Testing Colour-Matching Functions - Perception of Luminous Colour Differences of white LEDs in Relation to Ambient Luminous Colour and Age of Observers

Karin Bieske
Johannes Michl
Johannes Kolmer
Nicole Stubenrauch
Christoph Schierz
Department of Lighting Engineering
Technische Universität Ilmenau
Ilmenau, Germany
Karin.Bieske@TU-Ilmenau.de

Anja Frohnapfel
Zumtobel Lighting GmbH
Dornbirn, Austria

Alexander Wilm
OSRAM Opto Semiconductors GmbH
Regensburg, Germany

***Abstract*— Studies have revealed inconsistency in metamerism in that colour differences are perceived between LEDs even though the colour coordinates are identical when the CIE colour-matching functions (CMFs) are used for the calculations. The present investigation used LEDs in light boxes to test CMFs to find which modelled human perception best; also to find the influence of ambient luminous colour and the observer's age. For none of the CMFs tested was a correlation found between the luminous colour difference calculated and perceived by the subjects as a whole, without age differentiation. For young people, however, CMFs recommended by POLSTER were found to model colour perception better than the hitherto standard procedure. For older people, the colour-matching functions of the CIE 1931 and those recommended by POLSTER (2006 TUIL-10°A70) and by the CIE 2006-10°A70 (the latter corrected for age) model colour perception best. No effect of the ambient luminous colour was found.**

***Index Terms*-- age-related effects, Colour-matching functions, luminous colour perception, LED.**

I. INTRODUCTION AND STATE OF THE ART

Currently, the colour-matching functions (CMFs) for the CIE standard observer of 1931 are the standard in general colorimetry and the binning of white LEDs. Studies have revealed inconsistency in metamerism [1], [2]. Colour differences are perceived between LEDs even though the colour coordinates are identical when the CIE colour-matching functions are used for the calculations. POLSTER found colour differences between visually matched LED spectra and the results of calculations based on the CIE 1931 CMFs up to $\Delta u'v' = 0.0165$ [3]. KRAMER investigated which differences in luminous colours are just noticeable. The threshold values he found are in the range between $\Delta u'v' = 0.0004$ and $\Delta u'v' = 0.0018$ [4]. In some cases, the visible differences in luminous colour are so clearly perceptible that users find them unacceptable. POLSTER and KRAMER have investigated young subjects (30±6 and 28±7 years respectively), each using the same luminous colour for LED light source and surroundings. New CMFs (CIE 2006-2° and CIE 2006-10°) were published by CIE in 2006 on the basis of physiological data. This technical report also established age-related CMFs [5]. After making numerous colour-matching experiments, POLSTER has suggested new CMFs (2006 TUIL-2° and 2006 TUIL-10°) [3]. Early exploration of these suggestions showed a good correlation between the calculated and perceived luminous colour differences based on the CMFs recommended by POLSTER [3], [6]. These investigations were limited to young subjects. The colour perception is affected by many factors: the properties of the object, the viewing conditions and the observer. The effect of combinations of different luminous colours for the LED light source and the surroundings has not so far been considered.

II. RESEARCH ISSUES & HYPOTHESES

The aim of the present investigation was to test a variety of CMFs for their capacity to model colour perception. Younger and older people were included in the investigations. Comparing subject's ratings with the calculated colour differences $\Delta u'v'$ show how suitable the CMFs are in this respect. "Good" CMFs will deliver a high correlation between observed and calculated luminous colour differences.

From the early investigations, it can be hypothesised that the colour-matching functions recommended by POLSTER will be more successful than those of the standard in modelling the perception of luminous colours of white LEDs.

Because of aging in the human eye, older people perceive luminous colours differently from younger people, which means that age-related changes must be taken into account for in modelling the perception of luminous colours of light sources. CIE 170-1: 2006 addresses this issue and its performance requires verification [5].

