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A numerical analysis of recent colour rendition metrics

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The purpose of this paper is to show a possible way to move forward to a usable method for lighting practitioners to characterise and optimise the colour quality of white light sources for general interior lighting. First, correlations between recent colour rendition (colour quality) metrics are analysed. Second, linear and quadratic combinations of the two recently published Illuminating Engineering Society of North America metrics (R_f and R_g) are suggested to approximate two selected visually relevant colour quality metrics, the Memory Colour Quality Index and the NIST Colour Quality Scale Q_p index. Numeric values of the optimum coefficients of these (R_f, R_g) combinations are provided for a comprehensive set of 546 light source spectral power distributions in two correlated colour temperature groups, warm white and cool white. The performance of the different combinations used to describe the metrics ranged between poor and good.

1. Introduction

Since the beginning of the evolutionary development of mankind, lighting and light sources have always accompanied all activities of human beings. Until the end of the 19th century, daylight was most generally used exhibiting dynamically changing spectral power distributions, colour temperatures and illuminances depending on geographical position, weather, the time of the day and the time of the year. In those days, society was reliant on the use of oil lamps, gas lamps, firewood and candles in the evening. Visual perceptions of light sources and illuminated coloured objects were memorized by individuals in the context of these light sources and aesthetic requirements about light source colour and object colours arose which were incorporated into culture.

After about 1880, industrial electrification and the broad dissemination of incandescent lamps have resulted in a re-organization of working schedules and a more and more dramatic change of lifestyles. This tendency has been accelerated in the 20th century by the emergence of new light source technologies: Mercury-vapour lamps, sodium discharge lamps, fluorescent lamps and metal halide lamps. But the possibility of varying the colour properties of these light sources, i.e. their spectral power distribution, colour temperature or chromaticity was limited (by changing and optimizing their metallic and phosphor components) and classic lighting engineering has primarily concentrated on (achromatic) visual performance parameters like luminance, illuminance, glare and illuminance distributions often ignoring the perceived quality of the colour appearance of the illuminated coloured objects in the lit environment.

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Since about 2002, a new trend in lighting design and light source design has appeared: Human centric lighting (HCL). HCL exploits the flexibly variable spectral power distributions of LED based light engines. HCL means that lighting design concentrates on the human user of the lighting system including all relevant subjective properties (age, health, culture, region of living, region of origin, profession, individual needs, comfort, emotional well-being, visual performance, individual visual behaviour) and considering the objective conditions (lighting application, e.g. shop, office, hospital or school lighting, time of the day, time of the year, availability of daylight, shift work).

For HCL design, it is not only the illuminance, spatial distribution (direct and indirect light components), colour temperature or white tone chromaticity that should be varied and optimised. More importantly, the relative spectral power distribution of the light source should be made flexibly variable by using recent LED light engines with multiple, separately driven LED colour channels (multi-LED light engines). The colour rendition (or in other words: colour quality (CQ)) aspects of the light source (e.g. colour fidelity, colour preference, colour naturalness or colour vividness) represent an important optimization target for HCL: CQ aspects should be co-optimized with non-visual HCL aspects (e.g. the circadian aspect) at a later stage. To implement the HCL concept in lighting engineering, it is worth keeping in mind that the human brain reacts to electromagnetic radiation as a single entity, as a result of complex interactions of its visual and nonvisual pathways[1] including the subsystem of CQ assessments.

For an effective HCL design, according to the given application, different aspects of CQ[2] can be considered: colour fidelity, colour preference, colour vividness, Colour naturalness, colour harmony, etc. When the user of a general indoor lighting system assesses the visual CQ of the lit scene in an everyday situation, usually a colour preference judgement or a colour naturalness judgement is being made instead of the assessment of colour fidelity, i.e. the comparison with an inferred reference situation.[3–8] Therefore, to optimize the spectral power distribution of, e.g. a multi-LED light engine, a visually validated colour preference metric or colour naturalness metric is needed as a spectral optimization target with a set of boundary conditions, i.e. type and quality of the illuminant's white tone or the circadian stimulus (CS)[9] level (higher for office work, lower for a more relaxing atmosphere).

This paper concentrates on the colour preference aspect in relation to two CQ indices: the Memory Colour Quality Index (MCRI)[10] and the NIST Colour Quality Scale (CQS) Q_{p} index.[11] It has been pointed out that both metrics correlate well with the observers' visual colour preference judgements in the related experiments.[7,8,10,11] It has also been shown in visual experiments that neither the existing descriptors of colour fidelity (i.e. the colour rendering indices) nor one of the colour gamut metrics are able to describe the subjects' colour preference or colour naturalness judgements alone but combinations of both index types (fidelity index, gamut index) yielded better results.[3–6]

The underlying idea is that the colour fidelity concept does not allow for any chroma enhancement of the illuminated coloured objects compared to the reference light source, the colour gamut concept requires a high amount of chroma enhancement (to enhance perceived vividness) while the aspects of colour preference or colour naturalness imply a certain limited amount of chroma enhancement by the light source. The question is how to express the visually relevant limit of this chroma enhancement numerically by the use of a colour fidelity metric combined with a colour gamut metric. The aim of the present paper is to show an example of how to do so by concentrating on two selected metrics, MCRI[10] and CQS Q_p.[11] The aim is to express these two metrics numerically as a function of the two recently published and promising colour fidelity and colour gamut type metrics, R_f and R_g of the Illuminating Engineering Society of North America (IESNA) method.[12,13] The IESNA method is currently the focus of international attention and the present authors are convinced about the advantages of this method.

