Visual Colour-rendering experiments

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ABSTRACT

The colour-rendering index was introduced at the time when the second-generation fluorescent lamps (deLuxe type) have been brought onto the market. At the time of developing the compact fluorescent lamp phosphors, they have been optimised to achieve good efficacy and high colour rendering index, and not good visual colour rendering. Today, a major technological breakthrough has led to a new generation of light sources based on LED technology. The emission spectra of these is different from that of fluorescent lamps, thus optimising these to achieve a high colour rendering index could again lead to differences between calculated and observed colour rendering. Before one can recommend a new mathematical model for calculating a colour-rendering index, one has to re-investigate the existing model and its usefulness. In the present work we describe a series of visual investigations of three groups of LEDs with 4000 K correlated colour temperature and evaluate their correlation with the current method of colour rendering index as well as with possible updates of the calculation method. Also the question of updating the test samples gets consideration. Visual experiments have shown that the CIE Test Method is not a good predictor of visual perception. A method based on calculating colour differences using the CIECAM02 colour appearance model provides better correlation between visual and calculated colour rendering values. But to get to a proper colour rendering description the fundamental concept of determination has to be changed.

1. INTRODUCTION

LEDs get widespread use, not only as signal lights but for exterior and decorative lighting[1,2] automotive lighting[3] and start to penetrate into interior lighting[4,5] as well. For all white-light applications an up-to-date mathematical model for calculating colour-rendering index, correlating well with visual experiments is needed.

CIE introduced the current method for calculating a colour-rending index some thirty years ago[6]. During these thirty years several attempts have been made to update this publication and bring it in line with modern colorimetric practice (see e.g.[7]), but due to lack of the availability of convincing visual experimental data this has not taken place to date. Pilot experiments have shown that – in accordance with anecdotic earlier observations – the colour-rendering index does not always describe visual colour rendering correctly, especially in case of White LEDs (see CIE TC 1-62 interim report[8]).

The CIE Test Method[6] translates the definition of colour rendering[9] into selecting as a reference illuminant a Planck-radiator of the same correlated colour temperature (CCT) if the CCT of the test source is below 5000 K, and a phase of daylight of equal CCT if the CCT of the test source is above 5000 K. The next step is then to calculate the tristimulus values of selected Munsell test samples irradiated by both sources - perform a von Kries chromatic adaptation transformation if the chromaticity of the two illuminants is different - and calculate the colour difference for each test sample irradiated by the two illuminants. All colorimetric calculations have to be performed in the U*, V*, W* colour space. The final step is to convert the colour differences to a colour rendering index scale value and perform some averaging to get the general colour-rendering index R_a.

Several attempts were made during the last decades to extend or update the present method (see e.g.[7,10]), both by introducing new descriptors, such as a flattery index[11], a colour discrimination index[12], and by trying to introduce new basic calculation methods[13,14]. The general opinion of the lamp manufacturers was in all these cases that first one should re-check the present method using visual experiments.

Based on above considerations we started a series of experiments to first check the present test method by performing the steps of the recommended method using visual colour difference evaluation, and comparing these visual data with the present calculation method and with some possible updates of it. Results with a group of lamps at around 2700 K CCT was presented at the CIE San Diego Conference[15], in this paper we will report on investigations performed with a group of lamps with a CCT of 4000 K. A new calculation method should be suggested only if these experiments prove to be inadequate to describe colour rendering correctly.

2. VISUAL EXPERIMENTAL METHOD

The CIE Test Method is a mathematical version of a direct comparison of samples illuminated by the test source and a reference source, and the determination of the colour difference observed for each sample illuminated by the two sources. A double booth was constructed, where in one of the compartments a reference lamp illuminated the samples, in the other compartment different test light sources could be installed. Experiments were conducted with lamps of approximately 4000 K CCT. A lamp with good CIE colour rendering index was selected as reference and the other lamps as test sources.

During its debates, CIE TC 1-33 came to the conclusion that instead of the original CIE Test Samples (taken from an early edition of the Munsell Atlas), samples of the Macbeth Colour Checker Chart (MCC)[16] should be used. Two copies of the 24 sample edition of the MCC, placed in the two chambers of our visual observation booth were used in our experiments.

The task of the observer was to scale the visual colour difference between the corresponding chromatic samples of the MCCs. To aid the observer a grey scale was placed in the reference chamber, so that the observer could estimate the observed colour difference by comparing it to a given lightness difference of the grey scale. Observers were permitted to look into one or the other booth several times before they made their judgment. We tried to keep the chromaticity difference between the test and reference lamps low; so that the chromatic re-adaptation did not take a too long time.

