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Paper

Spectral Deviation: a New Parameter for Efficient Design of High Quality Tuneable White Lighting

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ABSTRACT

With the advance of medium and high power light-emitting diodes (LED), tuneable light sources with sophisticated spectral power distributions have been emerging. The increasing variety of LEDs and their spectral behaviour complicates their design as well. Most notably, many different parameters have to be taken into account to describe the quality of light. This paper introduces a new characteristic, *Spectral Deviation*, which both combines various light quality parameters into one single value and correlates with the most commonly used quality parameters. Our *Spectral Deviation* allows a more time efficient quality assessment of a designed spectral power distribution without complex calculations or colour space transformations. The parameter is derived directly from the spectral power distribution of a test illuminant as the sum of absolute differences to a standardized reference distribution. A weighting function is used to take the characteristic of human perception into account. An upper limit for the parameter is proposed for the design of new spectral power distributions. Our parameter can be used during the selection process of single-emitter LED for tuneable luminaires as a preselector. It eliminates undesired solutions before even calculating detailed quality parameters, allowing more possible combinations to be checked in the same time.

KEYWORDS: Spectral Deviation, high quality light, colour rendering, light-emitting diodes, tuneable light

1. Introduction

Every light source has its unique spectral power distribution (SPD). But in day-to-day life, we all prefer a simplified representation of this information. There are many parameters to describe the quality of light. However, no single parameter can be used to describe it unambiguously. Each parameter transforms the information of the SPD and this process is irreversible in most cases. For example, the colour space CIE1931 transforms the spectral information into a set of three coordinates x, y and z. But especially in the interesting area of "white" light, the same coordinates x, y and z can be achieved by many different SPD. As a result, most people use a set of parameters based on the application to indicate the quality of an illuminant regarding to its SPD.

Various colour rendering indices have been developed to describe the ability of light to show specific object colours. This is one of the most important properties of a light source destined to be used in general lighting, because it has a huge impact on the perception of objects in daily life. Comparability of these indices between illuminants is mostly achieved by the use of a standardized reference illuminant. Common to all rendering indices is the significant amount of colour samples used to determine the resulting score and the corresponding number of calculations and transformations which have to be done in order to obtain it.

With the variety of available light emitting diodes (LEDs), it becomes possible to design sophisticated and tuneable light spectra for specialized lighting applications such as agriculture or healthcare. One approach to create these spectra is the combination of multiple single emitter LEDs in one luminaire where each colour channel can be driven individually. The dependency of the spectral power distribution of a LED from temperature and current, analysed and modelled by Reifegerste[1] in 2008, complicates the design even more. The possible combinations of LED types and their driving currents cannot be surveyed by a human in an appropriate design time. The use of an optimization algorithm to find the optimal combination could be one approach to solve that problem. However, the evaluation of suitable combinations requires a faster and more efficient calculation than the current colour rendering indices offer.

A parameter is needed which can be acquired with rather simple and few calculations and disqualifies unsuited solutions. However, the parameter also must correlate with the presented parameters and their

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proposed values for high quality light in order to be significant. A colour space based approach cannot lead to the desired solution, because this is already done by most of the parameters. We propose the direct use of the spectral power distribution of the illuminant to derive a new parameter, similar to the Spectral Band from 1948[2]. However, the term *Spectral Band method* is not appropriate for this new parameter, because it will not use sub-bands which is explained in detail later in this paper.

In this paper, the crucial parameters to describe the quality of light are summarized and calculated for different illuminants used in general lighting to show that the new parameter is suitable as measure. Table 1 summarizes these parameter in order of reference in this paper. Afterwards, a new parameter is proposed which allows a more time efficient evaluation of the SPD under investigation regarding to its natural colour rendering qualities. Its new features are:

- improved definition of the SPD of the reference illuminant,
- reduced calculation effort to determine the actual score result,
- no dependency on object colour samples,
- no need for colour space transformations.

Furthermore, it is shown that the new parameter correlates with the commonly used colour rendering scores for high quality light.

Table 1 Crucial parameters to describe the quality of light.

Parameter	Symbol
Correlated Colour Temperature	CCT
Distance to reference white in CIE1976UCS	$\Delta u'v'$
Sum of absolute percentage deviation (Spectral Band Method Bouma 1937)	P_{1937}
Sum of absolute percentage deviation (Spectral Band Method BS950-1 1967)	P_{1967}
Maximum absolute difference (Spectral Band Method Gall and Lapuente 2003)	ΔL_{max}
Colour Rendering Index (CRI1974)	$CRI\ R_a$
Deep Red Colour Rendering Index (CRI1974)	$CRI\ R_9$
Saturated Blue Colour Rendering Index (CRI1974)	$CRI\ R_{12}$
Gamut Area Index	GAI
Color Quality Scale	Q_a
Color Fidelity Scale	Q_f
Color Preference Scale	Q_p
CRI2012	$CRI\ R_{a,2012}$

2. Crucial quality parameters for light sources

2.1 Parameter evaluation for selected light sources

The parameters in this section are calculated for selected light sources used in general lighting. We chose 18 spectral power distributions to make comparisons for this paper. Each distribution was measured with the same spectroradiometer in a light shielded box, except the daylight situations which have been measured inside a building with open windows. We selected the following distributions:

- three thermal radiators (a candle, a gas light and a halogen filled incandescent lamp),
- three daylight situations (sunny in direction south, sunny in direction north, cloudy in direction north),

Table 2 Quality parameter for measured spectral power distributions of various light sources.

SymbolUnit	CCT [K]	$\Delta u'v'$ [10^{-3}]	P_{1937} [%]	P_{1967} [%]	ΔL_{max}	$CRI\ R_a$	$CRI\ R_9$	$CRI\ R_{12}$	GAI	Q_a	Q_f	Q_p	$CRI\ R_{a,2012}$	$\Delta_{SD,w}$
High Quality light, if	—	—	—	—	≤2.0	≥93	≥85	≥85	≥80	—	—	—	—	≤2500
#1 Candle	2035	0.05	60	10	1.0	99	98	99	27	87	86	88	100	140
#2 Gas light	2962	1.22	198	82	0.6	92	69	80	39	86	87	84	96	1810
#3 Halogen lamp	2792	1.9	45	16	0.4	99	93	97	49	96	96	96	100	322
#4 DL[1] south sunny	5148	0.9	16	4	0.5	99	97	99	90	99	99	99	100	259
#5 DL north cloudy	5972	1.7	16	4	0.4	99	98	98	96	100	99	100	100	278
#6 DL north sunny	8865	1.0	14	7	0.3	99	98	99	104	99	99	100	100	413
#7 FL[2] ww	2812	10.4	2626	1551	3.1	83	0	45	41	78	79	76	74	59416
#8 FL nw	3842	4.1	2336	1560	2.5	82	26	49	76	80	79	82	78	58024
#9 FL cw	6420	10.5	2111	1581	1.6	79	27	54	92	81	80	84	81	61492
#10 RFLL[3] ww	3029	3.8	284	136	1.6	82	6	77	58	82	82	83	85	3613
#11 RFLL nw	3918	6.0	346	130	1.4	69	−37	34	64	71	71	71	73	5935
#12 RFLL cw	7122	8.6	345	177	1.9	76	−29	46	82	76	76	75	80	6561
#13 SELL[4] ww	2980	7.9	260	61	0.7	97	89	85	67	93	90	97	96	2103
#14 SELL nw	4957	0.6	326	134	1.4	80	2	51	83	78	78	78	82	5310
#15 SELL cw	7424	9.5	212	51	1.7	95	77	76	106	93	92	96	95	4261
#16 MTLL[5] ww	2912	9.6	237	109	0.7	97	95	94	69	94	88	99	96	2010
#17 MTLL nw	4264	1.3	128	24	1.1	98	96	87	81	97	96	96	97	1688
#18 MTLL cw	6468	3.5	125	15	1.6	96	81	90	93	95	95	95	96	2233

[1]Daylight, [2]Fluoroscence light, [3]Retro-fit LED light, [4]Single-emitter LED light, [5]Mixed tuneable LED light.

