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COLOUR PREFERENCE DEPENDS ON COLOUR TEMPERATURE, ILLUMINANCE LEVEL AND OBJECT SATURATION – A NEW METRIC

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ABSTRACT

A new metric ($R_{p,2019}$) is defined as a light source to predict the subjective colour preference impression of an interior scene containing coloured objects illuminated by this light source. The metric is based on the CIE2017 Colour Fidelity Index and the TM-30–15 Colour Vector Graphic. In addition to its dependence on object saturation level, the metric also includes the dependence on correlated colour temperature and on the characteristic illuminance level at the plane on which the coloured objects are arranged. The scale of the metric is labeled with criterion values corresponding to “good” or “very good” colour preference. The aim is to help lighting designers and engineers to determine the illuminance level, colour temperature and object saturation necessary to achieve “good” or “very good” colour preference.

Keywords: colour quality, colour preference, colour preference metric, colour fidelity, colour gamut, colour saturation, correlated colour temperature, illuminance level

1. INTRODUCTION

The concept of *colour quality of a light source* can be defined as the quality of the subjective impressions on the colour appearance of the coloured objects in an interior scene lit by that light source. Although colour quality is just one aspect of lighting quality, it plays an important role in interior lighting to achieve general user acceptance. Other aspects of lighting quality include brightness, visual clarity (the clear visibility of object surface structures), the avoidance of glare and the visibility of object shadows. Colour quality has several sub-aspects [1, 2] including:

– Colour naturalness [2–5]: the similarity of object colour appearance under a given light source to the colour appearance under daylight;
– Colour preference [2–7] (defined below);
– Colour vividness [2–4, 8]: the extent of how saturated the impression of a coloured object is;
– The similarity of object colours related to long-term memory colours [9]: the colour appearance of objects often seen in the past are stored in human colour memory, for example, banana, grass or skin;
– Colour discrimination ability [10–12]: the ability of the human visual system to distinguish between colours of a similar shade, for example, two versions of a greenish shade with slightly more or less blue;
– Colour harmony: the impression of colour harmony is related to the aesthetic appearance of colour combinations; for example red and orange or green and blue and yellow next to each other; the literature on colour harmony is abundant.

Among the sub-aspects, *colour preference* is possibly the most relevant one for lighting engineering according to its straightforward and generally understandable definition. This definition can be formulated as the “subjective extent of how an observer *likes* the colour appearance of the coloured objects in the room *under the current light source* taking all coloured objects into consideration" [1, 2, 13]. An important issue is that the observers' colour preference between different light sources depends on the viewing context or application field of lighting including restaurant, office, home or supermarket lighting [14].

The following parameters of the lighting system are known to influence the colour preference impression of the observers in an artificially lit interior scene:

1. Chroma shifts and hue shifts of the object colours (or test colour samples) between the test light source and its reference illuminant, see the TM-30–15 Colour Vector Graphic [2–5, 7, 13, 15], the Colour Vector Graphic represents how the colour appearance of different, selected object colours (test colour samples) changes if instead of the actual (test) light source a reference illuminant (a daylight spectrum or a blackbody radiator spectrum) is used;

2. The value of the colour fidelity index [2–5, 13,16]; the colour fidelity index expresses numerically how close the colour appearance of the test colour samples under a test light source is to the colour appearance of a reference illuminant at the same correlated colour temperature;

3. The size of the colour gamut [17, 18] which is equivalent to the *saturation level* of the illuminated coloured objects depending on the spectrum of the illuminant, the colour gamut of a light source spectrum expresses how many different shades of object colours including saturated colour shades can be observed under a given light source spectrum. *Object saturation level* is a property of the light source spectrum: it expresses, in average, how saturated the same coloured objects appear under different light source spectra;

4. The shape of the colour gamut (especially the amount of *red saturation* [13, 19–21]), the shape of the colour gamut can be elucidated as follows: in case of a certain light source spectrum, e.g. reddish object colours appear more saturated than in case of another spectrum. In this case, the colour gamut is more extended in the region of e.g. reddish hues;

5. The correlated colour temperature (CCT) of the white tone of the light source [2, 5, 21, 22], the correlated colour temperature means the shade of the white tone: CCT=2700 K is a yellowish warm white while CCT=7000 K is a slightly bluish cool white;

6. Distance of the white tone of the light source from the blackbody or daylight loci on a chromaticity diagram (expressed by the quantity *Duv* or $\Delta u'v'$) [21, 23–26]. If this distance is large then the colour of the light source spectrum will not be white, it will contain (perceptually) for example a disturbing shade of green;

7. The characteristic *illuminance level* (in lx) [27–29] on a "working plane" in the room on which the coloured objects are arranged.

It is interesting to describe some experimental findings in more detail at this point about the effect of three parameters, CCT, object saturation and illuminance level, on colour preference. This issue will be further elucidated in Section 2. Colour preference was found to be influenced by the CCT of the white tone (warm white, neutral white, cool white) illuminating the coloured objects [2]: a *higher* subjective colour preference was experienced under a *higher* CCT (4000 K) than under a *lower* CCT (2500 K) at the same object saturation level of the light source. In another study [5], colour preference was maximal at about CCT=5000 K (cool white) and not at CCT=3100 K (warm white). Previous studies [10, 30, 31] stated that another, related aspect of lighting quality, *scene preference* (the general subjective judgement about the lighting quality of a lit interior) *increases* with illuminance level (these studies did not change colour fidelity indices and object saturation levels and did not deal with colour preference specifically). In another study, subjective colour preference turned out to be a monotonically increasing function of illuminance level [32].

The problem is that today's colour preference metrics (either 1) ignores the CCT dependence and/or the illuminance level dependence and/or the colour *gamut shape* dependence (for example red saturation level dependence) of colour preference; and/or 2 do not use those new colorimetric descriptor quantities that result from the recent development of colour science including a new colour fidelity index, a new chromatic adaptation transform or a new colour space [15]. Accordingly, Table 1 summarizes the properties of a set of selected (more recent) colour preference metrics. Other colour rendition metrics including colour preference metrics were described and analysed in previous articles in detail [33, 34].

