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TM-30−15 AND CIE-CRI-RA: INVESTIGATION OF COLOUR RENDERING OF WHITE PC LEDS*

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ABSTRACT

The colour rendering properties of 21 phosphor converted LED light sources (pc LED) with different R_f and R_g values as in the Fidelity Index and Gamut Index of the TM-30–15 have been investigated. Scenarios illuminated by pc LEDs, a fluorescent lamp (FL) and a tungsten halogen lamp (THL) were presented to 34 subjects. An assortment of coloured objects was arranged identically in two adjoining booths and participants rated the test scenarios in comparison with the reference illuminant (THL). For colour quality, both indexes are reflected in the observer's ratings. The Fidelity Index strongly correlates with the colour difference and colour shift perceived; the Gamut Index with the subjects' ratings of the colour saturation. Participants found the best match with the fluorescent lamp (R_f = 80/ R_g = 100) to be the pc LEDs with R_f = 75/ R_g = 105 and R_f = 80/ R_g = 105.

Keywords: colour rendering, pc LED, TM-30–15

I. INTRODUCTION

Nowadays, light emitting diodes (LEDs) are used more and more in indoor lighting applications. In the first years, white light was produced by combining differently coloured LEDs (RGB-LEDs). Nowadays, phosphor converted LEDs (pc LEDs) are used. The light emitted by a blue LED is down-converted to light with a longer wavelength, using phosphors. This is then added to the original blue LED light, making white light. Commonly, the converter is a mixture of different types of phosphors to achieve a certain LED spectrum, which will affect the colour rendering properties. Correct description of these properties is a prerequisite to target setting in light source development. The current standard method of calculating these properties is the CIE colour rendering index (CRI) R_a, recommended in 1995 as CIE13.3 [1]. Studies have revealed inconsistency between this method and its rating by subjects especially in LED lighting [2]. Attempts to improve on it go back many years. On one hand, the method of calculation has been improved in reliance on new colorimetric discoveries; on the other, the spectral power distribution (SPD) of the light sources has been optimised, for instance by using different types of phosphors, as this is what largely defines colour quality. In 2015, the Illuminating Engineering Society (IES) published the Technical Memorandum TM-30–15, a new calculation method for colour rendering of white light sources [3]. There is international consensus that a single criterion is insufficient to describe colour quality for this includes many aspects. TM-30–15 combines colour fidelity, rated with the R_f index, and the colour gamut, rated with R_g index: this describes the area enclosed by the average chromaticity coordinates in each of 16 hue bins. Thorn-

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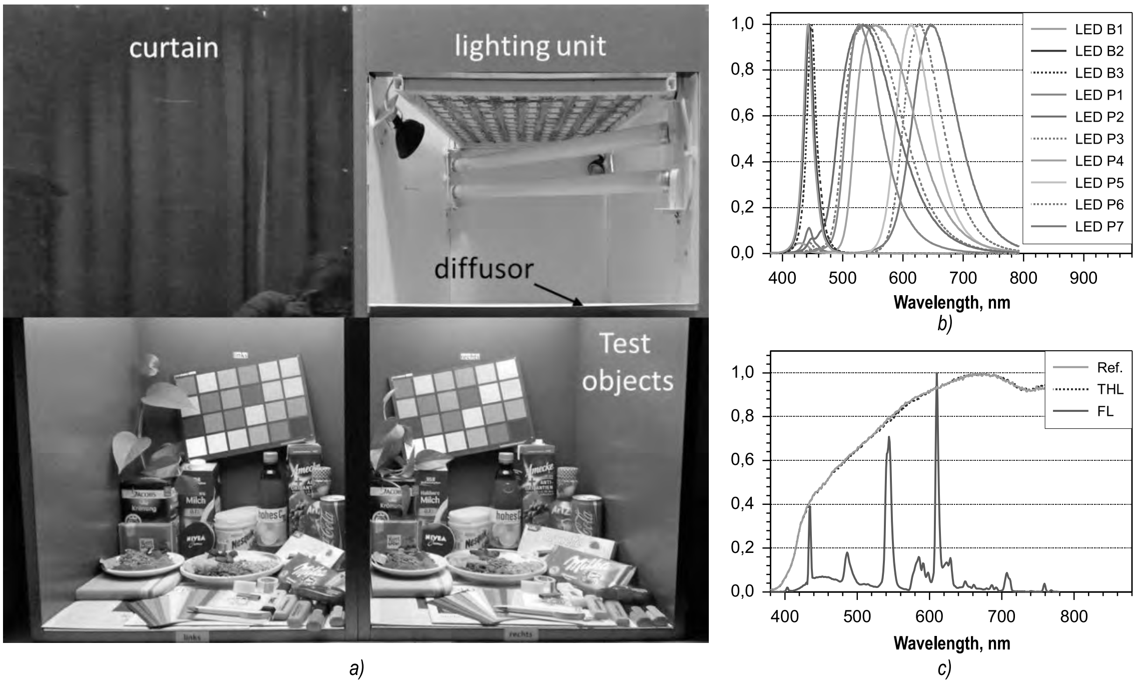

