highly on the choice of these samples constituting the set. Scientists and artists of the last centuries (e.g. Chevreul[3], Itten[4], Goethe[5], Munsell[6], Ostwald[7]) and today (e.g. Nemcsics[8]) developed their own colour systems and their own rules to establish harmonic sets of colours. To our best knowledge no systematic investigation was performed comparing above harmony scales. In this work, we will present a visual experimental method to quantify the visual impression of colour harmony. On a calibrated colour CRT monitor the appearance of certain surface colour samples illuminated by illuminant D65 were simulated. We used 8 sets composed of these samples, according to the prescriptions of 3 different theories [6, 8, and 9] of colour harmony.

Table 1.Types of colour harmony in the experiment to compare the Munsell and the Coloroid models

1.	Monochromatic harmonies
	a) same hue and value, but different chroma
	b) same hue and equal chroma, but different value
	c) same hue, increasing chroma, decreasing value
	d.) same hue, decreasing chroma, decreasing value
2.	Dichromatic harmonies
	a) complementary hues, equal chroma of 5, but different value
	b) complementary hues, equal chroma, but different value
	c) complementary hues, equal value, but different chroma
	d) complementary hues, different chroma and different value

Method

The perceived colour of the samples under a reference illuminant was simulated on the CRT monitor by using a computer program. Observers saw a harmonious set of samples on a grey background ($L^*=50$, x=0,313 y=0,331, D65 Y=20 cd/m^2) on the left half of the screen according to *one* theory of colour harmony. Another harmonious set of samples according to *another* theory of colour harmony could be seen on the right half. Observers had to answer the question of which half of the screen yielded a more harmonious visual impression. After that, they also had to scale their impression of colour harmony for each theory (or model) of harmony separately, on a 1-5 scale (5 corresponding to best harmony). We analyzed the types and rules of colour harmony in the Munsell system[6], and in the Coloroid system[8], using harmonious colour sets as shown in Table 1. We chose one surface colour sample as an anchor sample from the Munsell Atlas, and then, by using the Munsell and the Coloroid colour harmony models, we selected a harmonious sample or a harmonious pair of samples to this anchor colour sample, by using the Munsell Conversion Software v6.5.0 and the Coloroid Color Plan Designer 1.1 programs to transform sample notations into CIE tristimulus values.

Copyright 2006; Society for Imaging Science and Technology

In the RAL Design System[9], which is a manifestation of the CIELAB colour space, two colours are considered harmonious if their CIELAB lightness (L^*) values are equal and their CIELAB a^*, b^* coordinates have the same values but opposite signs.

We selected 10 anchor samples, and their harmonious counterpart with equal L^* but opponent a^* and b^* values by using the RAL® System 2.0 program. The harmonious counterparts for the 10 anchor samples in the Coloroid and Munsell harmony models were also chosen and their CIE tristimulus values were calculated. The CIE XYZ tristimulus values were reproduced on the calibrated CRT monitor. The anchor sample was visualized twice on the top, and the corresponding harmonious colour samples were visualized in one of the colour systems on the left-bottom, and in the other system in the right-bottom half of the screen (see Figure 2.b.).

