GRADING LED ILLUMINATION : FROM COLOUR RENDERING INDICES TO SPECIFIC LIGHT QUALITY INDICES

Viénot Françoise[a], Ezrati Jean-Jacques[b], Boust Clotilde[b,c], Mahler Elodie[a]

[a]Muséum national d'Histoire naturelle, CRCDG, Paris, France

[b]C2RMF, Paris, France, [c]Université de Nantes, France

ABSTRACT

Two experiments were designed and conducted with observers to grade the quality of light-emitting diodes (LED) illumination. The first one was based on colour discrimination. The second one was based on the judgement of colourfulness.

We conclude that clusters with red, green, blue, and/or amber LEDs do not allow satisfactory colour discrimination. Although they seem to locally enhance the colour gamut, they impair colour discrimination. We also conclude that LED clusters that include white LEDs plus a few correcting colour LED may render colours faithfully.

Keywords: Colour rendering, light quality, light emitting diodes, colour discrimination, colour appearance

1. PURPOSE :

LED illumination is an emergent technology. Besides offering compactness, adjustable intensity, maintenance saving and potential energy saving, various LED configurations allow to shape the light spectrum. It is particularly interesting for indoor illumination, because the quality of the light depends on the colour rendering that in turn depends on the spectrum. Most critical is the case of museum illumination that should be free from ultraviolet and infrared radiation, which is genuine in LED illumination. In a previous paper [1, 2], we reported the impairment of colour discrimination when colour normal observers were tested on the Lanthony desaturated D15 colour vision test. We also derived special Color Rendering Indices (CRIs) based on XIXth century colour photographs. Clusters with red, green, blue, and/or amber LEDs give low CRIs, even dramatically low for a few colour samples [3].

Here, we explore new methods to grade the quality of light, based on colour discrimination and on colour appearance [4, 5]. We compare the light quality of various LED configurations with that of conventional illumination.

2. METHODS

Investigations consisted of asking colour normal observers to perform a real task under real illumination.

Conventional illumination was provided by a filtered halogen tungsten lamps (Solux). Thus the colour temperature and the reference luminance were fixed.

Table I. Luminance L_v (cd.m^{-2}) on a white reference plate, colour specification *x*, *y*, colour temperature T_{cp} (K) and colour rendering indices R_{a8} and R_{a14} of the light emitted by the sources used in the appearance experiment. Similar values are available for the sources used in the discrimination experiment.

	Solux	RGB	RGBA	WWR	WWRGBA
L_v	162	166	162	159	161
x	0,3896	0,3893	0,3902	0,3881	0,3878
y	0,3861	0,3858	0,3894	0,3857	0,3862
T_{cp}	3838	3844	3846	3874	3885
R_{a8}	97,5	19,1	59,9	88,3	95,4
R_{a14}	96,6	3,6	51,3	83,8	93,2

LED configurations were a RGB cluster, a RGB plus Amber (RGBA) cluster, a two-phosphor cold White plus Red (WWR) cluster and a two-phosphor cold White + two-phosphor warm White + RGB + Amber (WWRGBA) cluster. The intensity of every LED type was adjusted so as to yield the fixed colour temperature and a fixed reference luminance, and to optimize the CIE colour rendering index (Table I).

The spectral energy distribution of all sources was measured using a Minolta CS-1000 spectroradiometer (Fig. 1).

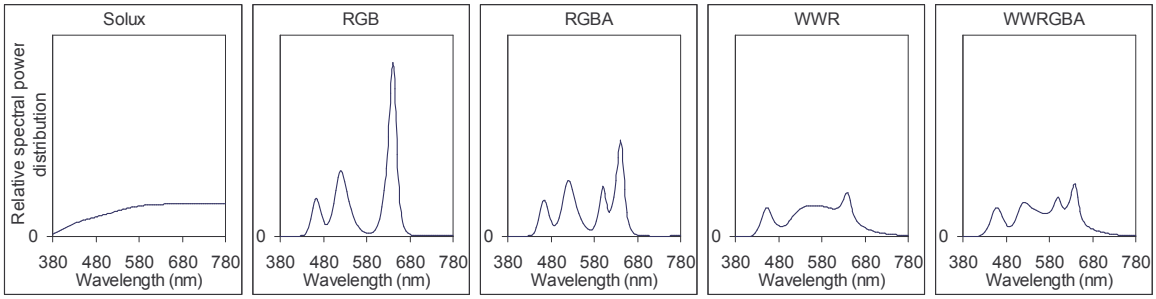

Figure 1. Spectral power distribution of the light emitted by the sources used in the appearance experiment, measured using the Minolta CS-1000 spectroradiometer. Similar curves are available for the sources used in the colour discrimination experiment.