Fig. 1. a) Experimental setup with two booths (width: 46 cm, depth: 48 cm, height: 96 cm), at the top the lighting units, curtained and exposed, and below the test objects; b) relative SPDs of the light sources: B stands for blue LED, P for fully converted LED with different types of phosphors; c) Ref. for reference illuminant (SoLux THL), THL for the Solux tungsten halogen lamp, FL for the OSRAM Sylvania fluorescent lamp

TON has shown that the larger the colour gamut, the better is the colour discrimination because the chromaticity coordinates are further apart in the colour space. There is also an assumption that light sources with larger gamut enable colours to be perceived as more saturated, more brilliant and more natural [5]. XU assumes that the size of the area enclosed is proportional to the maximum possible number of colours that can be represented [6]. RGB-LEDs are an example of LEDs with narrow SPD. They may have a large gamut index but the rendering of certain colour may be inexact. It therefore makes sense to combine the two indices.

ROYER has carried out an initial study of LED illumination in a test room with coloured objects. The illumination produces white light from seven types of tuneable, coloured LEDs with varying R_f and R_g values. The conclusion is that observers prefer LED light sources with Fidelity $R_f > 75$ and Gamut Index values $R_g \geq 100$ [7]. In the present work, this result is examined in respect of pc LEDs.

2. RESEARCH ISSUES AND HYPOTHESES

It is hypothesised that the ROYER requirements are fulfilled for white pc LEDs and that the R_f and R_g values in TM-30–15 reveal high correlation with subjective evaluation of colour rendering properties on the part of observers. The present work tests whether pc LEDs with identical CIE R_a values improve on the subjective evaluation of fluorescent lamps.

3. EXPERIMENTAL SETUP AND METHODOLOGY

Two adjoining booths with two sections, one for the illumination unit with diffuser and another for test objects, were used (Fig. 1, left). In one booth, the light sources installed were a tungsten halogen lamp (SoLux) and a fluorescent lamp (OSRAM Sylvania with CIE $R_a = R_f = 80$ and $R_g = 100$), together with three types of blue LED and seven different fully converted LEDs incorporating a variety of green and red phosphors. Combining a variety of LEDs enabled various SPDs to be produced which were identical to those of white pc LEDs. 21 combinations of LED with R_f values between 66 and 94 and R_g values between 92 and 114 were investigated in comparison with a reference, as were the FL and the THL. The reference lighting in the second booth was provided by a THL (SoLux, $R_f = R_g = 100$). All lighting conditions had identical luminous colours

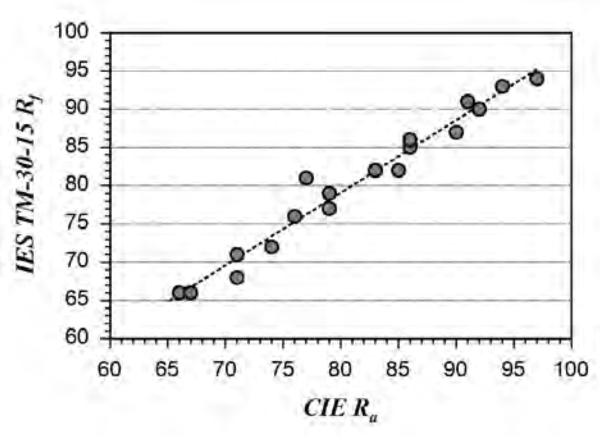

Fig. 2. Correlation between the R_a and R_f values, coefficient of determination R^2 = 0.98

