Evaluation of colour differences from LEDs in new colour systems

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Summary

In recent years there have been many studies evaluating thresholds for noticeable and tolerable colour differences. These results have been examined in retrospect within reference to the spectra of LEDs. All the well-known evaluations have used the colour matching functions (CMFs) of CIE 1931. However, these CMFs induce poor correlation between measured and observed colour differences. In 2006 new colour matching functions were released [CIE06; CIE15]. In the present work, these functions and the research of KRAMER [Kra14] are newly evaluated and novel colour discrimination ellipses are found in different colour systems. Overall, the parameters of the ellipses being similar, it will be possible to use the new systems employed in KRAMER'S study also for the binning of LEDs.

1 Introduction

LED light sources dominate the domestic and industrial lighting market and are used in nearly every application in daily life. A conventional luminaire will perhaps contain just one or at the most a few lamps. However, as there will be numerous LEDs in a LED luminaire, it is important that all of these small light sources should give a similar impression. Many studies carried out over time to determine noticeable and disturbing colour differences, the calculation of these differences was based on the colour matching functions of CIE 1931. Unfortunately a discrepancy is found between the measured and perceived colour differences. In 2006 the CIE published new colour matching functions [CIE06] with the intention of achieving a good correlation between measurement and visible colour variation. Studies on the part of SCHANDA, POLSTER and other researchers have found this to be the case, with still some room for improvement. All of them found that their functions fit well for their subject ratings and the light spectra considered.

It is also important to know which colour differences are noticeable or disturbing. The study carried out by KRAMER [Kra14] found an average perception threshold for colour differences $\Delta u'v'$ of 0.0017 for his investigated correlated colour temperatures (CCT). Many other scientists (e.g. [Bie10]) have found similar thresholds for various light sources. The studies vary in detailed experimental setup and subject group composition. MACADAM'S studies in 1942 [Mac42] found slightly higher thresholds and these studies have been used ever since as the basis of LED-binning, although KRAMER and other researchers maintain that they are poor descriptors of human perception under the constraints of LED-lighting observation conditions.

The lighting industry as a whole still employs the old colour matching functions (CIE 1931 [CIE04]). The actual binning is also based on inappropriate studies. Although the new colour matching functions exist, they have not come into use because there has been no review in respect of visible colour differences.

2 Colour Matching Functions (CMFs)

2.1 Standardized functions CIE 170-1:2006 and CIE 170-2:2015

The CMFs of the CIE 1931 are familiar in industrial and scientific communities. They are based on research carried out by WRIGHT and GUILD in 1930 but have long been subject to criticism. Already in 1964, new CMFs were established following the work of STILES and BURCH, as well as that of SPERANSKAYA. They were determined for a field size of greater than 4° and named CIE 1964 10° [CIE04]. They are well known, but have not been much used in practice.

In 1991, the CIE founded a committee to find a "Fundamental Chromaticity Diagram with Physiological Axes", which published its first Technical Report [CIE06] in 2006, setting the new recommendation in which the colour matching functions are based on the research of STILES and BURCH from 1959, enhanced with the ideas of STOCKMAN and SHARPE to calculate the cone fundamentals $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$. Relying on knowledge of absorption by the eye media and the macula, as well as the density of rods and cones, the colour matching functions for every field size between 1° and 10° can be calculated. These functions are noted in the second Technical Report [CIE15].

The new computation system means that not only the field size is variable but, also, the age can be changed with two formulas for the optical density of the ocular media, one for age up to 60 and the other for people 60 to 80 years old. Standardized functions are calculated for a person at the age of 32 years. These functions can be converted to the CMFs $\bar{x}_F(\lambda)$, $\bar{y}_F(\lambda)$ and $\bar{z}_F(\lambda)$ with one of the two matrices given in the CIE 170-2:2015 (2° or 10°). In Fig. 1 the conventional CMFs CIE 1931 are plotted together with the CIE 2006 2° CMFs.

