Memory Colour based Assessment of the Colour Quality of White Light Sources

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Abstract

This paper shortly describes the development, method and validation of a memory colour based metric for the assessment of the colour quality of white light sources. The basic assumption of the metric is that the colour quality of a light source increases as object colours closely resemble what is expected. The similarity with an object's memory colour is described by a set of similarity functions derived by modelling the observer ratings of the colour appearance of a set of real familiar objects. The ratings were obtained in a series of visual experiments in which familiar objects were presented in many different colours to a group of observers. The observers were asked to rate the presented object colour with reference to what they thought the object look like in reality. Based on the psychophysical data of an experiment conducted by the authors, as well as visual data from several visual studies described in literature the memory colour metric was validated, with high statistical significance (p<0.0001), as a metric with a high correlation (r=0.88) with the visual appreciation of light sources. A comparison with 12 other metrics showed it was significantly better at assessing the colour quality of white light sources in terms of visual appreciation.

Introduction

Colour rendering, referring to the impact of a light source on the colour appearance of objects, has been investigated for many decades. The current standard method, the colour rendering index R_a [1-2] developed in the sixties by the International Commission on Illumination (CIE), offers an objective measure of the colour rendering properties of a light source by calculating the colour differences between a set of coloured cards under the test source and a reference illuminant (of the same correlated colour temperature). However, over the past years it become increasingly clear that the CIE colour rendering index can sometimes fail to describe the colour rendering properties of white light sources, especially peaked or narrow-banded sources such as tri-band fluorescent lamps [3-4] and Light-Emiting-Diodes (LEDs) [5-9]. In the past several CIE technical committees have looked into the shortcomings of the CIE colour rendering index but for over 40 years no significant changes were made. Currently a CIE technical committee, TC1-69, is investigating the problems with the CIE colour rendering index in order to provide one or more alternatives or updates that correlate well with visual perception for all types of white light sources.

Although an objective measure like the CIE colour rendering index is required for many professional applications such as colour reproduction, printing and quality control, it may not be the best answer to the needs of lighting designers, architects and those in the shop and retail sector. End users and consumers are usually more interested in the more subjective aspects of colour rendering quality, i.e. in how appealing or how natural objects look. Several authors and representatives from the lighting community have expressed the importance of these more subjective aspects of colour rendering such as preference, attractiveness, colour discrimination, colour harmony, … [10-11]. Indeed, the need for such more subjective metrics was acknowledged by many of the members of TC1-69 and in July 2011 a new CIE technical committee, TC1-87, was established to *investigate available metrics with a view to possibly recommend a new assessment index or indices*.

Over the past decades, several such metrics have already been proposed: e.g. Judd's flattery index [12], Thornton's preference index [13], colour quality scale [14], colour saturation index [15], gamut area index [16], colour harmony index [17], feeling of contrast [18], memory colour quality metric [19-22], …

Many of them make use of a Planckian radiator or daylight phase as the *ideal* or *optimum* reference illuminant. However, studies have shown that many light sources score visually higher than their CIE reference illuminant [19, 23-24]. Therefore, evaluating the colour quality of light sources based on a comparison with a reference illuminant is difficult. Either one has to know which deviations should or should not be penalized or one has to know which illuminant can be considered perfect. In fact, for both of these approaches the knowledge of what objects ideally look like is required. But once this is known, the need for an illuminant as a reference becomes obsolete because one could then reference directly to the *ideal* chromaticities of the objects. Obviously, such an approach would also correspond more closely to the way people judge the colour quality of light sources in everyday life as nobody walks around with a reference source in their pockets to be able to judge the colour quality of the lighting in a room! Colours often look "wrong" when they are not what we expect or want them to be. Therefore, it is reasonable to assume that people are, consciously or subconsciously, judging the colour appearance of (familiar) objects against the colours they mentally associate with those objects, either in memory or in preference.

Based on the straightforward assumption that colour quality increases when object colours are rendered more closely to what is expected, the authors have developed a memory colour quality metric [19-20] that is able to assess the colour quality of a white light source [21].

