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Assessing color rendering in a 3d setup

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Abstract

The Color-Rendering Index (CRI) for light source is a quantitative measure of the capability to preserve color appearance of illuminated objects. Recently, CRI has had a renewed interest because of the new LED systems, which usually have a CRI rather low, but a good preservation of color appearance and a pleasant visual appeal. This article presents an experiment performed by human observers to assess the appearance preservation of colors under a set of light sources. Results are then compared with a range of available color rendering indices, in order to assess CRIs variability relative to human judgment.

Keywords: color rendering; light sources; color in context; color appearance; visual comfort; color preference; illuminants; radiometric measurements

1. Introduction

In 1965, the CIE proposed a procedure to specify the visual rendering properties of a light source [1], in order to measure how a light source preserves the color appearance of the objects observed under it. The method updated in 1974 [2], called Color Rendering Index (CRI), is still the used version, corrected with minor adjustments, in 1995 [3]. According to the CIE, Color Rendering Index is defined as: ‘Effect of an illuminant on the color appearance of objects by conscious or subconscious comparison with their color appearance under a reference illuminant’ [4]. The calculation of the CRI requires a reference illuminant, which embodies the idea of a perceptually correct light source. It follows that a maximum score is expected when considering light sources very close to the reference one.

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In the following, the procedure to calculate the standard CRI is summarized. The input of the procedure is the spectral power distribution of the test light source, for which the CRI has to be computed. A reference illuminant is calculated according to the correlated color temperature (CCT) of the test light source. A set of color samples (eight color samples are used to calculate the general color-rendering index, other six color samples with high chroma can be used for additional testing of the color-rendering properties of the light source [5]) is used to calculate the color shift when observed under the two light sources.

The color differences ΔE between the tristimulus values of corresponding samples, observed under the test light source and the reference light source, are calculated after a chromatic adaptation transform to adjust the chromaticity of the test illuminant. For each individual sample i, the specific color rendering index *Ri* is calculated with the following formula: $Ri = 100 - 4.6\ \Delta Ei$.

The final index *Ra* is calculated as an average on the eight samples. In practice, if the color samples are very similar when observed under both light sources, the differences will be minimal resulting in a CRI close to 100, indicating an excellent visual quality.

CRI has shown its limits with the advent of new types of lighting devices. In several cases, it does not return a reliable measurement, namely a measurement in accordance with the human visual system perception, mainly under narrow band light sources, such as three-band fluorescent lamps or white LEDs. These light sources, in effect, may have a pleasant visual appeal and a preservation of color appearance that are better than what indicated by their CRI.

Recently, several attempts to standardize a new method for the calculation of the color rendering have been made, but no one seems to be definitive. From the CIE Technical Report 177:2007, Colour Rendering of White LED Light Sources: “The conclusion of the Technical Committee is that the CIE CRI is generally not applicable to predict the colour rendering rank order of a set of light sources when white LED light sources are involved in this set.”

A number of alternative methods for the calculation of the color rendering have been proposed so far to improve the assessment of color rendering: e.g. CRI R96a [6], CQS [7], CRI-CAM02 UCS [8], CRI-00 [9], CRI2012 [10], GAI [11], RCRI [12]. These alternative color rendering indices, as well as a set of experiments to compare them with the results of human observation, are described in [13].

Nomenclature

CIE	Commission Internationale del l’Eclairage
CRI	Color Rendering Index
LED	Light Emitting Diode
CCT	Correlated Color Temperature
R_i	Specific color rendering index
R_a	Final Index (CRI)
ΔE	Euclidean distance in color space

2. The experiment description

Tests have been performed to assess how human visual system judges the color rendering of various light sources, including new LED systems, in order to have a baseline to compare with available color rendering indices. Recent work on color constancy has verified that our vision system behaves differently with 3D samples respect to 2D [14,15], thus building a 3D scene involves introducing shadows and inter-reflections, created by complex geometries, in order to reproduce what happens in everyday scenes. Then, the relation between the various color rendering indices of different light sources and the score given by users have been analyzed.

One of the aspects under test was the scaling of the values of rendering indices computed and estimated by observers, with the purpose to understand whether the scale is linear to human perception of color shift.

The experiment involved 48 students of the high-school ISIS Edith Stein, in Gavirate (Varese, Italy), 21 females and 27 males, aged between 14 and 18 years, with normal color vision. Aim of the experiment was to compare the

3D color samples, objects composed by plastic brick toys, observed under a reference light source and under a test light source (Table 1).

Observers were then requested to evaluate the differences for each pair of colors, asking them to assess how much the brick colors were similar. To help users in estimating color differences, a two step approach was proposed: at first a qualitative assessment, and then a score quantity are assigned, according to Table 2.