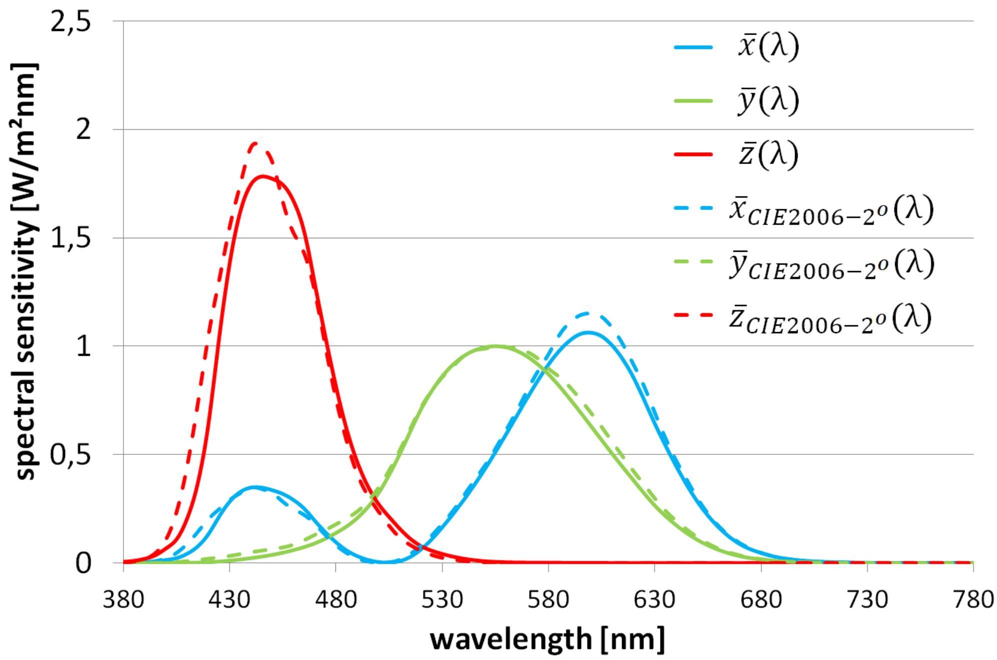

Fig. 1: Comparison between original colour matching functions CIE 1931 and the new functions from CIE 2006 2°

2.2 Further CMFs

The new CMFs serve the description of the human vision better than their predecessors but there are still possibilities for improvement. So in 2009 CSUTI and SCHANDA tested the new functions and found that the calculated colour difference between two matched light fields will be smaller if the function of the s-cone is shifted by -6 nm [Csu09, S.5]. Later POLSTER determined that a shift of -3 nm achieves the best fit for her group of subjects (age 30 ± 6) and spectra considered [Pol14].

The studies agree that the s-cone is the most important item. The s-cone, the blue spectral part, varies greatly for subjects of different age and for different field sizes. It is important to know the exact viewing conditions in order to select the best fit functions. In this study, the results of POLSTER, working at Technische Universität Ilmenau, have been included. The functions are named TUIL 2° and TUIL 10°.

Note: In this study the CIE (u', v') 1976 chromaticity diagram is used for all CMFs because it is the most uniform colour space for light sources recommended by the CIE [CIE TN 001:2014].

3 Colour discrimination ellipses by KRAMER

LEDs have always been sorted into bins according to the measured and calculated chromaticity coordinates, which is necessary because of manufacturing tolerances. Until now the bins resulted from MACADAM'S 1942 work [Mac42]. With his study, KRAMER created a new base for binning of LEDs in the investigated range of colour temperatures near the Planckian locus.

KRAMER used the setup shown in figure 2. The subject is positioned in front of a homogeneously illuminated hemisphere and looks at a circular test symbol. One half of it is steady as a reference and in the other the chromaticity coordinates vary within a chromaticity grid around the reference chromaticity coordinates. Reference and test colours have virtually identical spectral distributions.