The luminous colour of the surroundings will determine the chromatic adaptation of the eye. If the luminous colour of the surroundings is changed, the retinal cones can be expected to adapt, which will influence the colour perception. It is desirable to investigate the influence of the ambient luminous colour on the perception of luminous colour differences between LED light sources.

III. EXPERIMENTAL SETUP AND METHODOLOGY

Using simulation to establish the possibility of variation in the spectral distribution due to the manufacturing procedure, we selected 10 types of LED with $CCT = 4000$K which were likely to be relevant in a study of inconsistency of metamerism, then manufactured them and characterised them by colorimetry. We fitted them into boxes with diffusors for which the luminous surface was 30 cm by 30 cm. The mean luminance L was 800 cd/m² with a CCT of 3500 K. Two adjacent boxes were presented to the subjects in a room (l = 6.6 m, b = 4.2 m, h = 2.8 m) at a viewing distance of 1.7 m (i.e. at a viewing angle of 10°). At the sides of the room, there were two luminaires with fluorescent lamps with different luminous colours which serve to illuminate the background at a projection screen (2 m by 2 m, viewing angle of ~40°) at a mean luminance of 200 cd/m². The experiments were carried out with a variety of luminous colours in the surroundings (CCT: 2700 K, 4000 K, 6500 K) and also without any additional lighting there. Figure 1 shows the experimental setup. Figures 2 and 3 give an overview about the construction of the light boxes and the spectral distributions of them.

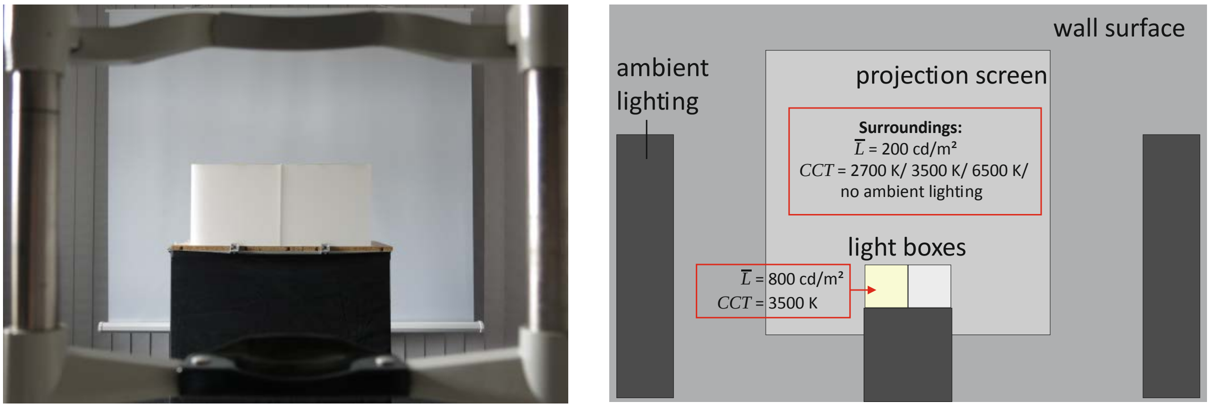

Figure 1. Left: Experimental setup photographed from the viewing position of the observer. Chin rest appears in the foreground, Right: Experimental setup, schematic drawing.

