VALIDATION OF A COLOUR RENDERING INDEX BASED ON MEMORY COLOURS

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ABSTRACT

In this paper the performance of a colour rendering index based on memory colours is investigated in comparison with the current CIE Colour Rendering Index, the NIST Colour Quality Scale and visual appreciation results obtained at CNRS at Lyon University for a set of 3000K and 4000K LED light sources. The Pearson and Spearman correlation coefficients between each colour rendering metric and the two sets of visual results were calculated. It was found that the memory colour based colour rendering index is significantly better at predicting visual appreciation and visual ranking of light sources than the current CIE CRI and NIST CQS.

1. INTRODUCTION

The CIE defines colour rendering as "Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant"[1]. This definition has been quantified by the CIE in a general colour rendering index, Ra[2, 3], which is a measure of the colour appearance shift of a set of standard coloured samples under a test and a reference illuminant.

The CIE Test-Colour-Method for calculating the colour rendering index was developed several decades ago and standardized in 1974[2]. In its early years the CIE CRI did seem to provide an adequate way of estimating the colour rendering capabilities of light sources. Over the past decades, there has been increasing evidence from visual experiments that the CIE Test Colour Method can fail to predict the actual visual rendering abilities of typical narrow-band light sources, e.g. tri-band fluorescent lamps[4, 5] and some white LEDs[6-10]. Several new metrics (NIST CQS[11], Colour Category Index[12], Darmstadt RCRI[13], Feeling of contrast[14], CRI-CAM02UCS[15]) have therefore been proposed during the last few years, especially in the framework of the CIE technical committee TC1-69 dealing with colour rendering of white light sources.

Like the CIE CRI, most, if not all, of these approaches are relative assessments involving the comparison of the colour appearance of a set of samples under a test source with its appearance under a reference illuminant.

Following Hering's idea[16] about the importance of familiar objects for colour perception in the natural world, a colour rendering descriptor was proposed previously by Smet et al.[17], based not on a similarity judgement of coloured cards under a test and a reference illuminant, but on the perceived similarity between an object's apparent colour and its memory colour*[1]: the higher the degree of similarity, the better the colour rendering.

*[1] Memory colours are defined as those colours that are associated with familiar objects in long-term memory.

2. METHODS

2.1 Memory Colour based Colour rendering Index, MCRI

To derive a memory colour based colour rendering metric the colour appearance of a set of nine familiar real objects, with colours distributed around the hue circle, was investigated in a series of visual experiments. The nine familiar objects chosen were a green apple, a banana, an orange, dried lavender, a smurf figurine, strawberry yoghurt, a sliced cucumber, a cauliflower and Caucasian skin. In the experiments the objects were presented in approximately one hundred different colours by placing them in a specially constructed LED illumination box which masked any clues to the colour of the illumination. In this way the illusion was created that the objects themselves changed colour.

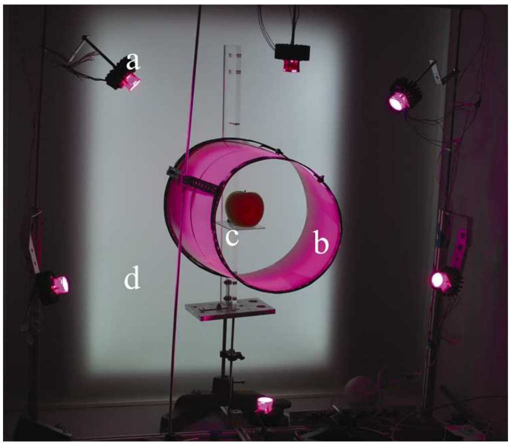

Figure 1: Interior of the LED illumination box. RGBA LED packages to change the object colour (a); Diffusing tunnel to mask specular reflections (b); Transparent object support (c); Luminous back panel to provide a constant adaptation point(d).