As can be seen from Table 1, in several cases, the illuminance dependence, the CCT dependence or the *colour gamut shape* dependence of colour

Table1. Properties of Selected (More Recent) Colour Preference Metrics
(The Concept of "Saturation", the Saturation Level of the Coloured Objects Caused by the Current Light Source, is Equivalent to the Size of the Colour Gamut)

Colour preference metric	Parameter Included	Parameter not included	Colourimetric Description	Test colour samples (TCS)
CQS Q_p [35]	saturation, CCT	illuminance, gamut shape	CIELAB	15 TCS [35]
CP [29]	illuminance, saturation, CCT	gamut shape	CIELAB	15 TCS [35]
LIKE [13]	saturation, gamut shape	CCT, illuminance	TM-30–15 [15, 36]	TM-30–15 [15, 36]
MCRI [9]	saturation, gamut shape (via memory colours)	CCT, illuminance	IPT colour space [37]	10 TCS [9]

preference is not included. The LIKE metric [13] includes the dependence on colour gamut shape. This is based on experiments at a fixed CCT (3500 K) and a fixed illuminance level (646 lx). The memory colour rendition index (MCRI) [9] is based on experiments at 5600 K (fixed) and 1150 lx (fixed). According to the above mentioned experimental evidence suggesting the significant effect of CCT *and* illuminance level (besides object saturation level) on colour preference, one previous metric (CP) was found to be able to model this dependence, see Eq. (1) [29].

$$CP = (14.089 \cdot \ln(E_{v,\,eq}) - 25.397) \times \\ \times [-0.003 \cdot \Delta C^{*2} + 0.0252 \cdot \Delta C^{*} + \\ +1.0192] + [-518.554((S/V)^{0,24})^2 + \\ + 864.872\,(S/V)^{0,24} - 356.578]. \quad (1)$$

Equation (1) [29] shows a dependence of this so-called CP (colour preference) metric on the so-called equivalent illuminance $E_{v,eq} = E_v \times \left(\frac{S}{V}\right)^{0.24}$ [38]. The quantity $(\frac{S}{V})$ represents the relative S-cone (short-wavelength sensitive human cone photoreceptor) signal which can be used as a proxy of correlated colour temperature [29]: the quantity $(S/V)^{0.24}$ was predicted [29] in case of a set of multi-LED spectra from CCT (in K) by Equation (2) with r^2=0.99. This prediction can be applied in practice if the value of $(S/V)^{0.24}$ is not readily available.

$$(S/V)^{0.24} = -0.0138 \cdot (CCT/1000)^2 + \\ + 0.1759 \cdot (CCT/1000) + 0.2859. \quad (2)$$

This means that, for example, a neutral white light source (at a higher *CCT* with higher S-cone signal values) exhibits a higher colour preference than a warm white light source at the same illuminance. There is a quadratic dependence on *object saturation level* in Eq. (1) peaking at a moderate object saturation level (ΔC^*=4.2). Object saturation level is expressed here by the quantity ΔC^* i.e. the mean CIELAB chroma shift of the 15 CQS test colour samples [35].

The quadratic term in Eq. (1) computed from the value of $\left(\frac{S}{V}\right)^{0.24}$ is intended to account for the following effect: warm white (3000 K) spectra at higher saturation levels result in less colour preference. As can be seen from the 4th column of Table 1, the CP metric [29] incorporates *CCT* and illuminance level dependence but it does not support more recent methods like the TM-30–15 concept [15, 36] or the new colour fidelity index [16].

According to the above considerations, the present article aims to define a new colour preference metric (so-called $R_{p,2019}$) by re-analysing and modelling two subjective (psychophysically obtained) colour preference assessment datasets resulting from previous experiments [3, 32]. The new colour preference index $R_{p,2019}$ shall exhibit the following features:

1. $R_{p,2019}$ shall include a dependence on illuminance level, CCT and object saturation level. According to the limitations of the underlying experimental datasets, we do *not* include *gamut shape* dependence and *Duv* dependence (*Duv* is the distance of the white tone of the light source from the blackbody locus or the daylight locus on a chro-

maticity diagram) in the present version of the new metric;

2. $R_{p,2019}$ shall be based on the following internationally well-known, recent and readily applicable quantities:

– A descriptor of object saturation level (caused by the light source spectrum) derived from the TM-30–15 Colour Vector Graphic,

– The value of R_f [16],

– CCT (K),

– E_v (lx);

3. $R_{p,2019}$ shall have a psychophysically relevant scale fitted to the subjective colour preference scale of the observers in the underlying experimental colour preference datasets [3, 32].

This scale [39] was labelled by rating categories including "very good", "good", "moderate". Therefore, a criterion value of the new index $R_{p,2019}$ can be readily determined for the "good" colour preference (as a minimum acceptance criterion of lighting design) if the spectrum of the light source and the illuminance level are known.

2. SUBJECTIVE COLOUR PREFERENCE DATASETS USED TO OBTAIN THE NEW COLOUR PREFERENCE METRIC ($R_{P,2019}$)

The colour preference metric $R_{p,2019}$ is based on a new mathematical analysis of two previously published subjective colour preference datasets resulting from two previous studies [3, 32]. In this Section, the experimental method and the findings of these studies [3, 32] are summarized. Both studies were laboratory tests in a dedicated experimental room with white walls and white cloths on the tables with different multi-coloured arrangements of coloured objects including artificial flowers, paintings, books, a multi-coloured textile object and Macbeth ColourChecker® charts, see Fig. 1. These arrangements represent a general indoor viewing environment with coloured objects to assess colour preference independent of a specific lighting application [14].

In the first study [3], a multi-LED engine with red, green, blue and warm white LEDs illuminated two still life arrangements with coloured objects (in Fig. 1 only the first one is depicted as an example) with a set of 36 white spectra at a fixed, single illuminance level of 750 lx at four CCTs (3100 K, 4100 K, 5000 K and 5600 K). Nine different multi-LED spectra were used at each CCT. Each one of these nine spectra represented nine different degrees of object saturation. This means that the multi-LED spectra used rendered the coloured objects more or less saturated. Observers assessed their colour preference impression of all coloured objects at the same time. "Colour preference" was defined for the subject as the "subjective extent of how the observer likes the colour appearance of the coloured objects under the current light source taking all coloured objects into consideration".