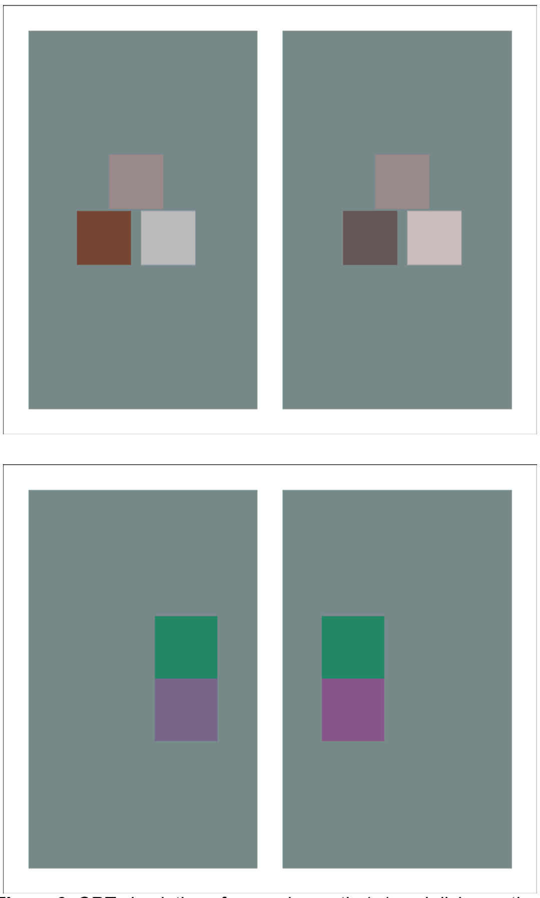


Figure 2. *CRT simulation of monochromatic (a.) and dichromatic (b.) harmonies. Sizes of all test samples are 5 x 5 cm.*

A computer program simulated the colour samples according to the monitor characterization model. A medium neutral grey, called N5 in the Munsell system, was used as background, with a 2 cm white border N9 of the Munsell system, to achieve the adaptation of the observer. 12 observers viewed the screen from a distance of 60 cm, as can be seen in Figure 3. This corresponded to a visual angle of 4.8 degrees. Their colour vision was controlled by the Farnsworth-Munsell 100 Hue test.

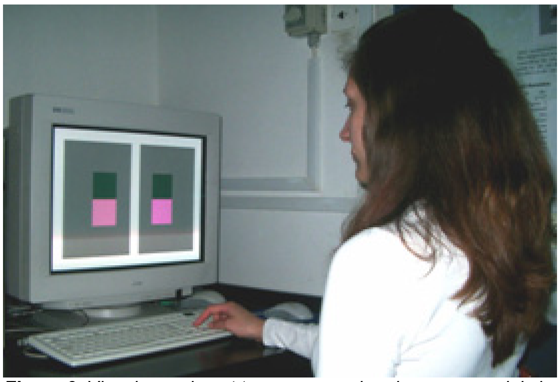
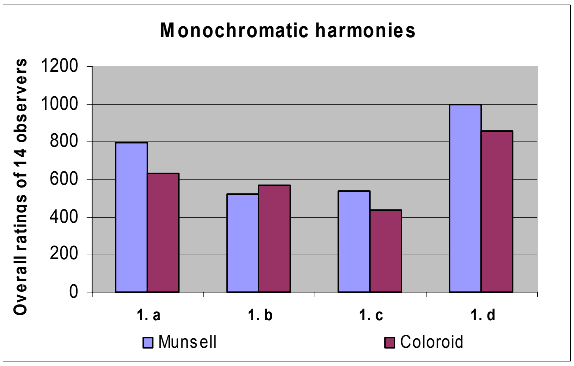


Figure 3. *Visual experiment to compare colour harmony models in a dark room*

Result and Discussion

In the following, the results of the visual experiments on comparing the theories of colour harmony [6, 8, 9] will be shown. In Figure 4.a, the rating of monochromatic harmonies can be seen. Results showed that observers found the appearance of the colour sets in the Munsell colour harmony model, in the case of monochromatic harmonies 1.a, 1.c, 1.d. slightly more harmonious than in the Coloroid model. Observers preferred monochromatic harmonies having equal chroma but different value (1.b) in Coloroid more, as opposed to Munsell. In case of dichromatic harmonies, the same tendency could be noticed. Complementary colours of opposite hues and equal chroma, but different value (2. b) had more rating points in the Coloroid model, than in Munsell's. All of our observers judged Coloroid more harmonious than Munsell for the test samples of set 2. b. Statistical analysis of the results is currently underway.

In Figure 5, the ratings of the 10 samples are shown to compare the RAL Design System with the two other systems. During the comparison of the RAL Design and the Coloroid Systems, observers found that the colour sets were more harmonious in the Coloroid model. In case of the comparison of the RAL Design and Munsell systems, the samples in the Munsell system were perceived to be slightly more harmonious than in RAL (see Figure 5).



