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VISUAL EXPERIMENTS ON COLOUR HARMONY: A FORMULA AND A RENDERING INDEX

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ABSTRACT
We investigated colour harmony in a series of psycho-physical experiments simulating the appearance of test colour samples on a well-characterized and well-calibrated CRT monitor with two and three colour combinations. Our results of scaled colour harmony were analyzed statistically. Based on this analysis, we present a new colour harmony formula (CHF). Certain light sources tend to distort the perception of colour harmony. We characterize a test light source by the extent of distortion of perceived colour harmony for certain test colour sample combinations that are harmonious under the reference light source. We suggest a harmony rendering index (HRI) quantifying the change of the value of CHF for certain test colour sample combinations if these combinations are viewed under the test light source instead of the reference light source. This HRI may supplement the current CIE colour rendering index.

Keywords: colour harmony, CRT simulation, colour harmony rendering, colour rendering, colour quality

1. INTRODUCTION
The principle of harmony is completeness according to Goethe[1], order according to Chevreul[2], and balance according to Munsell[3]. Judd and Wyszecki[4] define harmony as “when two or more colours seen in neighbouring areas produce a pleasing effect, they are said to produce a colour harmony”. To quantify the impression of colour harmony, Ou and Luo developed a “CH formula” [5] for two colour combinations. In the literature of colour harmony, we didn’t find any existing quantifying predictive model for three colour combinations. In the past, we compared several models of colour harmony [6] and now we present a new colour harmony formula (CHF) based on our recent experimental dataset. We also present an associated harmony rendering index (HRI).

2. METHOD
We simulated the appearance of test colour samples on a well-characterized and well-calibrated CRT monitor. 9 observers of good colour vision had to scale their colour harmony impression on a -5 to +5 scale (-5: disharmonious, 0: neutral, and +5 harmonious) for 2 and 3 colour combinations: diads (i.e. pairs) and triads. A grey background was shown for 2 seconds between the slides to eliminate the after-image effect. An example is shown in Figure 1. Test samples were chosen to cover the whole CIECAM02 space. We used test samples of 3 different lightness at 3 different levels of chroma and the most saturated colours of each examined hue: 2346 diads and 14280 triads.

Figure 1: Experimental images on the CRT monitor. Examples of 2 and 3 colour combinations (diads and triads).

3. RESULTS AND DISCUSSION
We analyzed scaled colour harmony as a function of the CIECAM02 chroma, lightness, and hue differences and sums among the diad and triad colours. Inter-observer and intra-observer agreement was calculated by the aid of RMS (root mean squared value). The inter-observer RMS was 2,64, and the intra-observer RMS was 2,75.
Classical principles of choosing harmonious colours were investigated [1,2,3,7]. Classical harmony principles do not always result in a good visual harmony impression. Equal lightness had always negative harmony scores and the dataset of non-equal lightness had better results. For diads, complementary hue is the main principle of classical colour harmony theories but this caused negative visual harmony values. Colour pairs having “neighbouring hue” [3] had the maximum RMS value. The equal hue and equal chroma properties [3] caused the best colour harmony scores.

In case of triads, the equal hue property had high visual colour harmony scores. Triads of the equal lightness property had always negative values and the neighbouring hue principle generated high visual harmony scores.

3.1 Colour harmony formula for two colour combinations (diads)

The member colours of “monochrome” harmonies share the same hue. Experimental results showed that two different models should be used for “monochrome” harmonies and for “non-monochrome” ones. Diads of monochrome harmonies harmonized very well if the lightness of the 2 samples was different. By increasing the chroma difference between the two colours, the visual colour harmony impression decreased, see Figure 2.

Based on Figure 2, the following formulae were constructed to predict colour harmony for monochrome two colour combinations:

\[
CHF_{2M} = 0.283 \cdot \left(3.275CHF_{2M., LDL} - 0.643CHF_{2M., LSUM} + 2.749CHF_{2M., Cdiff} + 4.773CHF_{2M., HP}\right) - 5.305
\]

(1)

\[
CHF_{2M., LDL} = 2.33 \cdot 10^{-5} |\Delta J|^3 - 0.004 |\Delta J|^2 + 0.211 |\Delta J| + 0.246
\]

(2)

\[
CHF_{2M., LSUM} = -9.6 \cdot 10^{-6} (J_{SUM})^3 + 2.424 \cdot 10^{-3} (J_{SUM})^2 - 0.1653 J_{SUM} + 4.7187
\]

(3)

\[
CHF_{2M., Cdiff} = 3.87 - 0.066 |\Delta C|
\]

(4)

\[
CHF_{2M., HP} = 0.361 \sin(1.511h) + 2.512
\]

(5)

where $|\Delta J|$ 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 symbol $HP$ indicates hue preference, and $h$ is the hue of the diad.