3. OBJECTIVE MEASUREMENTS AND COLORIMETRIC CALCULATIONS

Objective measurements were made with a Photo-Research 705 spectro-radiometer. The reference white was a PTFE reflectance standard. The spectral power distribution reflected from the MCC samples was measured under the same geometric conditions as measuring the white sample. For every light source a number of colorimetric calculations were performed:

- Special (R_i) and the general colour rendering indices (R_a) were determined by using the CIE Test Method[6] (using U*, V*, W* colour space and von Kries transformation).
- Special and general colour rendering indices were determined using the above method, but using the 18 MCC chromatic test samples (Rc_i) as well as the 10 samples recommended by CIE TC 1-33[7]. We used the No. 2 sample of the MCC instead of the Caucasian complexion spectrum recommended by CIE TC 1-33, and as there is no Oriental complexion colour in the MCC we selected an-other often-occurring sample, blue sky, as the tenth sample for our calculations.
- Colour differences were calculated by using the U*, V*, W* space (using a von Kries transformation to bridge the chromaticity difference between the test and reference sources), as well as CIELAB and CIECAM02[17] formulas (with built-in chromatic adaptations and with the following viewing condition parameters: F=1.0 c=0.69 N_c=1.0). These colour differences were compared with the visually observed differences.
- As a further possibility we investigated chromaticity distortions and changes in the gamut area spanned by the first 8 samples. We used this principle, suggested for colour preference description[18,19] adapted to modern colour spaces for our 4000 K CCT sources. In the following we show results obtained using the first 8 real MCC samples.

Figure 1 shows the gamut area for our LED cluster 2, both for the real MCC samples used in our visual experiments and the original CIE Test Samples. An extremely big distortion in the directions of yellow and blue chromaticities (line with full sign △) can be seen compared to the gamut of the reference source (line with full sign □). The size of the gamut area increases up to 120% of the gamut area of the reference source.

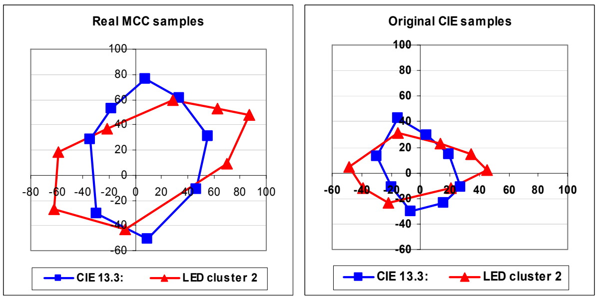

Figure 1: Gamut area of the LED cluster 2 test source in a*, b* plane for real MCC samples and samples for the CIE Colour rendering Test Method.

4. RESULTS

For different sources the distortion of the gamut and the change in size of the gamut area was different. The larger gamut means that these sources can render more colours, irrespective of their general colour-rendering index. We determined the size of the gamut area in pixels for the test and the reference illuminant, and calculated the (P(Test)/P(Ref)) ratio, representing the relative increase in gamut area.

In

Table 1 we show the results of six test sources. Here we compare the visual colour differences with colour difference calculated in CIE U*,V*W* space, and using the CIECAM02 model, as well as the R_a index calculated for the CIE Test Method and the “real” MCC samples and with the ratio between P(Test) and P(Ref). The correlation coefficients between the visual and the different other quantities are seen in **Table 1** too.

Table 1: Comparing the visual colour difference values with colour difference values and R_a indexes of the lamps and the ratio between P(Test) and P(Ref) at 4000 K.

4000 K	Visual ΔE	ΔE(CIE)	ΔE(CIECAM02)	R_a(CIE)	R_a(MCC)	P(Test)/P(Ref)
3-band Polylux XL fl. lamp	0,49	4,4	4,9	84,2	72,26	119,27%
De Luxe CoolWhite comp. fl. lamp	0,52	2,3	2,6	93,2	87,99	98,50%
CoolWhite fl. lamp	0,66	12,9	10,1	60,7	24,77	99,18%
CoolWhite comp. fl. lamp	0,71	5,0	5,6	82,0	69,82	125,85%
LED cluster 1	0,85	18,5	13,7	41,5	0,66	101,62%
LED cluster 2	1,65	1,7	32,6	5,4	-66,15	99,85%
Correlation coefficients (R^2)		0,03	0,96	0,87	0,85	0,11

It can be seen from the above investigation that colour rendering properties of a given light source can be divided into two major groups. First, if one defines colour rendering according to the CIE definition - scaling and averaging colour differences between numbers of colour samples – one should use a CIECAM02 based colour appearance model to make ranking between different types of lamps, which correlates well with visual observations. But, if one considers colour rendering as the maximum realizable number of colours, one should use the size of the gamut area represented by the illuminated samples for ranking between sources.

6. CONCLUSIONS

From the investigations we can conclude that the visual colour rendering is not well described by the CIE Test Method. As an interim solution one could recommend the use of the CIECAM02 model, or a CIECAM02 based colour difference formula[20]. But a more fundamental re-thinking of the concept of colour rendering seems to be appropriate[21]. All these might point into a direction that colour rendering calculation has to be based on a quite different evaluation of colour appearance, taking large colour difference, i.e. colour harmony and colour complementarity break into consideration.

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