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- three fluorescence lamps with different correlated colour temperatures (*CCT*, see Section 2.2),
- three retro-fit LED lamps with different *CCT* and
- three discrete single-emitter LED with different *CCT* and
- three settings of a six-channel LED light source developed by our research group.

The calculated results for each parameter of this section are shown in Table 2. It also includes the new proposed parameter Spectral Deviation. An additional line below the header indicates the requested values which should be achieved for high quality light in reference to actual literature[3].

2.2 Correlated colour temperature (CCT)

Among the first parameters used to describe the quality of light is the correlated colour temperature (*CCT*)[4].This parameter matches the temperature of an ideal black-body radiator with similar chromaticity to the measured spectral power distribution. The calculation is done by finding the temperature of a black-body radiator in kelvins (*CCT*) with its corresponding coordinates u_p, v_p in the CIE1960UCS colour space where the distance to the coordinates of the light source u_t, v_t is minimal:

$$\Delta uv = \sqrt{\left(u_p(CCT) - u_t\right)^2 + \left(v_p(CCT) - v_t\right)^2} \rightarrow \min. \qquad (1)$$

It should be noted, that the correlated colour temperature is only valid for a difference Δuv less than 0.05. The distance to the reference white point in Table 1 is calculated in the improved CIE1976UCS colour space as $\Delta u'v'$. The criterion for high quality light is more demanding than the original from the definition of the *CCT* and poses a challenge for the design of spectral distributions.

In general the *CCT* is used to describe the basic impression of the light colour in conjunction to a temperature sensation. A low *CCT* (less than 3300 K) with its corresponding red dominated SPD is described as "warm-white" (ww), a more equal distribution over the visible range between 3300 K and 5000 K as "neutral-white" (nw) and blue dominated spectra above 5000 K as "cool-white" (cw) or "daylight-white"[5]. Due to its calculation the spectral information is reduced into chromaticity coordinates; different SPD can result in the same *CCT*. Therefore, it cannot be used as a single measure to describe the quality of light alone. However, the *CCT* allows the use of a common standardized reference illuminant distribution for the definition of other quality parameters to achieve a better comparability of lights with different SPD.

The 18 chosen light sources in Table 2 were selected to represent the three areas of "white light". However, thermal radiators and daylight distributions do not cover all three areas. Because the light sources were chosen from actual installations of general lighting an exact match of the *CCT* was not possible.

2.3 Spectral band methods

Due to the incapability of the *CCT* to describe the quality of a light source as a single parameter, the question remains how to compare the quality of two light sources. Bouma[6] proposed in 1937 a method which divides the visible wavelength band into eight sub-bands. Both SPD, $S_1(\lambda)$ and $S_2(\lambda)$, are multiplied with the spectral luminous efficiency function $V(\lambda)$ and integrated over each sub-band (j=1…8):

$$L_{i,j} = \int_{\lambda_j}^{\lambda_{j+1}} S_i(\lambda) \cdot V(\lambda) \mathrm{d}\lambda. \qquad (2)$$

The percentage deviations p_j between both SPD are calculated for each band with:

$$p_j = \left(1 - \frac{L_{1,j}}{L_{2,j}}\right) \cdot 100\ \%. \qquad (3)$$

A maximum tolerance for p_j was also defined. Crawford[7] refined the spectral bands of the original method into six sub-bands. The CIE adopted this method in 1948[2] and it is used in the British Standard BS950-1[8] from 1967 with the sub-bands: 400-455-510-540-590-620-760 nm. The tolerance t_j was standardized with ±15%. The Standard itself and the work from Hunt and Pointer[2] describe the main purpose of the parameter to be an index of comparison between lamps from different manufactures with the same intended SPD. In this paper, the first SPD $S_1(\lambda)$ is given by the light source (#1 to #18). To ensure an equitable comparison with the new proposed parameter, we choose the reference distribution from section 3.2 as the second SPD $S_2(\lambda)$ and we use the sum of the absolute percentage deviations:

$$P = \sum_{n=1}^{j} \left| p_j \right|. \qquad (4)$$

The results in Table 2 are shown for the original approach from Bouma in 1937 (P_{1937}) and for the BS950-1 from 1967 (P_{1967}). They show a contradictory behaviour between the two approaches, especially for the light sources #7 to #12. For example, light source #10 achieves a score of 284 for P_{1937}, light source #11 a score of 346 and light source #12 a score of 345. The same sources achieve the scores 136, 130 and 177 for P_{1967}.

Gall and Lapuente[9] tried a similar approach in 2003. They use the mean value of the measured spectrum L'_j in six sub-bands 380-436-495-566-589-627-720 nm calculated by:

$$L'_j = \frac{1.0}{\lambda_{j+1} - \lambda_j} \cdot \int_{\lambda_j}^{\lambda_{j+1}} S(\lambda) \mathrm{d}\lambda, \qquad (5)$$

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referred to the mean value of the whole spectrum L'_g with:

$$L'_g = \frac{1.0}{780\,\text{nm} - 380\,\text{nm}} \cdot \int_{380\,\text{nm}}^{780\,\text{nm}} S(\lambda)\mathrm{d}\lambda\,. \tag{6}$$

Gall and Lapuente state[9], that for a good spectral distribution the maximum absolute difference ΔL_{max} between two adjacent bands, given by:

$$\Delta L_{max} = \max\left(\left|\frac{L'_j}{L'_g} - \frac{L'_{j+1}}{L'_g}\right|\right), \tag{7}$$

should not exceed the value 2. The values for ΔL_{max} are listed in Table 2. This criterion is met by almost all chosen light sources, except two fluorescence lamps #10 and #11. However, if we consider the other quality parameter not all presented light sources can meet the criteria for high quality light proposed by Khanh et al.[3]. Hence, it is difficult to determine the quality of light with this parameter alone.

2.4 Colour rendering index (CRI1974)

The CRI was introduced in 1965[10] and improved in 1974 as a quality parameter for the, back then, newly developed fluorescence lamps and describes the ability of a given SPD to render colours in comparison to a natural reference illuminant with the same correlated colour temperature. Therefore 14 test colours were specified. A black-body radiator is used as reference illuminant for a *CCT* below 5000 K, whereas for a *CCT* above 5000 K the CIE daylight illuminant has been specified. Each test colour appearance under the reference illuminant and under the test illuminant is calculated in the colour space CIE1964$U^* V^* W^*$ considering chromatic adaption with the Von Kries transformation. The difference in colour appearance ΔE is used to define a colour rendering index for each colour scaled to 100 as highest value:

$$R_i = 100 - 4.6 \cdot \Delta E_i\,. \tag{8}$$

The difference in colour appearance ΔE_i is calculated by:

$$\Delta E_i = \sqrt{\Delta W^{*2} + \Delta U^{*2} + \Delta V^{*2}}\,. \tag{9}$$

The mean value of the first eight colours is called *CRI* R_a, also with an upper limit of 100:

$$CRI\, R_a = \frac{1}{8}\sum_{i=1}^{8} R_i\,. \tag{10}$$

Figure 1 and Figure 2 show the coordinates U^*, V^* of the eight test colours used for the *CRI* R_a for the lights #8 and #17 of Table 2 in regard to those of their reference illuminants. The greater the dissimilarities of the polygons, the lower the score *CRI* R_a.