Subjects assessed their colour preference on an interval rating scale labelled by rating categories, see Fig. 2. The non-uniform spacing of the category labels along this rating scale is based on a previous study [39]. Observers in previous studies [3, 32] could use this interval rating scale labelled with categories successfully. The categories represented decision criteria and helped subjects put their rating

Fig. 1. Experimental room with multi-coloured arrangements of coloured objects in the two previous studies (left: first study [3] with Exp-1's arrangement; right: second study [32]) that constitute the basis of the present new colour preference metric ($R_{p,2019}$)
(Reproduced with permission from Lighting Research and Technology, both photos (left and right) contain copies of the MacBeth ColourChecker® Chart)

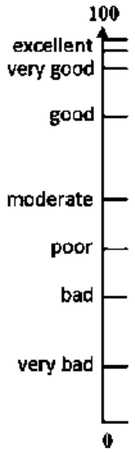

Fig. 2. Colour preference interval rating scale [39] labelled with the category 'excellent' at the value of 97.9; 'very good' at 91.6; 'good' at 79.6; 'moderate' at 52.9; 'poor' at 41.2; 'bad' at 26.5; and 'very bad' at 12.8 (*Reproduced with permission from Lighting Research and Technology [3]*)

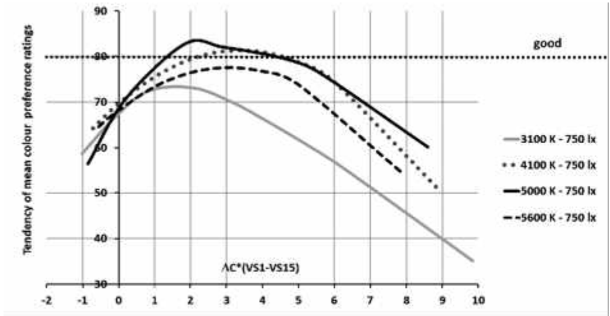

Fig.3. Tendencies of the observers' mean colour preference ratings as a function of object saturation level (ΔC^*) and CCT at the fix illuminance level of 750 lx in the first study [3]

cross on the scale [39]. Observers were instructed to put their rating cross at any place on the interval scale, not only at the categories (and they did so consciously). The category "good" with a value of 79.6 plays an important role in lighting design as a general acceptance criterion of the lighting system [29] from the point of view of colour preference.

The de-saturation or over-saturation of the coloured objects caused by the current light source was characterized by the mean *chroma difference* value (denoted by ΔC^*) of the CQS test colour samples VS1-VS15 [35] (a set of fifteen different homogeneous colour samples) when their chroma under the current light source was compared with their chroma under the reference illuminant. Depicting the observers' mean colour preference ratings as a function of ΔC^*, the following tendencies were obtained [3]. Neutral white (4100 K) and cool white (5000 K and 5600 K) resulted in higher subjective colour preference ratings than warm white (3100 K), see Fig. 3.

It can also be seen from Fig. 3 that colour preference ratings exhibited a maximum at a moderate object saturation level. The location of this maximal colour preference (in terms of ΔC^*) depended on CCT, higher CCTs requiring more object saturation. At 3100 K, the observers' mean colour preference ratings were always less than "good" (see Fig. 3) because the illuminance level of 750 lx was too low for the observers at this CCT so that their colour preference judgements were always worse than "good".

In the second study [32], subjects assessed the colour preference of a tabletop arrangement of coloured objects (see Fig. 1, right) illuminated by 36 different light sources with all 36 possible combinations of three object saturation levels (low with ΔC^* between –0.1 and 1.0; medium with ΔC^* between 1.7 and 4.4; and high with ΔC^* between 10.7 and 12.2), three CCTs (3000 K, 4100 K and 5600 K) and four illuminance levels (200 lx, 500 lx, 1000 lx and 1800 lx). Subjects assessed their colour preference impression by the use of the same rating scale (Fig.2). Mean colour preference ratings in this second study increased with increasing illuminance level monotonically and a logarithmic function was fitted to describe the illuminance dependence of colour preference [29], see the first multiplicative term of Eq. (1) and Fig. 4.

As can be seen from Fig. 4, mean subjective colour preference ratings increased with increasing CCT. Colour preference maxima generally occurred at the level of ΔC^*=4.2 (a medium saturation level) at every CCT and every illuminance level.

3. DEFINITION OF THE NEW COLOUR PREFERENCE METRIC ($R_{P,2019}$), ITS VALIDITY RANGE, COMPARISON WITH THE CP METRIC, AND VALIDATION

In this Section, the defining equations of the new colour preference metric ($R_{p,2019}$) are described. Equation (3) shows the main defining formula of the new colour preference metric.

$$R_{p,2019} = 0.70 \cdot R_f + p_1 \times \times \Delta C_t^2 + p_2 \cdot \Delta C_t + p_3. \quad (3)$$

In Eq. (3), R_f is the CIE2017 Colour Fidelity Index [16]. The symbol ΔC_t is the so-called total chroma difference defined by Eq. (4) while $p_1 - p_3$ are model parameters that depend on CCT and illuminance level, see Eq. (5).

