Getting Colour Right: Improved Visual Matching with LED Light Sources

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Introduction

With the addition of LED light sources to the palette of lighting options for lighting designers, the challenge of *getting colour right* in a project is getting harder and harder. Many designers have experienced this the hard way, with either very disappointing initial installations, or installations failing over time, and having to implement painful fixes. Getting colour right is not easy, but it can be done, and involves obtaining and checking the right specifications from the suppliers, and getting a good understanding of the principles of measuring and matching colour. This last aspect is the main topic of this paper, and we will not deal with the second equally important aspect, how the illuminated colours get distorted, i.e. with colour rendering. But before discussing these more complicated aspects, we will start with the basics of getting colour right.

The colour, or more precisely, the *chromaticity*, of *white* light sources falls into the vicinity of a slightly curved line in the CIE chromaticity diagram, called *Planckian locus*. This curve represents the chromaticity of the light emitted by an ideal black body when it is heated, and is similar to the light generated by an iron rod forged by a blacksmith, or a tungsten filament in a light bulb heated by the current flowing through the filament. The chromaticities of these are in general close to the Planckian locus, and are commonly denoted by the temperature of the black body closest in chromaticity in CIE 1960 chromaticity diagram. This temperature is called *correlated colour temperature* (CCT).

Incandescent lamps have a CCT of 2500 K to 3200 K. Daylight has higher CCTs between about 4000 K at sunset up to 7000 K and higher in case of radiant blue skies. With the invention of gas-discharge light sources, fluorescent lamps, and more recently, light emitting diodes (LEDs) it became possible to produce sources with any CCT, or to create light sources in which the CCT can be adjusted.

When moving away from thermal emission for light generation, and using plasma discharge, fluorescence, and solid state emission, it is important to characterize the light emission not only by CCT, but also by the distance to the Planckian locus. This distance is measured in the CIE 1960 chromaticity diagram, and is indicated by the symbol Δuv, or DUV. It is usual that if the chromaticity is above the Planckian locus the DUV is denoted by a positive number, if it is below, it is indicated with a negative number. If the DUV is too positive, the light source appears too greenish, or yellowish, if the DUV is too negative, the light source can appear to be purple, or pinkish, at same CCT.

To create uniform lighting, it is required that all the lights have the 'same colour', or more precisely, are *visually matched*. Due to manufacturing tolerances, temperature variations, and varying drive conditions, the chromaticity of light sources will vary. The sensitivity of the human eye to colour differences depends on many factors, but in simplified form can be characterized by ellipses in chromaticity diagrams, where the ellipses represent *standard deviations of colour matching* (SDCM) or *just noticeable differences of chromaticity* (JNDC). First work in this field was performed by MacAdam in 1942, and sometimes these ellipses are historically referred to as MacAdam ellipses, but much work has been done in this field since then, resulting in adoption of the CIE1976 u'v' chromaticity diagram, and the definition of colour difference formulas denoted by ΔE or DE, which are commonly used in checking the colour differences of textiles and printed materials. In the lighting industry measuring colour differences in CIE1976 chromaticity diagram is becoming common practice.

An example of SDCM ellipses transformed into CCT and DUV coordinates is shown in figure 1. In this case these are based on MacAdam's work. The smallest transformed ellipse in this graph is the SDCM ellipse. In many lighting applications larger chromaticity variations than this smallest ellipse can be allowed. In this plot 7 ellipses are shown, where the larger ellipses are scaled versions of the smallest ellipse, in steps from 2x to 7x. In this graph three *tolerance zones* are indicated: a green zone representing the tolerance area for accent and architectural lighting applications, the yellow zone for general lighting, and the red zone for lighting applications where colour differences are not important.

To get colour right, it is important that the light source chromaticities are, and stay within, these tolerances. This applies to initial chromaticity, as measured under actual operating conditions (at operating current, and operating temperature) in the luminaire, but also to chromaticity over time, also called *colour maintenance*.

Last but not least, recent investigations have shown that lights with exactly the same *measured* or *instrumental chromaticity* (same CCT and DUV) might look different or more precisely, do not *visually match.* This means that not only the colour of the illuminated objects differs, i.e. they have different colour rendering properties, but the shade of the white light the source emits is different as well. In the following sections we show how this can happen and how using an updated set of colour matching functions a good agreement can be reached between instrumental and visual colour matching.