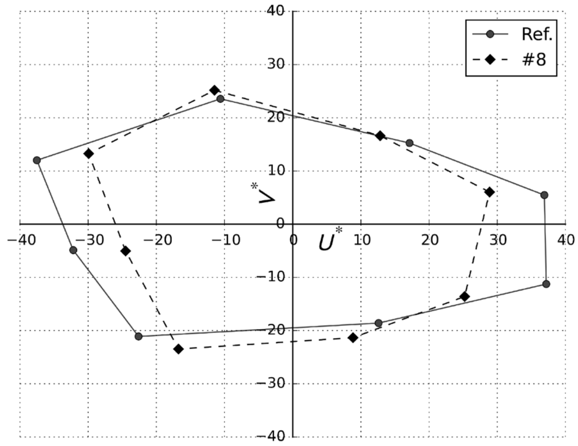

Figure 1 *CRI* R_a test colour coordinates U^*, V^* for light #8 and its reference illuminant.

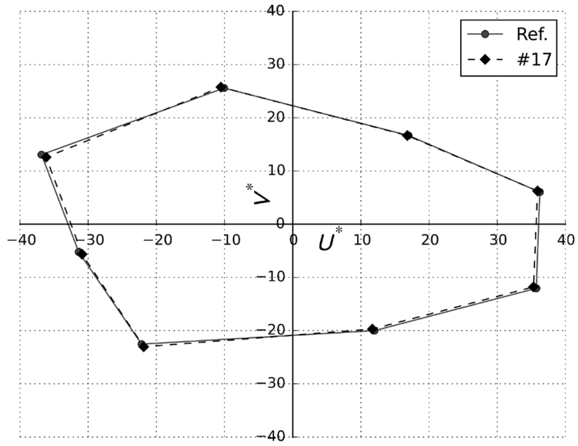

Figure 2 *CRI* R_a test colour coordinates U^*, V^* for light #17 and its reference illuminant.

Due to its definition all incandescent lamps or real daylight distributions achieve very high *CRI* R_a values (≥ 92), as seen in Table 2. The fluorescence lamps have a more average *CRI* R_a in range from 79 to 83, but can perform poor for single colour indices. Table 2 shows the colour index for deep red *CRI* R_9 and the index saturated blue *CRI* R_{12}. The daylight distributions and thermal radiators (except the gas light) score high (≥ 93), the fluorescence lamps score in range from 0 to 54.

Additionally, the value of the indices can be negative which is highly confusing for most people without proper knowledge who would except zero as the lower limit of the index's range. The selected retro-fit LED lamps also perform only average in *CRI* R_a in range from 69 to 82, but with even lower values for the special indices like *CRI* R_9 from −37 to 6. It is possible to achieve high *CRI* R_a (97) and admirable *CRI* R_9 (89) and *CRI* R_{12} (85) values with newer LEDs like light source #13 which show the continuing improvements of the used phosphor materials and the potential of future developments.

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Although the CRI1974 has proven inefficient to rate many spiked or narrow band sources, the need of a redefinition has significantly increased with the new possibilities in spectral design based on LED. The main disadvantages are the inaccuracy of the used formula to evaluate the difference in colour appearance, the limited amount of test colours and their questionable suitability in regard to their spectral reflectance characteristics. Many possible improvements of the CRI1974 have been published in the last ten years; some are described later in this paper. Sadly at the time of this paper, the CIE has not yet decided which parameter will succeed the CRI1974. In October 2015, the CIE[11] published a short statement on their website anticipating a new discussion about that issue in 2016.

2.5 Gamut Area Index (GAI)

Rea and Freyssinier[12] propose the use of a second parameter in combination with *CRI* R_a. They use the chromaticity coordinates of the eight standardized test colours of the CRI1974 in the CIE1976 uniform colour space to span a polygon and calculate its area. The gamut area of an illuminant with equal energy distribution (former CIE illuminant E) serves as reference and the value is scaled to 100:

$$GAI = \frac{GA_t}{GA_{r,E}} \cdot 100. \tag{11}$$

Figure 3 illustrates the gamut area of light #3 and #6 from Table 2 and the used reference gamut area.

Rea and Feyssinier suggest[12], that a light with high *CRI* $R_a \geq 80$ and with aGAI, $80 \leq GAI \leq 100$, is more preferred than a light with just a high *CRI* R_a value. An advantage of this parameter is the manageable amount of calculations needed to derive it, because many of them are already done in the original *CRI* R_a calculation.

Table 2 shows that the natural daylight meets the proposed criteria limits almost perfectly with a GAI score from 90 (#4) to 104 (#6). However, the incandescent lamps with their low *CCT*s perform poor due to their lack in rendering blue colours in regard to the reference illuminant. They only achieve a GAI score from 27 (#1) to 49 (#3). The radiator-like optimized retro-fit lamps (#7, #10) or single emitter LED (#13) yield similar results (41, 58 and 67). Rea and Freyssinier[12] use a warm-white light source with a small peak in the blue wavelength area to enhance its *GAI* which was more accepted by the participants than the radiator-like light source.

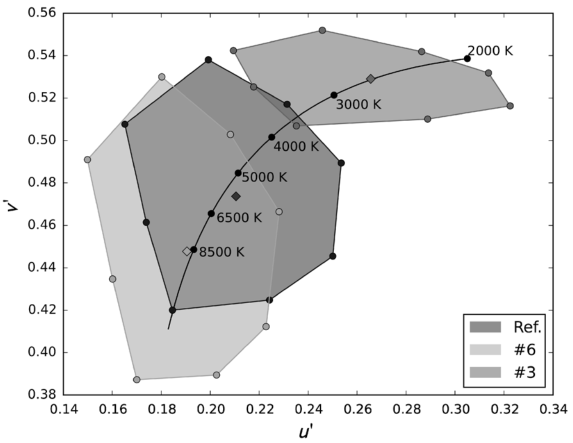

Figure 3 Gamut areas in CIE1976UCS for lights #3 and #6.

2.6 Color Quality Scale (CQS)

The Color Quality Scale published by Davis and Ohno[13] uses a set consisting of 15 saturated colours in distinction against the original CRI1974. Davis and Ohno state that a light source which performs well with saturated colours never fails at desaturated ones. The choice of the reference illuminant is identical to CRI1974. The necessary chromatic adaption uses the transformation CMCCA T2000[16] with the assumption of equal luminance. The calculated tristimulus values for test colours under the reference illuminant and the adapted tristimulus values for test colours under the test illuminant are transformed into the CIE1976$L^*a^*b^*$ colour space. The difference in colour appearance $\Delta E^*_{ab,i}$ and the difference in chroma $\Delta C^*_{ab,i}$ are calculated by:

$$\Delta E^*_{ab,i} = \sqrt{(L^*_{i,test} - L^*_{i,ref})^2 + (a^*_{i,test} - a^*_{i,ref})^2 + (b^*_{i,test} - b^*_{i,ref})^2} \tag{12}$$

and

$$\Delta C^*_{ab,i} = \sqrt{(a^*_{i,test} - a^*_{i,ref})^2} - \sqrt{(b^*_{i,test} - b^*_{i,ref})^2}. \tag{13}$$

Figure 4 and Figure 5 show the coordinates a^*, b^* of the 15 test colours under the reference and test illuminant for the lights #8 and #17 of Table 2.