Development of a colour quality metric based on memory colours

Memory colours and colour quality assessment in the past

Memory colours and preferred colours have long been of interest in many different areas of colour research, such as colour reproduction [25-29] and colour rendering [12-13, 30-34], because of their potential use as a reference to evaluate colour appearance, and hence the quality of a colour image or the colour quality of a light source. Several decades ago, Judd and Thornton, respectively proposed their flattery [12] and colour preference index [13]. However, to assess the colour quality of a light source they didn't reference to the memory colour chromaticity of a set of familiar objects. Instead, they calculated a *preferred chromaticity shift*, based on the work of Sanders [35] and Newhall [36] on memory and preferred colours, to correct the chromaticities of the CIE Munsell samples under the reference illuminant. The assumption that the corrected chromaticity of a Munsell sample is indeed the sample's memory colour is however highly questionable, as coloured cards generally do not have a memory colour associated with them. Furthermore, once both metrics have established an optimal chromaticity they use a Euclidean colour difference in a rather non-uniform colour space. However, colour tolerances for hue and chroma are not alike and people are generally more tolerant of chroma differences than they are of hue differences [30]. Clearly, these differences in tolerance should be taken into account to correctly assess the similarity with the memory colour. However, existing data on memory colours is usually limited to the determination of the chromaticity shift with respect to object colours under a natural illumination [25-26, 36-40]. Although, the constant domains and tolerances respectively established by Bodrogi & Tarczali [27-28] and Sanders [35] can indicate acceptability limits, they do not provide the necessary detail to enable a quantitative assessment of the colour appearance of the object. Yendrikhovskij et al. [41] did provide a complete description of the way observers rate the colour appearance of an object, but unfortunately only the ratings for a ripe banana were modelled. Furthermore, the ratings were obtained by displaying the object on a computer display [28-29, 41-42] or by using an abstract cue, such as the object name, without image context [25, 37, 40]. However it has been demonstrated that the naturalness of object representation, providing information on surface texture, shading, motion parallax and binocular disparity [43], has an influence on similarity ratings [41] and on colour constancy [44-45]. Self-luminous displays look different from what colorimetry predicts [46], and in a recent paper Oicherman, Luo, Rigg & Robertson [47] stated that colorimetric matches between computer displays and surface colours do not necessarily result in perceptual matches.

A new extended memory colour data set

For a memory colour approach to be successful new more extensive memory colour data, that met certain criteria, had to be collected [20]. First, the data should not be limited to the chromaticity of the memory colour, but should also include the response of an observer to a deviation from the memory colour. Obviously, this response might be different for chroma and hue, so the uniform colour space surrounding the memory colour had to be sampled sufficiently and uniformly. Second, the data set should include familiar objects with different hues as a colour quality metric is expected to be able to quantify colour quality across the hue circle. Third, for reasons explained above, the use of real familiar objects instead of computer images is preferable.

The required memory colour data was collected by the authors in a series of visual experiments in which a number of familiar objects were individually presented in over one hundred different colours to a group of 32 colour normal observers. The observers were asked to rate, on a 5 point scale, the presented object colour with reference to what they thought (memory) the object looked like in reality.

The colour of these objects was changed by placing them inside a specially designed illumination box (see Fig. 1) on a transparent support surrounded by a diffusing tunnel around which six tetrachromatic LED clusters were mounted. The clusters were composed of a red (R), green (G), blue (B) and amber (A) LED. The colour of the object was changed by individually controlling the output of each of the dyes in the LED clusters using pulsed-width-modulation controllers connected to a computer. The diffusing tunnel and transparent support masked any clues to the colour of the illumination, thereby creating the illusion that the objects themselves changed colour. At the back of the box, behind the object, a white self-luminous panel was placed to ensure the observer's state of adaption was kept constant.