The motivation behind this paper is that, at the time of writing, the authors are not aware of any visual experiment about how the IESNA R_f and R_g metrics correlate with visual colour preference judgements under technologically relevant light source spectral power distributions for general interior lighting. Thus, the aim of this paper is to provide numeric coefficient values to approximate the already visually validated MCRI and CQS Q_p metrics from the values of IESNA R_f and R_g for a given light source. The aim of the present article is to show a way to compute a visually relevant colour rendition metric for general interior lighting according to the HCL concept.

First, to prepare for the described approximation, all correlations among a selected set of today's recent CQ metrics will be analysed numerically with special attention to MCRI, Q_p, R_f and R_g. According to the most relevant CQ attributes for general interior lighting, the CQ metrics analysed are grouped into the following categories: colour fidelity indices, colour gamut indices and colour preference type indices. The analysis of the CQ index values has been carried out for two correlated colour temperature (CCT) groups of a large set of technologically relevant light source spectral power distributions: Warm white light sources and cool white light sources.

The selected set includes Commission Internationale de l'Éclairage (CIE) illuminants, conventional (non-LED) light source relative spectral power distributions and LED spectra. The reason for this grouping is that, in the HCL concept, warm white and cool white light sources represent two very distinct applications: Warm white light sources are intended for 'smart home' lighting providing a relaxing and emotionally active atmosphere while cool white light sources are thought to be primarily suitable for 'smart offices' in combination with natural daylight. This paper focuses attention on the warm white group and the cool white group of light sources. The neutral white group (with CCTs around 4000 K) will be considered in a subsequent work together with a more detailed analysis of further CQ indices.

2. Computational method

A set of 546 relative spectral power distributions with 1 nm spectral resolution between 380 nm and 780 nm was prepared for the computational analysis of a set of CQ (in other words colour rendition) indices. This set contained both real light sources (RGB LEDs, tungsten halogen lamps, neodymium lamps, hybrid multi-LED lamps and phosphor converted LEDs with one or more phosphor components) and CIE illuminants A, D, E and F. The set was divided into two groups: 326 warm white light sources (CCT = 2000–3672 K) and 220 cool white light sources (CCT = 4500–10000 K). The CCT range between 3673 K and 4499 K has not been dealt with in this paper. This will be the subject of subsequent work. Colorimetric properties and CQ indices were computed. Table 1 shows the minimum, mean and maximum values of these descriptor quantities of the light sources.

Table 1 shows four groups of CQ descriptors; colorimetric, colour fidelity, colour preference and colour gamut. CRI R_{1_14} denotes the mean value of all 14 special colour rendering indices.[14] In the case of MCRI, the value of the general MCRI (R_m) was

Table 1 Colorimetric properties and colour quality indices of the 546 light sources used in the computational analysis. Grouping of the colour quality (CQ) descriptors. All: all 546 light sources. FCI: Feeling of Contrast Index

		Warm white (326 light sources)			Cool white (220 light sources)			All (546)
CQ descriptor	Descriptor group	Min.	Mean	Max.	Min.	Mean	Max.	Mean
CCT (K)	Colorimetric	2000	2966	3672	4500	5949	10000	4168
Duv	Colorimetric	0.0000	0.0019	0.0153	0.0000	0.0033	0.0349	0.0025
CRI R_a [14]	Fidelity	73.2	91.2	100.0	70.2	87.1	100.0	87.4
CRI R_{1_14} [14]	Fidelity	63.2	87.7	100.0	58.9	82.5	100.0	82.8
GAI [3]	Gamut	80.2	97.0	111.6	76.0	93.5	122.0	94.9
CQS Qa [11]	Preference	14.1	86.3	100.0	22.2	85.3	100.0	84.4
CQS Qf [11]	Fidelity	15.7	85.1	100.0	23.3	84.3	100.0	83.1
CQS Qg [11]	Gamut	85.0	100.9	111.4	84.9	98.1	116.7	99.7
CQS Qp [11]	Preference	52.8	90.9	101.2	57.0	89.9	100.8	89.6
$R_{a,2012}$ [15]	Fidelity	61.3	90.1	100.0	65.6	88.6	100.0	87.7
MCRI [10]	Preference	74.8	88.4	93.4	70.8	86.4	94.9	86.9
FCI [16]	Gamut	96.0	121.5	148.3	70.1	98.9	140.9	111.8
IESNA Rf [13]	Fidelity	69.0	87.8	100.0	66.5	85.6	100.0	85.2
IESNA Rg [13]	Gamut	79.4	100.6	118.2	78.8	97.3	111.7	99.4

computed by using the 'degree of adaptation' parameter value of 0.9. To compute the values of the IESNA colour fidelity measure R_f and colour gamut measure R_g,[12,13] the following viewing condition parameters were used: $L_A = 60\,\mathrm{cd/m^2}$; $Y_b = 20$; $F = 1.0$; $c = 0.69$; $N_c = 1.0$. The value of D ($D = 0.908$) was computed from F and L_A according to the CIECAM02 equation. The values of L_A and D used in the computations of the present paper are different from the values specified in IES TM-30-15[13] which uses $L_A = 100\,\mathrm{cd/m^2}$ and sets the value of D to $D = 1$. The reason for the choice of the above different values was that, according to the opinion of the present authors, the adaptation luminance level is not so high in commonly occurring general lighting situations.