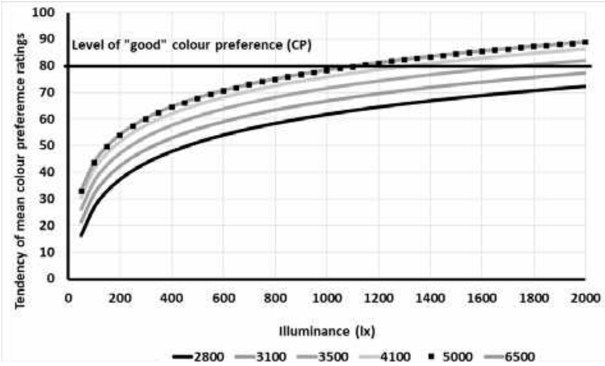

Fig. 4. Tendencies of the observers' mean colour preference ratings as a function of illuminance level (lx) and CCT in the second study [32] at the fixed object saturation level of ΔC^*=4.2 the level of maximum colour preference *(Reproduced with permission from Lighting Research and Technology [32])*

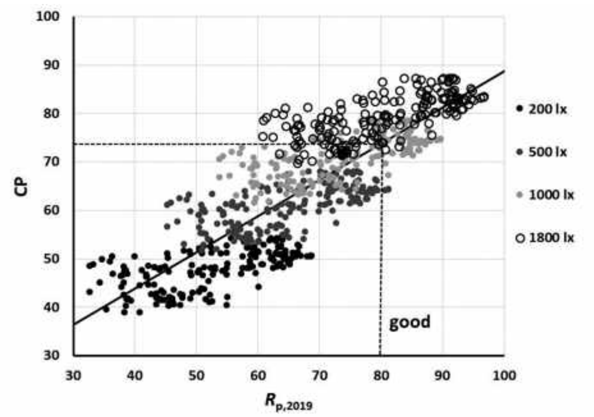

Fig. 5. Comparison of the values of $R_{p,2019}$ with the values of a previous metric (*CP*, Eq. 1) in case of a sample set of 180 light source spectra (see text) at four illuminance levels, 200 lx, 500 lx, 1000 lx and 1800 lx *(Best fit: $CP = 0.7476 \cdot R_{p,2019} + 13.965$ (r^2 = 0.71). The "good" colour preference level of $R_{p,2019}$ (79.6) is taken from the subjective scale of Fig. 2)*

$$\Delta C_t = \sum_{i=1}^{16} \frac{R_{cs,hi}}{100}. \quad (4)$$

In Eq. (4), the $R_{cs,\,hi}$ values (expressed in %; i=1–16) correspond to the "purely radial difference between vectors for the test and reference condition in each of the 16 hue bins" [20] in the TM-30–15 Colour Vector Graphic. The concept of *hue bins* can be defined as collections of test colour samples (with homogeneous coloured surfaces) of *similar* hues. There are 16 hue bins (i=1–16) evenly distributed along the hue circle: 1. red, 2. reddish-orange, 3. orange, 4. yellow, 5. greenish-yellow, 6. yellowish-green, 7. green, 8. bluish-green, 9. cyan-green, 10. cyan; 11. bluish-cyan, 12. blue, 13. bluish-violet, 14. violet, 15. purplish-violet, 16. purple. For example, the red hue bin (i=1) contains test colour samples of slightly different red tones. Colour Vector Graphic calculations are available in the TM-30 Calculation Tools. The sum of the $R_{cs,\,hi}$ values (ΔC_t) in Eq. (4) characterizes the overall saturating or de-saturating effect of the light source on the different coloured objects in the scene.

Equation (5) shows the dependence of the model parameters p_i (i=1–3) of Eq. (3) on CCT and illuminance level.

$$p_1 = a_1 \cdot CCT^2 + b_1 \cdot CCT + \\ + c_1 \cdot \ln(E_v + d_i) + e_i. \quad (5)$$

The optimum values of the parameters $a_i - e_i$ (i=1–3) of Eq. (5) (listed in Table 2) were obtained in the following way:

1. Only the light sources with ΔC_t values between –0.4 and 1.2 were considered from the set of the 36+36=72 light sources in the two studies described in Section 2 [3, 32], the reason is that the light sources of this set with ΔC^*>6.1 obtained only "moderate" or worse visual colour preference ratings, and this should not be the aim of interior lighting design, but therefore, we decided *not* to include these light sources in the fitting procedure; correspondingly, two light sources were excluded from the first study [3] and twelve light sources were excluded from the second study [32];
2. The values of R_f and ($R_{cs,\,hi}$ / 100) were computed for the remaining 58 light sources (their illuminance levels and CCT values were known);
3. Equations (4) and (5) were substituted into Eq. (3);
4. The sum of the squared differences between the 58 mean subjective colour preference ratings [3, 32] and $R_{p,2019}$ was minimized.

According to the above 4th condition, the numeric scale of the new colour preference metric $R_{p,2019}$ is equivalent to the visual scale labelled by the categories in Fig. 2. The value of $R_{p,2019}$ ≥79.6 shall be ensured during the lighting design procedure in order to achieve at least the criterion of "good colour preference" in the illuminated scene, see the caption of Fig. 2 in which the criterion val-

Table2. Optimum Parameter Values $A_i - E_i$ (I=1–3) in Eq. (5) Obtained by Fitting Eq. (3) to the Mean Subjective Colour Preference Ratings for 58 Light Sources of the Two Studies Described in Section 2 [3, 32]

i	a_i	b_i	c_i	d_i	e_i
1	$-1.074 \cdot 10^{-6}$	0.008406	-0.01883	0.000	-31.68
2	$-4.603 \cdot 10^{-6}$	0.04249	-0.4564	$1.02 \cdot 10^{4}$	-63.92
3	$-3.726 \cdot 10^{-6}$	0.03519	11.37	-51.6	-143.5

ues of the different colour preference categories are listed.

Concerning the fitting accuracy of the parameter values in Table 2, the mean absolute value of the difference between the value of $R_{p,2019}$ and the mean colour preference ratings of the observers in case of the 58 light sources equalled 2.0 (SD=1.9; min.=0.1; max. =7.2). This mean fitting accuracy (2.0 points on the rating scale of Fig. 2) is small compared to the distance of the adjacent rating categories on the rating scale (26.7 between "moderate" and "good" and 12.0 between "good" and "very good"). Pearson's correlation coefficient between the 58 mean colour preference ratings and the corresponding $R_{p,2019}$ values equalled r=0.97. During the development of the new metric, we also considered mathematically less complex versions but it turned out that we would need this level of complexity to achieve this fitting accuracy. In comparison, Pearson's correlation coefficient between the 58 mean colour preference ratings and the corresponding CP values (Eq. (1)) equalled r=0.75. The difference between the two correlation coefficients (r=0.97 and r=0.75) was statistically significant (p<0.001).

