Colour Fitting Formulae Used for Predicting Colour Quality of Light Sources

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Abstract: This study describes the development of a new measure intended to improve the description of light source colour quality. Previously, author has developed several colour fitting formulae [1] to describe observer's impressions of colour fitting for two- and three-colour combinations seen under well-defined viewing conditions. One of the applications of these formulae is to quantify the change of colour fitting that can occur on changing from one light source to another. Based on the colour fitting predictions of these formulae for a sample set of colours seen under reference and test light sources a new light source colour quality metric, the Colour Fitting Index is defined. Experiments were carried out to investigate the correlation between visual observations and this new colour quality metric.

Keywords: color, pattern, harmony

1   Introduction

The failure of the current CIE Colour Rendering Index [2] (CRI) for modern (especially LED based) light sources has been demonstrated. Experience has shown that the current CRI based ranking of a set of light sources containing white LED light sources contradicts the visual ranking [3-6]. Various attempts have been made to clarify the possible reasons [4-7] and to improve [8-9] the CRI, but no internationally adoptable solution has been found. One group of authors identified the reason for the failure as the use of the outdated CIE $U^*V^*W^*$ colour space and its colour difference metrics [10]. Several attempts have been made to evaluate the visual colour differences with new colour difference formulae [4-6]. Other authors believed that the small number of test samples may be the problem, and have tried to develop a sample-independent CRI [11] by calculating the maximum colour solids under reference and test illuminants. Others believed the choice of the reference illuminant to be the main problem [12] CIE Technical Committee TC 1-69, "Colour rendition by white light sources" decided to abandon colour rendering and to use colour quality as the generic term to describe the ability of a light source to render object colours, and to distinguish between colour fidelity (that might be described by colour differences observed between samples illuminated by test and reference sources), colour discrimination [13], colour preference [14], flattery [15] and visual clarity [16] A colour quality scale [17] has already been recommended. All these factors influence the final acceptance of a light source for

indoor lighting. Author wishes to extend the above list with a further aspect of colour appearance. The pleasantness of an interior depends to a large degree on the harmonious appearance of the colours seen side by side in the interior. Thus it seemed to be obvious to suggest as a further light source quality index a descriptor as to how strongly a light source distorts the fitting of colours seen in the environment. In the opinion of the author, it is possible that it is not the colour differences of the colour samples under the test light source and the reference light source (colour fidelity) which is visually relevant but the general appearance of *all* colours in the field of view under the test and reference light source, especially the *relation* between colour samples – this is the issue of "colour fitting" [18].

