Effect of Interreflections in a Room on the Colour Rendering of Light Source

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Abstract

Colour rendering indices are regarded as characteristics of a light source. The paper shows that the environment, where the lamp is used, has a major impact on the observed colour rendering. It is suggested that in selecting a light source for an environment the characteristics of the wall paint should be considered and selected accordingly. It is possible to achieve a higher average colour rendering index, as determined for the lamp alone if the source and paint are properly selected.

Introduction

The colour rendering index of a light source is mainly used to describe the characteristics of sources used in indoor lighting. Both the CIE Test Method[1] and all the different alternative methods described in the literature (see e.g.[2,3,4,5,6]) concentrate on the light source itself. But the lamp is used in a room, where the spectral distribution of the light reaching the observer and the objects seen by the observer is modified by multiple interreflections on the walls, ceiling and floor of the room and the furniture in the room. There are several effects that influence the final colour appearance of the objects, and these effects should be taken into consideration if the light source to be used in the interior is selected, some of these are of physical nature and thus can be precalculated, others – however – are of psychological character, where only some estimates can be done, based on current colorimetric knowledge.

The present paper shows how big the difference between the colour rendering index of a lamp, determined by the traditional method1and by considering the inter-reflection of the lamp-light on the walls of a simple empty room painted with different real life paints will be. The calculations assumed total immersion and 100% accommodation to the chromaticity of the lamp-light modified by the inter-reflections.

Test light sources

For the present study light sources were selected from the sources enumerated in the CIE publication on colorimetry[7] together with representative light emitting diodes (LEDs). Figure 1 shows the spectral power distribution of the sources used. Table 1 summarizes the lamp specifications.

As both CIE standard illuminant A and D65 have per definition a 100 % colour rendering, it was interesting to include also these sources to see how their colour rendering is influenced by the wall paint colour. No. 3 lamp (FL 4 is a standard warm white fluorescent lamp with halophosphate phosphor, No. 4 is a three band fluorescent lamp of older construction, No. 5 and 6 are cool white and warm white high colour rendering multi-band lamps. No. 7 is a blue LED + yellow phosphor type white LED, and No.s 8 to 10 are white LEDs constructed from three LEDs, a blue, a green and a red one, where the maximum wavelength of the red LED was different in the three cases, as this has high influence on the colour rendering of the source.

Table 1. Specification of lamps used.

No.	Lamp	CTT (K)	Nominal R_a
1	CIE st. illum. A	2856	100
2.	CIE st. illum. D65	6504	100
3.	CIE Fluor. Lamp FL 4	2940	51
4.	CIE Fluor. Lamp FL 11	4000	83
5.	CIE Fluor. Lamp FL 3.5	4086	95
6.	CIE Fluor. Lamp FL 3.12	2984	93
7.	White LED (blue LED + phosphor	2976	77
8.	R-G-B LED (465nm + 526 nm + 589 nm)	2788	44
9.	R-G-B LED (465nm + 526 nm + 619 nm)	2788	27
10.	R-G-B LED (465nm + 526 nm + 641 nm)	2788	-17

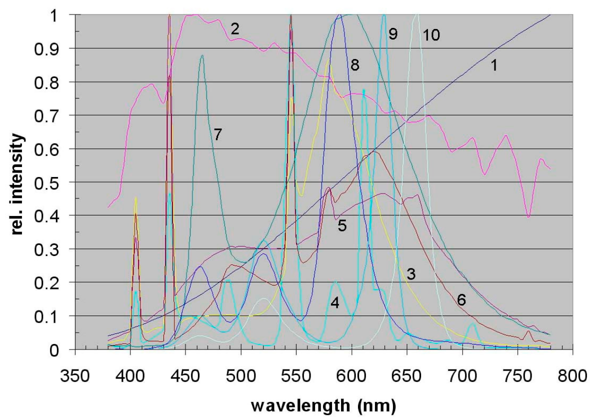

Figure 1: Spectral power distribution of the 10 sources studied.

Wall paints

Six pale wall paint colours have been selected. Their reflection spectra are seen on Figure 2.

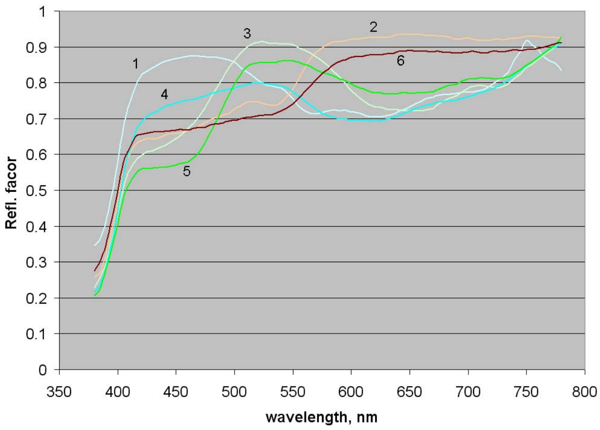

Figure 2: Reflection spectra of the six selected wall paints.