Concerning the validity range of the parameters in Table 2 according to the underlying experimental dataset, these parameters are valid for correlated colour temperatures between 3000 K and 5600 K, illuminance levels between 200 lx and 1800 lx and ΔC_t values between 0.4 and 1.2. The white points of the underlying experimental dataset were located in a range with $\Delta u'v' < 0.003$ above and below the blackbody locus (for CCT < 5000 K) or the daylight locus (for CCT ≥ 5000 K). According to this limitation and also because white points further away from the blackbody locus or daylight locus might contain visually disturbing tints (for example a greenish shade) [24, 40], $R_{p,2019}$ should not be applied to light source spectra with $\Delta u'v' \geq 0.003$.

The numerical predictions of $R_{p,2019}$ were compared with those of CP (see Eq. 1). Fig. 5 shows this comparison in the case of a set of 180 selected light source spectra. Latter set is a subset of 459 spectra including the 58 spectra used to derive the optimum parameter values in Table 2 [3, 32] plus the SPD library with 401 spectra of the R_f calculation tool made available in connection with the CIE publication [16]. The subset with 180 spectra was selected from the set of these 459 spectra in the following way:

1. Spectra with R_f < 70 were excluded (they are not relevant for interior lighting design);
2. Only the spectra in the validity range of $R_{p,2019}$ were used. This means that we considered only those spectra that exhibited CCTs between 3000 K and 5600 K and ΔC_t values between –0.4 and 1.2, the $R_{p,2019}$ and CP values were calculated at four illuminance levels, 200 lx, 500 lx, 1000 lx and 1800 lx, see Fig. 5.

As can be seen from Fig. 5, the relationship between the present $R_{p,2019}$ metric, see Eq. (3), and the previous *CP* metric [32], see Eq. (1), can be approximated by a linear function (R^2=0.71, see the caption of Fig. 5). As the underlying subjective colour preference datasets of both metrics were obtained using the same subjective rating scale (see Fig. 2), the absolute magnitudes of the two metrics can be compared. In tendency, the CP metric predicts about six units (see Fig. 2) lower colour preference values for the same light source spectrum at the same illuminance level. When the present $R_{p,2019}$ metric predicts "*good*" colour preference (79.6, see the caption of Fig. 2) in case of the sample illumination conditions of Fig. 5 then CP's prediction equals only 73.5 which can be considered as a "*good-moderate*" colour preference prediction.

The reasons for this absolute magnitude difference and also for the scatter of the data points are:

1. The CP metric is based just on the second dataset [32] while $R_{p,2019}$ also additionally incorporates the data of the first study [3] (see Section 2);
2. The two metrics are based on different colourimetric descriptor quantities and test colour sam-

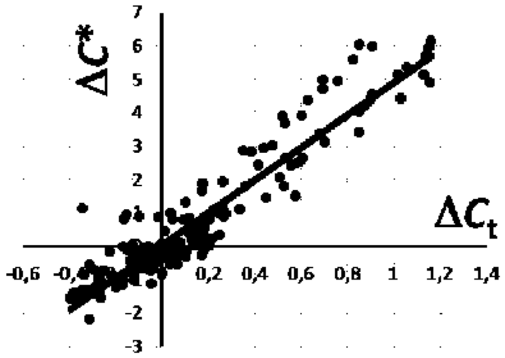

Fig.6. Comparison of two quantities used to describe the object saturating effect of the light source, ΔC_t (in case of $R_{p,2019}$, Eq. (3)) and ΔC^* (in case of CP, Eq. (1)) *(Fit line:* $\Delta C^* = 4.8645 \cdot \Delta C_t + 0.0434$ *(R^2=0.893))*

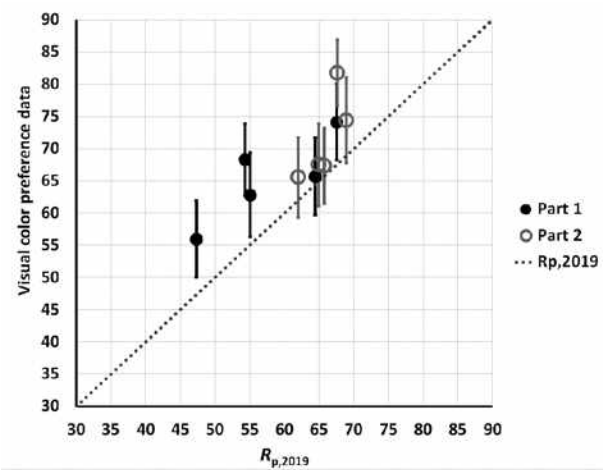

Fig.7. Comparison of the values of $R_{p,2019}$ with the mean subjective colour preference ratings (with 95 % confidence intervals representing inter-observer variability) resulting from two previous studies, "Part 1" [2] and "Part 2" [4] *(Two light sources were excluded from "Part 2" [4] because of* $\Delta u'v' \geq 0.003$*)*

ples (CIELAB and 15 CQS test colour samples for the CP-metric vs. CAM02-UCS and the 16 hue bins of TM-30–15 for $R_{p,2019}$), which are applied to a broad range of different types of light source spectra in Fig. 5. To further elucidate this, it is interesting to compare the two quantities used to describe the object saturating effect of the light source, ΔC_t (in case of $R_{p,2019}$, Eq. (3)) and ΔC^* (in case of CP, Eq. (1)), see Fig. 6.

As can be seen from Fig. 6, differences in maximum about 0.7 ΔC_t units (even fluctuations between "*desaturating*" and "*saturating*") appear along the abscissa at the same value of ΔC^* at the ordinate. This might cause large differences in the predictions of colour preference if the two metrics are applied to an arbitrary light source. This finding corroborates the importance of the use of the TM-30–15 method and the CIE2017 colour fidelity index R_f [16] in lighting design.