2   Experimental Method

2.1   Development of Colour Fitting Formulae

2.1.1   Stimuli and Procedure

A flat-screen colour CRT monitor with 6500K white point and 116 cd/m^2 peak white luminance was used to display all stimuli. All observations took place in a completely dark room where the colour monitor was the only light source. Colour vision of 13 observers was tested by the Munsell-Farnsworth 100 Hue Test. The viewing distance was 60 cm, the viewing area of the monitor was 32.5cm (horizontal) by 24.5 cm (vertical). Test colour samples were displayed on a middle grey background (J=50). The middle-grey background covered a rectangular area of 29cm (horizontal) by 20cm (vertical). There was a white frame around the screen boundary outside the middle-grey background. The size of each colour patch was 4.5cm x 4.5cm. The colour patches were spaced next to each other, see Fig.. 1 a, b. The task of the observer was to scale his/her colour fitting impression on a scale from -5 to +5, by clicking on the corresponding numbered button in the experimental computer program. 5 corresponded to best fitting and -5 corresponded to worst fitting and 0 corresponded to neutral colour fitting impression. After each scaling, a middle-grey background with a white frame was shown for 2s between the slides to eliminate the after-image effect. The colour stimuli were selected from all parts of the CIECAM02 colour appearance model [19].
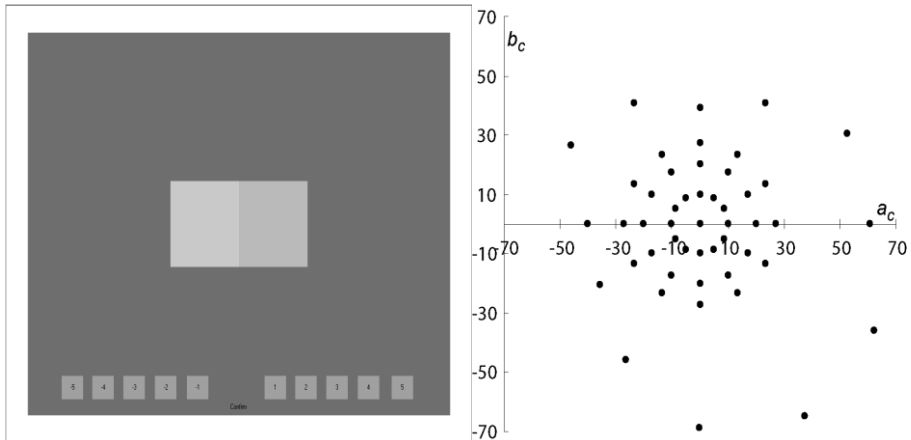
Fig.. 1.a. Screenshot of CRT monitor during experiments. b. Co-ordinates of stimuli on the CIECAM02 a_c-b_c plane.

In the two-colour fitting experiment, there were 2346 colour stimuli. Each stimulus consisted of two squared colour patches presented side by side, in the middle of the grey background. These stimuli were generated from 69 colours, combining all colours from this set of 69 ((69 x 68) ÷ 2=2346). This set also contained 273 two-colour combinations of monochromatic colour combinations (containing colours which share the same hue). The 69 colours were selected systematically from the CIECAM02 colour appearance model containing 5 achromatic and 64 chromatic test samples. Positions of the selected colour stimuli in the CIECAM a_c - b_c diagram can be seen in Fig. 1b. The chromatic colours were selected from 8 hues (with CIECAM02 hue angles of 0, 45, 90, 135, 180, 225, 270, and 315 degrees) and each hue consisted of 8 tones: vivid, pale, dull, dark, light greyish, greyish, dark greyish and the "spectral" (i.e. most saturated) colours. The 5 achromatic colours included the greyscale colours of CIECAM at J=15, 30, 60, 80, and 95. To examine the repeatability of the observer responses the whole experiment was repeated (once).

3   Results

The consistency of observer answers was examined by testing the inter-observer variability and the intra-observer variability of the colour fitting scores. Inter-observer variability (root mean squared) refers to the correspondence of the 9 observers' replies, and intra-observer variability refers to the repeatability of each observer's judgements. The mean value of inter-observer variability for the whole experimental dataset (measured on 2346 two-colour combinations) was 2.12, and the mean value of intra-observer variability was 2.44. Kolmogorov-Smirnov tests were carried out to investigate normality. Levene test showed the homogeneity of variances, so ANOVA could be performed without any transformations of the visual dataset. An ANOVA test was carried out to determine those factors that possibly influence the visual colour fitting

impression. For two-colour combinations lightness difference, chroma difference and hue difference were identified as the most important factors. Hue itself also influenced colour fitting: observers differentiated monochromatic colour combinations according to the hue of the constituent colours.