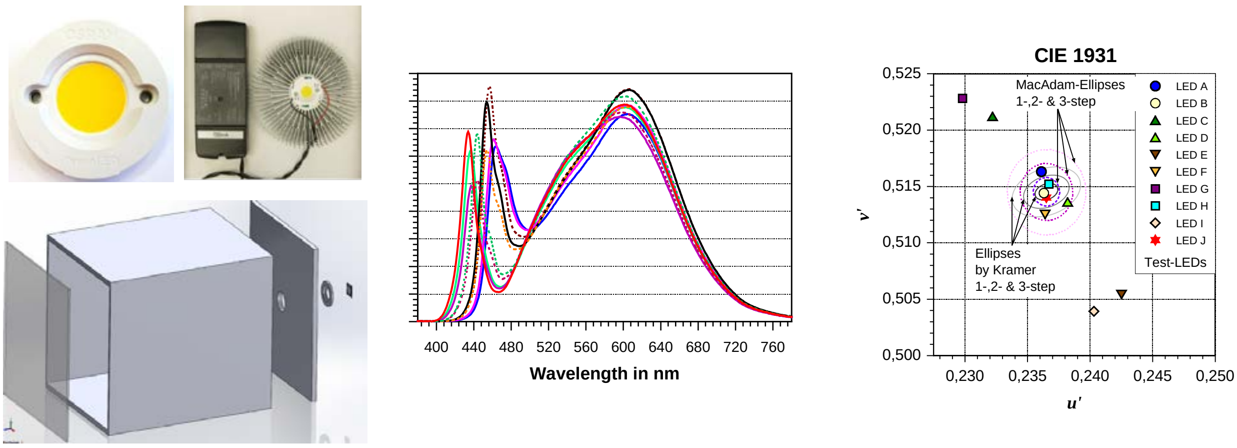

Figure 2. Top left: example of COB (chip on board) pc (phosphor converted) LED fitted onto a cooling unit. Below left: construction of light box with diffusor. Centre: spectra of the ten types of LED. Right: colour coordinates using CIE 1931 CMFs.

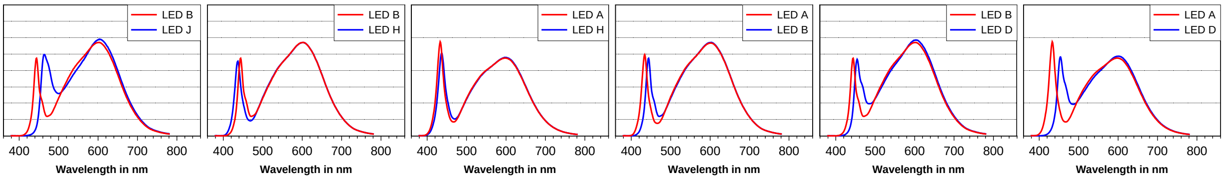

Figure 3. Samples of spectral distributions of different LED-combinations with small luminous colour differences Δ*u'v'* in CIE 1931.

The light boxes were evaluated by 41 young people (< 35 years, ∅ 24 ± 4 years) and 39 older people (> 60 years, ∅ 71 ± 6 years), who rated the luminous colour differences they perceived in the 23 LED-combinations tested. Among the subjects were 38 men and 42 women. The semantic scale shown in Figure 4 was used for the ratings by the subjects.

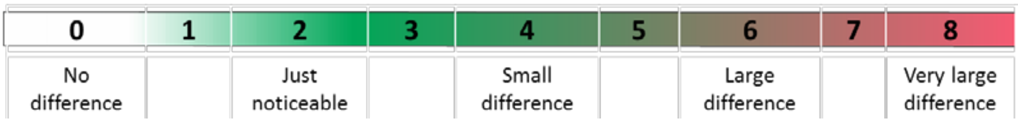

Figure 4. Scale for the rating by the observers.

The CMFs included in the investigation were the standard CMFs CIE 1931 and CIE 1964 [7], plus the CMFs CIE 2006-2° and CIE 2006-10° [5] and the CMFs 2006 TUIL-2° and 2006 TUIL-10° recommended by POLSTER [3]. An additional calculation was carried using the CIE 170-1: 2006 recommendation in respect of older people. These are the CMFs shown in Figure 5.

For each LED the colour coordinates were determined from its spectra and the different CMFs. From these data the colour difference Δ*u'v'* for each combination of LEDs was calculated [8]. Besides comparing the calculated colour differences with the subjective ratings of the participants in the experiment, we also focussed on the changes in colour perception attributable to ageing. The methodology we used is shown in Figure 6.