For validation, the numerical predictions of $R_{p,2019}$ were compared with the mean subjective colour preference ratings resulting from selected previous studies satisfying the following criteria:

1. Using the same rating scale as in the present article (see Fig. 2);
2. Using multi-coloured arrangements of miscellaneous coloured objects (similar to Fig.1) and not only objects in a specific hue range (e.g. red);
3. Using light sources in the validity range of $R_{p,2019}$.

According to these criteria, we selected two previous studies [2,4]. In the first study (so-called "Part 1") [2], five light sources (phosphor-converted LED, compact fluorescent lamps and tungsten halogen lamps) were used at 470 lx (fixed) and CCTs between 2300 K and 4100 K. In the second study (so-called "Part 2") [4], seven multi-LED light sources were used at 3220 K (fixed) and 550 lx (fixed). Two light sources of the second study [4] that were out of the validity range of $R_{p,2019}$ (because of $\Delta u'v' \geq 0.003$) were excluded from this analysis. Fig.7 shows the result of this comparison.

As can be seen from Fig. 7, $R_{p,2019}$ was able to predict the tendency of the mean subjective colour preference ratings. Pearson's correlation coefficient between $R_{p,2019}$ and these ten mean subjective colour preference ratings equalled r=0.78. The mean difference between the mean subjective colour preference ratings and the value of $R_{p,2019}$ equalled 7 units (STD: 4) on the rating scale of Fig. 2. This difference was significant in the case of five light sources, see those confidence intervals of the mean subjective ratings that do not overlap with the grey dot line of the $R_{p,2019}$ values in Fig.7. These differences did not cause a transition between two adjacent categories on the rating scale, e.g. "good" to "moderate", see Table 3.

It should be noted that the prediction of such subjective colour preference rating values that are *anchored* with categories (according to Fig.2) in the present article represents a different approach from other studies (e.g. [13, 33, 34]) that are based on the analysis of the *correlation* between a metric and a subjective rating value on an *arbitrary* scale. In the present article, we also analyse absolute differences on these anchored scales, and not only the

Table 3. Validation of the Numerical Predictions of $R_{p,2019}$ Based on the Mean Subjective Colour Preference Ratings from Two Previous Studies [2,4], *(See Also Fig. 7)*

	Interval scale (see Fig. 2)			Category (see Fig. 2)	
Study	Subj. rating	$R_{p,2019}$	Difference	Subj. rating	$R_{p,2019}$
"Part 1" [2]	68	54	14	good-moderate	moderate
"Part 1" [2]	63	55	8	moderate-good	moderate
"Part 1" [2]	66	64	1	moderate-good	moderate-good
"Part 1" [2]	74	68	7	good-moderate	good-moderate
"Part 1" [2]	56	47	9	moderate	moderate-poor
"Part 2" [4]	66	62	4	good-moderate	moderate-good
"Part 2" [4]	67	66	2	good-moderate	good-moderate
"Part 2" [4]	67	65	3	good-moderate	good-moderate
"Part 2" [4]	82	68	14	good	good-moderate
"Part 2" [4]	74	69	5	good-moderate	good-moderate

correlation, see Table 3. Possible reasons for these absolute differences include different observer panels, weather conditions, time of the day, time of the year. Another reason is viewing condition differences in "Part 2" [4] (in a viewing booth instead of a room) as well as the limited range of illuminance levels (470–550) lx without comparing them with higher illuminance levels in these two studies [2,4]. Therefore, further validating studies are necessary varying all three independent variables (illuminance, CCT, object saturation) systematically and with more data points in a real room.

4. APPLICATION OF $R_{P,2019}$ TO LIGHTING DESIGN

If the spectrum of a test light source to be applied in a lighting installation is known then the values of CCT, R_f, ΔC_t (Eq. (4)) can be computed. We can assume different illuminance levels at a "*working plane*" (for example a horizontal table surface in a room) on which coloured objects can be arranged. These coloured objects can be illuminated by the luminaire that contains the test light source. Fig. 8 shows the dependence of the value of $R_{p,2019}$ (Eqs. (3)-(5)) on illuminance level (E_v in lx) in case of four sample light sources of different type. Their spectra are shown in Fig. 9 while their CCT, R_f and ΔC_t values are listed in Table 4. Fig. 8 and Table 4 contain *criterion illuminance values* at which the value of $R_{p,2019}$ reaches the "*very good*" and "*good*" colour preference levels in case of the four different types of light source. Although the "*moderate*" level is rather irrelevant for lighting design, this level is also included in Fig. 8 for better understanding.

As can be seen from Fig. 8 and Table 4, it is not possible to reach neither the "*good*" nor the "*very good*" colour preference level by the aid of the 2nd spectrum (RGB LED) within the validity range of $R_{p,2019}$ (200–1800) lx. The reason is that this spectrum de-saturates the object colours (ΔC_t<0) and it has a lower R_f value (R_f =77). Just the opposite is true for the 1st spectrum (RGBW LED with R_f=90 and moderate object colour oversaturation,

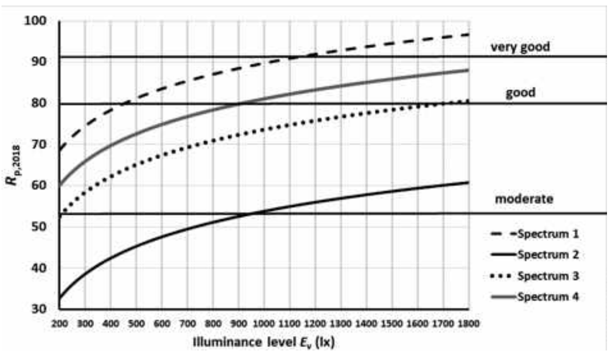

Fig. 8. Application of $R_{p,2019}$ to *interior lighting* design: dependence of $R_{p,2019}$ on illuminance (E_v in lx) for four sample light sources (see Fig. 9 and Table 4), where Table 4 contains the criterion illuminance values at which the value of $R_{p,2019}$ reaches the "*very good*", "*good*" and "*moderate*" colour preference levels