The original CRI1974 penalizes every colour deviation from the reference illuminant. Davis and Ohno suggest that a light source which increases object chroma is mostly accepted and can be beneficial. They introduce a correction factor called *Saturation Factor* which does not penalize the increase in chroma but does not reward it either. The corrected difference in colour appearance depending from difference in chroma $\Delta E^*_{ab,i,sat}$ is calculated by:

$$\Delta E^*_{ab,i,sat} = \begin{cases} \Delta E^*_{ab,i} & if\ \Delta C^*_{ab,i} \leq 0 \\ \sqrt{(\Delta E^*_{ab,i})^2 - (\Delta C^*_{ab,i})^2} & if\ \Delta C^*_{ab,i} > 0 \end{cases}. \tag{14}$$

For each test colour a *Special Color Quality Scale* Q_i can be derived by:

$$Q_i = M_{CCT} \cdot 10 \cdot \left(\ln\left(e^{100 - 3.1 \cdot \Delta E^*_{ab,i}} + 1\right) \right) \tag{15}$$

with a correction factor to adjust for smaller gamut

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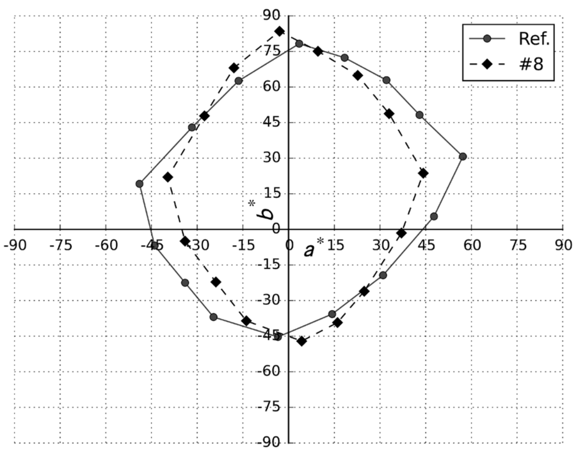

Figure 4 CQS test colour coordinates a^*, b^* for light #8 and its reference illuminant.

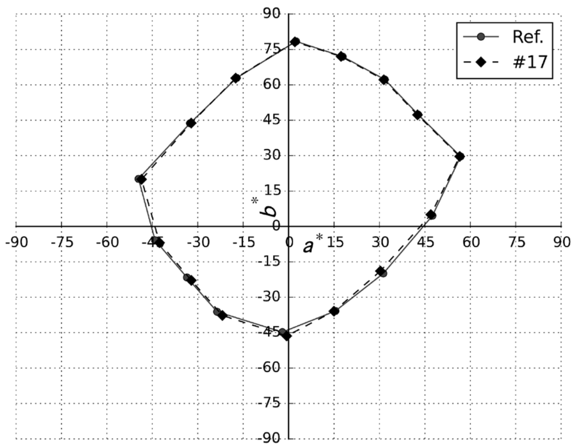

Figure 5 CQS test colour coordinates a^*, b^* for light #17 and its reference illuminant.

area of lamps with low *CCT*s:

$$M_{\mathrm{CCT}} = \begin{cases} 9.2672 \cdot 10^{-11} \cdot T^3 - 8.3959 \cdot 10^{-7} \cdot T^2 & \\ \quad +2.5500 \cdot 10^{-3} \cdot T - 1.612 & \text{if } T < 3500\,\mathrm{K} \\ 1 & \text{if } T \geq 3500\,\mathrm{K} \end{cases} \quad (16)$$

The *General Color Quality Scale* Q_a is calculated similarly by using the root mean square of the colour differences $\Delta E^*_{\mathrm{rms}}$:

$$Q_\mathrm{a} = M_{\mathrm{CCT}} \cdot 10 \cdot \left(\ln \left(\mathrm{e}^{100-3.1 \cdot \Delta E^*_{\mathrm{rms}}} + 1 \right) \right) \quad (17)$$

and

$$\Delta E^*_{\mathrm{rms}} = \sqrt{\frac{1}{15} \sum_{i=1}^{15} (\Delta E^*_{\mathrm{ab},i,\mathrm{sat}})^2} \,. \quad (18)$$

The used formulas avoid confusing negative numbers and scale the output in a range from 0 to 100. In Table 2 the reached scores for the chosen lamps are similar to those from CRI1974. The rounded values for the light sources #10 and #12 are the same for both parameters with 82 and 76. Although the candle is no longer used in general lighting, it shows the impact of the correction factor M_{CCT} for low *CCT* light sources in a resulting difference of 12 between both parameters.

Davis and Ohno also respect the need of more specific information for special applications aside from general lighting. They introduce additional parameters; the *Color Fidelity Scale* Q_f without the saturation factor to score naturalness of colour appearance in respect to the reference illuminant like the original CRI1974 and the *Color Preference Scale* Q_p with an additional reward for increased chroma. These values are listed for completeness in Table 2.

2.7 CRI2012

Smet et al.[14] propose another approach to update the original CRI1974 in 2013. The basic principle is still the same; determine the rendering of special colour samples under the test illuminant compared to a reference illuminant. Therefore, the colour difference for each colour sample must be calculated. The new general *CRI* $R_{\mathrm{a},2012}$ uses the same method to determine the reference illuminant as CRI1974. The proposed test colour samples are called "*HL17 colour set*" or short "*HL17*" and consist of 17 samples. The spectral colour distribution of each test colour can be calculated using a mathematical formula. The derivation of this formula[14] is not repeated here. The colour differences ΔE_i are calculated in the CAM02-UCS[15] colour space based on CIECAM02[16] with its coordinates J', a'_m, b'_m values with:

$$\Delta E_i = \sqrt{(\Delta J')^2 + (\Delta a'_\mathrm{m})^2 + (\Delta b'_\mathrm{m})^2} \,. \quad (19)$$

Figure 6 and Figure 7 show the coordinates a'_m, b'_m of the HL17 test colours under the reference and test illuminant for the lights #8 and #17 of Table 2.

The resulting *CRI* $R_{\mathrm{a},2012}$ is finally calculated and scaled with:

$$CRI\ R_{\mathrm{a},2012} = 100 \cdot \left(\frac{2}{e^{k \cdot |\Delta E_{\mathrm{rms}}|^{1.5}} + 1} \right)^2 \quad (20)$$

with

$$k = \frac{1}{55} \quad (21)$$

and

$$\Delta E_{\mathrm{rms}} = \sqrt{\frac{1}{17} \sum_{i=1}^{17} \Delta E_i^2} \,. \quad (22)$$

For each test colour sample a special colour rendering index *CRI* $R_{\mathrm{i},2012}$ can be calculated by:

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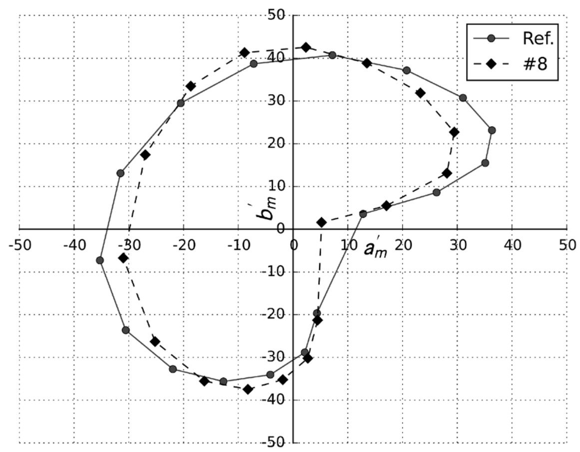

Figure 6 HL17 test colour coordinates a'_m, b'_m for light #8 and its reference illuminant.