Results indicated that small lightness differences had low visual colour fitting scores, see Fig. 2a. As lightness difference increases, the fitting score also increases. Colour pairs having higher average lightness were proved to be more fitted than pairs of lower average lightness. For chroma differences, a linear decrease of colour fitting can be observed if chroma difference increases, see Fig. 2b.
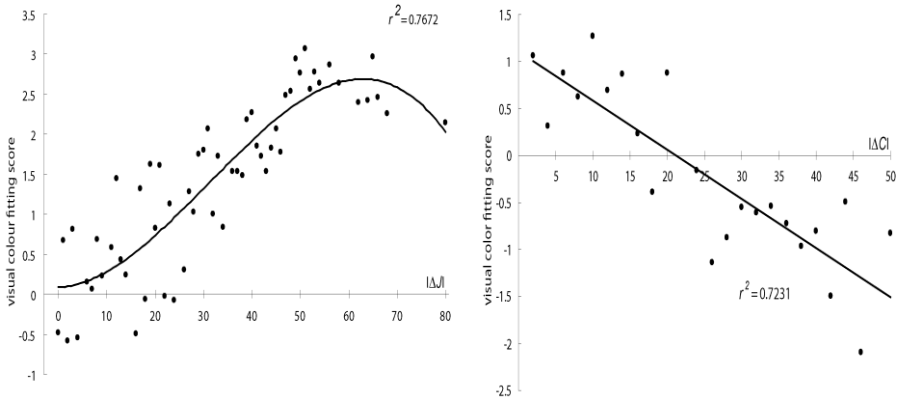

Fig. 2. Colour fitting judgements as a function of a. CIECAM02 lightness (*J*) difference b. CIECAM02 chroma (*C*) difference.

From these results, some general rules can be formulated for colour fitting. By depicting these results in a colour space, general patterns of colour fitting can be observed. From the perceptual attributes of the constituent colours, the extent of colour fitting can be predicted, see the next Section.

3.1   Colour Fitting Model for Monochromatic Two-Colour Combinations

In case of monochromatic two colour combinations, the hues of the two constituent colours are equal or almost equal ($|h_1 - h_2| < 5°$), and that is why hue difference is not a relevant factor affecting colour fitting. On the other hand, the hues of some colours produce higher perceived fitting than others. The best fitting formula is defined by Eq. (1).

$$CHF_{2M,HP} = 0.361\sin(1,511h) + 2.512 \qquad (1)$$

Combinations of equal lightness have the lowest colour fitting scores. Lightness difference has a global maximum at about $|\Delta J| = 30$ absolute lightness difference and

combinations of extreme lightness differences are in turn less fitted. The best fitting formula is defined by Eq. (2).

$$CHF_{2M,Jdiff} = 2.33 \cdot 10^{-5} |\Delta J|^3 - 0.004 |\Delta J|^2 + 0.211 |\Delta J| + 0.246 \quad (2)$$

Maximum colour fitting can be realized if the chroma difference is at its minimum. As the chroma difference increases the colour fitting score decreases linearly. The best fitting formula is defined by Eq. (3).

$$CHF_{2M,Cdiff} = 3.87 - 0.066 |\Delta C| \tag{3}$$

Considering lightness sum (J_{sum}), minimal colour fitting score can be observed in case of low lightness sum, maximum is at high lightness sum. The best fitting formula is defined by Eq. (4).

$$CHF_{2M,Jsum} = 0.0268 J_{sum} - 0.656 \tag{4}$$

Eqs. (1)-(4) are further transformed to obtain CHF_{2M}, the correlate of colour fitting, see Eq. (5).

$$CHF_{2M} = 0.283 \cdot \left(3.275\, CHF_{2M,Jdiff} - 0.643\, CHF_{2M,Jsum} + 2.749\, CHF_{2M,Cdiff} + 4.773\, CHF_{2M,HP} \right)$$
$$- 5.305$$

$$\tag{5}$$

In Eqs. (1)-(5), $|\Delta J|$ is the absolute value of lightness difference between the two colours, J_{sum} is the lightness sum of the samples, $|\Delta C|$ is the absolute value of chroma difference, the subscript HP indicates hue preference, and h is the hue of the composition. (Note that all correlates of colour appearance are defined in CIECAM02.)