2.1 Correlations among the CQ indices

Similar to the scheme of Table 1, Table 2 shows the computed correlation coefficients (r) among the colour fidelity, colour gamut and colour preference indices. Selected cross-comparisons across the CQ index groups are also shown. Computations were carried out for the warm white group and the cool white group of light sources separately and then, for all 546 light sources.

Concerning the relationship between colour fidelity indices and colour gamut indices represented by the pairs R_f–R_g and Q_f–Q_g in Table 2, the low correlation coefficients indicate a certain degree of independence of the colour gamut and colour fidelity metrics, especially within the warm white group of light sources. In the context of describing colour preference or colour naturalness as a combination of the two metrics (colour fidelity and colour gamut), this independence allows for an independent variation of each component and the possibility of combining them.

This combination will be less efficient if the CQ index pair R_a–Gamut Area Index (GAI) (that exhibits higher correlation coefficients especially in the cool white group of light sources) is used instead of R_f–R_g and Q_f–Q_g. It can also be seen from Table 2 that fidelity metrics generally correlate well among each other. Lower correlation coefficients occur in the case of warm white light sources and also in the important case when the compared metrics are based on different colour spaces and different test colour sample sets, e.g. R_a

Table 2 Pearson's correlation coefficients (r) among the colour fidelity, colour gamut and colour preference indices and selected cross-comparisons across different colour quality index groups

R	Descriptor group	Warm white only	Cool white only	All light sources
R_a–R_{1_14}	Fidelity	0.97	0.99	0.98
R_a–Q_f	Fidelity	0.66	0.90	0.76
R_a–$R_{a,2012}$	Fidelity	0.73	0.95	0.82
R_a–R_f	Fidelity	0.87	0.96	0.92
R_{1_14}–Q_f	Fidelity	0.68	0.90	0.77
R_{1_14}–$R_{a,2012}$	Fidelity	0.82	0.96	0.88
R_{1_14}–R_f	Fidelity	0.93	0.96	0.94
Q_f–$R_{a,2012}$	Fidelity	0.66	0.90	0.76
Q_f–R_f	Fidelity	0.74	0.91	0.81
$R_{a,2012}$–R_f	Fidelity	0.93	0.97	0.94
GAI–Q_g	Gamut	0.67	0.91	0.79
GAI–FCI	Gamut	0.87	0.87	0.72
GAI–R_g	Gamut	0.43	0.57	0.58
Q_g –FCI	Gamut	0.82	0.84	0.76
Q_g–R_g	Gamut	0.86	0.89	0.88
FCI–R_g	Gamut	0.46	0.60	0.54
Q_a–Q_p	Preference	0.95	0.96	0.95
Q_a–MCRI	Preference	0.45	0.75	0.58
Q_p–MCRI	Preference	0.55	0.80	0.67
R_f–R_g	Fidelity-gamut	−0.11	0.57	0.19
R_a–GAI	Fidelity-gamut	0.33	0.78	0.56
Q_f–Q_g	Fidelity-gamut	−0.04	0.50	0.16
R_f–MCRI	Fidelity-preference	0.69	0.80	0.75
$R_{a,2012}$–MCRI	Fidelity-preference	0.71	0.82	0.74
R_g–MCRI	Gamut-preference	0.00	0.61	0.31
R_f–Q_p	Fidelity-preference	0.70	0.88	0.79
R_g–Q_p	Gamut-preference	0.18	0.72	0.39

versus Q_f, R_{1_14}–Q_f or Q_f–$R_{a,2012}$. Figure 1 shows the light sources in the R_a versus $R_{a,2012}$ (left ordinate) and R_a versus R_f (right ordinate) diagrams.

As can be seen from Figure 1, the CIE R_a colour rendering index (abscissa) correlates better with IES R_f values ($r^2 = 0.76$) than with $R_{a,2012}$ values ($r^2 = 0.53$). There are several outliers from the general trend including the light sources WW30 and CW76 (RGB LEDs, see the inset diagrams in Figure 1). The reason is that RGB LED light sources accentuate the non-uniformity of the $U^*V^*W^*$ colour space used in case of R_a compared to the CAM02-UCS, the more uniform colour space used to compute R_f values.

Concerning the colour gamut metrics, the reason for the relatively low correlation between GAI–R_g and FCI–R_g is that R_g uses a high number of test colour samples compared to GAI and feeling of contrast (FCI) (99 vs. 8 or 99 vs. 4) hence R_g is able to cover the colour gamut of the light source more uniformly. Figure 2 shows the light sources in R_g versus FCI and R_g versus GAI diagrams.