- Colour rendering indices (Table I)

For every illumination, we calculated the general and special colour rendering indices (CRI) R_{a8} and R_{a14} according to the Test-Colour Method as recommended by CIE [6, 7].

- Colour discrimination

We investigated the colour discrimination potential of LED configurations asking observers to classify a collection of 32 laboratory manufactured samples distributed along a colour circle in the CIELAB colour space (L* = 80, C^*_{ab} =constant, $DeltaE^*_{ab}$ step = 3 CIELAB units). Every observer performed the test under all illuminations. Forty colour normal observers participated in the experiment.

- Colour appearance

We computed CIECAM02 *Chroma* and *Colourfulness* of 38 NCS colour samples (Blackness=05, Chromaticness=20; two samples of the series are not manufactured by NCS) for every illumination [8].

Twenty colour normal observers orally rated the apparent colourfulness of the NCS surfaces on a 0–10 scale, under all illuminations. The neutral grey was fixed at the “0” end of the scale. The only constraint that was given was that the rating value should increase as the colourfulness appeared to increase.

3. RESULTS

- Colour rendering indices

Ranking last, the RGB LED cluster yields very low general and special colour rendering indices R_{a8} and R_{a14} (CRI: RGB < RGBA < WR < WWARGB < Solux). R_{a14} of LED clusters decreases, due to the bad ratings for the additional test-samples (Table I). Only LED clusters including white LEDs yield acceptable CRIs larger that 80.

- Colour discrimination

For each illumination, we counted the number of observers who failed in ordering the samples, in order to describe the colour discrimination efficiency of the light sources used in the real experiment (Fig. 2). The RGB and the RGBA clusters produce about twice more errors than the WR cluster, the WWRGBA cluster and the Solux incandescent lamp (Fig. 3).

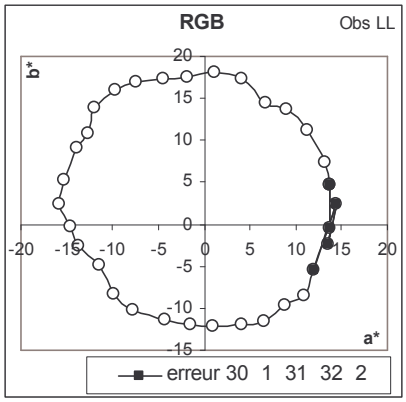

Figure 2. Specification of the 32 samples of the C32 test in *a* b**, computed for an equi-energy illuminant. Example of errors produced by one observer screening the samples under RGB illumination.

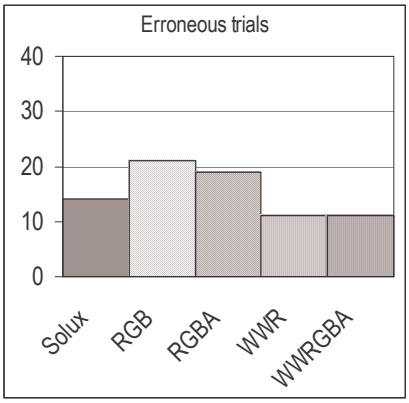

Figure 3. Number of observers, out of 40, who failed the discrimination test under a given illumination.

- Colour appearance

The NCS samples that are at constant chromaticness and blackness vary in saturation, lightness and colourfulness along a two-cycle per hue circle pattern. Nevertheless, they proved to be appropriately selected to evaluate any change in colourfulness.

On the one hand, CIECAM02 predicts variations of *Colourfulness* and *Chroma* depending upon LED illumination (Fig. 4). We note that the *Colourfulness* predictions and the *Chroma* predictions are similar.

On the other hand, observers orally reported that the colourfulness of colour samples apparently increased under RGB and RGBA ($p<0,05$) LED clusters (Fig. 5). Eventually, the similarity of the model prediction and the observers' ratings is obvious.