The light colour of the setup is variable within the white region. The investigation was done at 2700K, 4000K and 6500K correlated colour temperatures. Because of the differences in LEDs used, the spectra of the test symbol and the surroundings differ slightly. Detailed information about the experimental setup, the results and much more is to be found in [Kra16].

During KRAMER'S study it was the task of the subjects to choose whether the two fields looked "equal" or "unequal". There is a typical grid with the answers of one subject in Fig. 3. The design of the grid was rectangular in CIE 1931 coordinates. The grid shown in Fig. 3 is distorted because it has been recalculated to the CIE 2006 10° CMFs for the spectra considered.

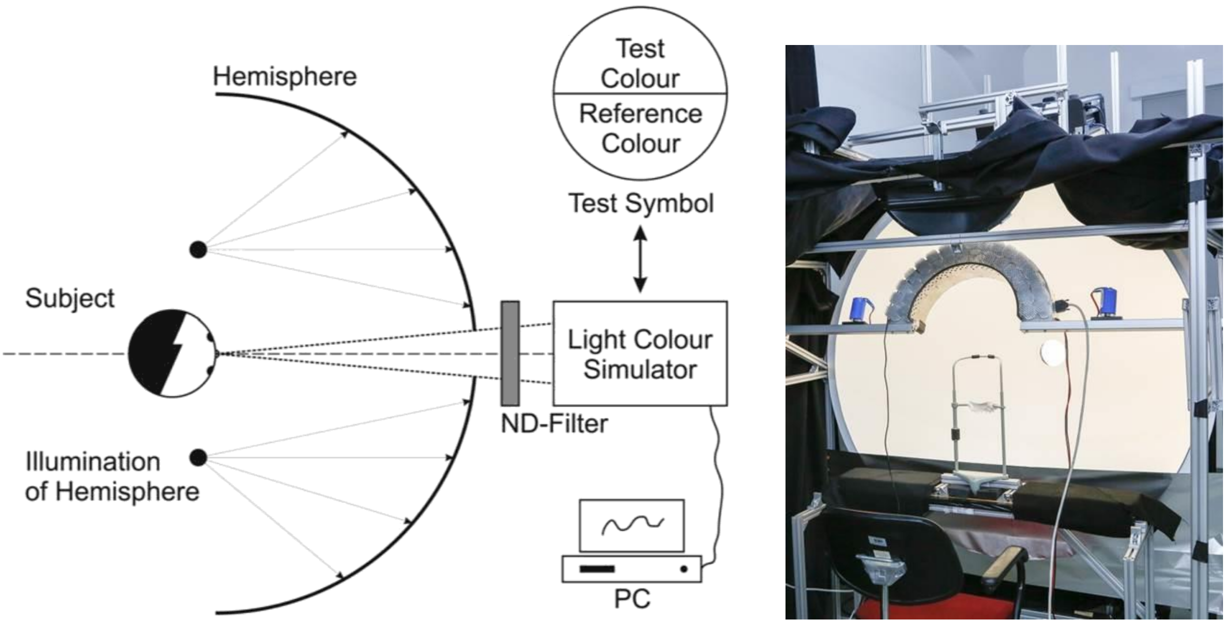

Fig. 2: Left: Schematic representation of the experimental setup. A light colour simulator back-lights a test symbol, which is evaluated by a subject [Kra16].
Right: Experimental setup: the position of the subjects head is fixed by means of a chin rest. The hemisphere is uniformly illuminated by the semicircular LED lighting system above the subject [Photograph: Ingo Herzog]