As can be seen from Figure 2, the colour gamut descriptors of cool white light sources

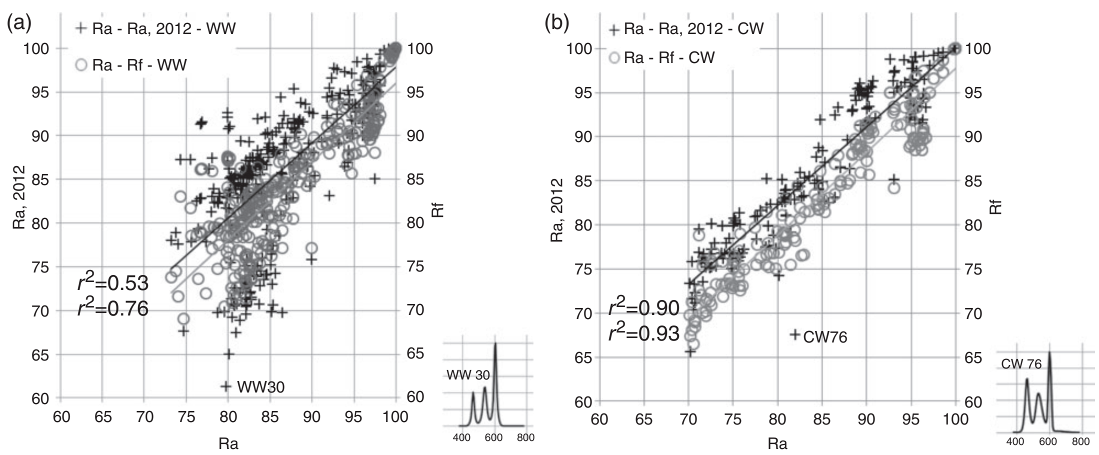

Figure 1 The 546 light sources in R_a vs. $R_{a,2012}$ (left ordinate) / R_f (right ordinate) diagrams. Left: warm white group, right: cool white group. Inset diagrams: RGB LED light sources WW30 and CW76

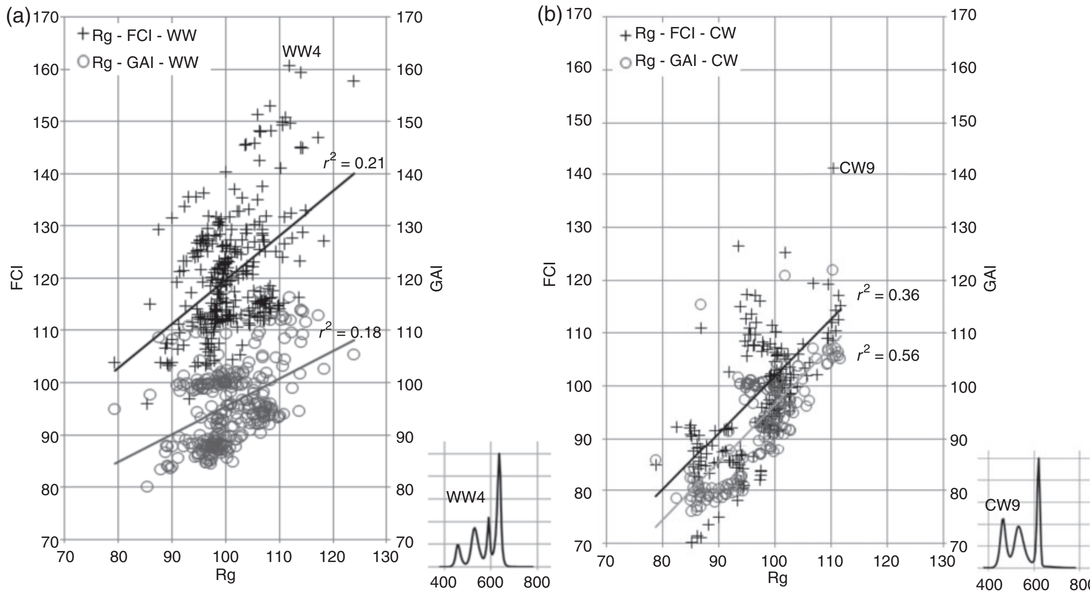

Figure 2 The 546 light sources in R_g vs. FCI (left ordinate) and R_g vs. GAI (right ordinate) diagrams. Left: warm white group, right: cool white group. Inset diagrams: RGBA light source WW4 (left) and RGB light source CW9 (right)

generally exhibit lower values than those of warm white light sources. Outlier points include WW4 (RGBA LED) and CW9 (RGB LED). The reason is that RGB and RGBA light sources obtain unexpectedly high FCI ratings due to the strong spectral peaks of the coloured LED components interacting with the highly saturated red-yellow-green-blue test colour samples of the FCI metric. For GAI and R_g, there are less differences between the warm white group and the cool white group as well as less scatter among all light sources. The reason is that these two indices use more extended sets of test colour samples that also include desaturated samples, hence these indices are less sensitive to strong spectral peaks.