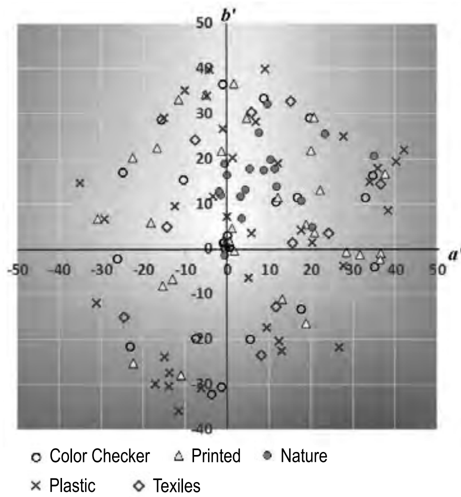

Fig. 3. Chromaticity coordinates of the test objects in the CIE CAM02-UCS when illuminated with a Planckian radiator at T = 3800 K

(CCT = 3800 K) and the same illuminance level in the centre of the floor of the booth (E = 400 lx). This experimental setup reflects the fact that both the CIE CRI R_a and the TM-30–15 are reference-based methods. Fig. 1 right shows the relative SPDs of the light sources.

The R_a values are almost identical with the R_f values, differing by an average of only one point with a maximum of four. The coefficient of determination for the lighting conditions tested is R^2 = 0.98 (Fig. 2).

An assortment of identical coloured objects was arranged equally in the two booths. The choice of objects ensured that a wide range of hue, saturation and lightness was covered. The chromaticity coordinates of the objects are shown in Fig. 3. They were objects from daily life: they included plants, food, consumer goods, office and printed materials, and colour rendition charts (Colour Checker). The SPDs of selected LED scenarios and the R_f-R_g combinations are shown in Fig. 4.

There were 34 participants between 23 and 48 years old (∅ 35 ± 7 years), 10 of them women. They filled in a questionnaire, firstly evaluating the colour rendering properties experienced simultaneously in the two booths. This evaluation was of differences in object colour perceived under the test and the reference light source according to the criteria of colour difference (CD), saturation (S), brightness (PB), temperature (T), colour shift (CS), likeability (LA) and naturalness (NN). In addition, the subjects were asked which of the object colours matched their expectation (EP) for the objects and how they rated the overall colour quality (CQ) of the objects independently of the reference. The questionnaire is shown in Fig. 5.

The differently lit scenarios were presented in random order. There was a repeat of the test for four scenarios. The mean values and intervals of confidence ($CI_{95\,\%}$) were calculated in respect of the subjects' responses and of the experimental parameters R_a, R_f and R_g. The coefficient of determination (R^2) was established for the linear regression across the mean of the ratings. Analysis of variance and post-hoc tests were carried out for the comparison between LED light sources and the FL.

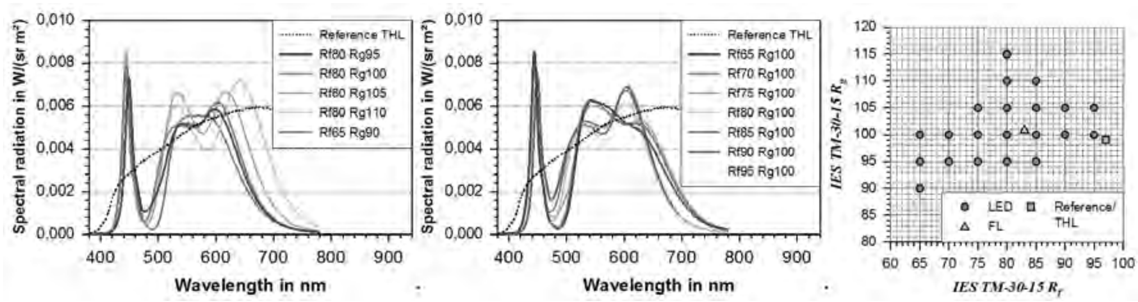

Fig. 4. Spectra of selected scenarios (left and centre); R_f-R_g combinations for all scenarios in the experiments (right)