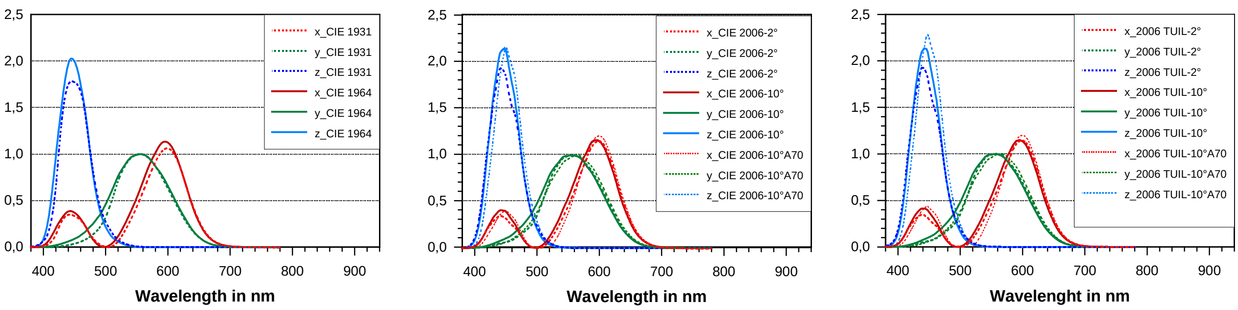

Figure 5. CMFs tested in the investigation.

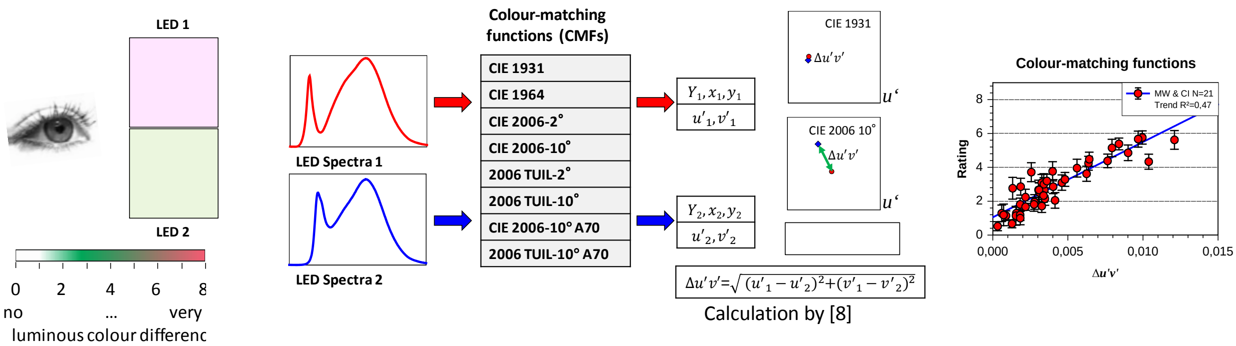

Figure 6. Method of investigation.

We analysed the data by linear regression of the subjective ratings versus calculated colour differences Δ*u'v'* for each CMFs. High correlation in the data is associated with high coefficient of determination R^2 and a high goodness of fit (TABLE I). The coefficient of determination is a value between 0 and 1. Additionally, the statistical significance of the results was analysed.

TABLE I. INTERPRETATION OF COEFFICIENT OF CORRELATION R^2

R^2	Values up to 0.05	Values up to 0.2	Values up to 0.4	Values up to 0.8	Values over 0.8
Interpretation	No or low correlation	Low correlation	Moderate correlation	Highly correlated	Very highly correlated

IV. RESULTS

TABLE II summarises the mean ratings (Mean) and the intervals of confidence 95% (CI) for the LED-combinations represented in Figure 3. There are clear inconsistences using the standard CMFs. Where the colour difference is small it is not perceived as such by the observers and ditto for larger differences. It is also clearly age-related. Figure 7 shows relevant results diagrammatically. Mean subjective Ratings (Mean ± CI) of N Subjects for selected LED-Combinations represented in Figure 3