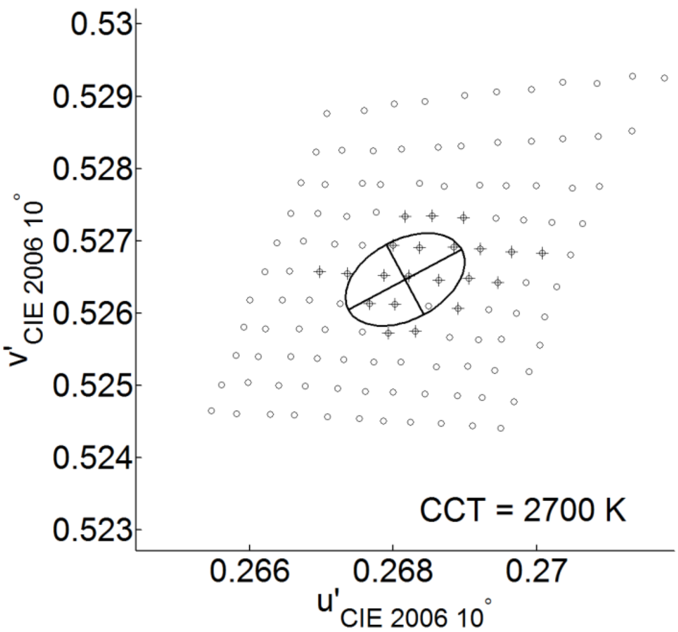

Fig. 3: A typical grid tested in the study. The circles indicate one chromaticity coordinate investigated. “Empty” circles indicate the response “unequal”, those with the “+” indicate “equal”. In addition an ellipse has been plotted for 61% probability of not being able to detect the respective colour difference [Kra16]

The average ellipses were calculated for each correlated colour temperature and can be found in Tab. 1. KRAMER used CIE 1931 CMFs for his work. It can be assumed that the ellipses found are not significantly different in size and shape, but vary in orientation. As the system is not equidistant the differences, also in size and shape, within the chromaticity diagram can be wide.

Tab. 1: Calculated data of the discrimination ellipses from 22 subjects. $\boldsymbol{a}$ is the semimajor axis, $\boldsymbol{b}$ the semiminor axis, $\boldsymbol{\varphi}$ the counter-clockwise rotational angle of the semimajor axis against the abscissa and $\boldsymbol{A}$ the area of the ellipse.

CCT	$a \cdot 10^3$	$b \cdot 10^3$	$\varphi\ in\ °$	$A \cdot 10^6$
2700 K	1,025	0,598	12,0	1,925
4000 K	1,024	0,743	44,4	2,389
6500 K	1,158	0,685	81,2	2,494

Furthermore the ellipses were compared with the data of MACADAM. The ellipse of 6500K is very similar, but the other two are indisputably different: the orientations are nearly perpendicular to each other. The differences are based on the surrounding light and can be explained by chromatic adaptation (VON KRIES transformation): MACADAM used only CIE illuminant C (6774K). This is really close for the 6500K ellipse, but clearly different for the other two CCTs. The ellipses found by KRAMER are of practical value and conform to the experience of the industry.

4 Data Evaluation

To find discrimination ellipses in different colour systems the data from KRAMER'S experiment can be used. All of the calculations were done in MATLAB®, so the program had to be adapted to the new CMFs for the evaluation.

As input, the software needed the currently investigated colour matching functions and the spectra of the 101 chromaticity grid points for each CCT to calculate the grid in the particular system. Using the answers of every subject, the response grid (like the one in Fig.3) was calculated. Out of this the mean ellipses were estimated and the data of the ellipses noted. The process chart is shown in Fig. 4.