Table 1. List and properties of the light sources used in the experiments

Position	B1S1	B2S1	B3S1	Reference	B1S2	B2S2	B3S2
Nominal Power (W)	20	11	11	42	8	3	30
Nominal Flux (lm)	1250	650	600	630	345	270	806
Measured Illuminance (lx)	913	546	457	390	338	171	470
Measured CCT (K)	2969	7566	4393	3050	3441	3178	3239
Chromaticity Coordinates (x,y)	0.45, 0.42	0.32, 0.35	0.38, 0.39	0.46, 0.40	0.43, 0.40	0.45, 0.44	0.45, 0.40
Type	Fluorescent	Fluorescent	Fluorescent	Halogen	LED	LED	Halogen IRC
Energy class	A	A	A	C	A	A	B

Table 2. Qualitative and quantitative evaluation methods of the bricks color differences

The observed patches are:	Qualitative evaluation	Quantitative evaluation
Identical	ID	100
Similar	SIM	80-99
Different	DIF	50-79
Very different	VD	1-49
Completely different	CD	0

2.1. Experiment setup

Four wood boxes were constructed with size: 1m × 1m × 0.8m. Each box was covered internally with a white paper to avoid the change in appearance among the bricks [16] and the upper part of the box was screened with a panel, to avoid that direct light which reaches the observers eyes. Four identical plastic brick constructions were placed inside the four boxes. In each test box, two light sources were housed, only one at a time was turned on. In Figure 1, a representation of the experimental setup is shown.

The experiments were conducted in a semi-dark room without time limits and the observers completed the experiment after an adaptation period to the light. For clearness with the students, and then to avoid misunderstanding, the whole test has been carefully explained in advance and continuously supervised by one of the authors, to solve any possible doubt of the observers. All boxes have been place on one-meter high tables, observers have been encouraged to find autonomously their preferred position. No constraints were present for the visual field.

Six light sources were tested: three fluorescent, one halogen, and two LED lamps. Another halogen light source was used as reference, having the color-rendering index equal to 100. In Table 1, some of the features of the light sources used in the experiment are described, according to the following labels. Position: B1S1 means that the light source is positioned in the Box number 1 and it is defined as Source number 1 (since in each box there are two light sources). The second light source placed in the same box is defined by the position B1S2, etc. We let the observers adapt to the average luminance level, similar in all the boxes.

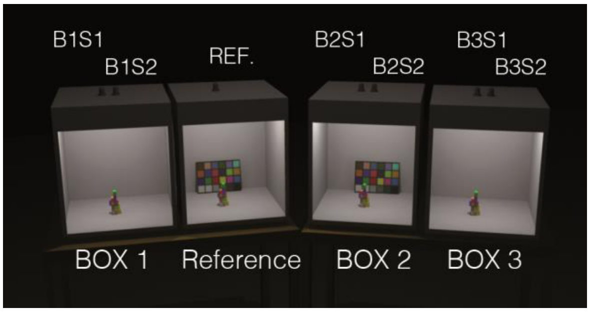

Fig. 1 Simulation of the experimental setup.

There are no biological evidences of sensory adaptation to the color of the light. Color constancy is mainly the result of brain activity. This allows us to watch simultaneously different boxes that generate in our vision system, various color appearances according to the spatial distribution of luminance. Figure 2 shows graphs of the measured normalized spectral power distribution of the seven light sources. Every lamp was turned on before the measurements and before starting the test, according to a scheduling suitable to guarantee the stabilization of emitted flux. For each booth and for each lamp, chromaticity and illuminance at the booth base have been measured on nine symmetric positions around the target. Chromaticity was highly stable with practically null variance, and illuminance had an average standard deviation around 10% across the whole base area of the booth.

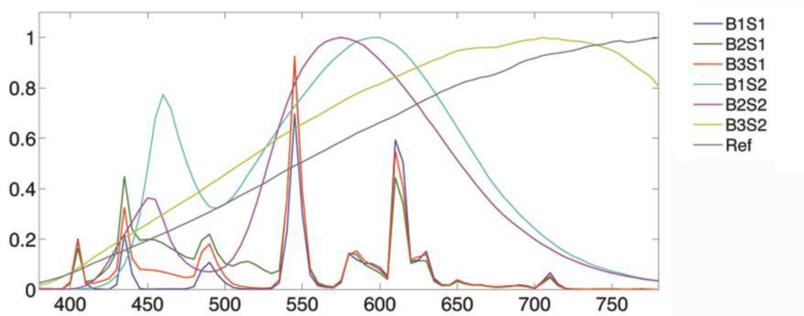

Fig. 2. Normalized spectra of the light sources used in the experiment

Four identical plastic brick toys (placed in the four booths with the same orientation) were used. Observers were asked to examine six selected colored bricks (orange, green, white, blue, yellow, and red), shown in Figure 3 together with their spectral reflectance.