LED-combination	BJ	BH	AH	AB	BD	AD
CIE 1931	$\Delta u'v'$=0.0008	$\Delta u'v'$=0.0012	$\Delta u'v'$=0.0019	$\Delta u'v'$=0.0019	$\Delta u'v'$=0.0020	$\Delta u'v'$=0.0034
CIE 1964	$\Delta u'v'$=0.0046	$\Delta u'v'$=0.0051	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0011	$\Delta u'v'$=0.0009	$\Delta u'v'$=0.0002
CIE 2006-10°	$\Delta u'v'$=0.0057	$\Delta u'v'$=0.0061	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0012	$\Delta u'v'$=0.0014	$\Delta u'v'$=0.0004
2006 TUIL-10°	$\Delta u'v'$=0.0084	$\Delta u'v'$=0.0100	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0013	$\Delta u'v'$=0.0034	$\Delta u'v'$=0.0046
Younger subjects' rating (N = 41)	5.4± 0.4	1.3 ± 0.2	0.7 ± 0.2	0.7 ± 0.2	2.8 ± 0.3	3.0 ± 0.3
Older subjects' rating (N = 39)	2.1 ± 0.3	2.2 ± 0.3	2.1 ± 0.2	3.3 ± 0.4	2.4 ± 0.4	4.1 ± 0.4
All subjects' rating (N = 80)	3.2 ± 0.4	1.9 ± 0.2	1.6 ± 0.2	2.4 ± 0.3	2.6 ± 0.2	3.6 ± 0.3