Concerning the colour preference index group, Q_a correlates well with Q_p but neither Q_a nor Q_p correlates well with MCRI for the warm white light sources. The cross-comparison among different index groups yields in some cases low correlation coefficients, especially in the warm white group for R_a–GAI and MCRI–R_g. Negative correlation coefficients also occur in case of R_f versus R_g and Q_f versus Q_g. Figure 3 illustrates the correlation of the IESNA R_f and IESNA R_g indices for the two groups of light sources, cool white and warm white.

As can be seen from Figure 3, the correlation between R_f and R_g is low. This again implies a certain level of independence of the quantities IESNA R_f and IESNA R_g and this opens the way to associate R_f and R_g according to the motivations described in the Introduction, in order to express CQS Q_p and MCRI in terms of linear or quadratic combinations of R_f and R_g. Accordingly, the aim of the next section will be to approximate MCRI and Q_p with the best fitting linear and quadratic combinations of R_f and R_g value pairs within a given light source group (warm white or cool white) and also for all 546 light sources.

2.2 Combining R_f and R_g to predict MCRI and CQS Q_p

In order to combine R_f and R_g to approximate MCRI and Q_p, the following expressions were used:

$$CQ_{lin} = aR_g + bR_f \tag{1}$$

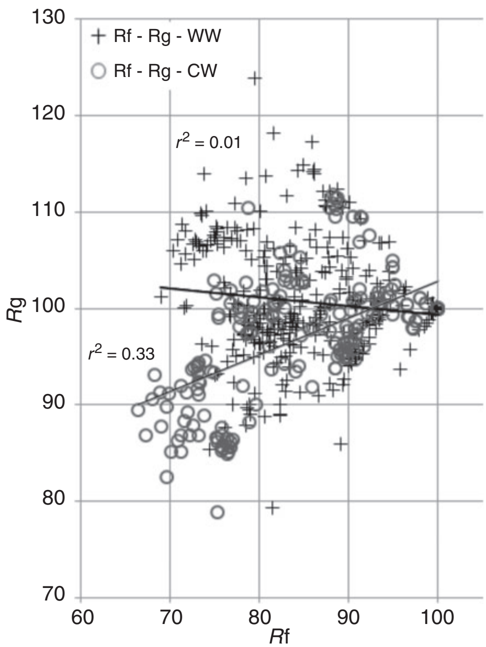

Figure 3 The 546 light sources in the R_f–R_g diagram grouped into two categories: warm white (ww) and cool white (cw) light sources

$$CQ_{quad} = cR_g^2 + dR_g + eR_f + f \tag{2}$$

The hypothesis of the present numeric approach is that colour preference should have a minimum or a maximum in terms of the vividness attribute (i.e. the saturated, brilliant colour appearance of the coloured objects under the current light source) associated with the colour gamut descriptor R_g. According to this hypothesis, the ${R_g}^2$ term was included but the ${R_f}^2$ term was excluded. To find out the best fitting parameter values, the parameters *a*–*f* were varied to maximize the coefficient of determination (R^2) between the two expressions in equations (1) and (2) and MCRI or Q_p. Table 3 shows the best fitting parameter values in equations (1) and (2) and the resulting values of the coefficient of determination (R^2). As can be seen from Table 3, in the case of Q_p (the CQS colour preference metric) as a linear function of R_g (the IESNA colour gamut metric) and R_f (the IESNA colour fidelity metric) exhibiting coefficients of determination in the range $R^2 = 0.56$–0.84, the coefficient *b* representing the contribution of R_f is substantially higher than the coefficient of the contribution of R_g. In the context of CQ analysis, this finding means that colour preference enhancement in terms of CQS Q_p requires a relatively higher amount of colour fidelity content combined with a smaller amount of colour gamut

Table 3 Best fitting parameter values in equations (1) and (2) and the resulting values of the coefficient of determination (R^2)

	Light source	Warm white		Cool white		All	
Model	Parameter	MCRI	Q_p	MCRI	Q_p	MCRI	Q_p
Linear	*a* (for R_g)	0.3804	0.2890	0.5225	0.3996	0.4201	0.3099
	b (for R_f)	0.5753	0.7094	0.4141	0.5965	0.5289	0.6901
	R^2	0.14	0.56	0.55	0.84	0.36	0.68
Quadratic	*c* (for ${R_g}^2$)	0.0147	−0.0258	0.0107	−0.0009	0.0078	−0.0140
	d (for R_g)	−2.9279	5.5578	−1.8880	0.5983	−1.4325	3.1037
	e (for R_f)	0.3999	0.6875	0.4352	0.5948	0.4326	0.6447
	f (const.)	198.6657	−266.1074	131.0910	−10.8005	114.7093	−134.6050
	R^2	0.54	0.60	0.69	0.84	0.60	0.69