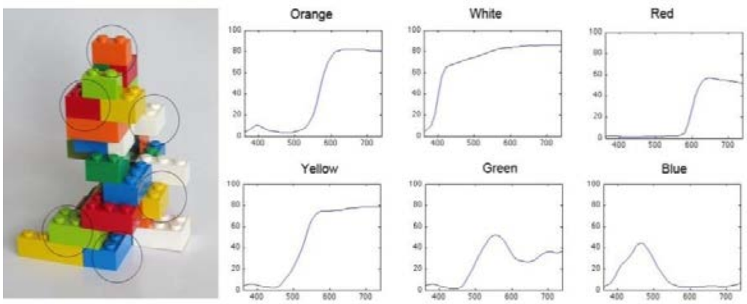

Fig. 3. Construction used in the experiment and spectra of the different bricks.

3. Experiment results

The data regarding the score (mean μ and standard deviation σ) of all the colored bricks observed under the six light sources are shown in Table 3. It is possible to note that the fluorescent lamp in B2S1 has a result quite close to the lamps in B3S1 e B1S2, even if the CCT is rather different from the reference light source. For all the presented methods, except R96a and GAI, the reference illuminant is calculated according to the correlated color temperature (CCT) of the test light source (see table 1). If the CCT is less or equal to 5000K, the spectrum of the reference illuminant is calculated as black body radiation, otherwise it is calculated as spectral power distribution of a daylight illuminant. The GAI method uses instead the equal energy illuminant in its calculation, while R96a provides for a choice among six illuminants. In the specific: 1) B1S1 and B2S2 - black body radiation at 2950 K; 2) B1S2 and B3S2 - black body radiation at 3450 K; 3) B3S1 - blackbody radiation at 4200 K; and 4) B2S1 - D65.

Table 3: Mean and standard deviation for every toy brick.

	Orange	Green	Red	White	Blue	Yellow	Avg
B1S1: μ	89	83	81	87	92	81	86
B1S1: σ	12	12	15	15	13	15	13.7
B2S1: μ	83	74	74	83	80	75	78
B2S1: σ	14	18	17	20	18	17	17.3
B3S1: μ	83	79	82	86	86	76	82
B3S1: σ	14	15	17	18	15	16	15.8
B1S2: μ	83	90	72	81	86	75	81
B1S2: σ	17	11	20	20	17	19	17.3
B2S2: μ	65	76	61	71	74	71	70
B2S2: σ	21	20	20	20	20	21	20.3
B3S2: μ	89	90	92	92	92	90	91
B3S2: σ	15	12	13	12	12	13	12.8

The ranking (from higher to lower) given by the users are: Halogen lamp B3S2 (score 91), Fluorescent lamp B1S1 (86), Fluorescent lamp B3S1 (82), LED lamp B1S2 (81), Fluorescent lamp B2S1 (78), LED B2S2 (70).

4. A comparison between the perceptual rendering index and the calculated indices

In Table 4, the color rendering indices calculated using the methods previously mentioned (Standard CIE CRI, CRI-00, GAI, CRI R96a, CRI-CAM02 UCS, CQS, RCRI, CRI2012) are reported.

Table 4: Color rendering indices calculated for every light source. The last line indicates users evaluation

	B1S1	B2S1	B3S1	B1S2	B2S2	B3S
Std. CRI	80	83	78	83	63	98
CRI 00	76	86	80	84	63	98
GAI	45	98	79	61	40	57
R96a	58	79	78	84	62	75
CAM02UCS	79	85	80	84	67	97
CQS	80	85	80	82	71	96
RCRI	71	89	74	89	62	100
Ra2012	68	69	76	85	69	99
User: 3D	86	78	82	80	70	91

It can be observed that for different light sources the indices may under – or over-estimate the experimental results and that the range of values of the different indices is very variable.

5. Conclusions

In this article, the open issues of color rendering measure were discussed. Starting from the knowledge of the different color rendering indices developed by researchers with the purpose of replacing the standard CIE CRI, and in order to have a baseline to better understand the mechanism of color rendering assessment, a test with users was designed. In particular, the experiment compared a set of color samples observed under a reference light source and under a test light source. 3D objects were used in order to introduce shadows and inter-reflections as in everyday scenes. Then, a comparison between the results obtained with users and a set of indices available in literature was carried out. Assessing color rendering among various illuminants is a complex task, indeed it can lead to different results according to many aspects: the colors under test, the user’s experience, the context in which colors are analyzed, and many other factors. Nevertheless, the correlation indices between users’ observation and various indices shows that the standard CRI is the method that still performs best.

As it is well known that color sensation derives from both the stimuli at the point but also from the spatial distribution of the other stimuli in the scene, a future challenge could be the implementation of the differential and spatial nature of our visual perception in the next indices, in order to have methods able to deal with given contexts and within specific applications [17].

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