3.2 Colour Fitting Model for Dichromatic Two-Colour Combinations

In case of dichromatic two-colour combinations, hue difference was also found to be a relevant factor of colour fitting impression. This can be seen in Fig. 5e showing mean colour fitting score as a function of absolute hue difference ($|h_1-h_2|$).
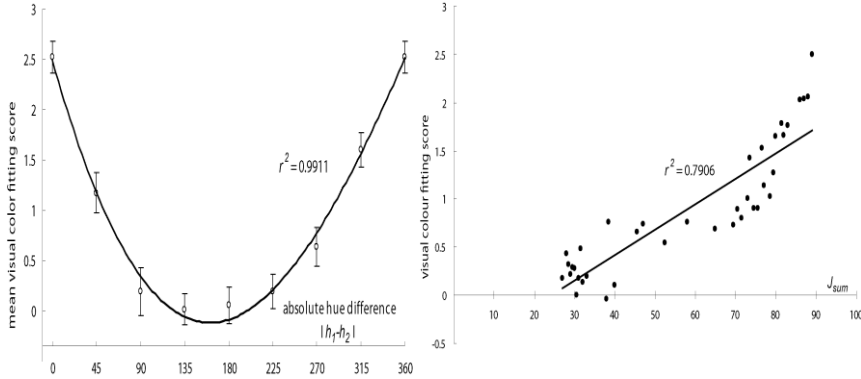

Fig. 3. Colour fitting judgements as a function of a. absolute hue difference ($|h_1-h_2|$) difference b. CIECAM02 lightness (J) sum.

The curve fitted to lightness difference shows similar tendencies to monochromatic colour combinations (as introduced th Fig. 2.a.). This curve is defined by Eq(7). Perceived colour fitting as a function of lightness difference has a global maximum at the value of $|\Delta J|=60$ and dichromatic two colour combinations of extreme lightness difference were found to be less fitted. A further lightness-related effect is that those dichromatic two colour combinations in which both constituent colours have high lightness are perceived to be more fitted than those of low lightness. The mean perceived colour fitting score shows a linear tendency with the J_{sum} value of the two constituent colours, see Fig. 3b and Eq(8).

Regarding chroma difference, perceived colour fitting is at its maximum if the chroma difference is minimal. With increasing chroma difference, the colour fitting score decreases linearly, see Eq(9).

Based on Eq 7-12, the following formulae were constructed to predict the visual colour fitting for "dichromatic" (or "non-monochromatic") two-colour combinations.

$$CHF_{2D} = 0.47 \cdot \begin{pmatrix} 0.515\,CHF_{2D,Jdiff} + 0.391\,CHF_{2D,Jsum} + 0.205\,CHF_{2D,Cdiff} \\ + 1.736\,CHF_{2D,Csum} + 2.187\,CHF_{2D,hdiff} + 5.104\,CHF_{2D,HP} \end{pmatrix} - 2.283$$

where

$$CHF_{2D,Jdiff} = 2.5 \cdot 10^{-5} |\Delta J|^3 + 3 \cdot 10^{-3} |\Delta J|^2 - 2.2 \cdot 10^{-2} |\Delta J| + 0.158 \quad (7)$$

$$CHF_{2D,Jsum} = 10^{-3}(J_{sum})^2 - 0.119 J_{sum} + 0.939 \qquad (8)$$

$$CHF_{2D,Cdiff} = -0.053|\Delta C| + 1.172 \qquad (9)$$

$$CHF_{2D,Csum} = -0.051 C_{sum} + 2.36 \qquad (10)$$

$$CHF_{2D,hdiff} = 8 \cdot 10^{-5}(|h_1 - h_2|)^2 - 0.0279|h_1 - h_2| + 2.3428 \qquad (11)$$

$$CHF_{2D,HP} = \frac{4 \cdot 10^{-5}(h_1)^2 - 0.0127 h_1 + 1.4035 + 4 \cdot 10^{-5}(h_2)^2 - 0.0127 h_2 + 1.4035}{2}$$

(12)

