Summary A combined colour rendering—colour preference index for complexion colours is proposed, having its maximum for a source, whose spectral distribution is equal to that of the reference source, but for other sources depends also on the components of the colour difference vector, i.e. lightness, chroma and hue differences. It is based on calculations performed in CIELAB space, using Nayatani type chromatic adaptation transformation to D65 reference illuminant and is backed by visual observations of preferred skin tones and comparative studies of different light sources.

A combined colour preference – colour rendering index

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List of symbols

CCT correlated colour temperature
CPI colour preference index
CRI colour rendering index
ΔC^*_{ab} metric chroma difference
ΔE^*_{ab} CIELAB colour difference
$\Delta E^{*\prime}_{ab}$ modified CIELAB colour difference taking colour preference into account
ΔH^*_{ab} metric hue-difference
Δh^o_{ab} metric hue angle-difference
E_{opt} illuminance providing largest R'_{13} value for given illuminant
R_a general colour rendering index
R^{LAB}_{13} special colour rendering index for CIE Test Sample No. 13, calculated in CIELAB space and D65 reference illuminant
R'_{13} combined colour rendering—colour preference index for CIE Test Sample No. 13 calculated according to present paper
k modifying factor of ΔC^*_{ab}
l modifying factor of ΔH^*_{ab}
L^*_{ab} CIELAB lightness
h^o_{ab} CIELAB hue-angle
C^*_{ab} CIELAB chroma

1 Introduction

At the early stage of developing gas discharge light sources it was observed that the colour characteristics of the human complexion influence the acceptability of a new type of light source considerably (see e.g. the detailed investigation by Buck and Froelich[1] of the Caucasian, Negroid and Asiatic complexion spectral reflectance curves).

For clarity of viewing the two most important parameters of the light source are its correlated colour temperature (CCT) and its colour preference index (CPI). Despite the fact that the CPI has not been standardised internationally and it is not even on the present working programme of the CIE, in many respects it seems to be more important than the colour rendering index (CRI) as it gives an estimate of whether the given source will be accepted or rejected by the ordinary observer or user.

Sanders[2] published preferred chromaticities for a number of natural objects. Also in his studies the chromaticity of human complexion played an important part. Pracejus[3] introduced the gamut area in the CIE 1960 UCS diagram produced by the chromaticities of the eight basic CIE test samples used for colour rendering evaluation, as a measure of light source acceptance (using also a further 'acceptability factor' depending on CCT). In the same year Judd[4] introduced the term *flattery index* for describing colour preference of light sources. He started from the CIE CRI calculation method, but used as reference chromaticities memory colours which seem to be usually more saturated than the actually observed average chromaticities of well-known objects (see also Bartleson[5]). As most light sources reproduce the colours of well-known objects less saturated than the memory chromaticities of these objects, the findings of Pracejus[3] do not contradict those of Judd[4]. In averaging the special flattery indices of different objects Judd gave high weight to complexion chromaticity. The preferred chromaticities as defined by Judd were used in a great number of calculations ever since their publication.

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Haft and Thornton[6,7] published investigations based on gamut area, Ohta and Wyszecki[8] developed a method for determining the spectral power distribution needed at rendering objects in prescribed colours.

Two neglected points in most investigations were the difference between real complexion reflectance spectrum and reflectance spectrum of CIE Test Sample No. 13 (Munsell 5 YR 8/4), used for simulating it, which, however, deviates considerably from the human complexion spectrum (Einhorn[9], Schultz[10]), and that preferred complexion chromaticity seems to be luminance factor dependent (Schanda and Nemcsics[11]).

Some years ago the CIE Technical Committee on Colour Rendering decided to abandon the term flattery index as it might be misused in some commercial applications (e.g. at the butcher's, grocery stores, etc.). Somewhat later the item was taken off the working programme for it was thought to be too complicated to reach international agreement in a question highly motivated by regional (cultural, ethnical, etc.) differences.

In recent years much concern has been aired on the ethics of applying a CPI. For example, Kohmoto and co-workers[12] deliberately developed lamps with high CPI for foodstuffs, Einhorn[9], on the other hand, questioned the applicability of CPI for selecting lamps to be used in supermarkets, etc., and recommended that its application should be restricted to social-lighting, where preferred CCT is in the region of 2800-3000 K. In some countries legislation forbids the use of lamps with flattery properties in illuminating meat and meat products.