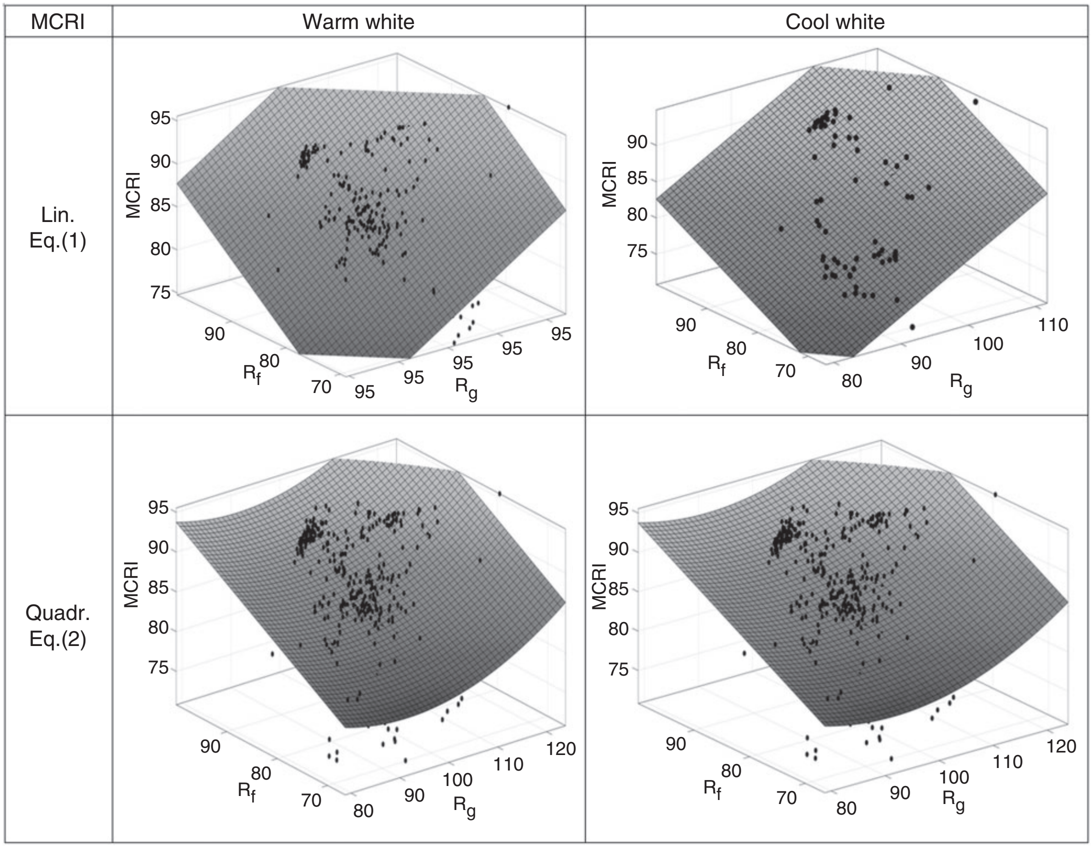

Figure 4 Surfaces above the horizontal R_f–R_g plane represent model equations (1) and (2) with the best fitting parameters from Table 3. Ordinate: MCRI. Data points: individual light sources

(or object chroma) enhancement. For MCRI, this tendency is weaker for the warm white group. In contrast to Q_p, the approximation of MCRI requires for cool white light source spectra more weighting for R_g ($a = 0.5225$) than for R_f ($b = 0.4141$).

It can also be seen from Table 3 that, MCRI and Q_p values can be better approximated by both the linear and the quadratic combinations of R_f and R_g for cool white light sources than for warm white light sources (compare the R^2 values). The model equations (1) and (2) with the best fitting parameters (taken from Table 3) are visualised in Figure 4 (for MCRI) and in Figure 5 (for Q_p) as surfaces above the R_f–R_g plane with either MCRI or Q_p on the ordinate. Light sources are represented by individual data points in R_f–R_g–MCRI space or in R_f–R_g–Q_p space.

As can be seen from Figure 4, the linear equation produces an oblique plane above the plane of the R_f–R_g value pairs to predict the values of the MCRI metric. The best fitting plane is different for warm white and for cool white. The best fitting quadratic surface of the MCRI prediction exhibits a shallow minimum as a function of R_g in the lower R_g range.

As can be seen from Figure 5, similar to Figure 4, the best fitting plane is different for