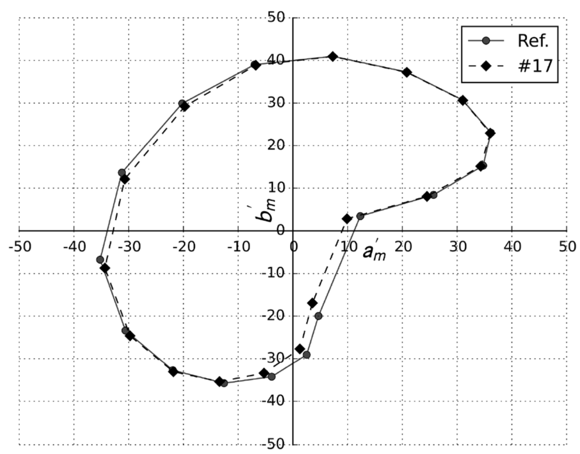

Figure 7 HL17 test colour coordinates a'_m, b'_m for light #17 and its reference illuminant.

$$CRI\ R_{i,2012}=100\cdot\left(\frac{2}{e^{k|\Delta E_i|^{1.5}}+1}\right)^2. \tag{23}$$

The *CRI* $R_{a,2012}$ and CRI $R_{i,2012}$ use a 0–100 scale like CQS to avoid confusing negative values. Using the unmodified colour differences to quantify the quality of a test illuminant, the *CRI* $R_{a,2012}$ is more like the *Color Fidelity Scale* Q_f. The improvement of CRI2012 in regard to CRI1974 is not that obvious comparing the results listed in Table 2. Only minor changes occur. The biggest difference can be found for light source #7 with *CRI* R_a 83 and *CRI* $R_{a,2012}$ 74. This could be related with the factor k in Eq. (21). Smet et al. chose that factor to scale the CIE FL illuminants to keep their original values.

3. Proposition of a new parameter: Spectral Deviation

As mentioned earlier, most of these parameters require a lot of calculations and transformations between different colour spaces. A new parameter, the *Spectral Deviation* Δ_{SD}, has been proposed by Stapel, Heimpold, Drechsel and Reifegerste[17]. It provides a fast and efficient evaluation of light sources. Due to further improvements the old calculations are not repeated in this paper, but the new approach is presented instead. The parameter uses a reference spectral power distribution $S_r(\lambda)$ to calculate the deviation of the tested distribution $S_t(\lambda)$ in regard to $S_r(\lambda)$. As implicated by its name, the deviation to the reference should be as small as possible, with an ideal score of no deviation at all (Δ_{SD} equals zero). The choice of $S_r(\lambda)$ to achieve high quality lighting accepted by most users is as important as difficult.

3.1 Definition of the reference illuminant

The human population is accustomed to different sources of light, dominated by the natural daylight in its variations and artificial light sources such as fire, oil lamps, candles and, since the 19th century, incandescent lamps. All these light sources have one thing in common: a spectral power distribution without narrow peaks or gaps. The SPD of the reference illuminant should be derived from those distributions. The original approach[17] to use the Planckian radiator for all *CCT* has proven to be inefficient for higher *CCT* and has changed to an approach which uses the Planckian radiator for low *CCT* and the daylight equivalent for higher *CCT* like in CIE1974. However, the reference illuminant in CIE1974 changes from a Planckian radiator to a Daylight illuminant at a *CCT* of 5000 K. Thus, the change in the reference SPD is rather abrupt.

The European Broadcasting Union[18] (EBU) uses such a linear interpolation between 3400 K and 5000 K. This approach results in a sufficiently smooth reference distribution which can be seen as accepted by most people due to its natural origin or its cultural history for artificial lighting. However, recent studies show that the perception of *white* lighting deviates from this approach[19]. The lack of a standardized formula to create a SPD for the chromaticity coordinates presented by Rea and Freyssinier prevents the use of these new results as a reference for now. The calculations of Δ_{SD} allow a later substitution of $S_r(\lambda)$ without the need of rescaling the parameter. The formulas for the calculations of $S_r(\lambda)$ are repeated in this paper for completeness.

3.2 Calculation of the Spectral Deviation Δ_{SD}

Step 1: Calculate the correlated colour temperature for the test illuminant T_t

The first step is the calculation of the colour temperature for the test illuminant[20]:

$$T_t = CCT(S_t(\lambda)). \tag{24}$$

The parameter can only be used, if the condition for a valid CCT is met, as mentioned in Section 2.2.

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Step 2: Calculate the spectral power distribution of the reference illuminant $S_r(\lambda)$

The spectral power distribution of the reference illuminant $S_r(\lambda)$ depends on T_t and is given by:

$$S_r(\lambda)=\begin{cases} S_P(\lambda,T_t) & \text{if } T_t<3400\,\text{K} \\ S_{P-D,lin}(\lambda,T_t) & \text{if } 3400\,\text{K}\le T_t<5000\,\text{K} \\ S_D(\lambda,T_t) & \text{if } 5000\,\text{K}\le T_t<25000\,\text{K} \end{cases}, \quad (25)$$

with the wavelength λ in nanometres [nm] and T_t in kelvins [K]. The values of the distribution are normalized for S_r (560 nm)=100[4].

The normalized spectral power distribution of a Planckian radiator $S_P(\lambda, T_t)$ is then given by:

$$S_P(\lambda,T_t)=100\cdot\left(\frac{560}{\lambda^5}\right)\cdot\frac{e^{\frac{1.4388\cdot10^7}{560\cdot T_t}}-1}{e^{\frac{1.4388\cdot10^7}{\lambda\cdot T_t}}-1}. \quad (26)$$

The CIE[4] standardized the calculation of daylight illuminants in 2004. The normalized spectral power distribution of the daylight illuminant $S_D(\lambda, T_t)$ is calculated by:

$$S_D(\lambda,T_t)=S_0(\lambda)+M_1S_1(\lambda)+M_2S_2(\lambda), \quad (27)$$

where $S_0(\lambda)$, $S_1(\lambda)$ and $S_2(\lambda)$ are standardized component functions[4] of the daylight illuminant's distribution by the CIE. The two factors M_1 and M_2 are calculated from the chromaticity coordinates $x_D(T_t)$ and $y_D(T_t)$ for the daylight equivalent in CIE1931:

$$M_1(T_t)=\frac{-1.3515-1.7703\cdot x_D+5.9114\cdot y_D}{0.0241+0.2562\cdot x_D-0.7341\cdot y_D} \quad (28)$$

and

$$M_2(T_t)=\frac{0.0300-31.4424\cdot x_D+30.0717\cdot y_D}{0.0241+0.2562\cdot x_D-0.7341\cdot y_D}. \quad (29)$$