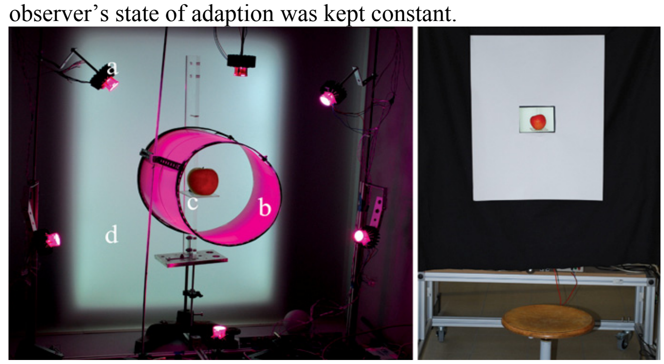

***Figure 1**. Left: inside view of the LED illumination box: (a) RGBA LEDs, (b) diffusing tunnel to mask specular reflections, (c) transparent support, (d) self-luminous back panel. Right: outside view of LED illumination box.*

For each familiar object a uniform grid of approximately one hundred apparent object chromaticities was created by calibrating the illumination box using the spectral radiance of the R, G, B and A LEDs at the object location and the spectral reflectance of the familiar object. During the experiments the sequence of RGBA illumination settings, each resulting in a different apparent object colour, was randomized. To avoid interference of possible bad ratings due to a low luminance, the luminance was kept constant within 10%.

Object chromaticities were calculated from the measured spectral radiance using the CIE 10° observer and were represented in IPT opponent colour space developed by Ebner and Fairchild [48]. IPT was selected because of its reported good hue uniformity [48]. As IPT space has D65 as white point, all tristimulus values were first transformed to their corresponding colours under D65 using the CAT02 chromatic adaptation transform.

The experiments were repeated for a set of ten familiar objects with hues spread around the hue circle: a green apple, a ripe banana, an orange, dried lavender, a smurf, strawberry yoghurt, sliced cucumber, cauliflower, Caucasian skin and a neutral gray sphere. The good inter observer agreement suggested an average observer could be postulated for each object by pooling the observer ratings. The pooled ratings were modelled in IPT colour space by a bivariate Gaussian function that was slightly modified to scale the ratings and take the observer variability into account.

The model required seven parameters: two to account for the scale and observer variability, two to describe the memory colour chromaticity and another three for the shape and orientation of the Gaussian surface. An example of a modelled rating function is given in Fig. 2.

An analysis of the shape and orientation of the modelled rating functions suggested that observers were more tolerant for deviations in chroma than they were for hue, thereby justifying the use of the IPT colour space with its excellent hue uniformity. It also indicates the importance of using a (non-Euclidean) colour distance measure that takes into account these inherent differences in human response to chroma and hue.

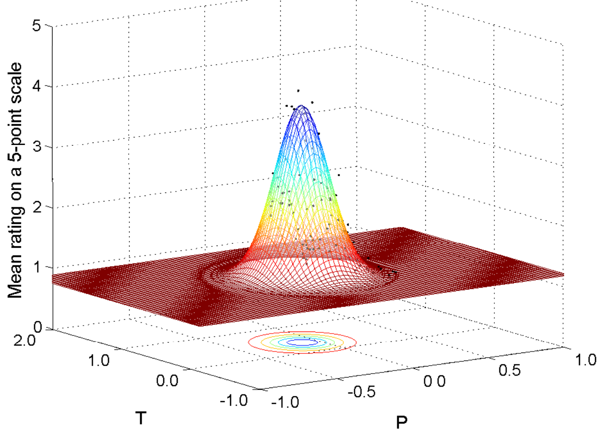

***Figure 2**. The rating function and mean observer ratings for an apple.*

A new memory colour quality metric

Based on the modelled rating functions a set of similarity functions were determined that describe the similarity of any object chromaticity with the memory colours of the familiar objects [19]. As colour quality is assumed to be directly related to the similarity of an object's apparent colour with its memory colour, these similarity functions form the basis of the memory colour quality metric. Practically, the colour quality of a white light source is determined as follows. For each familiar object a special memory colour quality indicator value, S_i, is obtained by calculating the function value of the similarity function $S_i(X)$ at the IPT object chromaticity, X_i, under the test source:

$$S_i(X_i) = e^{-\frac{1}{2}[(X_i - a_{i,3})^T \begin{pmatrix} a_{i,5} & a_{i,7} \\ a_{i,7} & a_{i,6} \end{pmatrix} (X_i - a_{i,4})]} \qquad (i = 1..10) \qquad (1)$$