Observers were asked to rate, on a 5 point scale, the similarity of the perceived object colour to their idea of what the object looks like in reality. These colour appearance ratings were then pooled and modelled in the uniform IPT colour space[18] by a modified bivariate Gaussian distribution *R* as described in equations 1.

$$R(P,T) = a_1 + a_2 \cdot S(P,T);$$

$$S(P,T) = \exp\left(-\frac{1}{2}\left(d^2(P,T)\right)\right);$$

$$d^2(P,T) = \left(X - X_c\right)^T \cdot \Sigma^{-1} \cdot \left(X - X_c\right); \qquad (1)$$

$$X = \begin{pmatrix} P \\ T \end{pmatrix}; \quad X_c = \begin{pmatrix} a_3 \\ a_4 \end{pmatrix}; \quad \Sigma^{-1} = \begin{bmatrix} a_5 & a_7 \\ a_7 & a_6 \end{bmatrix};$$

The model requires seven parameters: a_1 and a_2 to scale the ratings and a_3 to a_7 to describe the similarity distribution *S(P,T)*. The distribution centre X_c, representing the most likely location of the memory colour, is located at (a_3,a_4), while the shape and orientation of the distribution is determined by the inverse of the covariance matrix ∑. The function *d(P,T)* describes the elliptical *d*-contours of the bivariate Gaussian surface in IPT space and is often referred to as the Mahalanobis distance.

A more elaborate description of the illumination box, the visual experiments and the modelling of the colour appearance ratings by the bivariate Gaussian distribution can be found in a forthcoming paper[19].

Because the similarity distributions *S* enable a quantitative evaluation of the colour appearance of each of the familiar objects, they form the basis of the memory colour based colour rendering evaluation.

A general colour rendering index based on memory colours is obtained as follows. First, for the entire set of familiar objects, the object chromaticity under the test light source is calculated. Second, these apparent chromaticities are inputted into the corresponding similarity distribution *S*, resulting in a set of special colour rendering indices describing the degree of similarity with the object’s memory colour. Third, the general colour rendering index is obtained by taking the geometric mean of the nine special colour rendering indices. The geometric mean was chosen because it is less susceptible to outliers and it is more suitable for values that are exponential in nature, such as the function values of the similarity distribution.

To ensure that most classical sources retain their former CIE CRI, the MCRI was rescaled such that its values for the fluorescent sources F1-F12 are nearly identical with the CIE CRI values. This rescaling approach has also been adopted by the NIST CQS. An advantage is that comparisons between different colour rendering metrics is made easy and that lamp manufacturers do not need to get used to a new scale, they just have to be aware that some light sources might have values larger than 100, which indicates that the light sources has a higher visual appreciation than many of the CIE reference illuminants.

2.2 Visual appreciation experiments

Jost-Boissard et al. investigated the quality of lighting in terms of naturalness and attractiveness by a paired comparison method in two series of visual experiments using familiar objects.

In a first series, nine light sources with a correlated colour temperature of approximately 3000K were compared[20]. The nine sources consisted of a halogen, a fluorescent and 7 LED clusters:

- WA cluster, with white and amber LEDs.
- WR cluster, with white and red LEDs.
- WCR cluster, with white, cyan and red LEDs.
- WGR cluster, with white, green and red LEDs.
- WAR cluster, with white, amber and red LEDs.
- WGARC (CRI) cluster, with white, green, amber, red and cyan LEDs optimized for CIE CRI.
- WGARC (spec) cluster, with white, green, amber, red and cyan LEDs which approximate the spectrum of the reference source (Planckian radiator at 3000K).

The objects used were a tomato, a red apple, an orange, a banana, a lemon, an endive, a leek, a green apple and a courgette. All objects were displayed simultaneously. The illumination level at the object location was 230 lux ± 3%.

A group of 45 observers (21 female, 24 male) with normal colour vision as tested by the Farnsworth D15 test participated in the experiment. Using a double viewing booth observers were shown all possible light source combinations in a random order. For each combination they had to assess which light source was most natural and which was most attractive. Thurstone analysis (case V) was used to create an interval scale for naturalness and attractiveness. The results for attractiveness are shown in Table I.

Table I: Thurstone scalings for 3000K light sources[21].

Light source	Thurstone scaling
WR	100
WGR	91
Halogen	81
WCR	76
WGARC (spec)	73
Fluorescent	55
WGARC (CRI)	55
WAR	39
WA	0

Similar experiments were performed for a set of eight 4000K light sources. The LED clusters used were similar to the ones from the 3000K experiments, except that they were set at a correlated temperature of 4000K. The illumination level at the object location was 210 lux ± 3%. A group of 36 observers (17 female, 19 male) with normal colour vision participated in the experiment. Thurstone scalings for attractiveness are shown in Table II.

Table II: Thurstone scalings for 4000K light sources[21].