These chromaticity coordinates are dependent on T_t and are given by:

$$x_D(T_t)=\frac{-4.6070\cdot10^9}{T_t^3}+\frac{2.9678\cdot10^6}{T_t^2}+\frac{0.09911\cdot10^3}{T_t}+0.244063 \quad (30)$$

for 4000 K≤T_t<7000 K,

$$x_D(T_t)=\frac{-2.0064\cdot10^9}{T_t^3}+\frac{1.9018\cdot10^6}{T_t^2}+\frac{0.24748\cdot10^3}{T_t}+0.237040 \quad (31)$$

for 7000 K≤T_t<25000 K and

$$y_D(x_D)=-3.000\cdot x_D^2+2.870\cdot x_D-0.275. \quad (32)$$

As mentioned in Section 3.1, a linear interpolation between the Planckian radiator and the daylight equivalent should be used for the range between 3400 K and 5000 K. However, the interpolation from the EBU[18] cannot be used with T_t, because it would create a distribution for the reference illuminant with a different CCT. The primary reason is, that the Planckian and Daylight loci do not join in the CIE1931 colour space. The EBU corrects this by changing the calculation method of the CCT in Step 1. However, we propose to use an empirical correction function to derive a corrected correlated colour temperature T_c for the linear interpolation given by:

$$T_c(T_t)=1434.7+\sqrt{5559.5\cdot T_t-15.0598\cdot10^6}. \quad (33)$$

The corrected colour temperature T_c guarantees that the reference illuminant and the test illuminant have the same correlated colour temperature with an accuracy of ±4.5 K. Without this correction, the CCT of the reference illuminant can deviate up to 115 K from the CCT of the test illuminant.

The reference distribution with linear interpolation can now be calculated with:

$$S_{P-D,lin}(\lambda,T_t)=\frac{S_D(\lambda,5000\,\text{K})\cdot(T_c(T_t)-3400\,\text{K})}{(5000\,\text{K}-3400\,\text{K})}+\frac{S_P(\lambda,3400\,\text{K})\cdot(5000\,\text{K}-T_c(T_t))}{(5000\,\text{K}-3400\,\text{K})}. \quad (34)$$

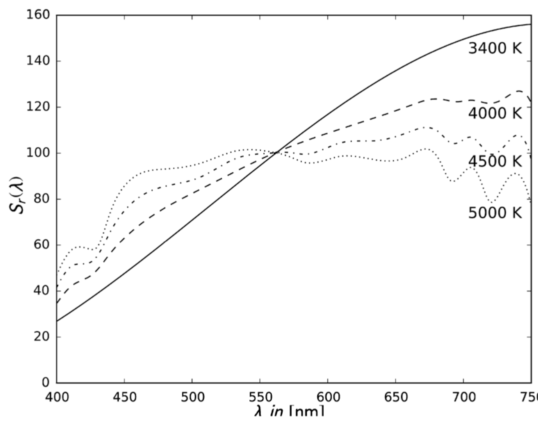

Figure 8 Linear interpolation for $S_r(\lambda)$ for selected CCT.

Figure 8 illustrates the spectral power distribution of the reference illuminant with linear interpolation between 3400 K and 5000 K.

Step 3: Normalize the spectral power distribution of the test illuminant $S_{t,n}(\lambda)$

$S_r(\lambda)$ is calculated as a relative power distribution. The spectral power distribution of the test illuminant $S_t(\lambda)$ must be scaled accordingly. A factor k_t is used to normalize the distribution such that the value at 560 nm is 100 (the same as for the reference illuminant distribution):

$$k_t=\frac{100}{S_t(560\,\text{nm})} \quad (35)$$

The normalized spectral power distribution for the test illuminant $S_{t,n}(\lambda)$ is given by:

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$$S_{t,n}(\lambda)=k_t \cdot S_t(\lambda). \tag{36}$$

Figure 9 and Figure 10 show the normalized spectral power distributions for the lights #8 and #17 of Table 2 and the distribution of their reference illuminants.

Step 4: Calculate Spectral Deviation Δ_{SD}

The Spectral Deviation Δ_{SD} is calculated as the integral of absolute differences between the normalized distributions $S_{t,n}(\lambda)$ and $S_r(\lambda)$ over the visible range:

$$\Delta_{SD,w}=\int_{380\,nm}^{780\,nm} \underbrace{\left|S_{t,n}(\lambda)-S_r(\lambda)\right|}_{\Delta S(\lambda)} d\lambda. \tag{37}$$

Step 5: Apply spectral weighting function $w(\lambda)$

Stapel et al.[17] stated, that the parameter Δ_{SD} is often dominated by deviations in areas with less significance in human perception. This behaviour of the parameter is undesired in regard to the intended use during the design process of single-emitter LED for tuneable luminaires. All deviations have the same impact on the parameter value which is contradictory to human perception. Hence, the parameter should reflect the significance of the deviation according to human perception.

We propose the use of a weighting function based on all three colour matching functions to take human perception into account. The use of only one function, for example $V(\lambda)$, would neglect the colour perception of humans. However, the original approach used by Stapel et al.[17] proved to be inefficient as it led to an increased penalization of deviations for the blue and red wavelength regions. The new approach for the weighting factor is given by:

$$w(\lambda)=\begin{cases} 0.0 & \text{if } \lambda<390\,\text{nm} \\ \dfrac{\bar{z}(\lambda)}{\max(\bar{z}(\lambda))} & \text{if } 390\,\text{nm} \le \lambda<441\,\text{nm} \\ 1.0 & \text{if } 441\,\text{nm}\le\lambda<599\,\text{nm} \\ \dfrac{\bar{x}(\lambda)}{\max(\bar{x}(\lambda))} & \text{if } \lambda\ge 599\,\text{nm} \end{cases} \tag{38}$$

with $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$ being the colour matching functions based on the cone fundamentals standardized by the CIE[21] in 2006. The borders were chosen from the maximum values of $\bar{x}(\lambda)$ and $\bar{z}(\lambda)$ with the given resolution of 1 nm by CIE. However, these colour matching functions are only given in the range from (390…830) nm.

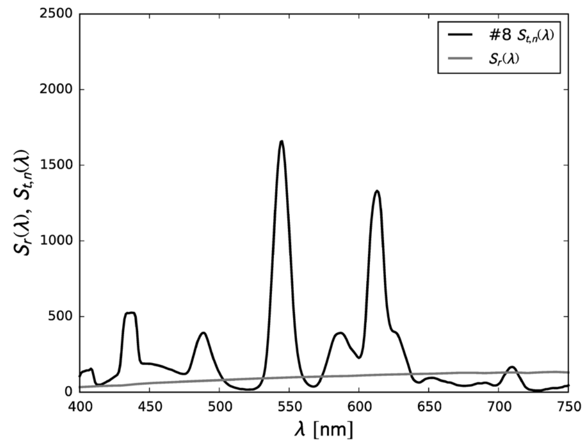

Figure 9 Normalized SPDs for light #8 and its reference illuminant.

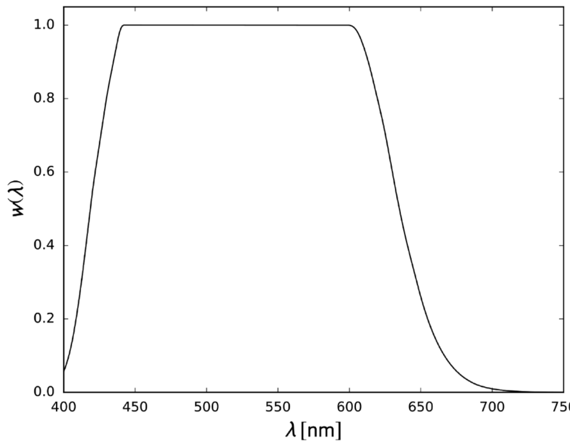

Figure 11 Improved weighting function $w(\lambda)$.