Visual colorimetry versus instrumental colorimetry

The CIE 2° colorimetric system was established in 1931 (see CIE[1]). As the spectral luminous efficiency ($V(\lambda)$) function was selected as one of the colour matching functions, an error was introduced in the blue part of the spectrum. This error results in visual colour differences for LEDs while the instrumental colours match. A CIE technical committee, TC 1-36, is working on an improved colorimetric system that corresponds better to the visual assessment, and published a tentative cone fundamental based system of colour matching functions (CMFs)[2]. Our experiments showed that with these the errors between instrumental and visual match is halved.

By conducting experiments using RGB-LEDs, as well as Xicato's white LED modules, and broad-band white and coloured light sources at the University of Pannonia, a modified, further optimized set of CMFs was established[3]. The CMFs are shown in figure 2 (x_M, y_M, z_M), together with the original CIE 1931 colour matching functions (CIE x, y, z), and the CIE TC 1-36 CMFs (x_F, y_F, z_F). As can be seen the main differences are in the blue part of the spectrum.

An example of the results of these experiments is shown in figure 3. It shows the results for visually matched samples, where the corresponding spectral power distributions were evaluated using CIE 1931 CMFs, CIE TC 1-36 Fundamental CMFs, and the newly developed Modified Fundamental CMFs from the University of Pannonia (CMF-UP). These are visually matched samples, so the bars in the graph should be small. The improvement of the agreement between the visual and instrumental matches is well seen going from the CIE 1931, the TC1-36, to the University of Pannonia modified CMFs.

In another experiment we compared high colour rendering (CRI) and low CRI LED modules of similar chromaticity. Task was to rank the colour difference between the reference (X05) high CRI and the six low CRI modules. The results are shown in Table 1. Columns represent different tested modules, while the rows show scores of the differences. The first row shows results of the visual test, while the other rows represent the calculated differences using the different colour matching functions. As can be seen from table 1, the UP-CMFs describe the visual rank order quite well, while the CIE 1931 CMFs perform poor.

Conclusions

Getting *'colour right'* requires careful checking of the specifications of lighting fixtures and light sources with regard to initial chromaticity specification, and colour maintenance. Due to insufficient standards in this field this can be tricky, and our advice is to work only with capable suppliers. Getting to '*colour perfect*' requires the effort of lamp suppliers, luminaire makers, and lighting designers, and starts with the light source manufacturers adopting the results of over 70 years of colour research in the lighting field, especially if they are committed to participate in the 21st century lighting market.

As an example of this we can state that based on our experiments the colour of LED modules do not visual match traditional sources if the CIE 1931 CMFs are used. Visual matching will be greatly improved if the CIE TC 1-36 recommended CMFs are used, but the best results so far have been obtained with the Modified Fundamental based CMFs developed at the University of Pannonia.

References

1 CIE (2004) Colorimetry, 3rd ed. CIE 15:2004.

2 CIE TC 1-36 (2010) Fundamental chromaticity diagram with physiological axes Draft Chapter 7.3: Development of chromaticity diagrams based upon the principles of the CIE XYZ system .

3 Csuti P, Schanda J, Petluri R, McGroddy K, Harbers G (2011) Improved color matching functions for better visual matching of LED sources. CIE Conference Sun City 2011.

Figures and Tables

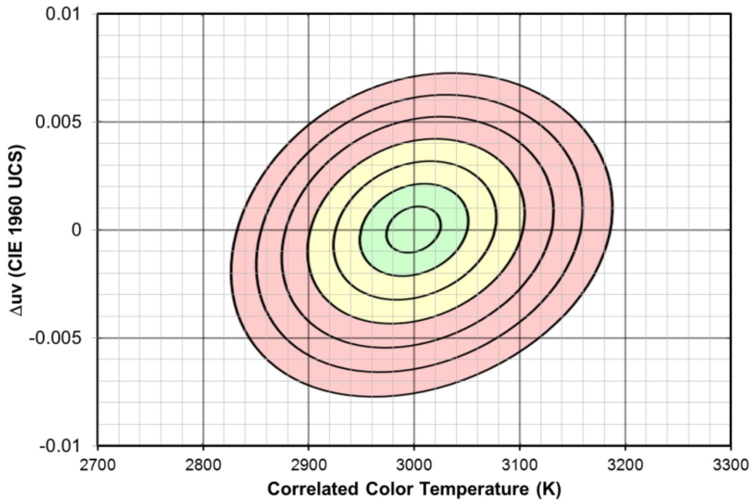

Fig 1: Ellipses indicating the sensitivity of the human vision system to differences in chromaticity for a 3000 K CCT light source.