Light source	Thurstone scaling
WGR	100
WR	83
WGARC(spec)	71
WCR	69
WGARC (CRI)	66
Fluorescent	65
WAR	37
WGA	0

3. RESULTS AND DISCUSSION

Validation of the memory colour rendering index

The performance of the memory colour based colour rendering index (MCRI) was investigated in comparison with the current CIE Colour Rendering Index[3], the NIST Colour Quality Scale (CQS) [11] and the visual appreciation results obtained by Jost-Boissard et al.[20, 21].

Pearson correlation coefficients between each colour rendering metric and the two sets of visual results (section 2.2) have been calculated. The Spearman correlation coefficient has also been calculated, because it gives an idea about how well a colour rendering metric ranks light sources according to visual results. All results are shown in Table III.

Table III: Pearson and Spearman correlation coefficients of the three colour rendering metrics with the visual appreciation results obtained by Jost-Boissard et al.

		CRI	CQS	MCRI
3000K	**Pearson ρ**	0.15	0.49	0.66*
	Spearman ρ	0.03	0.42	0.62
4000K	**Pearson ρ**	0.26	0.47	0.63
	Spearman ρ	0.05	0.19	0.62

* Type I error: α=0.05.

It was found that the overall level of correlation is rather low for all three metrics, whereby the CIE CRI performs the worst and the MCRI the best for both the 3000K and 4000K set.

Although the overall level of correlation of the MCRI with visual results is rather low, this does not mean that it fails to adequately predict the actual colour rendering properties of the light sources. The low correlation with visual results can be explained by the fact that in the visual experiments no cyan, blue or magenta objects were present, while this region of the hue circle is being taken into consideration in the colour rendering metrics. To investigate this effect, i.e. the obscuring of the correlation with the visual results, the three metrics were calculated using only the special colour rendering indices in the green-yellow-red region of the hue circle. The MCRI was recalculated with the blue and purple samples (smurf and lavender) omitted. The CIE CRI was recalculated using special colour rendering indices *1-4, 9-11 & 13-14*, while indices *7-15* were used in the CQS calculation. The results for these modified colour rendering metrics are shown in Table IV

Table IV: Pearson and Spearman correlation coefficients of the three colour rendering metrics, using only special indices in the green-yellow-red region of the hue circle, with the visual appreciation results obtained by Jost-Boissard et al.

		CRI	CQS	MCRI
3000K	**Pearson ρ**	0.18	0.58	0.96*
	Spearman ρ	0.03	0.38	0.88*
4000K	**Pearson ρ**	0.30	0.54	0.97*
	Spearman ρ	0.21	0.29	0.90*

* Type I error: α=0.05.

Comparing these results with those found using all the special colour rendering indices, there is indeed a very slight increase in correlation for the CIE CRI, a slight increase for CQS and a substantial increase for the MCRI. This obscuration of the correlation with visual results suggests that in order to test any colour rendering index properly it is important that visual experiments be performed with objects spanning the entire hue circle.

All further analysis is therefore limited to the modified colour rendering metrics. For both the Pearson and the Spearman correlation coefficients, the CIE CRI performs again the worst for both light source sets. The CQS comes in second and the MCRI performs by far the best. The superior predictive quality of the MCRI is clearly visible in Figures 2 and 3, where the colour rendering indices of the three different metrics are shown together with the results from the visual experiments.

