Optimizing Color Rendering Index Using Standard Object Color Spectra Database and CIECAM02

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Abstract

As CIE general color rending index (CRI) still uses obsolete color space and color difference formula, it should be updated for new spaces and new formulae. The aim of this study is to optimize the CRI using ISO standard object color spectra database (SOCS) and CIECAM02. In this paper, proposed CRIs were optimized to evaluate light sources for four types of object colors: synthetic dyes for textiles, flowers, paint (not for art) and human skin. The optimization was based on polynomial fitting between mean color variations (ΔEs) and visual image differences (ΔVs). The former was calculated by the color differences on SOCS's typical/difference sets between test and reference illuminants. The latter was obtained by a visual experiment based on four virtual scenes under 15 different illuminants created by Autodesk 3ds Max. The proposed CRIs outperformed the old CIE standard on fitting our visual data. The results would be useful to develop new light sources.

Introduction

CIE Color Rendering Index (CRI) is a popular tool for lighting industries to evaluate the color characteristics of various light sources. However, the CIE general CRI only used 8 Munsell color samples to estimate color variations under obsolete CIE 1964 U*V*W* color space.[1] The index suffers from lack of generality, less sensitivity to illuminant metamerism and perhaps low correlation to visual color variations. A new CRI is therefore urgently needed to the industries for accurate estimation.

ISO/TC130 released a standard object color spectra database (SOCS) in 2003 for color reproduction evaluation.[2] The database covered wide range of natural and artificial object color spectra and therefore is an idea reference for developing new CRIs. On the other hand, CIE TC8-01 recommended CIECAM02 color appearance model for cross-media color reproduction.[3] As chromatic adaptation plays an important role on visual perception, $U^*V^*W^*$ should be replaced by CIECAM02. However, CIE has not yet recommended any color difference formula for CIECAM02 applications.[3] The aim of this study is therefore to evaluate the performance of proposed CRI based on the SOCS and CIECAM02. How to evaluate its performance also is a difficult question. The answer of this study is to create series of virtual scene using Autodesk 3ds Max™ to simulate the color appearance of real-world objects under test illuminants and their CCT (correlated color temperature) corresponding reference lighting (daylight or blackbody radiance). Four types of real-world objects were tested in this study including synthetic dyes for textiles, flowers, paint (not for art) and human skin. The test illuminants were CIE F1~F14 together with three types of white LEDs. Observers were asked to scale overall color differences of the virtual scene between the test and its reference conditions. The resulted scores (ΔVs) were used to optimize the proposed CRI. The ΔVs also compared to the CIE general CRI to see how it can be improved by introducing SOCS and CIECAM02. The results would be useful to develop new light sources.

The following sections will introduce the setup and data analysis of the experiment.

Test Illuminants

CIE released 14 representative spectral power distributions of fluorescent lamps known as F1~F14. Their CCTs range between 2940K and 6500K whose

general CRI (Ra) are within 51 to 95. As white LED has been regarded as the most important light source in near future, it must be involved in CRI optimization. The study used real measurements of a Warm White LED (Luxeon LXHL-BW03, 3329K), a Cool White LED (LXHL-PW03, 5733K) and a set of RGB LED Cluster (Luxeon LXHL-PD09//PM09/PB09, 1:5:1, 6310K) for CRI evaluation. Their general CRI (Ra) were 90.8, 71.7 and 36.7 respectively. A previous study[4] indicated that RGB LED clusters have low Ra. Our evaluation confirms the fact.

Color Difference Formulae

The CIE CRI method applied Euclidean distance of CIE 1964 $U^*V^*W^*$ uniform color space for calculating color differences (denoted as ΔE_{UVW}). The same method can be applied to ΔE_{ab} and CIEDE2000 (denoted as ΔE_{00}) for CIE 1976 LAB color space. As mentioned before, CIECAM02 color appearance model has been recommended by CIE for cross-media color reproduction, Euclidean distance of its (J,a_C,b_C) space denoted as ΔE_{CAM} therefore was tested for the CRI optimization. There is no CIE color difference formula to date associated with the CIECAM02. But a previous study[5] showed a CIEDE94 type formula named CAM02-LCD5CDE (denoted as ΔE_{LCD}) performed well for evaluating large color differences. In this study, the viewing parameters for CIECAM02 was LA=20 and Yb=20 with average surround. The 5 metrics were evaluated for CRI optimization. Note, in CIE CRI, 100 Ra indicates a perfect color match between reference and test illuminants. But in this study, we regarded it as a special type of color difference evaluation so that zero score in the proposed metrics indicating the perfect match.