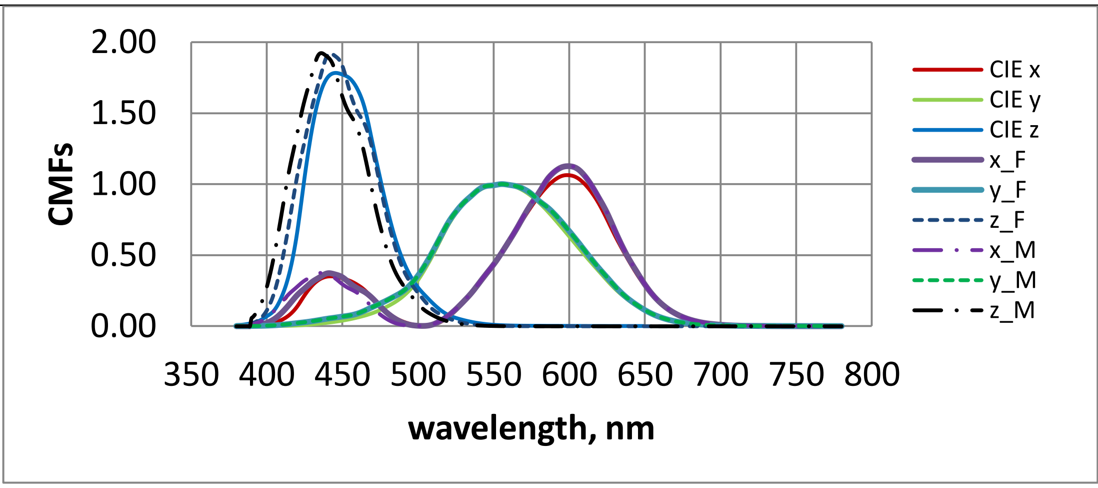

Figure 2. The three sets of CMFs used in the experiments.

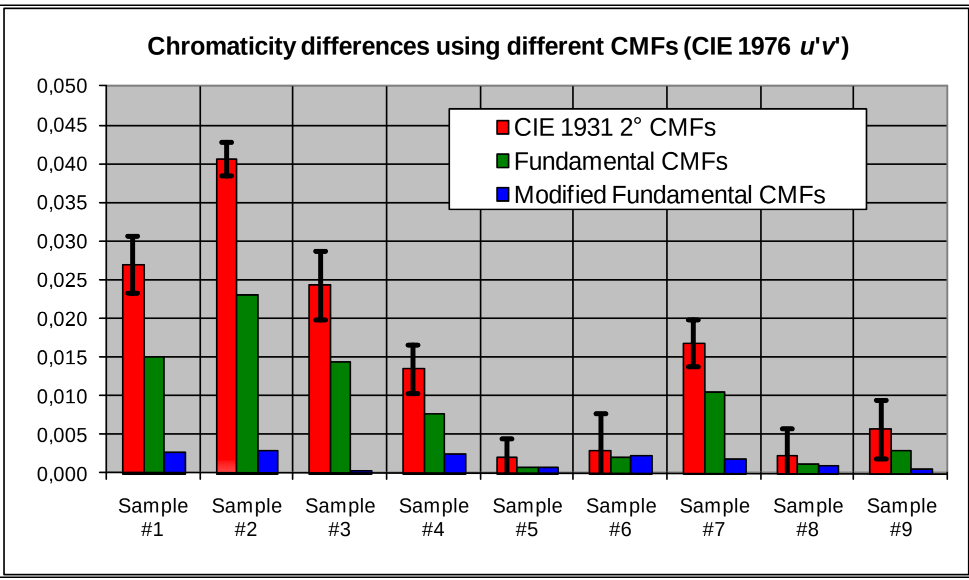

Figure 3. Results of matching 9 samples, comparing the different CMF sets; error bars show standard deviation of the visual settings.

Table 1. Visual difference and CIELAB colour differences based on the three CMFs.

	X11	X15	X13	X16	X12	X14
Visible difference to X05 (reference)	**28.7**	**29.3**	**52.8**	**61.8**	**65.5**	**76.8**
CIE 1931	7.66	6.52	5.68	5.09	6.65	4.62
TC 1-36 CMFs	4.35	3.56	2.79	1.70	3.58	3.23
UP CMFs	1.28	2.02	2.24	4.15	2.52	6.61