In our further investigations we will restrict ourselves to social lighting problems, nevertheless extending the investigations to somewhat higher colour temperatures as well, as preferred colour rendition might be necessary also in daylight-supplementing situations. The area of investigation is, however, restricted to complexion colour, thus deliberately excluding all aspects of commercial applications where the sale of goods under 'flatter light' might be considered.

2 Preferred complexion chromaticity

Preferred complexion chromaticity is definitely dependent on geographical location. In our experimental investigations we concentrated therefore on Europe and investigated the preferred human skin tones for the so-called Caucasian type.

Pilot experiments[11] showed that colour contrast, e.g. hair colour, background chromaticity, etc. highly influences the subjective appraisal. On the other hand we were interested only in the tri-stimulus values. Problems arising from differences in spectral reflectance could be eliminated by using only one standard illuminant. Therefore, a photographic technique was used, taking pictures of the back of some subjects and then distorting the chromaticity by the help of the processing. To avoid the influence of the discoloration of the hair, etc., cut-outs of these photos were mounted on medium grey background and viewed simultaneously under standardised lighting conditions. In parallel instrumental colorimetry was performed on the same areas under the same illuminant.

Table 1. Preferred colour of skin tones.

Sample	L^*_{ab}	h^{o}_{ab}	C^*_{ab}
CIE Test Sample No. 13	80.2	61.7	24.1
Skin tone Pref. 35 per cent	75.4	75.7	19.7
Skin tone Pref. 25 per cent	61.3	62.9	21.8
Skin tone Pref. 15 per cent	55.9	64.3	24.2
Skin tone Pref. 13 per cent	54.6	53.6	29.0
Skin tone Pref. 12 per cent	55.6	68.2	33.6

Results showed a definite correlation between chroma and lightness. Table 1 summarises these results.* For lighter skin tones such with lower chroma are preferred. A highly sun-tanned skin can be more saturated to be preferred. Preferred skin tones are usually more saturated than the CIE Test Sample No. 13.

3 Proposed combined colour rendering—colour preference index

From above studies the conclusion was drawn that it might be more appropriate not to define independent colour rendering and colour preference indices, but modify the present special colour rendering index (CRI) for Test Sample No. 13 (R_{13}) in such a form that it takes colour preference into account.

In developing this combined formula the following points were considered:

(1) Calculations should be performed using the CIELAB space instead of the CIE 1964 UCS space as the former gives better correlation with visual scaling results (Mori and Fuchida[13]).

(2) D65 should be used as reference illuminant, as it is hoped that the applied chromatic adaptation formula can bridge the differences among illuminant chromaticity, and real colour evaluation should be done with this illuminant.

(3) The Nayatani[14,15] chromatic adaptation transformation equation should be used which allows to take different levels of adaptation illuminance into consideration (Schanda[16]), as this again shows the best correlation with visual experiment results (Fuchida and Mori[17]).

(4) The scaling of the index should make a direct comparison with the CIE CRI possible, therefore the constant in the equation coupling CRI-es to colour differences was changed from 4.6 to 5.78 so that for warm white (WW) fluorescent tubes a general CRI (R_a) equal to 50 was provided[16].

From above considerations it is suggested that the following formulae should be used to calculate a modified CRI—CPI: R'_{13}

*Visual scaling of the same photos was performed also in the laboratory of Dr. Barthes, France, and the author is indebted to him for his courtesy in supplying the results.

$R'_{13} = 100 - 5.78\, E^{*\prime}_{ab}$

where

$$E^{*\prime}_{ab} = \left[(\triangle L^*_{ab})^2 + k(\triangle C^*_{ab})^2 + l(\triangle^*_{ab})^2 \right]^{1/2}$$

is a modified colour difference,

where $\triangle C^*_{ab}$ is metric chroma difference, $\triangle H^*_{ab}$ is metric hue difference

$$k = \begin{cases} 1.4 \\ 1/1.4 \end{cases} \quad \text{if} \quad \triangle C^*_{ab} \text{ is } \begin{cases} \leqq 0 \\ > 0 \end{cases}$$

$$l = \begin{cases} 1.4 \\ 1/1.4 \end{cases} \quad \text{if} \quad \triangle h^o_{ab} \text{ is } \begin{cases} > 0 \\ \leqq 0 \end{cases}$$

where $\triangle h^o_{ab}$ is metric hue angle difference.

