Dimensions of light source colour quality

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Abstract

For the lighting industry, it is important to optimize the colour quality of the lit visual environment by improving the spectral power distributions of novel light sources. In the present work, two colourful still lifes (so-called tabletop arrangements) were built from several real objects. Visual experiments were carried out to scale the different aspects (dimensions) of colour quality (fidelity, harmony, acceptability, visual clarity, brightness and preference) under incandescent, fluorescent as well as RGB LED and white phosphor LED lamps. The visual ranking among these light sources depended on the particular dimension of colour quality. Generally, the incandescent lamp obtained the best ratings. But in the first still life, the colour harmony ratings of the white LED lamp and the colour gamut ratings of the RGB LED lamp exceeded the incandescent lamp's ratings. In the second still life, the brightness ratings of the fluorescent lamp and the harmony ratings of the white retrofit LED lamp exceeded the incandescent lamp's ratings. To optimize a novel lamp for a given application, the most important dimension of that application can be considered.

Introduction

The concept of light source colour quality includes different aspects of the observer's general evaluation about the colour perception of the objects in a visual environment (e.g. an office or a living room) lit by the light source. In literature, several such aspects (dimensions) of colour quality were identified [1, 2]. Some of these aspects may consist of more constituent dimensions (e.g. visual clarity, see below). The most widely known dimension is *colour fidelity* (also called colour rendering) i.e. the conscious or subconscious comparison of the colour appearance of the objects with their appearance under a reference illuminant [3]. Some visual tasks require easy *colour discrimination* among adjacent colours. "*Visual clarity*" can be related to the general brightness sensation of the environment, to the perception of large colour differences among the objects ("feeling of contrast") and also to the perception of fine colour shadings (i.e. noticeable local contrasts). *Colour preference* is a dimension which seems to have three sub-dimensions related to the aesthetic judgement about the vividness, choice and naturalness of all objects - considering each object separately [4]. *Colour harmony* expresses an *aesthetic* judgement about the *relationship* among the colours of (selected) objects in the scene. *Colour acceptability* is the aspect of colour quality related to making a judgement about the whole scene - whether the colour distributions (colour histograms of the fine colour shadings) of the objects are congruent with their shape and texture as recalled from long-term visual memory [5, 6]. However, no publication was found about a comprehensive visual assessment of all of the above dimensions and their relationship to measured colour distributions and existing colour quality metrics. Uniform standalone colour patches cannot be used to assess visual clarity, colour harmony or colour acceptability. Instead of standalone colour patches, a complex colourful arrangement of objects (a still life or so-called tabletop) is used in the present work.

For the optimal design of modern light sources, it is important to devise appropriate mathematical formulae to describe the above dimensions of colour quality from the colour measurement of the visual environment. Guo and Houser [7] compared following colour quality indices for several light sources computationally: the CIE colour rendering index (R_a), Judd's "flattery" index (R_f), Thornton's colour preference index (CPI), Thornton's colour discrimination index (CDI), Xu's colour rendering capacity (CRC), Fotios's cone surface area (CSA) and Pointer's colour rendering index (R_P). Significant correlations were found between R_a and R_f, CPI, CRC, R_P; R_f and CPI, CRC, R_P; CPI and CDI, CRC, R_P; CDI and CRC, CSA, R_P; CRC and CSA, R_P as well as CSA and R_P. A factor analysis showed two components, a colour gamut (area or volume) based component (explaining CSA, CRC and R_P) and a reference light source based component (explaining R_a, R_P, R_f and CPI). Szabó et al. [8] compared their new colour harmony rendering index R_{hr} with R_a and the colour quality scale CQS [9] for several light sources computationally. R_a correlated well with CQS but there was a negative correlation between R_a (and CQS) and R_{hr}. Recently, CIECAM02 based uniform colour spaces (UCSs) were published [10] and a so-called CAM02-UCS colour rendering index was defined [11]. Another recent method uses the same UCS to define an ordinal rating scale based colour rendering index (RCRI) [12] derived from the predicted number of excellent and good ratings of a set of test colours. In the RCRI formula, it is possible to change the weightings of "excellent" and "good" colour rendering (e.g. it may be possible that only the number of "excellently" rendered test colours is important) and also, to change the weightings of the individual test colours (e.g. it may be possible that "reddish orange" is more important than "bluish green" for colour rendering). However, these weightings have not been optimized in the RCRI formula.

Guo and Houser's [7] two components were corroborated by Rea and Freyssinier-Nova [13] who stated that a gamut area based index together with R_a were suitable to predict visual judgements about colour discrimination, vividness and fidelity. In accordance with this finding, Hashimoto et al. [14] proposed a gamut area based index together with R_a to describe *visual clarity*. Combined fidelity-preference indices were also introduced, e.g. the above mentioned CQS and Schanda's [15] combined preference–rendering index. The attractiveness, naturalness and suitability of fruit and vegetable colours were assessed by Jost-Boissard et al. [16]. R_a did not correlate well with the subjective judgments but attractiveness correlated well with a gamut area index [13]. However, colour discrimination ability correlated well with R_a [17]. *Acceptability* studies were also carried out [6] but the mathematical modelling of acceptability is unsolved because a combination of an image colour appearance model, a comprehensive model of colour constancy and an image colour difference model is needed [5]. Indeed - although in conventional models, surfaces are considered homogenous – real surfaces exhibit *textures* with large within-surface chromatic variations affecting chromatic induction and colour discrimination hence all dimensions of light source colour quality.