Table 4. Application of $R_{p,2019}$ to Interior Lighting Design

*(Criterion illuminance values at which the value of $R_{p,2019}$ reaches the "very good" and "good" colour preference levels in case of the four different light source spectra (examples) shown in Fig. 8. *: it is not possible to reach the "good" category within the validity range of $R_{p,2019}$ (200–1800) lx)*

Spectrum					Criterion illuminance (lx) for the category	
No.	**Type**	R_f	**CCT (K)**	ΔC_t	**good** $R_{p,2019}$**=79.6**	**very good** $R_{p,2019}$**=91.6**
1	RGBW-LED	90	3993	0.61	440	1170
2	RGB-LED	77	3243	-0.34	*	*
3	RGBW-LED	88	4840	-0.17	1650	*
4	Fluorescent lamps	89	5091	0.05	890	*

ΔC_t=0.61): the "*good*" colour preference level can be reached at 440 lx while the "*very good*" level can be reached at 1170 lx if this light source is used to illuminate the coloured objects. Using the 3rd spectrum or the 4th spectrum, only the "*good*" level can be achieved at 1650 lx and 890 lx, respectively, according to their colorimetric properties.

Fig. 8 supports the procedure of ensuring high colour preference in lighting design. The luminaires containing a particular light source shall be designed (and later installed) in the room to provide at least the "*good*" criterion illuminance level at a working plane on which the coloured objects to be illuminated are arranged. After the design of the lighting installation, the electric power necessary to achieve this criterion illuminance level ($P_{el,\ crit}$) will be known and a measure of *electric efficiency for colour preference*, $\eta_{p,2019} = \frac{R_{p,2019,crit.}}{P_{el.,crit.}} = \frac{79.6}{P_{el.crit.}}$ (in W^{-1} units). These values can be calculated for every possible installation with different light sources. Thus, different theoretical lighting installations can be compared and the most efficient installation can be selected. A new metric of electric energy efficiency was published [41] recently but the latter metric was intended to characterize *light sources* and not lighting installations and it was not intended to predict colour preference.

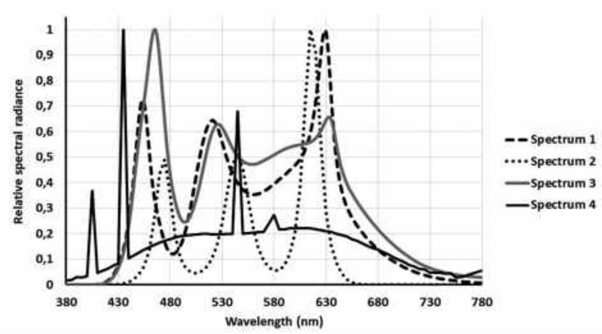

Fig. 9. Relative spectral radiance of the four samples of light sources in Fig. 8
1: RGBW-LED; 2: RGB-LED; 3: RGBW-LED;
4: Fluorescent lamp

Table 5 compares the colour preference levels to be obtained according to the $R_{p,2019}$ index at 500 lx and 1200 lx, respectively, in case of the four light source spectra in Fig. 9. As can be seen from Table 5, the colour preference level (predicted by $R_{p,2019}$) increases 10–11 points on the colour preference scale (Fig.2) if the illuminance level is increased from 500 lx to 1200 lx. This increment corresponds to a change between two categories in case of the 1st (good→very good) and 2nd (poor→moderate) light sources. For the 3rd and 4th light sources, such a full categorical shift does not occur.

It is also interesting to depict the dependence of the value of $R_{p,2019}$ on correlated colour temperature. Fig. 10 shows a computational example using Eqs. (3) and (5), independent of any specific light source spectrum, in case of R_f=84 and E_v=500 lx with different CCTs in the validity range (3000–5600) K and with different ΔC_t values as parameters. The following values were used: ΔC_t=1.2, 0.9435 (that maximizes the value of $R_{p,2019}$ in case of R_f=84 and E_v=500 lx), 0.8, 0.4, 0.0 and –0.4 (a de-saturating ΔC_t level).

As can be seen from Fig.10, according to the prediction of $R_{p,2019}$, the best colour preference takes place between 4500 K and 4800 K (neutral white – cool white) according to the tendencies of the un-

Table 5. Colour Preference Levels to be Obtained at 500 lx and 1200 lx in Case of the Four Light Source Spectra in Fig. 8 According to the $R_{p,2019}$ Index

Spectrum				E_v=500 lx	E_v=500 lx	E_v=1200 lx	E_v=1200 lx	500 lx →1200 lx
No.	R_f	CCT (K)	ΔC_t	$R_{p,2019}$	$R_{p,2019}$ Category	$R_{p,2019}$	$R_{p,2019}$ Category	$R_{p,2019}$
1	90	3993	0.61	81	good	92	very good	11
2	77	3243	-0.34	45	poor	56	moderate	11
3	88	4840	-0.17	65	moderate-good	76	good	11
4	89	5091	0.05	73	good-moderate	83	good	10

derlying experimental colour preference dataset. The magnitude of the absolute maxima of the $R_{p,2019}$(CCT) curves depends on the saturation level (ΔC_t). As $R_{p,2019}$ was constructed on the basis of artificial installations of coloured objects in an experimental room with white walls and white cloths (see Section 2), the CCT tendencies in Fig. 10 are expected to be valid to predict colour preference for different types of formal or official situations or working environments including offices, schools, exhibitions, conferences, lecture rooms, breakfast rooms in hotels or public vehicle interiors. For applications that require a more relaxing atmosphere (for example romantic evening events, dinners, creative mental activities), lighting installations with a lower CCT and a lower illuminance level might be more appropriate. In the latter case, colour preference should not be the (primary) aim of lighting design.

5. DISCUSSION

The new colour preference metric ($R_{p,2019}$) models the experimental finding that colour preference depends on CCT, object saturation and illuminance level. The metric has a built-in semantic interpretation of its numeric scale in terms of intuitive rating categories ("very good", "good", "moderate", see Fig.2). Criterion illuminance values can be derived to establish a "good" or "very good" colour preference level in case of a given lighting installation (see Fig. 8) except for spectra with poor colour rendition properties (for example the spectrum No. 2 in Fig. 9) that cannot reach the "good" colour preference level.