SOCS Database

The ISO/TR 16066 standard object color spectra database (SOCS) contains more than 50,000 samples for spectral-based color evaluation. It also lists a small group of data sets (denoted as Typ/Diff) to represent typical spectra and their metamers of both artificial and natural object colors. The group contains only 365 samples and therefore is an idea source to replace CIE test-color sample (TCS) No.1-8 for CRI. The SOCS collected spectral data from 9 object categories, but the present study only focuses on 4 sub-sets including synthetic dyes for textiles, flowers, paint (not for art) and human skin. The correlation between original SOCS and Typ/Diff must be known. Table 1 shows the number of samples of each set and the R^2 (the square of Pearson's correlation coefficient) of CRIs (15 test illuminants) between the SOCS and Typ/Diff. As can be seen, all R^2 are very high. It suggests that the use of Typ/Diff sets would give you very similar results to that of original SOCS. Note that some fluorescent and specular samples in the original sets were excluded in the comparison.

Table 1. R^2 between SOCS-based CRI and Typ/Diff-based CRI.

SOCS data		textiles	flowers	paint	Skin	All
original sets		1682	148	336	8570	53413
Typ/Diff set		30	50	15	30	365
R^2	ΔE_{UVW}	0.984	0.983	0.956	0.999	0.997
	ΔE_{CAM}	0.990	0.970	0.901	0.999	0.998

Test Images

A ViewSonic VX2235WM 22" LCD was used for the visual experiment. The LCD was calibrated by GretagMacbeth Eye-One Match 3 to meet sRGB standard. After the calibration, we characterized the LCD using GOGO model.[6] Its mean and max errors for 125 color samples were 1.8 and 3.4 ΔE_{00} respectively. Its inverse model was used to convert objects' XYZ values to displays RGB for assigning diffuse colors in 3ds Max. The XYZ values were obtained by integrating the spectra of the illuminants, objects and color matching functions from 380~780nm in 5nm interval. Because the white points of most of test illuminants are not D65, all XYZ values were multiplied by 0.95 to reduce gamut clipping. To eliminate the influence of ambient lighting, all objects including backgrounds in the virtual scenes are matte. The spectral reflectances of all backgrounds (walls), except images for 'paint test', were equal to 80%.

In 3ds Max, a standard 'Omni Light' was located at 4m distance in front of main objects with 30-45 degrees depression angle. It's important to know whether the lighting would shift RGB values intensively. The degree of color shift was tested by setup a $1m^2$ matte plane with 125 RGB patches at 4m distance in front of the omni light, and a camera viewed the surface from its normal. The mean ΔE_{RGB}

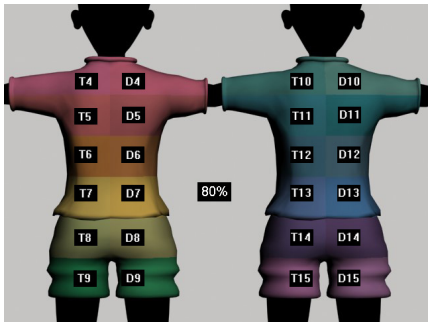

Figure 1. The layout and IDs of the 'Textiles' image.

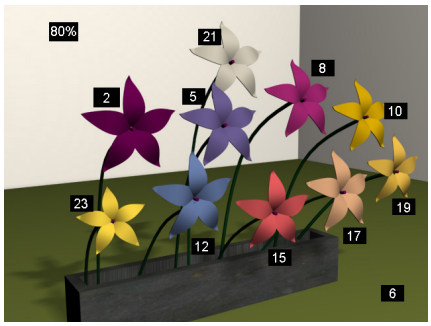

Figure 2. The layout and IDs of the 'Flowers' image.