Do you perceive a colour difference between the objects in the left booth and those in the right booth?					
Colour difference (CD)	1 = none	2 = small	3 = moderate	4 = great	5 = very great
How do you find the colours of the objects in the left booth in comparison to those on the right hand side?					
Saturation (S)	1 = very saturated	2 = somewhat saturated	3 = no diffe-rence	4 = somewhat unsaturated	5 = very unsaturated
Brightness (PB)	1 = very bright	2 = somewhat brighter	3 = no diffe-rence	4 = somewhat darker	5 = very dark
Temperature (T)	1 = very warm	2 = somewhat warmer	3 = no diffe-rence	4 = somewhat cooler	5 = very cool
Colour shift (CS)	1 = none	2 = small	3 = moderate	4 = large	5 = very large
Likeability (LA)	1 = very nice	2 = somewhat nicer	3 = no diffe-rence	4 = somewhat less nicer	5 = much less nice
Naturalness (NL)	1 = very natural	2 = somewhat more natural	3 = no diffe-rence	4 = somewhat less natural	5 = very unnatural
In which booth do the colours of the objects better match your expectation?					
Expectation (EP)	1 = left	2 = right	3 = both	4 = neither	
Ignoring the right hand side, how do you rate the colour quality of the objects in the left hand booth?					
Colour quality (CQ)	1 = very good	2 = good	3 = moderate	4 = bad	5 = very bad

Fig. 5. Items in the questionnaire (translation from the German version)

4. RESULTS

There is a diagrammatic summary of the questionnaire results in Fig. 6. The figures used are mean values and bares are intervals of confidence across all subjects (N = 34).

It can be seen in the diagrams and from the coefficients of determination for the linear regression R^2 in Fig. 6 and from Table I, that subjective colour quality rating is indeed a multi-dimensional problem and that both indices, R_f and R_g, are important aspects. While the R_f value gives a good description of colour difference, colour shift and the perception of colour as warmer or cooler in comparison with the reference light source, the R_g value is an explicit reflection of saturation rating. Whether a scenario is perceived to be likeable depends very much on how saturated the colours appear. Both indices are important in the rating of naturalness. At constant R_f value, pc LEDs have a more likeable and saturated effect the higher the R_g value up to a certain point. As the R_f value rises, so does the subjective colour rendering rating. The fidelity index R_f correlates very strongly with the CIE R_a value, so that here both indices are similarly applicable. Responses to the question on expectation of the colour of objects related to those seen under the test and reference light sources are shown on the left Fig. 6. The diagram shows the absolute frequency with which the object colours seen match those expected. Responses were given as to whether this was true for a single scenario in one of the booths (either the test or reference booth), or for both, or for neither. Represented is the "both" response has been shared in the Fig. 7 between the test and reference scenario.

As shown in the diagram, the colours of the objects are not better than the subjects' expectation when the LED light source tested has values R_f < 90 and $R_g \leq 100$. LED light sources with $R_f \geq 80$ and $R_g = 110$ are rated as better than the reference illuminant. The FL ($R_f = 80$, $R_g = 100$) investigated is