The object chromaticity X_i is determined by first calculating the CIE 10° tristimulus values under the light source using the spectral reflectance of the object. Secondly, the tristimulus values are then converted to their corresponding colour using the CAT02 chromatic adaptation transform. Finally, the IPT object chromaticity X_i is calculated from the corresponding tristimulus values. For a white light source, a general memory colour quality index S_a is calculated as the geometric mean of the special indicator values S_i:

$$S_a = \sqrt[n]{\prod_{i=1}^{n} S_i} \qquad (1)$$

This number describes the overall agreement of the apparent object chromaticities with their memory colours and hence overall colour quality.

Validation of the memory colour based metric

Psychophysical experiments conducted by the authors [19] as well as independent visual data collected from literature [8, 16, 24, 49-53] were used to validate the memory colour quality metric [21].

The performance of the metric was assessed by calculating the average Spearman correlation of the metric values with the visual data from several studies according to the method of Hunter-Schmidt [54]. The psychophysical studies had investigated the colour quality of light sources in terms of visual appreciation (attractiveness and/or preference) and naturalness (fidelity).

The memory colour quality metric was found to correlate highly (r=0.88, p<0.0001) with the visual appreciation of light sources. The correlation with naturalness was low (r=0.45, p<0.0001).

For comparison, the performance of 12 other colour quality metrics was also calculated. The set of metrics included all proposals to TC1-69 for which a detailed calculation procedure was available, as well as two other memory colour based metric proposed in the past: CIE R_a [1-2], *CRI-CAM02UCS* [55] with a 35 uniform sample set, $CQS_{a,f,p}$ [14], *RCRI* [56], *FCI* [18], *GAI* [57], mean(CIE R_a, *GAI*), *CSA* [58], memory colour quality index S_a [19, 30], Judd's flattery index [12] and Thornton's colour preference index [13]. The average correlation of each of the metrics for the two aspects of colour quality is plotted in Fig. 3.

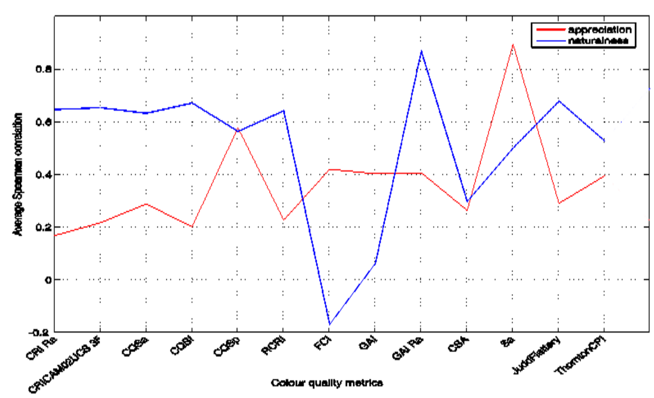

***Figure 3**. The average Spearman correlation of the thirteen investigated colour quality metrics with the perceived colour quality obtained in 9 psychophysical studies in terms of visual appreciation and naturalness.*

The memory colour quality metric was found to be statistically (p<0.0001) better than all other metrics investigated in terms of visual appreciation.

The correlation analysis also revealed that the *arithmetic average of the Gamut Area Index and the CIE colour rendering index* had the highest correlation (*r*=0.85, *p*<0.0001) in terms of naturalness.

The two other memory colour based colour quality metrics, Judd's Flattery index [12] and Thornton's Colour Preference Index [13], were found to perform poorly in terms of visual appreciation (resp. r=0.29 and r=0.39) and moderately in terms of naturalness (resp. r=0.68 and r=0.53), probably due to the reasons stated earlier.

Conclusion

The idea of using memory colours as references to assess the colour appearance of objects, and hence colour quality of a light source was successfully implemented by the authors. The memory colour quality metric developed by the authors, not only takes the chromaticity of the memory colour of an object into consideration, but also the psychological response to a deviation from the memory colour. This response is described by similarity functions derived from the colour appearance ratings of real familiar objects in a psychophysical experiment. The resultant memory colour quality metric has been shown to correlate highly with the visual appreciation of white light sources.

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