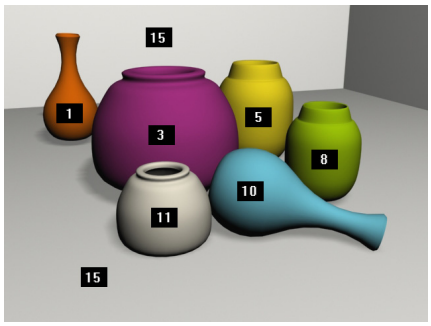

Figure 3. The layout and IDs of the 'Paint' image.

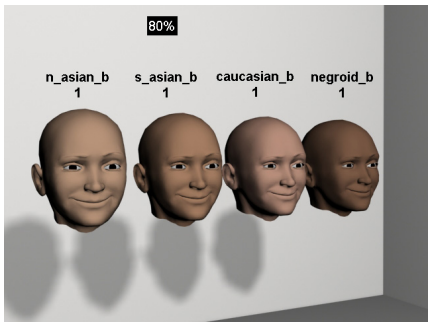

Figure 4. The layout and IDs of the 'Skin' image.

of assigned RGB values and their pixel values in the rendered scene were just 0.65. It suggests the setup is reliable for color rendering.

Four virtual scenes were created to test CRI for textiles, flowers, paint and skin respectively. Color assignment of the virtual objects is shown as follows:

- **Textiles** (synthetic dyes): 24 object colors from both the typical (textiles_s. T) and the difference (textiles_s-d, D) sets were assigned to the cloths of two children. The IDs of all patches are shown in Fig. 1. To avoid the effects of skin colors, the two human bodies were black.
- **Flowers**: 10 flower samples were selected evenly from typical 'flowers_leaves' set and a leaf sample in the set was assigned to the ground. Their IDs are referred to Fig.2.
- **Paint**: 6 paint samples were chosen evenly from typical 'paint' set and the least white sample in the set was assigned to the walls and floor. Their IDs are shown in Fig.3.

Skin: 4 bare skin simples, for north Asian, south Asian, Caucasian and Negroid, selected from the typical sets were assigned to four virtual heads. In order to reduce the effects of other colors, no hair was included. Fig.4 illustrates their IDs.

Experimental Setup

We wrote software in Matlab 7 to collect observers' opinions on the image color differences between a virtual scene under a test illuminant and its reference illuminant. Referring to Fig.5, the reference and test images were always displayed on left and right sides respectively. The software allows observers to score visual image difference of the two images from 0 to 30. The experiment was performed under dark condition. On the screen, pressing 'Reference Pair' button on bottom-right will show a reference pair of images as Fig.6. The content is CIE TCS No.1-8 under CIE F2 illuminant (right) and blackbody radiance at 4230K (left) respectively. 12 observers have been told that the visual difference of the reference pair is 10. All judgment must be based on this magnitude. The experiment allowed observers

pressing the 'Reference Pair' button anytime when they forgot the reference magnitude. In this experiment, there were 15 illuminant pairs, 4 virtual scenes and 12 color normal observers (ages form 22 to 38). The mean scores of the 12 observers were regards as ΔVs. How accurate it can be predicted by different CRI metrics will be estimated in the next section.

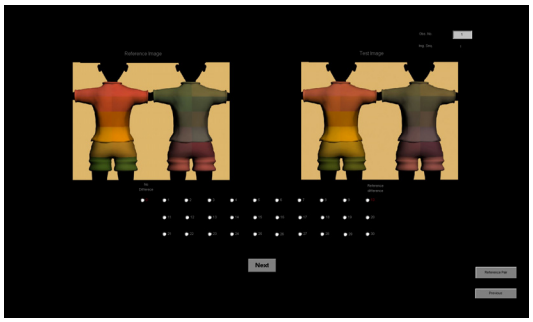

Figure 5. The interface of the psychophysical experiment.