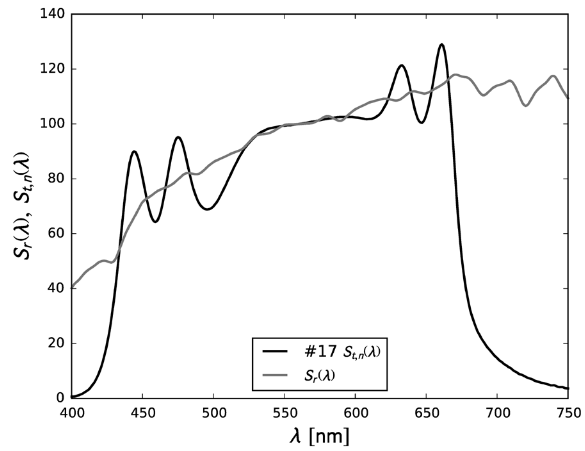

Figure 10 Normalized SPD for light #17 and its reference illuminant.

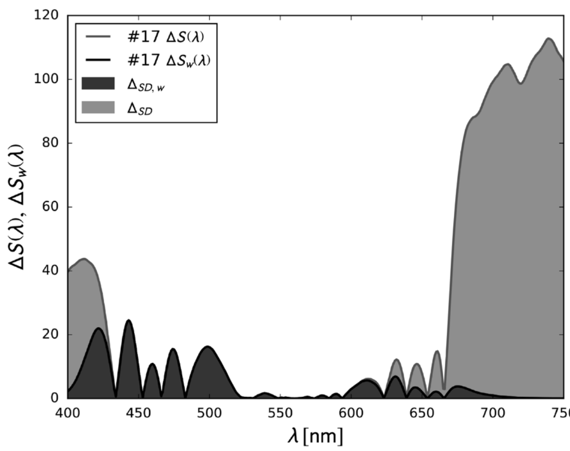

Figure 12 Spectral Deviation and weighted Spectral Deviation for the light #17.

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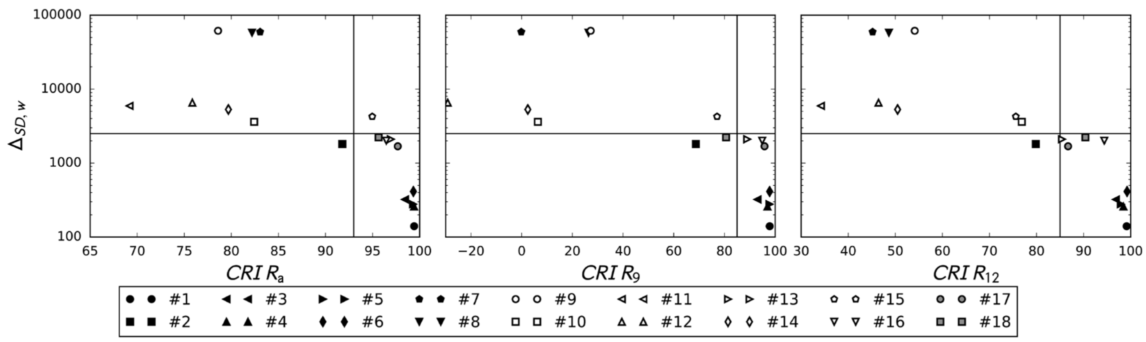

Figure 13 Comparison between CRI1974 and Spectral Deviation for the selected light sources.

The visible range is still considered from (380…780) nm. Because $\bar{z}(\lambda)$ has almost reached zero at 390 nm, the weighting function is set to zero in the range from (380…390) nm.

Figure 11 illustrates the improved weighting function $w(\lambda)$.

The weighted Spectral Deviation $\Delta_{\mathrm{SD,w}}$ is finally calculated by:

$$\Delta_{\mathrm{SD},w}=\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}}\underbrace{w(\lambda)\cdot\left|S_{\mathrm{t,n}}(\lambda)-S_{\mathrm{r}}(\lambda)\right|}_{\Delta S_{\mathrm{w}}(\lambda)}\mathrm{d}\lambda. \tag{39}$$

Figure 12 shows the weighted and not weighted Spectral Deviation for the light #17 of Table 2 and the effect of the weighting function in the border regions of the visible spectrum.

This new approach for the weighting function not only avoids the problem of increased penalization of blue and red wavelength regions but also scales the impact of the deviations according to the perception of the human eye.

4. Discussion and limitations

It was stated, that the new parameter allows a more time efficient quality assessment of light spectra compared to the other parameters such as CRI1974, CRI2012 and CQS. The Spectral Deviation uses no colour space to measure the quality of a spectral power distribution. All colour spaces require at least three integrals to derive the tristimulus values X, Y and Z. Additionally, CRI1974, CRI2012 and CQS use a set of test colours. For each test colour, the tristimulus values have to be calculated for the distribution of the test illuminant and the distribution of the reference illuminant. This increases the number of needed integrals to six. With a set of 14 test colours (CRI1974) this accumulates to 84 integrals (CRI2012: 102 integrals, CQS: 90 integrals). The Spectral Deviation requires only one integral and can be calculated up to 84 times faster than the CRI1974 regardless of the used platform.

Figure 13 shows a comparison between the CRI1974 parameters ($CRI\ R_{\mathrm{a}}$, $CRI\ R_9$ and $CRI\ R_{12}$) and the proposed Spectral Deviation $\Delta_{\mathrm{SD,w}}$. The figure contains the borders for high quality light for the CRI1974 system ($CRI\ R_{\mathrm{a}}\geq 93$, $CRI\ R_9\geq 85$ and $CRI\ R_{12}\geq 85$) proposed by Khanh[3] and our proposed border for the Spectral Deviation ($\Delta_{\mathrm{SD,w}}\geq 2500$). Its derivation will be explained later in this section. The borders divide the diagram into four areas. The upper left area contains light sources which have not a high quality light regarding both parameters whereas the lower right area contains the high quality light sources. All light sources should be in either of these two areas assuming a perfect correlation. However, the correlation is not perfect as seen in Figure 13. For example, the gas light does not reach the high quality values for $CRI\ R_9$ and $CRI\ R_{12}$, but falls below our proposed value for high quality light. Table 3 contains the calculated Pearson correlation coefficient between the Spectral Deviation and the CRI1974

Table 3 Pearson correlation coefficients for Spectral Deviation and Spectral Band Methods to other parameters.

	$\Delta_{\mathrm{SD,w}}$	P_{1937}	P_{1967}
$CRI\ R_{\mathrm{a}}$	−0.480	−0.493	−0.482
$CRI\ R_9$	−0.425	−0.457	−0.425
$CRI\ R_{12}$	−0.602	−0.628	−0.598
GAI	−0.054	−0.122	−0.083
Q_{a}	−0.476	−0.511	−0.483
Q_{f}	−0.488	−0.523	−0.498
$CRI\ R_{\mathrm{a,2012}}$	−0.662	−0.694	−0.664

Table 4 Pearson correlation coefficients for Spectral Deviation and Spectral Band Methods to other parameters after excluding fluorescence light sources #7, #8 and #9.