The constants k and l were chosen tentatively to be equal and reciprocal above and below the maximum ($\triangle C^*_{ab} = 0$, $\triangle H^*_{ab} = 0$).

Further experiments are needed to reach to more accurate values.

4 Application of the combined CRI-CPI formula

Above equations were used to calculate R'_{13} values for a number of light sources.

Table 2 gives some examples of these calculations. In the first column information on the lamp type is to be found, the first five of them being lamps for 'social lighting', where the fifth is illuminant A; the next four are fluorescent lamps used for daylight supplementing purposes. The last two examples are high pressure lamps (mercury and metal-halide) of similar CCT.

In columns 2 to 4 light source characteristics according to CIE Publ. 13.2[18] are to be seen. Column 5 shows R_{13} values calculated by using D65 reference illuminant and Nayatani transformation[16].

Column 6 presents values according to the recommended method, using D65 illuminant as reference. In calculating the values shown in the last two columns a further possibility offered by the Nayatani chromatic adaptation transformation, taking illuminance levels into consideration, was used as well: E_{opt} is the illuminance providing the largest R'_{13} value.

Comparing the first five illuminants it is striking how low the CRI's are if D65 illuminant is used as reference source. This is, however, a more weighty question, not tackled in detail in this paper: are colours seen under daylight the ultimate reference values or should the distorted order of colours as seen, e.g. under CIE Standard Illuminant A also be regarded as a practical reference? The combined index (R'_{13}) is, however, always about 30 per cent higher than the pure CRI (R^{LAB}_{13}), pointing out the fact that in CIELAB space the corresponding colour of CIE Test Sample No. 13 is more saturated and/or more reddish than the reference colour. It is also interesting to note that a much higher R'_{13} value can be reached if the illuminance is reduced to one third—one fourth of its original value—a computation result in good agreement with visual evaluation.

WW de Luxe and WW-Triband are very similar according to this calculation, the exaggerated high difference between the R_{13} value of these two lamps has been practically eliminated.

The second group of lamps with CCTs in the range of 4000 to 4300 K shows some further interesting facts: the standard fluorescent lamp (Daylight) and the high-pressure mercury lamp have higher R^{LAB}_{13} values than R'_{13} ones, which shows that the corresponding colours in D65 illuminant space are located in the undesirable direction compared to the colour point of the Test Sample No. 13. The relatively large differences among Daylight de Luxe, Special and Triband found by classical calculations are practically eliminated. It is more difficult to check whether this is a real effect or not, because the chromaticity of these lamps differs considerably despite the fact that standard CCT calculations yield almost the same value. (If CCT is calculated in CIELAB space (Schanda[20]) the CCT of the de Luxe lamp will be 4370 K, that of the Special lamp 4075 K and that of the Triband lamp 3900 K, differences seen also in lamp chromaticity.)

5 Conclusion

Summing up these results we may state that for appreciative viewing colour preference is of import-

Table 2. Colour rendering—colour preference indices of some light sources.

Lamp type	T_c	R_a	R_{13}	R^{LAB}_{13}	R'_{13}(1000lx)	$R'_{13}(E_{opt})$	E_{opt}
Warm White	3070	51.6	47	24	27	41	300
Homelite	2680	62	59	20	29	52	250
Warm White de Luxe	2890	80	80	32	42	64	300
WW Triband	2990	82	97	32	42	66	300
Illuminant A	2854	100	100	27	38	65	250
Daylight	4270	62	57	54	51	53	600
Daylight de Luxe	4070	84	84	67	71	79	550
Daylight Special	4100	90	93	67	71	80	550
Daylight Triband	4050	81	96	67	72	80	550
HP-Mercury	4090	39	31	38	30	34	550
HP-Metal halide	4100	78	77	63	63	68	600

ance. In this respect the colour shift of human complexion colour seems to be the most important factor. Irrespective of geographical location people prefer if their complexion colour is distorted in the direction of higher saturation and/or reddish hue and dislike if it is distorted in the direction of smaller saturation and/or greenish hue.

Therefore the incorporation of this preference into the R_{13} index has been suggested: the maximum of the new index is at the colour point of maximum fidelity (CRI = 100), but the colour space is distorted in such a way that moving into more saturated and/or reddish colours the index drops less rapidly than if moving in the opposite direction.

The suggested R'_{13} index is based on calculations performed in CIELAB space, using Nayatani type chromatic transformation to D65 reference illuminant and is backed by visual observations of preferred skin tones and comparative studies of different light sources.

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