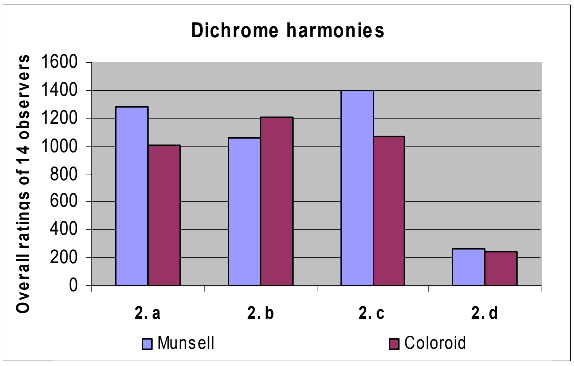
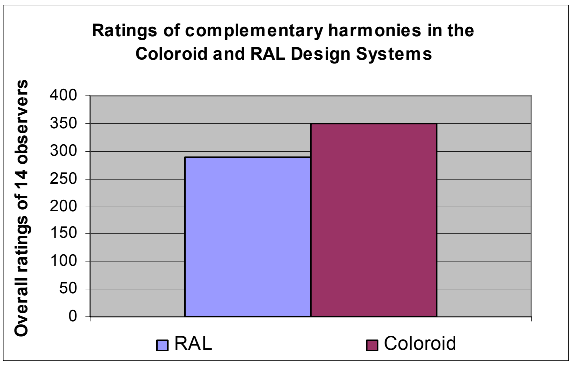


Figure 4. *Visual impression of colour harmony scaled on the scale 1-5 (5 = best) viewed by 14 observers. The height of each column corresponds to the sum of the ratings of all observers (ordinate). The types of colour harmony (abscissa): 1. a: monochromatic (same hue and value, but different chroma); 1. b: monochromatic (same hue and chroma, but different value); 1. c: monochromatic (same hue, increasing chroma, decreasing value); 1. d: monochromatic (same hue, decreasing chroma, decreasing value); 2a: complementary colours of opposite hues, equal chroma of 5, but different value; 2b: complementary colours of opposite hues, equal chroma, but different value; 2c: complementary colours of opposite hues, equal value, but different chroma; 2d: complementary colours of opposite hues, different chroma and different value.*



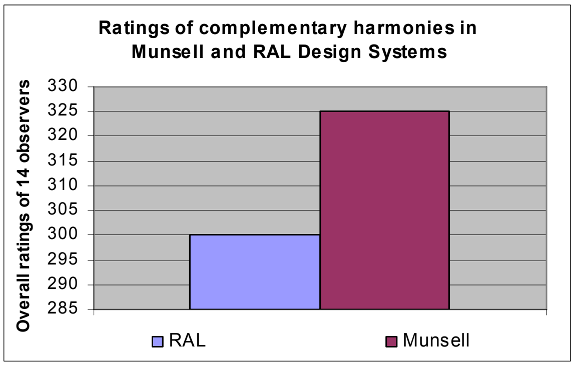


Figure 5. *Visual impression of colour harmony scaled on the scale 1-5 (5 = best) viewed by 14 observers. The height of each column corresponds to the sum of the rating scales of all observers (ordinate). Along the abscissa: The Color order systems observed: RAL Design, Coloroid.*

Illuminant (light source) dependence of colour harmony

In this phase of the experiments, we intended to study the harmony distortions produced by different light source spectra compared to the harmony found under CIE illuminant D65. The relative spectral power distributions of D65 and a white RGB LED cluster were used as reference and test light sources as shown in Figure 6. To implement this simulation, the spectral reflectance curves of Munsell chips were measured and their CIE XYZ tristimulus values under D65 were calculated. An earlier study in our laboratory[11] showed that CRT simulation represented reasonably well the colour perception of the paper sample. After that, a harmonious Munsell pair was visualized under D65 in the left half of the screen, and the same pair was shown on the right half of the screen under the white RGB LED light source for which the white point was set equal to D65.