Besides the above advantageous properties, the new metric has the following limitations. The validity range of its input parameters is limited: the metric cannot be used for warm white spectra with CCTs less than 3000 K and for cool white light sources with CCT>5600 K. Its illuminance level dependence is also limited to the range of 200 lx to 1800 lx. This range covers, however, typical illuminance levels of today's general interior lighting practice.

Concerning saturation levels, light sources with ΔC_t >1.2 tend to over-saturate coloured objects and they generally obtain "moderate" or worse visual colour preference ratings. This should not be the aim of lighting design. In case of such higher saturation levels (ΔC_t >1.2), the value of the metric decreases rapidly. Accordingly, such light sources should not be applied in general interior lighting al-

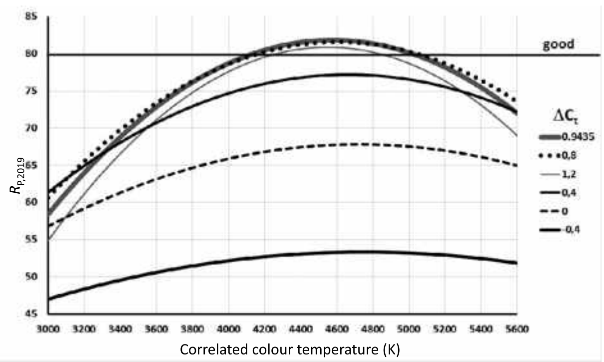

Fig.10. Dependence of the value of $R_{p,2019}$ on correlated colour temperature (CCT) in case of the fixed values R_f=84 and E_v=500 lx

(Computational example when Eqs. (3) and (5) with different ΔC_t values as parameters (see the legend) are using, and the absolute maximum of $R_{p,2019}$ occurs in case of ΔC_t = 0.9435, if R_f=84 and E_v=500 lx are fixed)

though they might have a special application including the lighting of theatre scenes for a strong emotional effect. A further limitation is the dependence of subjective colour preference ratings on lighting application [14], as already mentioned at the end of Section 4.

Experimental evidence suggests that the shape of the colour gamut (especially the red saturation component) influences the subjects' colour preference assessments [13, 19, 20] significantly. This red saturation factor was not included in the present $R_{p,2019}$ metric due to the limitations of the underlying subjective colour preference datasets [3, 32]: in their experimental method, the effect of CCT and illuminance was not combined with the change of *red* saturation level. This should be the task of a subsequent study. The red saturation effect is especially significant if dedicated spectra saturating red object colours are used (see the Colour Vector Graphic in Fig. 2 of [13]). The LIKE model (see Table 1) was developed to describe this effect. The LIKE model uses the parameters IES R_f [15], $R_{cs,\,h16}$ (as a proxy for red saturation; this quantity is also used in Eq. (4) of the present article as a component of the sum of all 16 $R_{cs,\,hi}$ values) and the parameter ψ (that represents the best-fit ellipse's rotation angle; this ellipse approximates the shape of the IES TM-30–15 Colour Vector Graphic).

Illuminating a scene of coloured objects, the *white tone* of the light source is usually also visible on white or neutral grey surfaces (walls, table cloths, window sills, curtains, furniture) and this white tone perception interacts with the impression of colour preference of the coloured objects. The CCT dependence of white tone perception (warm white, neutral white, cool white) and its interaction with colour preference is included in the CQS [35], CP (Eq. (1)) and $R_{p,2019}$ (Eqs. (3)-(5)) metrics. However, it was reported [25, 42, 43] that the distance of the white tone's chromaticity from the blackbody locus (expressed in terms of *Duv* or $\Delta u'v'$) also influenced colour preference. Chromaticities below the blackbody locus were generally preferred. The cause of this effect was identified by simulation [26]: "illuminants with chromaticity below the blackbody locus (that is, negative *Duv*) are more likely to have higher scores for relative gamut than illuminants on or above the blackbody locus while maintaining high scores for fidelity" [26]. This effect is not included in the new colour preference metric ($R_{p,2019}$) of the present article.

6. CONCLUSIONS AND OUTLOOK

Applying the scheme of Fig. 8 during the design of the lighting for an interior space, the colour preference vs. illuminance curves of different light source types (or different settings of a multi-LED light source) can be compared and the most energy efficient light source providing the "good" colour preference level can be selected. If only one light source is given then the *criterion illuminance value* can be computed for "good" colour preference depending on the number of luminaires (containing this light source) to be installed in the room and the height of the luminaires above the table on which the coloured objects shall be illuminated.

According to the viewing conditions of the experimental datasets underlying the new colour preference metric (a neutral environment with white walls, white tablecloths and miscellaneous coloured objects), the metric should be valid for different types of official, formal situations or working environments. For other applications including the lighting of living rooms or dining rooms in the evening and special collections of coloured objects (e.g. red makeup, blue jeans or important memory colours like banana or skin tone), a different colour preference metric should be applied.

According to Table 5, the typical interior illuminance level of 500 lx (the most common horizontal illuminance level required by the standard for general workplace illumination [44]) is often not enough to reach the "good" colour preference level. To do so, the illuminance level shall be increased either by allowing for daylight in the room or by increasing the electric energy consumption of the luminaires (if possible) in case of a demanding application (the related economic considerations are out of the scope of the present article).

A validation study using the same semantically labelled colour preference scale (see Fig. 2) is currently underway in a spacious experimental room with a multi-LED illumination system allowing for the variation of lighting parameters in a broader range than in the previous studies. The effect of all relevant variables, illuminance level, correlated colour temperature (from 2800 K up to 6500 K), and the white tone's chromaticity distance from the blackbody locus, object saturation level and red saturation are being varied. The aim is to validate and extend the framework of Eqs. (3)-(5) and re-optimize the model parameters of Table 2. The current value of the weighting factor 0.70 of the colour fidelity component (R_f) will also be fine-tuned.

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