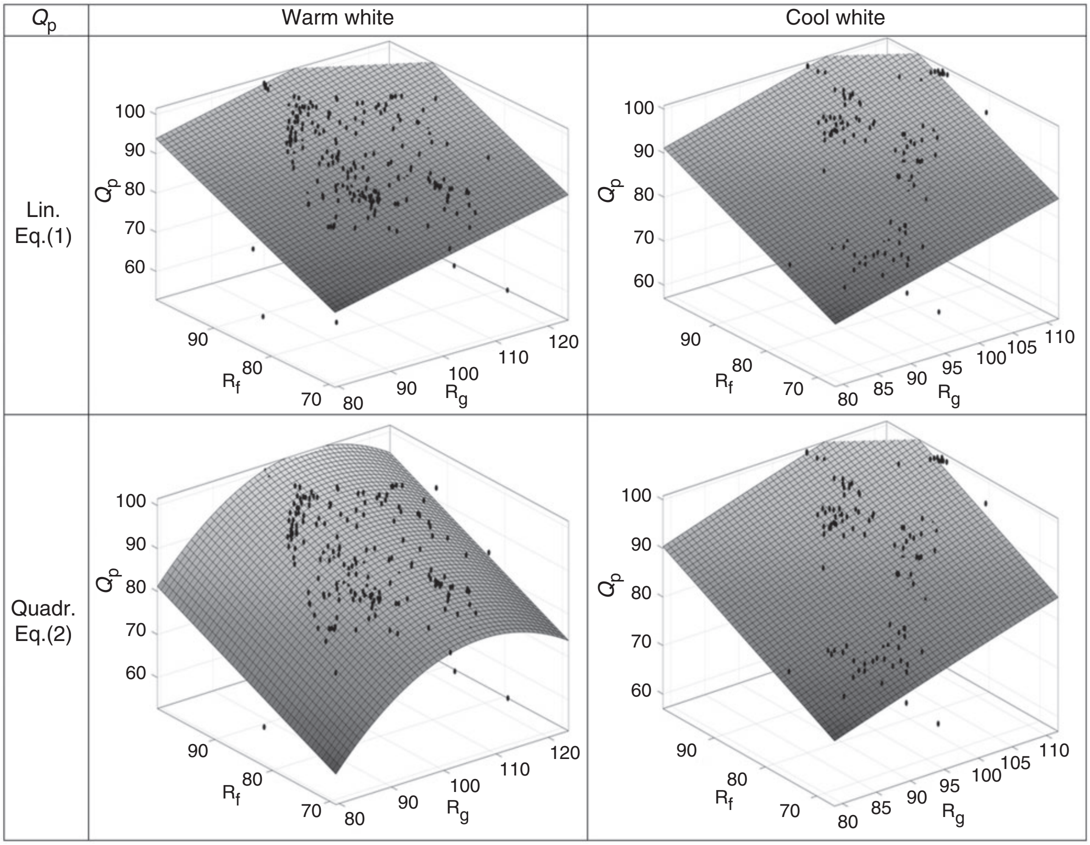

Figure 5 Surfaces above the horizontal R_f–R_g plane represent model equations (1) and (2) with the best fitting parameters from Table 3. Ordinate: Q_p. Data points: individual light sources

the warm white group and the cool white group. In contrast to the MCRI surface in Figure 4, the quadratic surface of Q_p has a maximum as a function of R_g. This means that, for light sources with a high value of the colour gamut descriptor R_g, the colour preference index Q_p decreases in case of warm white light sources. Cool white light sources do not exhibit this behaviour. In this case, as the quadratic coefficient c is small (-0.0009), the surface of equation (2) is similar to the plane of equation (1), compare the two 'cool white' diagrams in the right column of Figure 5.

3 Discussion and conclusions

The motivation of this paper is to show a possible way to move forward to provide a usable method for lighting practitioners to characterise and optimise the CQ of white light sources for general interior lighting. As was pointed out, although there are higher or lower correlations among the analysed CQ indices within the fidelity and gamut index groups, due to their advanced features, it is advantageous to consider the recent IESNA metrics R_f and R_g[12,13] in order to report light source CQ for general indoor lighting applications for lighting practitioners in a concise manner.

Although CQ experts might use more complex descriptions like a set of special indices related to individual object colours or complex colour distortion diagrams, practitioners need a more straightforward and generally applicable method. In this respect, the advantages of the IESNA method[12,13] include the use of an extended set of 99 representative test colour samples (to avoid a false spectral optimization target for lighting practice) and the perceptually uniform, modern CAM02-UCS colour space (to provide perceptually relevant special index values for the individual test colours in any region of colour space).[17]

In this paper a possible way has been shown to derive a visually relevant single-number metric for any light source by the aid of a pair of IESNA R_f and R_g values (using a slightly modified viewing condition) to characterise the colour preference property of the light source. It has been shown (see Table 3) that the performance of the method of equations (1) and (2) depends on the type of the light source (warm white, cool white) and the equation used (linear, quadratic). A usable modelling accuracy ($R^2=0.84$) was reached by Q_p's model for the cool white light source group only. Note that all models in the present article rely on the approximations of *numeric* colour preference metrics (MCRI and Q_p). The index combination method will be applied by the authors to visual data in the near future. The aim of the present paper is just to show the possibility of such a method and not to recommend the coefficients in Table 3 for practical use at this stage. Concerning the correlations among the indices (Table 2), a possible reason for the relatively low correlations is that R_g, FCI and GAI use different reference illuminants. In a subsequent study, it will be interesting to change the reference illuminant and investigate this possibility (in the present paper, only the original definitions were considered).