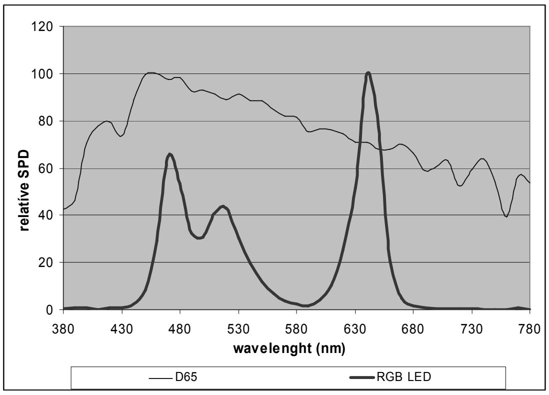
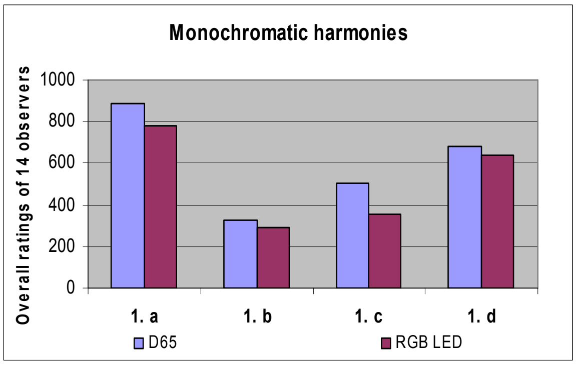


Figure 6. *Relative spectral power distributions of D65 (thin curve) and our test white RGB LED light source (thick curve).*

Copyright 2006; Society for Imaging Science and Technology



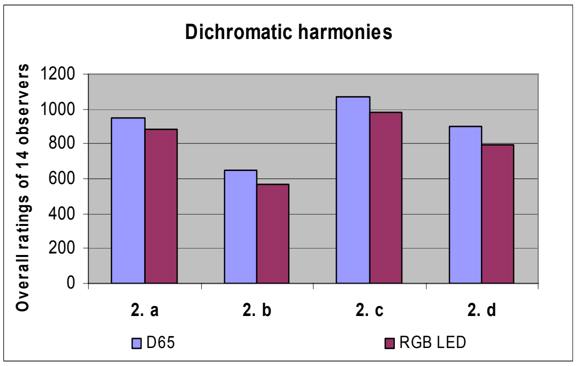


Figure 7. *Harmony impression of test samples illuminated by the reference illuminant (D65) and the white RGB LED light source. Harmony impression was scaled on the scale 1-5 (5 = best) viewed by 14 observers. The height of each column corresponds to the sum of the rating scales of all observers (ordinate). The types of colour harmony (abscissa): 1. a: monochromatic (same hue and value, but different chroma); 1. b: monochromatic (same hue and chroma, but different value); 1. c: monochromatic (same hue, increasing chroma, decreasing value); 1. d: monochromatic (same hue, decreasing chroma, decreasing value); 2a: complementary colours of opposite hues, equal chroma of 5, but different value; 2b: complementary colours of opposite hues, equal chroma, but different value; 2c: complementary colours of opposite hues, equal value, but different chroma; 2d: complementary colours of opposite hues, different chroma and different value.*

As can be seen in Figure 7, the observers' internal harmony impression falls off in case of every type of harmony we examined, by changing the reference illuminant to the white RGB LED light source.

Another type of harmony in the Munsell model, called "diminishing series" was also implemented as a further harmonious colour set. It contained 6 colours of different hues, values and chromas, by using 5 colours as test samples and 1 colour as a background (see Figure 8).

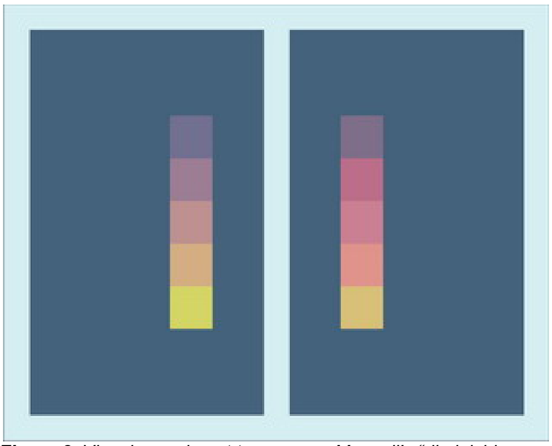


Figure 8. *Visual experiment to compare Munsell's "diminishing series" under the reference and the test illuminants.*

As can be seen from Figure 9, the result of our visual experiment was in agreement with the "distorting" picture of Figure 10, i.e. the visual harmony impression of the selected diminishing series was significantly better under D65 than under the white RGB LED light source.