The wall paints, as shown in Table 2, have high reflectance and are all of low chroma, they are wall paint colours that are frequently used in modern interiors.

Table 2. Characterization of the wall paints (verbal description and CIELAB values under D65 illumination

No.	Verbal descriptor	*L**	*a**	*b**
1	Pale blue	89,9	-2,1	-7,4
2	Pale yellow	92,6	5,0	12,6
3	Greenish	94,0	-14,3	14,1
4	Bluish green	89,4	-6,0	0,7
5	Stronger greenish	92,6	-109	18,5
6	Move	90,6	5,9	8,8

The model room

The so called cube model was used to calculate the multiple diffuse interreflection effects in the room[8] to determine the spectral irradiation one can expect for the above mentioned ten light sources and six wall-paints on a white surface in the middle of the room. This is a simple spectral radiosity method, but accurate enough to calculate the sometimes significant spectral changes after the multiple light reflections. We plan to continue the investigations with more complex scenes too.

To evaluate the effect of the interreflections we compared the colour rendering index, calculated using the CIE Test Method[1]. In this study we have assumed that the observer adapted to the "white paper placed on the virtual table" in the middle of the room, further studies are needed to check for mixed adaptation produced by the white background and the large area wall surface. As well known, in case of almost total immersion in a coloured environment, the colour appearance of the immersing colour shifts[9], just as the colour appearance of the test samples. This could be eventually taken into consideration by using a mixed adaptation[10] in the colour appearance model chromatic shift equation, but this was not done in the present study.

The theoretical and numerical background of the cube model

The solution of the problem of multiple interreflections is described in the computer graphics by the rendering equation. It can be applied for scenes containing diffuse surfaces by a finite approximation referred in the literature as the *radiosity method*[11, 12, 13]. This method subdivides the scene to N elementary surfaces or 'patches'. Each of them can be characterized with its A_i surface, ρ_i reflectance factor in the [0,1] interval, and E_i self-emission [$W \cdot m^{-2}$]. Using the classical notations the radiosity equation for a given wavelength is:

$$B_i = E_i + \rho_i \sum_{j=1}^{N} F_{ij} B_j \qquad (1),$$

where F_{ij} form factors depend on the geometrical relationship (visibility, solid angle, cosine factor) between patches i and j. The B_i [$W \cdot m^{-2}$] radiosity values are the solution of the equation (1), which gives the *radiant exitance* of patch i after the interreflection process. The radiosity is the sum of self-emission and the product of irradiance and reflectivity, namely in formula (1) the sum is equal to the (spectral) *irradiance*.

(1) can be solved for a closed environment with surfaces of equal reflectivity very easily in closed form[14, 15]. The model of interreflection contains the term of a geometrical series, thereby the overall amplification factor of the process is $\rho/(1 - \rho)$. To illustrate the effect, these factors are for reflectance factors of 0.5, 0.7, 0.8, 0.9 and 0.95 equal to 1, 2.33, 4, 9 and 19, respectively. For higher reflectivity the amplification factor increases dramatically. In a multispectral case, when this process is realized independently at each wavelength, the curve of spectral reflectance changes according to the above described way. The high peaks will be significantly increased, or after normalization, the low values nearly disappear. The visual effect due to adaptation mechanism is very complex, but these changes result typically in a hue-shift and in an increase in chroma. Bright environments with cold bright surfaces will look bluish, while a warm white will acquire an overall brownish colour because of above reasons. This phenomena can be observed on photos and is known in the painting too.

The numerical solution of the radiosity equation (1) can be done using very costly but efficient hierarchical and Quasi-Monte-Carlo techniques[16]. We apply in this paper a multispectral approach using 81 different wavelengths between 380 nm and 780 nm. The 81 independent radiosity problems require a very high computation cost. Thereby we apply a simple, but from colouristic aspects correct model. That is the cube model[8] with closed form solution.

This model includes just 6 patches, corresponding to the 6 sides of a cube. We can solve the corresponding radiosity system of equations in a closed form, working in this way with a high spectral resolution. The input data are, for every wavelength and patch, the reflectance factor ρ_i and the self-illumination E_i [$W \cdot m^{-2}$]. The form factors F_i are approximately equal to 0.2 for each (i,j) pair (note that this is a very good approximation). The form factor F_{ii} is 0. Let also in this simple model the area A_j be equal to 1.The i-th row of the 6*6 matrix for a given wavelength is then

$$[\, -0.2\,\rho_i\,,\ -0.2\,\rho_i,\ \ldots,\ 1,\ \ldots,\ -0.2\,\rho_i\,] \qquad (2)$$

This simple problem can be solved in closed form

$$B_i = f(E_1, E_2, E_3, E_4, E_5, E_6, \rho_1, \rho_2, \rho_3, \rho_4, \rho_5, \rho_6) \qquad (3)$$