4 Colour Harmony Rendering Index

Perceived colour fitting is subject to change when the light source illuminating the colour samples changes from a reference light source to a test light source. Distortion of colour fitting can be observed if there are very different and *non-systematic* colour shifts - concerning both magnitudes and directions [20] - among the samples in the CIECAM02 colour space [19]. Similar to the concept of colour rendering, author suggests calculating the differences in colour fitting predictions (using his recently developed models) for a set of test colour sample combinations between the appearance of test samples under the test light source and the reference light source. These differences will characterize the "colour fitting" property of the test light source by quantifying the extent of distortion of the perceived colour fitting of a set of test colour combinations that are fitted under the reference illuminant. A "colour fitting index" (R_{hr}) can be calculated e.g. by the following formula:

$$R_{hr} = 100 + k * \sum_{i=1}^{n} CHF_{i,ref} - CHF_{i,test} \qquad (13)$$

where $CHF_{i,ref}$ is calculated under the reference light source, $CHF_{i,test}$ under the test light source, n indicates the number of test colour sample combinations (fitted under the reference light source) used to compute R_{hr}, and k is a constant, which was optimised to achieve reasonable R_{hr} values. The optimised value of k is 5. CHF_{2M}, CHF_{2D} can be substituted in equation 13 depending on the set of monochromatic or dichromatic test colour combinations used.

The test colour combinations to calculate HRI were chosen to fulfil the following criteria:

1. Test colour combinations shall contain colour samples that can be often seen together in everyday life. One group of test combinations contains human skin (dark or light skin) as anchor samples.

2. Test colour combinations shall span the more fitted and less fitted regions of the predictions of the colour fitting formulae, to describe increasing and decreasing tendencies of colour fitting under the different test light sources.

In Fig. 4, the results of the visual estimation experiment (mean colour fitting scores measured on a scale of -5 to +5 are plotted against the Colour Fitting Index (R_{hr}) of the test light sources.

5   Discussion

In this paper, colour fitting experiments are described in order to develop a new quantitative model. New colour fitting formulae were developed to predict colour fitting based on CIECAM02 correlates of the member colours of two- and three colour combinations. Visual colour fitting was measured on an 11 category scale from -5 (meaning completely unfitted) to +5 (meaning completely fitted). Fundamental rules of colour fitting were identified.

In the second part of this paper, colour fitting has been investigated to develop a new Colour Fitting Index (R_{hr}) that can be used to describe light source colour quality. This R_{hr} metric is based on the colour fitting predictions, provided by four recently developed colour fitting formulae. These formulae predict colour fitting from the CIECAM02 correlates of the member colours of two- or three-colour combinations.

This colour fitting index (R_{hr}), based on the recently developed colour fitting formulae showed good correlations with the results of the experiments. The authors suggest using R_{hr} to supplement the current Colour Rendering Index of the CIE to describe the colour quality of light sources.
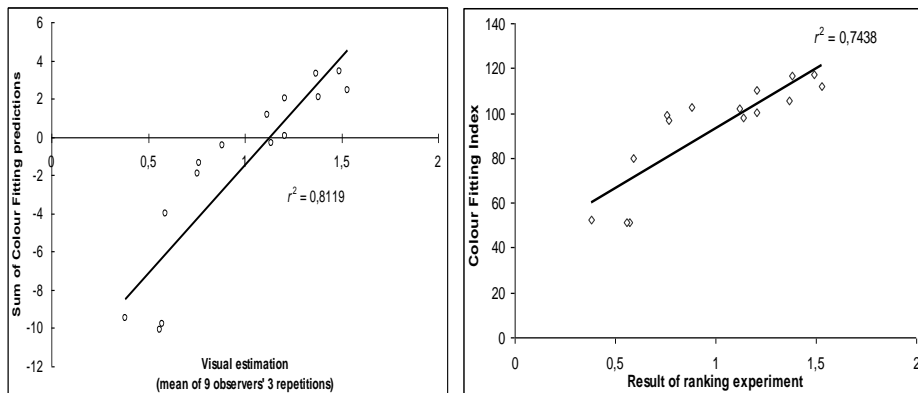

Fig. 4. The relationship between the mean colour fitting scores of the visual estimation experiment and the value of R_{hr} of the test light sources.

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