It is interesting to look at the shifting of the CIELAB coordinates. In Figure 10, we depicted the CIELAB a^*, b^* coordinates of the member colours of a diminishing series under D65 illuminant and the white RGB LED cluster.

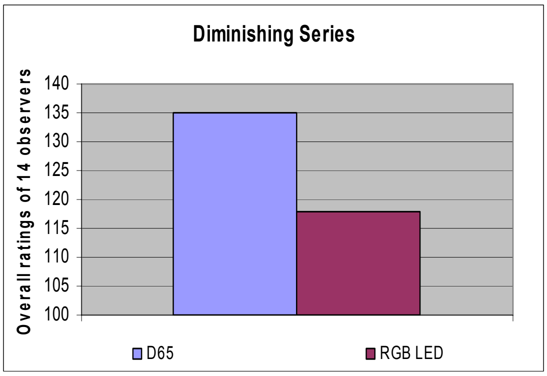


Figure 9. *Visual harmony impression of "Diminishing series" under reference and test illuminant, (rating of 14 observers on the scale 1-5 (5=best)).*

As can be seen from Figure 10, the directions and dimensions of the colour shifts are very different caused by the three-band spectrum of the white RGB LED light source (see Figure 6). This may be the reason for the distortion of the visual impression of colour harmony.

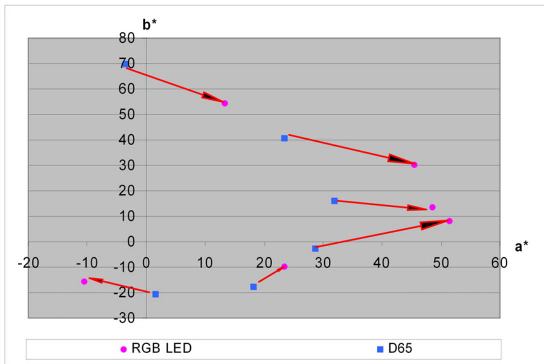


Figure 10. *Colour coordinates of a Munsell harmonious set called "Diminishing series" under a reference illuminant (blue squares), and under a white RGB LED light source (pink circles).*

Investigation of the CH formula

Similar to the concept of colour rendering[10], scaling the visual impression of colour harmony can be a very important new method to describe the perceived colour quality of the visual environment illuminated by different light sources. Several mathematical formulas are known trying to quantify the colour harmony impression. A so-called "CH formula"[1] was developed by Li-Chen Ou, Ronnier Luo, and their co-workers, at the University of Leeds, which describes the colour harmony impression of two-colour harmonies. This formula establishes a 10-degree scale ranging from -5 to +5. Positive values mean harmonious, negative values mean disharmonious pairs of colours. We examined the correlation between the results of our visual experiments and this CH formula[1].

First we selected 10 pairs of colours from 5 numeric domains of the predictions of the CH formula. Table 2 shows these 5 groups.

Table 2. The 5 numeric domains of the CH formula [1] selected for visual verification.

1.	+1 ≤ CH ≤ +1.39
2.	+0.46 ≤ CH ≤ +0.63
3.	-0.03 ≤ CH ≤ +0.1
4.	-0.57 ≤ CH ≤ -0.43
5.	-0.91 ≤ CH ≤ -1

All 10 pairs of colours were simulated on the monitor on a middle grey background (L^*=50, x=0,313 y=0,331, D65 Y=20 cd/m^2), with a 2 cm white border to achieve the adaptation of the observer.

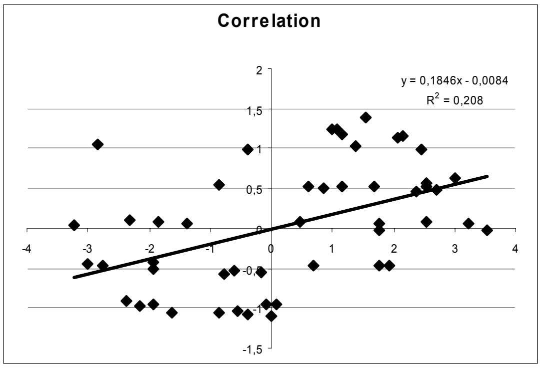


Figure 11. Correlation between the observers' judgement and the prediction of the CH formula.