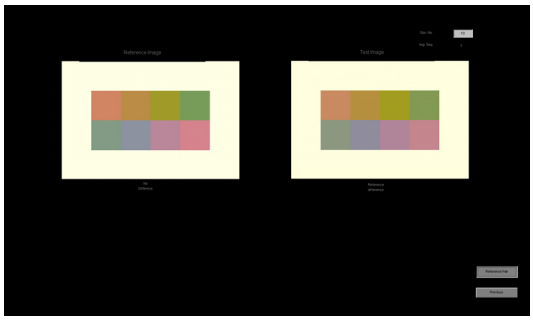

Figure 6. Layout of the reference image pair.

Results

Because the experiment asked the observers to compare each image pair simultaneously, the white points of each pair of illuminants in CRI calculation must be equal. In this study, the white point of test illuminant was replaced by that of its reference illuminant for CRI calculation. The correlations between the 5 CRI metrics were estimated by the coefficient of variation (CV).[7] Low CV values indicate good data fitting to visual results. The initial results are shown in Table 2. As can been seen, using the 365 Typ/Diff spectral samples would result in lower CVs than using the general 8 CIE test-color samples. Compared with the 5 metrics, CICAM02-based metrics performed slightly better.

Table 2. CVs of CIE TCS-based CRIs and Typ/Diff-based CRIs.

Spectra	CRI	Textiles	Flowers	Paint	Skin	All
CIE TCS No. 1-8	ΔE_{UVW}	30.7	29.8	24.3	46.8	35.3
	ΔE_{ab}	20.9	33.4	27.6	38.8	31.8
	ΔE_{00}	22.9	34.3	27.0	37.2	31.8
	ΔE_{CAM}	19.0	30.9	25.2	37.3	29.9
	ΔE_{LCD}	19.1	31.0	25.0	37.0	29.8
Typ/Diff (365)	ΔE_{UVW}	22.2	17.5	18.6	36.2	26.4
	ΔE_{ab}	14.1	22.4	22.0	33.9	25.4
	ΔE_{00}	15.8	23.0	23.8	30.9	25.2
	ΔE_{CAM}	14.5	20.0	19.9	34.2	24.8
	ΔE_{LCD}	14.6	20.8	20.5	33.8	24.9

Table 3. CVs of the proposed CRIs.

New CRI	Textiles	Flowers	Paint	Skin	Mix	All
ΔE_{UVW}	18.5	12.4	16.1	21.1	17.0	23.3
ΔE_{ab}	14.5	16.1	14.5	13.4	14.4	22.0
ΔE_{00}	17.2	16.5	16.0	13.0	15.6	22.1
ΔE_{CAM}	14.4	12.5	14.0	15.0	13.9	21.6
ΔE_{LCD}	14.5	13.0	13.4	14.8	13.8	21.6
Sample no.	30	50	15	30	125	365

Modeling

The CVs can be further improved by the following modifications:

- Treat each object category individually. For example, using 'textiles_s' set from the Typ/Diff to fit the ΔVs of 'Textiles' images. Apply this modification solely did not decrease the CVs significantly.
- Apply 2nd order polynomial regression on the mean ΔE metrics to fit the ΔVs. It diminished the CVs of 'Skin' images significantly.
- Add CCTs to the polynomial function, all CVs reduced a bit. The CVs of 'Skin' images decrease more obviously. Due to the coefficient for CCT is positive, it suggests that skin color differences are more noticeable under high CCT illuminants.
- We noticed that when an observer cannot see any color difference between a test image and its reference, he/she would give a score of zero. It means the difference is below the visual threshold of perceptibility. However, the image pair still has certain color differences. We found if we heighten all ΔVs by 1 unit, the CVs would be slightly decreased. The modification is equivalent to substrate the constant term (c_0) of the polynomial function by 1.

After combining the above four modifications, CVs of the proposed CRIs are shown in Table 3. In general, CIECAM02-based metrics performed slightly better than all the others. Each metric has its own strength.