	$\Delta_{\mathrm{SD,w}}$	P_{1937}	P_{1967}
$CRI\ R_{\mathrm{a}}$	−0.900	−0.832	−0.903
$CRI\ R_9$	−0.899	−0.812	−0.874
$CRI\ R_{12}$	−0.946	−0.852	−0.851
GAI	0.139	−0.115	−0.192
Q_{a}	−0.832	−0.835	−0.888
Q_{f}	−0.833	−0.871	−0.916
$CRI\ R_{\mathrm{a,2012}}$	−0.918	−0.857	−0.909

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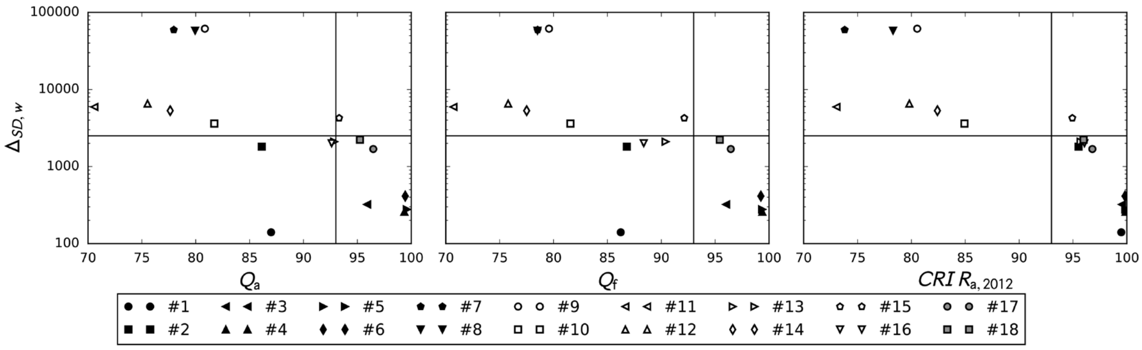

Figure 14 Comparison between CQS, CRI2012 and Spectral Deviation.

parameters. The correlation coefficient may look only average. However, removing the three extreme values for the Spectral Deviation of the fluorescence lamps (#7, #78and #9) from the data set results in higher correlation coefficients shown in Table 4. Hence, the correlation coefficients should be calculated with a bigger data set in future works.

CQS and CRI2012 are the most prominent replacement candidates for the old CRI1974 system. Our parameter should correlate with both systems. Figure 14 shows a comparison between the Q_a, Q_f and $CRI\ R_{a,2012}$ parameters and the Spectral Deviation. The CQS Qp parameter is not shown, because it rates vividness instead of naturalness of colour appearance. Due to the lack of a border value for high quality light in actual literature for these three parameters, the border value of the $CRI\ R_a$ parameter is used to divide the diagrams into the four areas. The correlation between Spectral Deviation and the CQS parameters is not as good as to the CRI2012 parameter or the CRI1974 parameters. There are more light sources in the lower left area of the diagram than in Figure 13. They are high quality light sources regarding to our parameter but not to the compared parameter. The slightly change of the formula for linear interpolation for certain CCT and the correction factor for low CCT in the CQS calculation could produce these minor exceptions. The correlation with the $CRI\ R_{a,2012}$ is very good. Only one high quality light does not fall below our proposed constraint. However, this light source #15 does not achieve the high quality values for all presented parameters proposed by Khanh[3]. The correlation coefficients in Table 3 are only average, too, except the one for $CRI\ R_{a,2012}$. They are again dominated by the three extreme data points of the fluorescence lamps and improve after removing the outlaws, shown in Table 4.

Our parameter does not correlate with the parameter GAI. The correlation coefficient in Table 3 is almost zero and does not improve significant after removing the fluorescence lamps in Table 4. The GAI penalizes nearly Planckian distributions which are the reference for low CCT. As mentioned earlier, the choice of the reference distribution for low CCT remains debatable and an adjustment in future works could lead to a better correlation with GAI.

As seen in Figure 13 and Figure 14, the scale of $\Delta_{SD,w}$ can span over four decades, especially for artificial lighting. A transformation or scaling of the parameter into a better range only adds more calculations what would be contradictory to the original claim to create a parameter with less calculation effort. The Spectral Deviation from the chosen reference illuminant should be as small as possible to achieve high quality light. The derivation of an upper constraint value for the Spectral Deviation to indicate high quality light from the limited data set is difficult. The data set should be extended in future works. Furthermore, the constraint value should categorize the light sources as well as the other presented parameters into high and non-high quality light sources.

The light source #13 from Table 2 represents a light source close to the border of high quality light regarding the presented parameters. Its Spectral Deviation is 2103. The light source #15 only achieves high quality values for some parameters. Its Spectral Deviation is 4261. The upper constraints for the Spectral Deviation should be inside that area. We propose an upper constraint value for $\Delta_{SD,w} \leq 2500$ for a high quality light. Figure 13 and Figure 14 show, that this choice allows a good categorization of the 18 selected light sources.

Table 3 and Table 4 also list the correlation coefficients for the spectral band method of Bouma P_{1937} and Crawford P_{1967} in regard to the presented parameters. The correlation coefficients of the Spectral Deviation are not always higher than those from the old spectral band methods. However, the calculation used to derive the parameter is extended substantially by this paper to allow a better comparison. Especially the use of the same reference illuminant for the calculation of the deviations was never mentioned in the original publications.

Compared with Spectral Band methods in section 2.2, the new parameter uses the same basis, the SPD, to derive the score value. However, the calculation process of the proposed Spectral Deviation differs in three

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significant points. It does not require multiple integrals in sub-bands but uses only one integral in the visible wavelength band. Therefore, the dependency of the parameter on the borders of the sub-bands is avoided. As already mentioned in section 2.2, this dependency can result in a contradictory behaviour of the score values for high quality light sources. Even with standardized sub-bands, the choice of these sub-bands remains debatable and was made for the manufacturing process of fluorescence lamps. Furthermore, the approach from Bouma[6] and Crawford[7] use the spectral luminous efficiency function $V(\lambda)$ as weighting function, but the blue and red parts of the spectrum are needed for good colour rendering properties. The Spectral Deviation only reduces the impact of the near ultraviolet and far red wavelengths of the visible spectrum, because they do not contribute to either colour or brightness perception. The third difference to the other Spectral Band methods is the explicit definition and use of a reference distribution of high quality light. Even if this reference can be updated in the future to take new insights in white light research into account, it will ensure the comparability between different light sources per definition. All other Spectral Band methods do not specify a reference or, in case of Gall and Lapuente[9], do not even use a reference.

However, our parameter should not be used as a quality measurement alone in special applications which require more detailed information about colour rendering of special colours such as skin tone, textile colours or dyes used in art. The achievable measurement quality is also limited by the spectral power distribution of the reference illuminant.

5. Summary

The quality of light is a very difficult feature to describe analytically. The spectral power distribution contains a lot of information but it is not suited for a concise characterization. Therefore, several parameters have been introduced over the past years to combine the information into a single score. The most commonly used parameters have been summarized in this paper and their values have been calculated for measured spectral power distributions of the daily life. The increasing number of parameters and their high calculation effort complicates the design of new spectral power distributions significantly. Therefore, a new single parameter, the Spectral Deviation $\Delta_{SD,W}$ has been introduced with a reduced calculation effort to quickly assess the spectral power distribution towards its potential to be high quality light. It has been shown that the new parameter and the suggested limit for new designs correlate with the old CRI1974 colour rendering index and its two most important replacement candidates. This accelerates the design of new sophisticated spectral power distributions because the designer can concentrate on one parameter only. Using an optimization algorithm, unfit candidates are rejected from the detailed calculations of other parameters, thereby increasing the number of reviewed distributions in the same time.

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