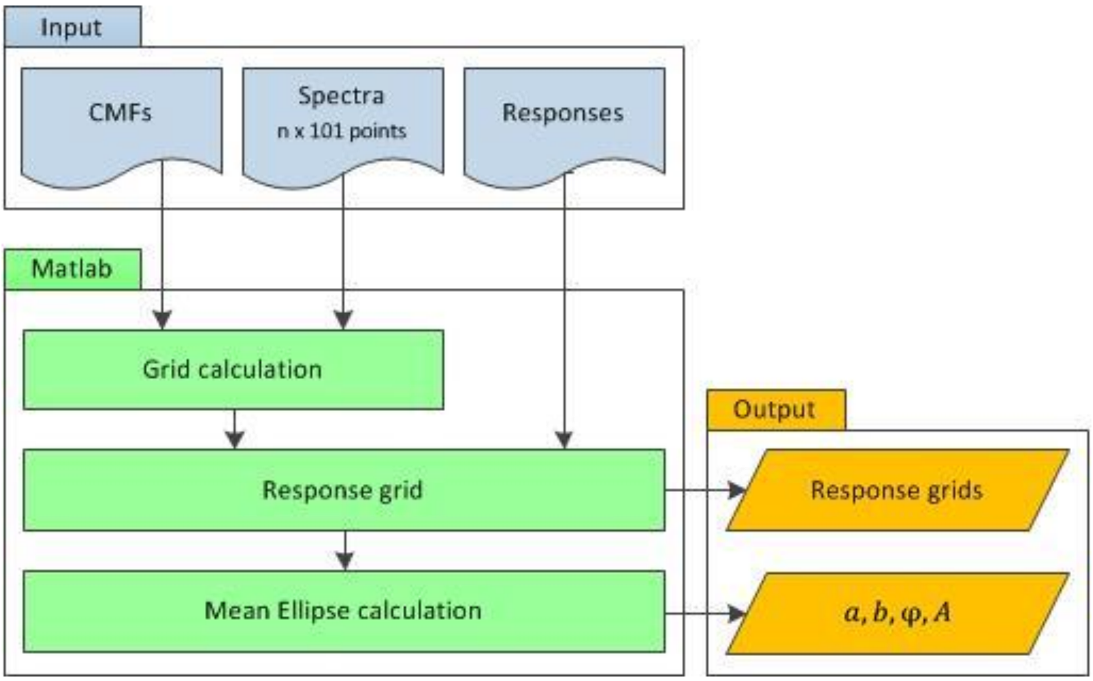

Fig. 4: Process chart of the ellipse calculation. The Input CMFs have to be changed to get the ellipses in the other colour systems.

5 Results

In Tab. 1 the data of the ellipses in KRAMER'S study are shown, i.e. the data based on CIE 1931 chromaticities. In the following table six different CMFs have been considered. Beside the conventional system CIE 1931 2° (data are shown again for better comparison), there are data based on the chromaticities of the CIE 1964 10°, and the newly recommended CIE 2006 2° and 10° systems. In addition the TU Ilmenau results are tabulated for 2° and 10° field size.

Tab. 2: Parameters of the ellipses for the systems with different colour matching functions

2700 K	$a \cdot 10^3$	$b \cdot 10^3$	φ in °	$A \cdot 10^6$
1931	1,025	0,598	12,0	1,925
1964	0,984	0,521	19,4	1,609
CIE06 2°	1,015	0,528	13,1	1,683
CIE06 10°	1,040	0,519	18,3	1,696
TUIL 2°	1,003	0,486	12,0	1,533
TUIL 10°	1,013	0,477	16,6	1,520

4000 K	$a \cdot 10^3$	$b \cdot 10^3$	φ in °	$A \cdot 10^6$
1931	1,024	0,743	44,4	2,389
1964	1,039	0,621	38,6	2,027
CIE06 2°	1,025	0,665	38,7	2,142
CIE06 10°	1,051	0,613	37,3	2,024
TUIL 2°	1,000	0,633	36,6	1,987
TUIL 10°	1,015	0,578	35,5	1,843

6500 K	$a \cdot 10^3$	$b \cdot 10^3$	φ in °	$A \cdot 10^6$
1931	1,158	0,685	81,2	2,494
1964	1,079	0,619	68,9	2,099
CIE06 2°	1,099	0,661	71,2	2,282
CIE06 10°	1,076	0,621	67,3	2,100
TUIL 2°	1,075	0,647	68,1	2,185
TUIL 10°	1,030	0,600	63,5	1,940

As an example, in Fig. 5 box plots of the area $\boldsymbol{A}$ are shown. It can be easily seen that neither the data for the two axes, nor the angle changes greatly and in no case significantly. It can be assumed that the colour discrimination threshold ellipses in the CIE (u', v') 1976 chromaticity diagram are not significantly different in size, shape or orientation within the investigated range of colour temperatures of the colour systems considered. So it can be said that all the systems shown here are similar. Between the systems calculated differences in chromaticity coordinates which are noticeable and disturbing vary only up to 20%.