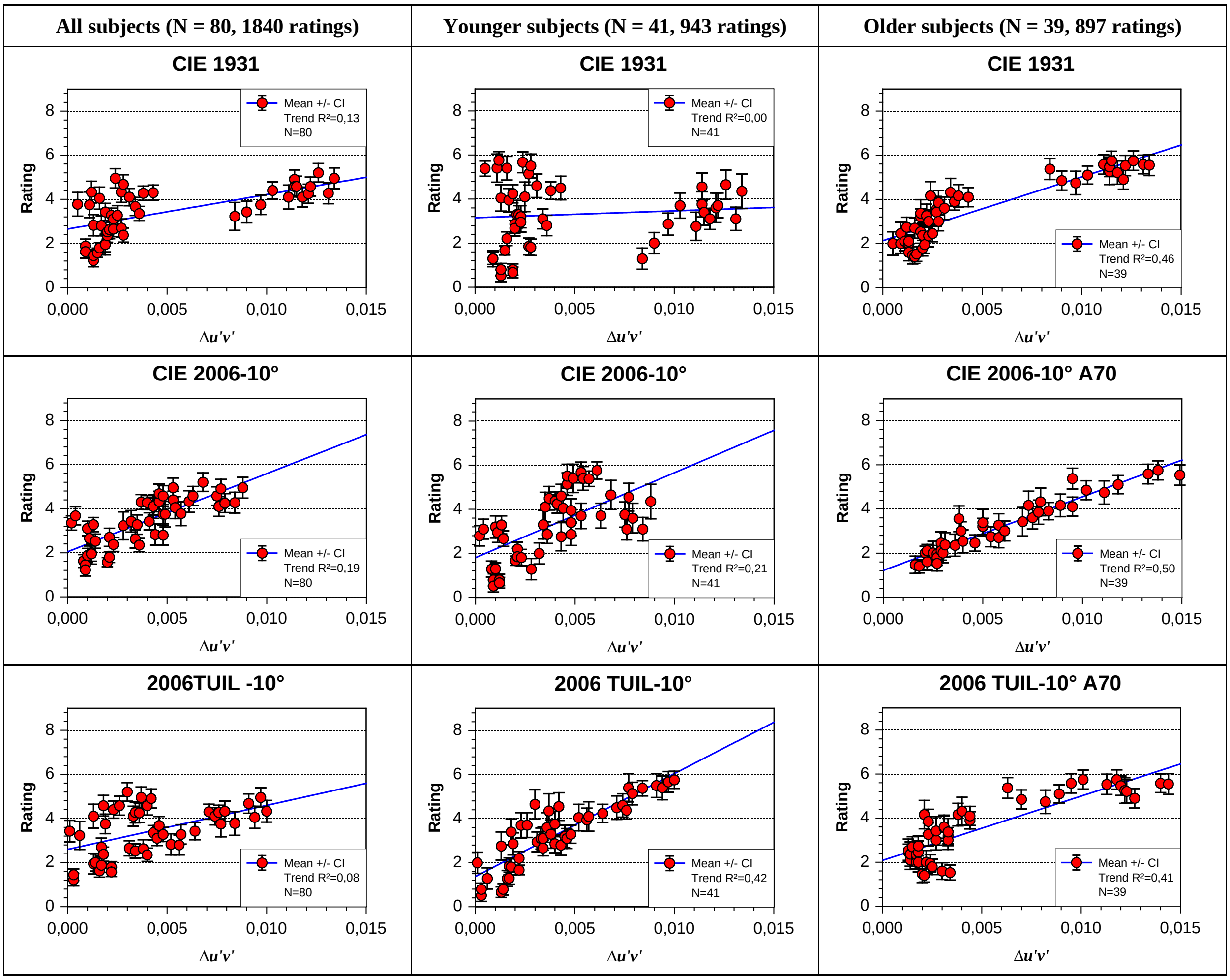

Figure 7. Results of the investigations: mean and Confidence intervals (CI 95%), linear regression function, coefficient of determination R^2: results of the ratings of N subjects.

There is a summary of coefficients of determination in TABLE III. For the subjects as a group, without age differentiation, no correlation was found between the calculated luminous colour differences and those perceived, for any of the CMFs tested. The best compromise is achieved by the 2006 TUIL-2° proposal. There are significant differences between the two age groups. For younger people, the CMFs recommended by POLSTER model colour perception better than the standard procedure used to date. For older people, the colour-matching functions of CIE 1931 and those recommended by POLSTER (2006 TUIL-10°A70) and by the CIE (CIE 2006-10°A70) model colour perception best (A70 denotes the age correction in the respective CMFs).

TABLE II. COEFFICIENT OF DETERMINATION R^2

CMFs/ Subjects	All Subjects N = 80, 1840 ratings	Young Subjects (< 35 y.), N = 41, 943 ratings	Old Subjects (> 60 y.), N = 39, 897 ratings
CIE 1931	0.13	0.00	0.46
CIE 2006-2°	0.16	0.04	0.39
2006 TUIL-2°	0.26	0.34	0.19
CIE 1964	0.18	0.12	0.25
CIE 2006-10°	0.19	0.21	0.17
2006 TUIL-10°	0.08	0.42	0.02
CIE 2006-10° A70	0.18	0.03	0.50
2006 TUIL-10° A70	0.11	0.00	0.41

As regards the influence of the luminous colour of the ambient lighting, the analysis of the data revealed noting of significance. Samples of the results are shown in Figure 8. However, the perception of LED luminous colour itself was found to vary in relation not only to age but also to the luminous colour of the surroundings.