Colour preference is possibly the most important attribute of CQ for general interior lighting applications. In this article, the MCRI and Q_p metrics were selected as descriptors of colour preference (their suitability was pointed out in previous literature studies as mentioned in the Introduction) and the aim of the present paper was to seek suitable combinations of the IES R_f and R_g values to approximate MCRI and Q_p values in a computational analysis for a comprehensive set of light source spectral power distributions. Two plausible R_f–R_g combinations (linear or quadratic) were considered and the numeric optimum values of the coefficients converting any (R_f; R_g) pair into MCRI and Q_p values are reported. It is pointed out that, because of the combined use of daylight and Planckian radiators as reference light sources in the IESNA method, it is worth considering separate CCT groups in the numeric analysis.

It should be noted that, in a typical general indoor lighting situation, the user of the lighting system will not only look at a certain (homogeneous) colour stimulus but a certain combination of (structured) coloured objects is being observed and judged. This judgement results from cognitive colour processing influenced by previous colour experience (colour memory), cultural background (learned judgement principles), the context of the scene (object shape, texture), the intent of the observer (visual performance, aesthetics or emotional well-being) and the type of lighting application (office, kitchen, hotel, wellness, industry, retail). The complexity of the visual stimulus to be judged implies that subjects tend to express their judgements on discrete so-called 'semantic' judgement scales[18] consisting of a set of categories (e.g. very good, good, moderate, low, bad, very bad) about all visual CQ attributes including colour preference and colour naturalness.

Accordingly, an important aim of further work should be to provide the category limits in terms of MCRI, Q_p or equations (1) and (2)

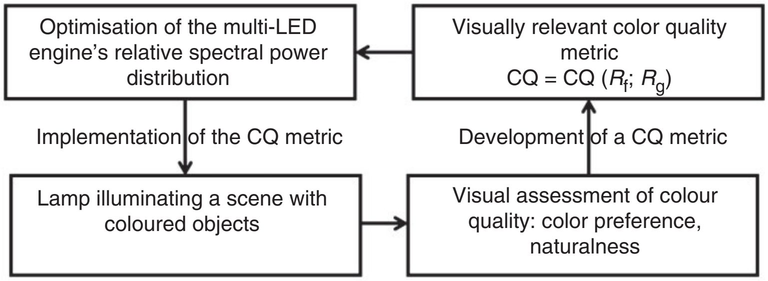

Figure 6 Flow chart for the spectral optimization of a light source for high colour quality

for the categories 'very good' and 'good' (as lighting practitioners do not aim at optimizing for 'moderate', 'low' or 'bad' colour preference). If, during the procedure of spectral optimization (see Figure 6), the value of the visually relevant CQ index is greater than its 'good' category limit then the light source's spectral power distribution can be considered as 'acceptable'.

As can be seen from Figure 6, the spectral optimisation procedure for the highest user acceptance of the light source should start from the results of visual assessments of CQ in which a suitable CQ metric should be found. This metric can be expressed, in turn, in terms of R_f and R_g value pairs (as suitable input parameter values) and used to find an optimum spectral power distribution implemented in a real lamp (e.g. a multi-LED engine). The lamp illuminates a scene with coloured objects with its optimized spectral power distribution by optimising, e.g. the pulse-width modulation (PWM) driving values and certain currents for all colour channels of the multi-LED light engine. The optimal spectrum should be validated in a subsequent visual colour preference study.

It should be noted that the CQ optimisation as part of general HCL optimisation should also consider some further constraints including a high-quality white point and the required CCT range associated with the amount of CS[9] of the spectrum (e.g. a high circadian component at a high CCT). However, the use of the luminous efficacy of radiation (LER) concept should be avoided in a HCL concept as the concept of LER considers the luminance (i.e. $V(\lambda)$-weighted) mechanism only. Hence, LER results in a loss of light rays in the blue and red spectral ranges which are important for both higher CQ and to set the level of the CS.

To characterise the absolute amount of light emitted from the light source in the optimisation algorithm, it is essential to consider a broad spectral range (broader than $V(\lambda)$). Instead of using the concept of luminous flux, i.e. weighting the absolute spectral power distribution of the lamp that implements the optimised colour preference metric by $V(\lambda)$, the upper envelop function of the spectral sensitivities of human vision mechanisms,[19] the universal luminous efficiency function[20] or a brightness-based spectrally weighted quantity using, e.g. $V_{b,10}(\lambda)$[21] can be considered.

Concerning the related future work of the present authors, neutral white light sources and further CQ indices will be included in similar computations. Also, visual colour preference studies with different types of light sources and different application contexts (immersive and non-immersive viewing of different coloured object combinations) providing more or less object over-saturation are currently underway. One aim is to validate and improve equations (1) and (2) and to provide visually validated coefficient sets (similar to Table 3) depending on the application.

Note that the ratios of the best fitting linear parameter values (a/b) vary between Q_p and MCRI implying the hypothesis that the general colour preference metric to be used may depend on the context of the lighting application, e.g. immersive home lighting for a longer stay at a moderate illuminances or shop lighting in which the user's attention is concentrated on a spatially limited, special set of coloured objects at higher illuminances. Accordingly, the aim of the spectral optimisation can be either short-term preference or short-term acceptance (in which possibly a relatively higher proportion of the colour gamut metric with higher colour vividness provides the optimum) or long-term acceptance (in which possibly the concept of naturalness associated with a lower amount of the colour gamut metric shall be used).

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