We depicted the harmony judgments of our 14 observers and the predictions of the CH formula in the same diagram of Figure 11. As can be seen from Figure 11, there is some correlation (r^2=0.208; p=0.001) between our visual results and the predictions of the CH formula.

Whether the CH formula is also able to predict the *distortion* of colour harmony by using a test light source different from the reference light source, is a further question. To examine the effect of changing the illuminant, we chose 100 harmonious complementary colour pairs from the Munsell Atlas. We calculated their CH values under a reference illuminant (D65), and under a white RGB LED light source.

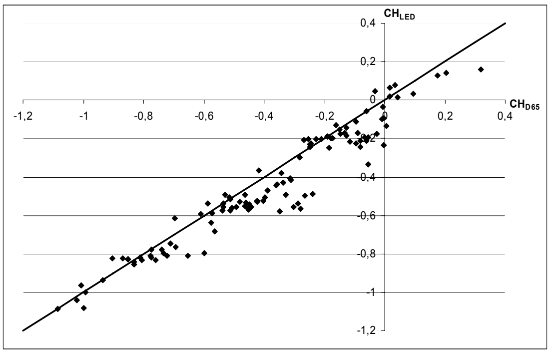


Figure 12. Predictions of the CH formula under D65 vs. the white RGB LED light source for 100 harmonious complementary colour pairs.

As can be seen from Figure 12, despite the fact that the CH formula evaluates sample pares predicted by Munsell to be harmonious differently, the change in harmony produced by the change of illuminating light source shows good correlation between the predictions for harmony under the two sources studied. (We used up to now two sources of extreme colour rendering, and further experiments have to show how it will change for less extreme colour rendering sources.) But the CH formula can be regarded as a candidate for a descriptor of the distortion of colour harmony by changing the light source and thus the CH formula is a candidate for a new colour quality descriptor of any light source.

It can also be seen from Figure 12 that the CH formula usually predicted negative values for the complementary colour pairs that should be harmonious according to Munsell. The reason for this may be that the early colour harmony models were elaborated by painters and psychologists while this mathematical formula was constructed by engineers having a "technological" point of view. It is necessary to check these computational results against visual experiments and these investigations are currently underway in our Laboratory.

By changing the test illuminant, the appearance of each harmonious colour pair changes. It may be very interesting to calculate the correlation between the CH value and the calculated colour difference between the reference illuminant and the test light source. The light sources we used for this computation and their CCTs are shown in Table 3.

Table 3. Test light sources used in the computational comparison of the CH values with colour differences

No.	Source	CCT
1	CoolWhite comp. fl. lamp	3875
2	3-band Polylux XL fl. lamp	3970
3	De Luxe CoolWh. Comp. fl. l.	3672
4	Halogen lamp 1	3953
5	CoolWhite fl. Lamp	4140
6	LED cluster 1	4008
7	White LED 1 (with phosphor)	7580
8	LED cluster 2	2935
9	White LED 2 (with phosphor)	4691
10	Halogen lamp 2	2983

 Copyright 2006; Society for Imaging Science and Technology

As can be seen from Table 3, our test light sources had very different CCTs and therefore we transformed the test samples by the aid of the CIECAM02 colour appearance model, and computed all colour differences by a recent CIECAM02 based formula optimised for large colour differences called LCD5CDE[12]. Then the CH values of the 80 test sample pairs under different test light sources (see Table 3) were also calculated and the colour difference values and CH values were averaged for each light source separately. Results are shown in Figure 13.

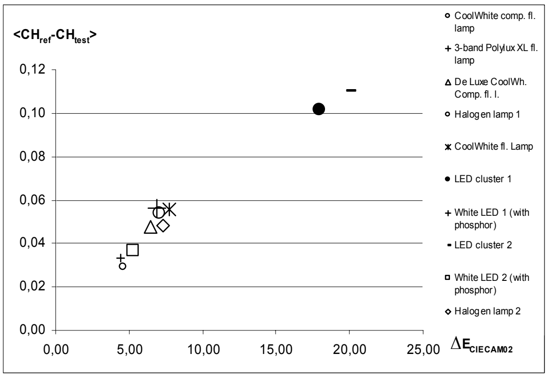


Figure 13. *Average of CIECAM02 colour differences and predicted CH values for 10 test light sources.*

As can be seen from Figure 13, both the colour differences and the CH value differences are high in case of the white LED with phosphor and RGB LED light sources. The smallest value occurs in case of the halogen lamps. A significant correlation (R^2=0.974, p=0.001) can be observed between the changes of the CH value and the computed colour difference values.