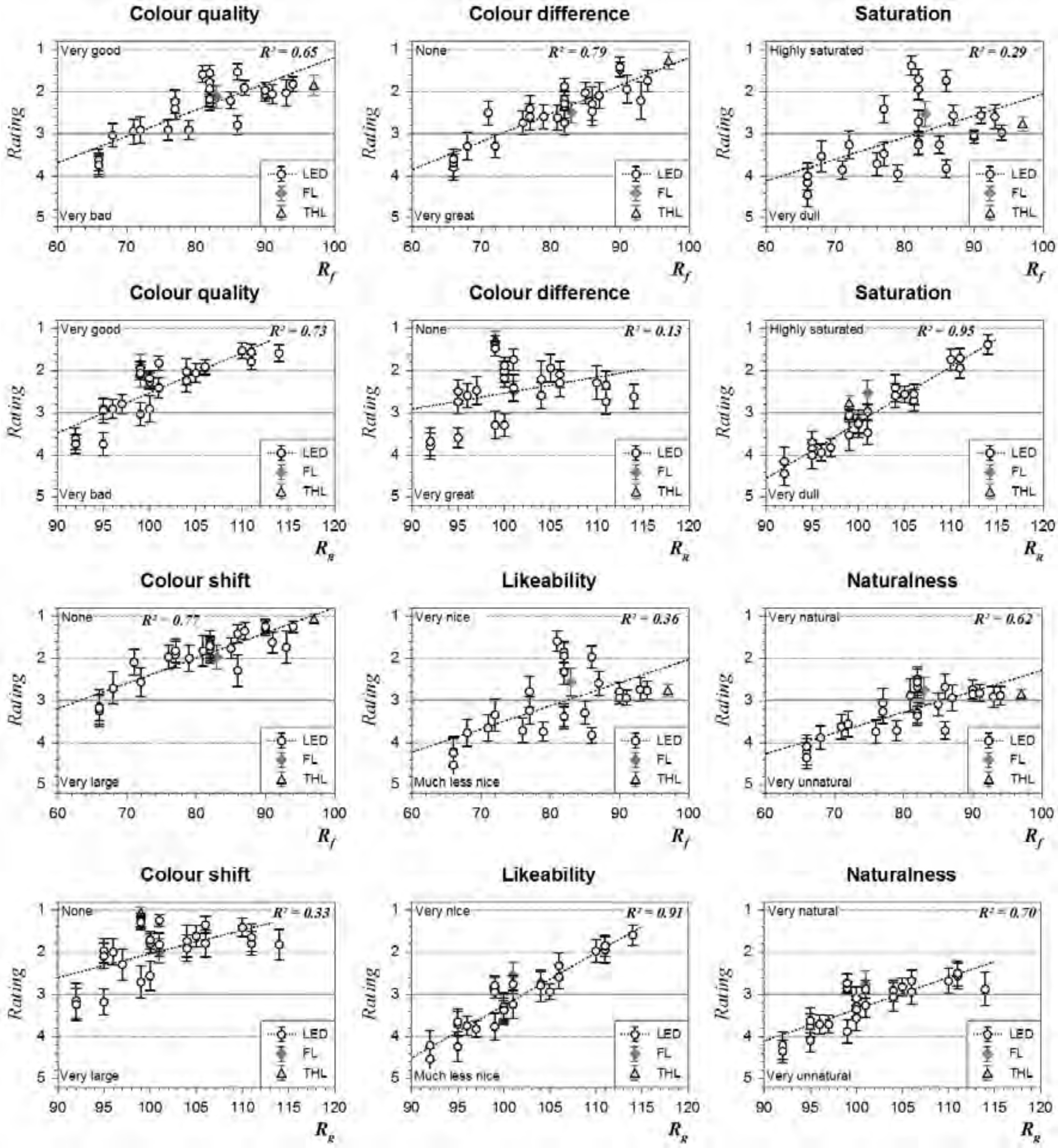

Fig 6. Subjective ratings (mean values and intervals of confidence *CI* 95 %) for R_f and R_g (the linear regression was determined for the LED scenario ratings, and the coefficient of determination R^2 for this is shown)

greatly preferred to the reference and adjudged better than the LED lighting with the same R_f and R_g values.

Table 2 gives a summary of the comparison of ratings for LED types compared with FL (R_f 80, R_g 100). The figures given are the probability p with a level of significance of $\alpha = 0.05$. At the same R_f and R_g values the general colour quality was rated identically, but the colours of the objects are perceived to be less saturated, less natural and less likeable than under the FL (Fig. 7, right). There is no significant difference in the rating of LED types R_f 75, R_g 105 and R_f 80, R_g 105 as compared with the FL. This leads to the assumption that it would be possible to compensate for slight differences in R_f value by a slight increase in saturation.