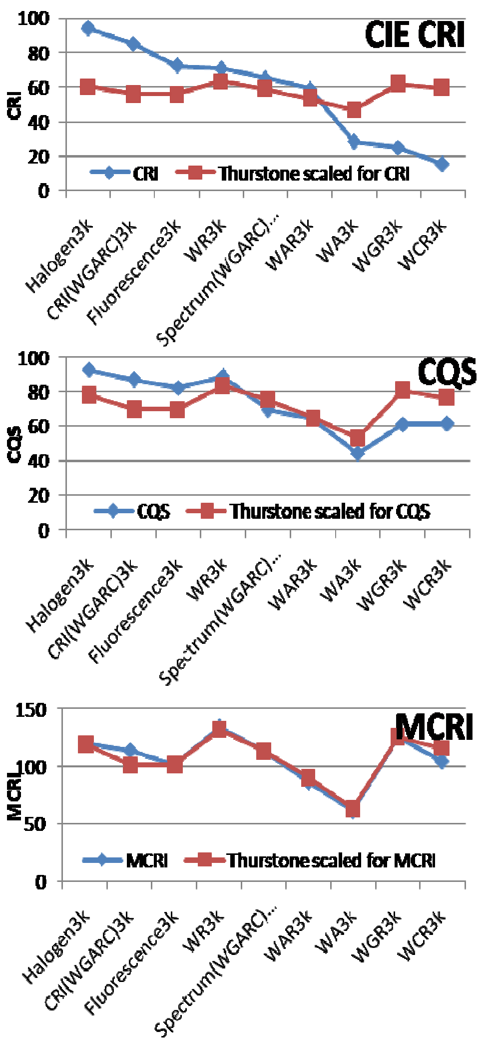

Figure 2: Predictive performance of the CIE CRI, NIST CQS and MCRI for the 3000K light sources.

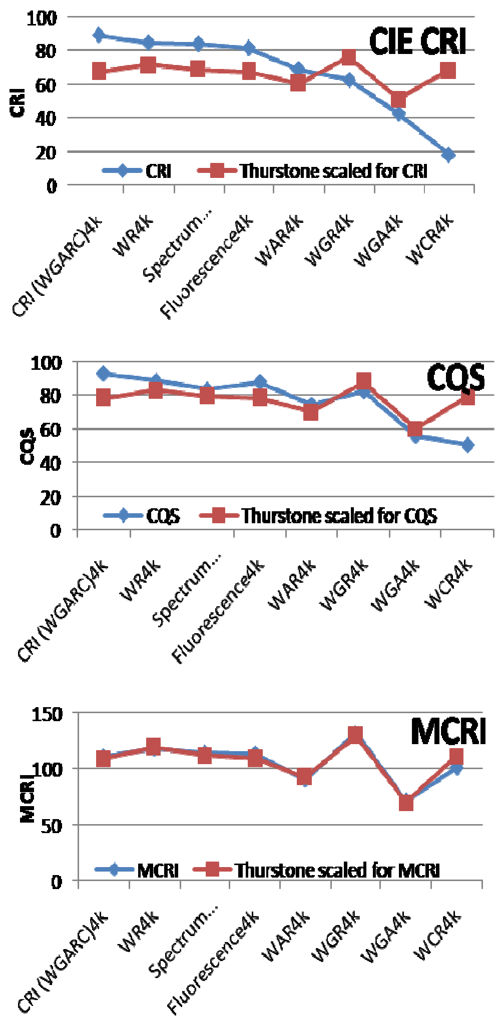

Figure 3: Predictive performance of the CIE CRI, NIST CQS and MCRI for the 4000K light sources.

The statistical significance of these finding was checked by cross comparing the correlation coefficients of the three colour rendering metrics. Because the correlation coefficients of the different metrics were calculated using the same Thurstone scale values they cannot be treated as independent values. The method of Meng, Rosenthal and Rubin for comparing correlated correlation coefficients [22] was therefore used. Results (p-values for H_0: *"no difference"*) are shown in Table V.

The p-values for the Pearson correlation confirm that the MCRI performs significantly better than both the CIE CRI and CQS for the 3000K and 4000K light sources. Furthermore, only in the case of the 3000K light sources is there a significant difference between the CQS and CIE CRI. The Spearman correlation, indicating how well a colour rendering metric was able to predict the correct rank order of the light sources was also compared. It was found that CIE CRI did not significantly differ, while there was a significant difference between the MCRI and both the CIE CRI and the CQS.

4. CONCLUSIONS

It was shown that a colour rendering index based on memory colours is not only feasible, but that it is also significantly better at predicting visual appreciation and visual ranking of light sources than the current CIE CRI and NIST CQS

Table V: Statistical significance of the difference in predictive performance of the various colour rendering metrics using Meng, Rosenthals and Rubin's method for comparing correlated correlation coefficients. Values shown are the two-tailed p-values with the null hypothesis that the two compared correlation values are equal.

3000K	**CRI**		**CQS**	
	Pearson ρ	**Spearman ρ**	**Pearson ρ**	**Spearman ρ**
CQS	0.047	0.070	-	-
MCRI	0.001	0.014	0.004	0.040

4000K	**CRI**		**CQS**	
	Pearson ρ	**Spearman ρ**	**Pearson ρ**	**Spearman ρ**
CQS	0.055	0.590	-	-
MCRI	0.002	0.025	0.003	0.023

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