The performances of ΔE_{CAM} and ΔE_{LCD} were similar. In the table, 'Mix' item shows mean CVs of its left four items. Compared with the CVs of the CIE general CRIs in Table 2. The improvement is significant.

$$CRI_{type} = c_1 \cdot \left(\overline{\Delta E}\right)^2 + c_2 \cdot \overline{\Delta E} + c_3 \cdot CCT + c_0 \quad (1)$$

Table 4. Optimal parameters of the proposed ΔE_{CAM}-based CRI.

	Textiles	Flowers	Paint	Skin	All
C_1	-0.0279	0.0181	0.0123	-0.105	-0.0366
C_2	2.527	0.975	1.166	3.180	2.799
C_3	4.33e-4	4.69e-04	-1.04e-04	1.37e-03	6.54e-04
C_0	-2.440	-1.421	-0.207	-9.678	-4.621

The general form of the proposed CRI is shown in Equ. 1. Note if the CRI value is lower than 0, it must be clipped to 0. The optimal parameters for proposed ΔE_{CAM}-based CRI are shown in Table 4. The parameters would result in the clipping when the mean ΔE is close to zero. It means that the differences are likely below the visual threshold of perceptibility.

As mentioned before, the illuminants of the reference pair were CIE F2 and its corresponding blackbody radiance. The CIE general CRI (Ra) of F2 is 64 and a perfect color match in Ra is 100. Based on our experimental design, they should map to 10 and 0 respectively in the proposed CRIs. Hence, one unit in the proposed CRIs is roughly equal to 3.5 units in the CIE's CRI.

Fig. 7 and Fig. 8 compare the performance of both CIE general CRI and the proposed ΔE_{CAM}-based CRI on fitting the ΔVs. The improvement is clear. However, the proposed CRI is still imperfect and therefore need more studies to enhance its performance.

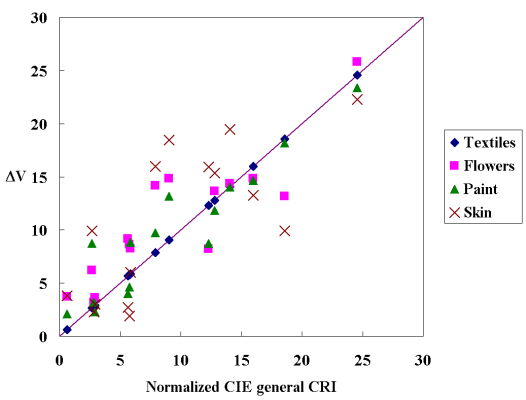

Figure 7. ΔVs vs. the normalized CIE general CRIs.

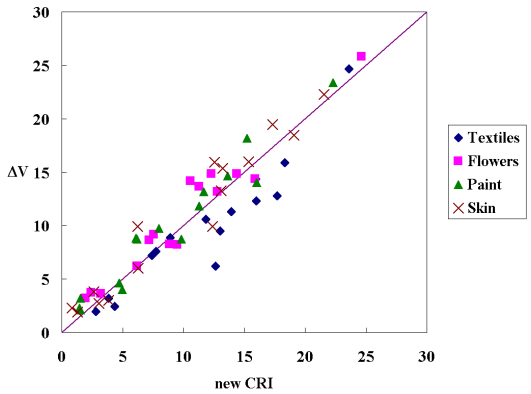

Figure 8. The ΔVs vs. the proposed ΔE_{CAM}-based CRIs.

Conclusions

The present study applied the standard object color spectra (SOCS), new color spaces and new color difference formulae to optimize CRIs. 4 virtual scenes with 15 different illuminants created by 3ds Max were used for a psychophysical experiment to collect visual data. The proposed CRIs used polynomials to fit the visual data and the resulted metrics outperformed the old CIE standard.

Three future works should be done: (1) The visual experiment asked observers to compare the test and reference images simultaneously. It would introduce a chromatic adaptation problem. The experiment also should be done using memory match technique. (2) The general CRI (Ra) of the RGB LED cluster is very low. Its color variation influenced the data fitting most. Therefore, more low Ra illuminants should be included in the optimization to reduce its influence. (3) The proposed CRI should be optimized for more categories of object colors.

Acknowledgements

The author would like to thank all observers and the support from National Science Council Project # NSC95-2221-E-128-007.

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