5. SUMMARY

The likeability of the colour of an object (as compared with the reference) cannot be predicted solely on the basis of the value in the Fidelity Index R_f. This index, like the CIE CRI R_a, serves to describe the difference in colour only in relation to colour appearance as compared with that under reference illuminant, which means that the refe-

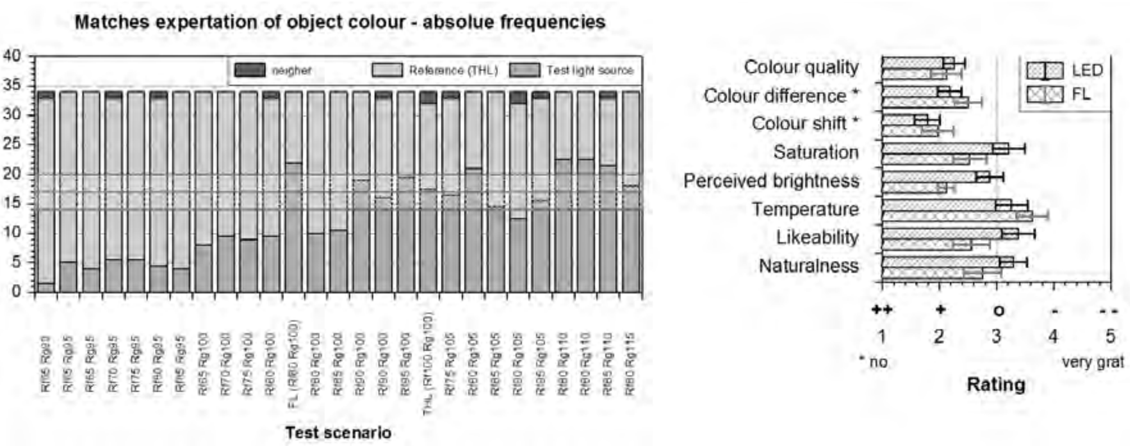

Fig. 7. Absolute frequencies of responce that object colours match expectation (left); responces for LED (R_f = 80, R_g = 100) and FL (R_f = 80, R_g = 100) – mean and intervall of confidence (CI 95 %), N = 34 (right)

Table I. Coefficient of determination R^2 of the linear regression

Item	R^2 for R_a	R^2 for R_f	R^2 for R_g	R^2 for CQ
Colour quality CQ	0.62	0.65	0.73	1.00
Colour difference CD	0.80	0.79	0.13	0.58
Saturation S	0.25	0.29	0.95	0.77
Colour shift CS	0.77	0.77	0.33	0.79
Perceived brightness PB	0.01	0.01	0.41	0.17
Temperature T	0.55	0.63	0.06	0.52
Likeability LA	0.32	0.36	0.91	0.85
Naturalness NN	0.61	0.62	0.70	0.92

Table 2. Summary of comparison between LED and FL (values given are probability p; statistical significance is denoted by italices)

R_g	95			100					105		
Item/ R_f	**75**	**80**	**85**	**75**	**80**	**85**	**90**	**95**	**75**	**80**	**85**
Colour quality CQ	*0,000*	*0,000*	*0,000*	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Colour difference CD	1,000	1,000	1,000	1,000	0,082	0,277	*0,000*	*0,000*	1,000	1,000	0,622
Colour shift CS	1,000	1,000	0,910	1,000	1,000	1,000	*0,000*	*0,002*	1,000	1,000	*0,030*
Saturation S	*0,000*	*0,000*	*0,000*	*0,000*	*0,000*	*0,002*	*0,037*	0,303	1,000	1,000	1,000
Likeability LA	*0,000*	*0,000*	*0,000*	*0,026*	*0,000*	*0,009*	1,000	1,000	1,000	1,000	1,000
Naturalness NN	*0,000*	*0,000*	*0,000*	0,185	*0,036*	1,000	1,000	1,000	1,000	1,000	1,000
Colour coding:	*FL significantly better*			*LED significantly better*				no significant difference			

rence spectrum will always be the criterion. There is no statement as to which of the colours' appearance, under test or reference light source, is better. It makes sense to incorporate the fidelity index with the gamut index into the evaluation and to set targets for the development of light sources. The present investigation indicates that $R_f \geq 80$ and $R_g \geq 100$ are useful prescriptive values. The perceived naturalness of the object colour correlates with both the R_f value and the R_g value, in that the subjects evaluated scenarios illuminated at $R_f \geq 80$ and $R_g \geq 100$ as similar to or better than the reference. This result tallies with Royer [7]. The high correlation between the R_a and R_f value, see Fig. 1, indicates the experimental results are also applicable to the R_a colour rendering index.