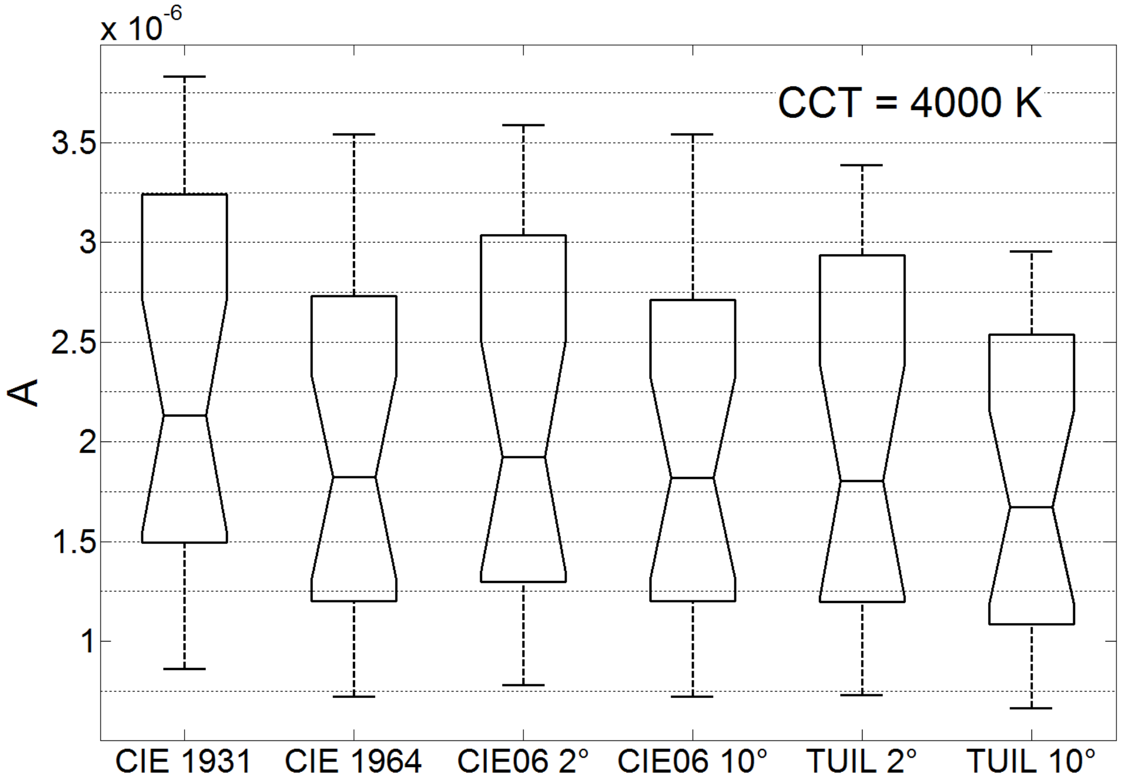

Fig. 5: Notched box plots of the ellipse area A for the different colour systems

6 Conclusion and Outlook

In this study, colour discrimination ellipses as representation of subject data acquired in a study by KRAMER were transferred into systems of different colour matching functions. KRAMER's experimental setup, method and results are discussed. The evolution of different CMFs is also explained.

In summary it can be said that the chromaticity systems are different in their degree of uniformity and suitability to different groups of people. Nevertheless their discrimination threshold ellipses are similar in size, shape and orientation. There are no significant differences between the six systems considered in this study. Thus the various thresholds found can be adapted to the new CMFs. Binning should be possible in the different colour systems presented.

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7 Literature

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