The spectral radiosity of observed wall *i* at each wavelength is a closed non-linear function of the spectral reflectance values of this wall *i*. This fact can be used in parametric inverse radiosity problem with pre-described spectral radiosity values. The closed form solution can be obtained using *a*, *b* and *c* auxiliary terms:

$$a = \sum_{i=1}^{6} E_i (1 + 0.2\rho_i)^{-1}, \qquad b = \sum_{i=1}^{6} \rho_i (1 + 0.2\rho_i)^{-1} \qquad (4)$$

$$c = \sum_{i=1}^{6} B_i = \frac{a}{1-b} \qquad (5)$$

We compute the radiosity solution Bi using the constant c in (5) :

$$B_i = (E_i + 0.2\, c\, \rho_i)(1 + 0.2\rho_i)^{-1}, \quad i = 1,\ldots,6 \qquad (6)$$

We used in our calculations for the 4 walls the same wavelength-dependent ρ_i values, while for the ceiling and floor the 0.9 and 0.3 wavelength-independent reflectivity values were used. In a case of indirect ceiling lighting according to this paper only one of the self-emissions is non-zero. A directional point light source after a first shot step gives a secondary self-emission for every wall and for the floor.

Results

Table 3 shows the effect of the wall paint on the effective correlated colour temperature of the environment. In this table we ordered the lamps – after the two standard illuminants – according to increasing correlated colour temperature (Tcc), to better show the effect of the wall paints. Columns 4 to 9 show the change in the apparent Tcc due to the interreflection of the light in the room. As can be seen with some paints – as known from practice – the ambient appearance of the environment can be influenced to appear wormer or colder. The effect on different sources can be quite different in magnitude. Compare e.g. the six sources with roughly 2800 K CCT, where three-fold differences can be observed.

Even more interesting is if one checks the change in the general colour rendering index (R_a)due to the influence of the wall paint colour. Table 4 summarizes these effects. As can be seen, even for the ideal illuminants (CIE st. illum. A and D65), the wall paint colour can decrease the apparent R_a by up to 20 units. In a number of cased for one and the same lamp R_a increases for one paint and decreases for another. Naturally for the RGB-LED3 (No. 10) the slight increase of the very low R_a value will not make the general appearance mach better, but e.g. the R_a of RGB-LED 1(No. 8) and the warm white fluorescent lamp (No.3) will not so much anymore.

Table 3. Change in the observed correlated colour temperature due to the influence of the wall paint colour

No.	Lamp:	Tcc	Paint 1	Paint 2	Paint 3	Paint 4	Paint 5	Paint 6
1	Ill.A	2856	372	-621	551	289	164	-548
2	Ill.D65	6504	2492	-2351	-423	506	-1007	-1928
8	GRB-LED1	2788	325	-450	303	238	55	-389
9	RGB-LED2	2788	611	-844	965	488	336	-737
10	RGB-LED3	2788	510	-945	1121	407	391	-836
6	DeLuxFl.	2976	413	-667	540	313	157	-579
7	WW-LED	2976	448	-617	424	290	70	-541
3	WW-Fluor.	2940	259	-476	344	212	93	-418
4	Tri-Band	4000	769	-1142	453	420	7	-946
5	DeLuxFl.	4086	918	-1177	406	431	-71	-1003

Table 4. Change in the general colour rendering index due to the influence of the wall paint colour

No.	Lamp:	R_a	Paint 1	Paint 2	Paint 3	Paint 4	Paint5	Paint 6
1	Ill.A	100	-6	-6	-13	-3	-8	-4
2	Ill.D65	100	-4	-4	-20	-5	-13	-4
8	GRB-LED1	44	6	-13	2	5	0	-9
9	RGB-LED2	27	2	2	15	4	6	0
10	RGB-LED3	-17	4	-10	28	7	11	-10
6	DeLuxFl.	93	3	-5	-11	0	-7	-2
7	WW-LED	77	3	-8	-7	3	-4	-4
3	WW-Fluor.	51	4	-6	-5	1	-4	-3
4	Tri-Band	83	1	3	-14	-4	-9	3
5	DeLuxFl.	95	-1	-2	-14	-2	-9	0

In this short paper we can not deal with all aspects, if one looks into the shifts of the special colour rendering indices, one can find further peculiar phenomena, but we will have to discuss this to a later paper, where also the influence of more sophisticated colour rendering calculations will be dealt with.

Conclusion

In the paper we have shown that in selecting a light source for the illumination of an interior scene it is not enough to look for a high colour rendering source, but the wall paint of the interior has to be considered as well. By not proper selection of the wall paint the apparent (perceived) colour rendering can deteriorate, on the other hand by proper selection of the paint and the source, even with a somewhat lower colour rendering index source a pleasing ambient can be produced.

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