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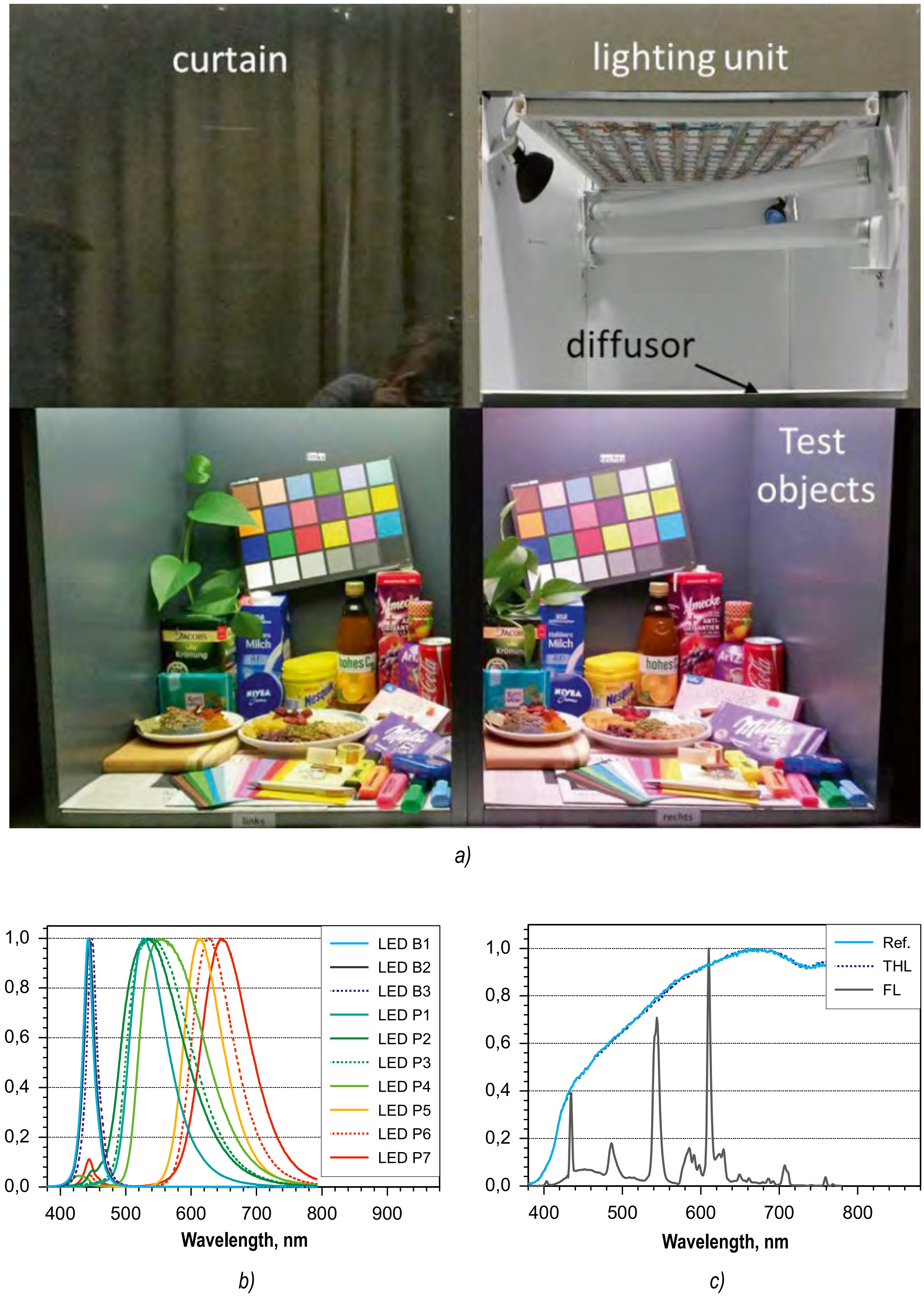

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