For “non-monochrome” diads, hue difference is also an important factor in predicting the visual colour harmony impression, see Figure 3.
**Figure 3:** Predicting perceived colour harmony for non-monochrome (“dichromatic”) diads as a function of a) CIECAM02 absolute lightness difference, b) absolute chroma difference, c) hue difference (visual colour harmony score is mean of 9 observer’s 2 repetitions)

Based on Figure 3, the following formulae were constructed to predict visual colour harmony for “non-monochrome” diads:

\[
CHF_{2D} = 0.47 \left( 0.515 CHF_{2D, Jdiff} + 0.391 CHF_{2D, Csum} + 0.205 CHF_{2D, Cdiff} + 1.736 CHF_{2D, Lsum} + 2.187 CHF_{2D, Ldiff} + 5.104 CHF_{2D, HP} \right) - 2.283
\]  

\[
CHF_{2D, Jdiff} = 2.5 \times 10^{-3} |\Delta J|^3 + 3 \times 10^{-3} |\Delta J|^2 - 2.2 \times 10^{-2} |\Delta J| + 0.158
\]  

\[
CHF_{2D, Csum} = 10^{-3} (J_{sum})^2 - 0.119 J_{sum} + 0.939
\]  

\[
CHF_{2D, Cdiff} = -0.053 |\Delta C| + 1.172
\]  

\[
CHF_{2D, Lsum} = -0.051 C_{sum} + 2.836
\]  

\[
CHF_{2D, Ldiff} = 8 \times 10^{-5} (|h_1 - h_2|^2 - 0.0279 |h_1 - h_2|) + 2.3428
\]  

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

where $|\Delta J|$ is the absolute value of lightness difference between the two colours, $J_{sum}$ is lightness sum of the samples $|\Delta C|$ is the absolute value of chroma difference, $C_{sum}$ is the sum of chroma, $|h_1 - h_2|$ is the absolute value of the hue difference, the symbol $HP$ indicates hue preference, and $h_1$ and $h_2$ are the CIECAM02 hue angles of the two colours of the diad.

**Figure 4:** Correlation of predicted harmony and visual harmony: a) monochrome two-colour harmony - CHF$_{2M}$ (Eq. (1)), b) non-monochrome (dichromatic) two-colour harmony - CHF$_{2D}$ (Eq. (6)).
The correlation between \( \text{CHF}_{2M} \) (Eq. (1)) and \( \text{CHF}_{2D} \) (Eq. (6)) and the mean visual colour harmony scores is depicted in Figure 4.

3.2. Colour Harmony Rendering Index

Colour harmony is subject to changes when the light source illuminating the colour samples changes from a reference light source to a test light source. Distortion of Colour harmony can be observed if there are very different and non-systematic colour shifts - concerning both magnitudes and directions - among the samples in the CIECAM02 colour space[8]. Similar to the concept of colour rendering[9], we suggest to calculate the CHF differences of a set of test colour sample combinations - between the test light source and the reference light source. These differences will characterize the "colour harmony rendering" property of the test light source by quantifying the extent of distortion of the perceived harmony of a set of test colour combinations that are harmonious under the reference illuminant. A "harmony rendering index" (HRI) can be calculated e.g. by the following formula:

\[
HRI = 100 - k \times \sum_{i=1}^{n} \left| \text{CHF}_{\text{ref},i} - \text{CHF}_{\text{test},i} \right|
\]  

(13)

where \( \text{CHF}_{\text{ref},i} \) is calculated under the reference light source, \( \text{CHF}_{\text{test},i} \) under the test light source, \( n \) indicates the number of test colour sample combinations (harmonious under the reference light source) used to compute \( HRI \), and \( k \) is a constant. Both \( \text{CHF}_{2M} \) (Eq. (1)) and \( \text{CHF}_{2D} \) (Eq. (6)) can be substituted in Eq. (13) depending on the set of test colour combinations to be described in a future publication.

REFERENCES


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