Conclusion

By comparing the theories of colour harmony, the superiority of the Munsell system can be proved for the case of the examined colour combinations except for monochromatic and dichromatic harmonies having equal chroma but different value.

Harmonious colour combinations harmonious under D65 will be less harmonious under the white RGB LED light source. We need to extend our experiments to show the effect of changing the illuminant to include other light sources like tungsten halogen lamps, and different types of fluorescent lamps. These investigations are currently underway.

We suggest characterizing a test light source by the extent of the distortion of the perceived harmony of certain sets of test colour samples that are harmonious under the reference illuminant. Therefore we are currently thinking of the concept of a so called "colour harmony rendering index" intended to supplement the current CIE colour rendering index.

References

[1] Li-Chen OU, Ming Ronnier LUO: A Study of Colour Harmony for Two-colour Combinations

[2] Judd DB, Wyszecki G. Color in Business, Science and Industry, Third Edition, John Wiley & Sons, New York, 1975

[3] Chevreul, M. E., The Principles of Harmony and Contrast of Colors. Translation by C. Martel (1854) from the French edition of 1839. Reprinted in 1981, New York: Van Nostrand Reinhold.

[4] Itten, J., The Art of Color. Translation by Ernst van Haagen from German "Kunst der Farbe". New York: Van Nostrand Reinhold, 1961.

[5] Goethe, J. W., Theory of Colours. Translation by C. L. Eastlake (1840) from the German "Farbenlehre" of 1810. Reprinted in 1970, Massachusetts: The MIT Press.

[6] R. Van Nostrand, Munsell: A Grammar of Color, Reinhold Book Coorporation, 1969.

[7] Ostwald, W., The Color Primer. Edition by F. Birren from the German "Die Farbenfibel" of 1916. Reprinted in 1969, New York: Van Nostrand Reinhold.

[8] A. Nemcsics, Farbenlehre und Farbendynamik, Akadémiai Kiadó, Budapest, 1993.

[9] http://www.ral.de/farben/en/index.html

[10] Commission Internationale de l'Éclairage. Method of Measuring and Specifying Colour Rendering Properties of Light Sources. CIE 13.3-1995.

[11] Ferenc Szabó, Norbert Sándor, Peter Bodrogi, János Schanda: "Colour rendering of white LED light sources: Visual experiment with colour samples simulated on a colour monitor" (International Lighting Congress and CIE Midterm meeting 2005 LEON, Spain)

[12] C. Li, M. R. Luo and G. H. Cui, Colour-Differences Evaluation Using Colour Appearance Models, 11th Color Imaging Conference, Scottsdale, Arizona, 2003

Acknowledgement

We would like to acknowledge Flexinform (http://www.flexinform.com) who allowed us to use the Coloroid Professional 1.1 program in our colour harmony computations. One author (P.B.) would like to acknowledge the support of the Bolyai János Research Scholarship of the Hungarian Academy of Sciences. An other author (J.Sch) acknowledges the support of the Miescher Foundation.

Biography

Ferenc Szabó holds a Masters Degree in Information Technology from the University of Veszprém, Hungary. He is a PhD student in Information Technology at the Pannon University (Veszprém), Department of Image Processing and Neurocomputing. His research topic is colour harmony and colour rendering.

Peter Bodrogi obtained his MS degree at the Eötvös Loránd University of Budapest (Hungary) as a research physicist in 1993. He obtained his PhD degree in 1999 in information technology at the University of Veszprem. Currently, he is associate professor at the Pannon University (Veszprém).

Janos Schanda, physicist, is DSc of the Hungarian Academy of Sciences and professor emeritus of the Pannon University, and current Secretary of the CIE.