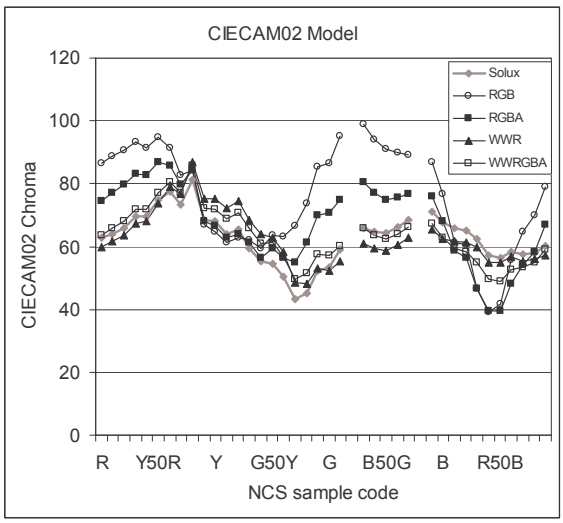

Figure 4. CIECAM02 *Chroma* predictions for Solux and LED illuminations.

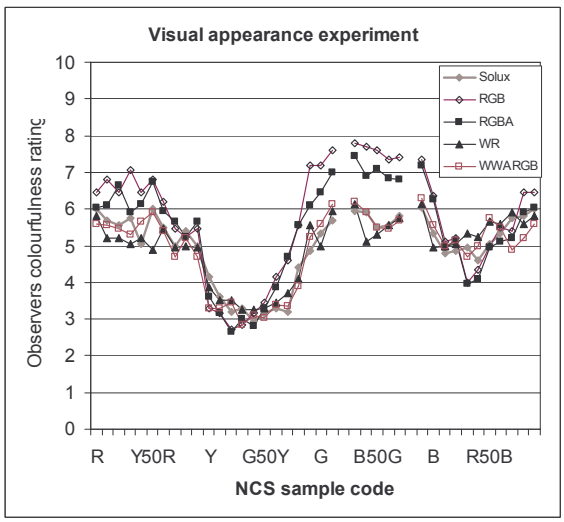

Figure 5. Average colourfulness rating of 20 observers.

While the neutral grey sample was always present at the "0" position of the scale, several observers used almost all the available 0–10 scale to score the samples. Thus, it was impossible to show any absolute increase of colourfulness. Despite this difficulty, the distribution of the colour samples was severely modified with RGB and RGBA LED illumination. Other observers seemed to be able to maintain a personal scale across all illuminations, providing some absolute judgements of colourfulness. Thus, although individual results of several observers are noisy, the trend of colourfulness changes is clear. The apparent scale is expanded with RGB and RGBA

illumination for almost all observers. When individual results are summed and averaged, yellowish-red and bluish-green samples tend to get more colourful under RGB or RGBA illumination than under WWR, WWRGBA or Solux illumination (Fig. 5).

Indeed, RGB illumination physically tunes all spectral reflectances around three spectral peaks, while it impoverishes the spectral signal between the peaks. Therefore, the purity of the stimulus increases, resulting in saturation enhancement. It is noteworthy that the saturation enhancement occurs in only two regions of the hue circle, while the RGB LED cluster narrows the light spectrum within three spectral bands, and the RGBA LED cluster narrows the light spectrum within four spectral bands. Precisely, saturation is at most enhanced for cyan and red colours which are the ones that excite at most the Parvo channel of the visual system. This demonstrates that how the saturation enhances cannot be predicted only from the stimulus. Colour appearance results from a visual process that begins with the absorption of photons by three families of cones, the exiting signals of which are processed through the Parvo and the Konyo chromatic post-receptoral channels. Rather than thinking in terms of tuning the stimulus, thinking in terms of tuning the spectral sensitivity of the receptors would better explain the modification of appearance.

Further, apparent saturation may increase although the available distribution of hues may narrow to a few number categories. Such a distortion of hue should be further investigated.

4. CONCLUSION

We conclude that LED clusters with RGB or RGBA LEDs impair colour discrimination. Surprisingly, these clusters seem to enhance the colourfulness around yellowish-red and bluish-green hues. So the apparent extension of the colour gamut is at the expense of colour discrimination.

We also conclude that LED clusters that include white LEDs plus a few correcting colour LEDs may render colours faithfully. We recommend such configurations for museum illumination.

We also recommend to develop light quality indices, or colour quality grades that fully describe the colour impairments that are induced in terms of colour attributes, colour distribution and colour function. In any case, control of the spectral power distribution is necessary to grade the quality of light.

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Françoise VIÉNOT, MNHN, CRCDG, 36 rue Geoffroy Saint-Hilaire, 75005 Paris, France, vienot@mnhn.fr
Jean-Jacques EZRATI, C2RMF, Palais du Louvre, 14 quai François Mitterrand, 71001 Paris, France, jean-jacques.ezrati@culture.gouv.fr.
Clotilde BOUST, C2RMF & Université de Nantes, France, clotilde.boust@culture.gouv.fr