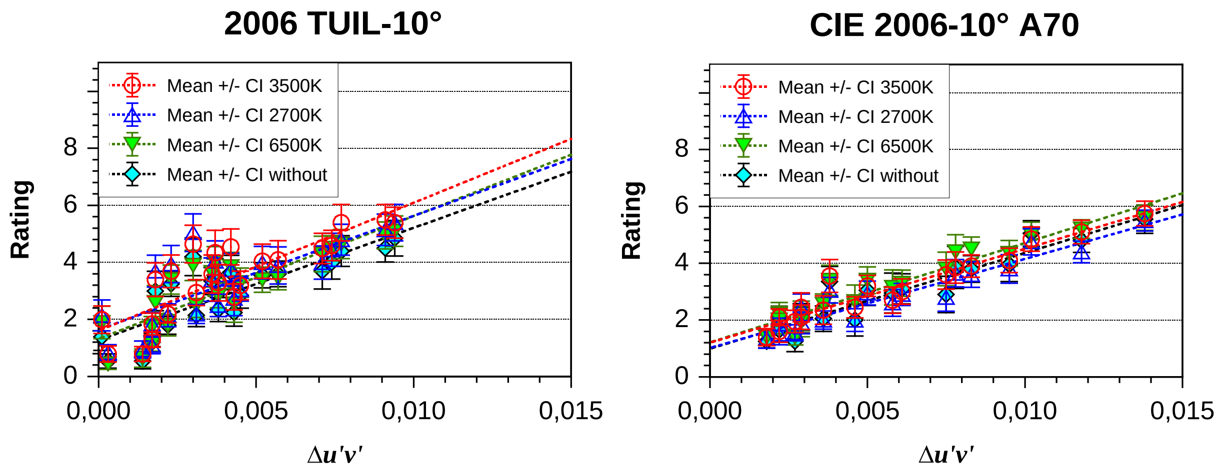

Figure 8. Ratings of luminous colour differences (mean and Confidence intervals 95% (CI) and linear regression functions for different ambient luminous colours and without any ambient lighting for younger people N = 20 (left) and older people N = 20 (right).

V. CONCLUSION

It is here shown that the binning of LEDs on the basis of the standard CIE 1931 CMFs fails to prevent users from perceiving marked differences in luminous colour differences despite the fact that the colour coordinates are similar. It may be useful to classify the LEDs on the basis of different CMFs. There may also be useful in checking the age-related effects of particular combinations of LED. As the ambient lighting as tested seems to be of no relevance, generalisation to practical applications is acceptable.

ACKNOWLEDGEMENT

This study took place in cooperation with OSRAM Opto Semiconductors GmbH and Zumtobel Lighting GmbH and was supported by the German Federal Ministry of Education and Research (BMBF) within the research project UNILED II (support code: 13N13395).

References

[1] K. Bieske, P. Csuti and J. Schanda, “Colour appearance of metameric lights and possible colorimetric description,” in *Proc. 2006 CIE Expert Symposium on Visual Appearance*, pp. 137-139.

[2] P. Csuti and J. Schanda, “Colour Matching Experiments with RGB-LEDs,”. *Col Res Appl*, vol. 33, pp. 108-112, Feb. 2008.

[3] S. Polster, “Neue Spektralwertfunktionen für die korrekte Bewertung von LED-Spektren und Einführung eines Metamerie-Index für Beobachterfeldgrößenabhängigkeit,“ Ph.D. dissertation, Dept. Lighting Eng., Univ. TU Ilmenau, Germany. Der Andere Verlag, 2014.

[4] G. Kramer, „Farbdiskrimination - Ein empirischer Ansatz für die Gruppierung weißer LEDs,“ Ph.D. dissertation, Dept. Lighting Eng., Univ. TU Ilmenau, Germany. Der Andere Verlag, 2014.

[5] *CIE Fundamental Chromaticity Diagram with Physiological Axes – Part 1*, CIE 170-1, 2006.

[6] S. Polster, K. Bieske, „Neue spektrale Empfindlichkeitsfunktionen zur Erfassung visueller Farbgleichheit bei LED-Spektren,“ in *Proc*. 2013 Lux junior, pp. 1-14.

[7] *DIN EN ISO 11664-1 Farbmetrik - Teil 1: CIE farbmetrische Normalbeobachter*, DIN EN ISO 11664-1, July 2011

[8] *DIN EN ISO 11664-5 Farbmetrik - Teil 5: CIE 1976 L*u*v* Farbenraum und gleichabständige u’, v’-Farbtafel*, DIN EN ISO 11664-5, January 2017