Typical objects (e.g. flowers, fruits, vegetables or toys) have typical colour distributions in a colour appearance space [5]. In the present paper, it will be shown that there are characteristic changes in these colour distributions if a different light source illuminates the same objects, e.g. a high colour rendering white LED lamp instead of a poor colour rendering RGB LED lamp. In the present study, two so-called still lifes (or tabletop arrangements) were constructed from colourful real objects. These two still lifes were illuminated by light sources of different spectral power distributions at the same correlated colour temperature. The still lifes were measured by an imaging colorimeter under each light source. Subjects were asked to scale the different dimensions of the colour quality of the still lifes. Light source related changes of the measured colour distributions of the first still life in CIECAM02 colour space are evaluated. Answers of the subjects about the still lifes on different colour quality scales are presented. The relationship among these scales is analyzed.

Method

Two still lifes (or tabletop arrangements) were constructed in a viewing booth illuminated diffusely with five (in the first still life, SL1) or three (in the second still life, SL2) light sources. Each light source had a correlated colour temperature of about 2900K (SL1) and 2600K (SL2). Only one light source was on at a time. The five light sources (SL1) included a tungsten halogen lamp (TUN, reference light source), a fluorescent lamp (FL), a high colour rendering white LED lamp (HC3L), a low colour rendering white LED lamp (C3L), and an RGB LED lamp (RGB). The three light sources (SL2) included a tungsten halogen lamp (TUN, reference), a compact fluorescent lamp (CFL) and a white phosphor retrofit LED lamp (LED). Figure 1 shows SL1 under two light sources, HC3L and RGB; as well as SL2 under TUN. The colour distributions of the two still lifes were measured under every light source by an imaging colorimeter of high spatial resolution. Both still lifes included a white standard to transform the measured tristimulus values (XYZ) to CIECAM02. The luminance of the white standard was 230 cd/m^2 (SL1) and 110 cd/m^2 (SL2), respectively.

Figure 1. *Still life (1st arrangement, SL1) under the high colour rendering white LED lamp (HC3L, left) and under the RGB LED lamp (RGB, middle). The distribution of colours in CIECAM02 colour space was analyzed within the black frame (middle, see also Fig. 3). Right: 2nd still life (SL2)*

In both still life experiments, following questions were asked about colour quality:

1. Fidelity (F): Are the colours under the test light source similar to the colours under the reference light source (TUN)?
2. Harmony (H): Is the relationship among the colours aesthetic (harmonious)?
3. Acceptability (A): Does the colour distribution of each object agree with the shape and texture of that object (according to the observer's long-term visual memory of that object)?
4. Visual clarity 1 (V1): About local colour contrasts: are there well-perceptible continuous colour transitions and shadings within the objects?
5. Visual clarity 2 (V2): Are there large colour differences among the different colour categories in the image, is the colour gamut large?
6. Brightness (B): Is the still life (generally) bright?
7. For the 2nd still life, there was a further question concerning the general preference judgement (P) of all object colours by considering each object separately.

Observers had to indicate their answer on an open continuous scale. For the reference light source, the value of the scale was fixed at 100 for all questions. Observers had to evaluate the still life under every light source separately. By request, they could return to every light source unlimited times. Observers were not aware of the type of the light source (they were denoted by numbers in the experiment). The light source itself was hidden. Four observers of normal colour vision took part in the observations of the 1st still life and five observers of normal colour vision took part in the observations of the 2nd still life.

Results and Discussion

Typical objects have typical colour distributions ("colour signatures") in the CIECAM02 a_C-b_C diagram. The change of the colour distribution of the still life by changing the light source from the white LED lamp (HC3L) to the RGB LED lamp (RGB) of SL1 is shown in Figure 3 by the example of 12 selected objects. The mean CIECAM02 J, a_C, b_C values were computed for some characteristic parts of these 12 objects, see Figures 2 and 3.

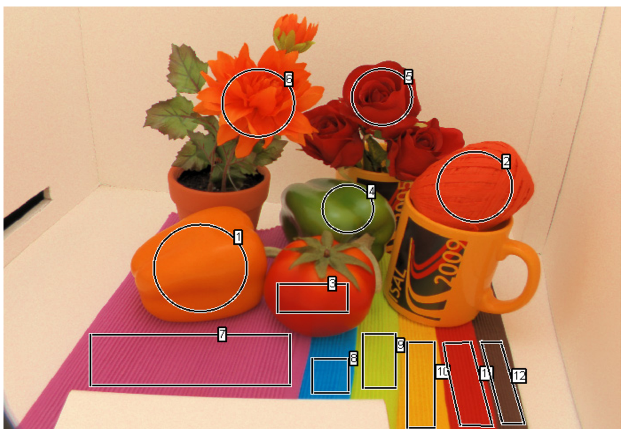

Figure 2. *Parts of the 12 objects of the 1st still life (SL1) for which the mean XYZ and CIECAM02 J, a_C, b_C values were computed. For each object, the pixels within the indicated regions (rectangles or circles) were considered to compute the mean values.*

In Figure 3, the high-resolution image of the imaging colorimeter was sampled randomly and only the colour distributions of 2 x 5000 pixels are shown (5000 colours for RGB and 5000 colours for HC3L).

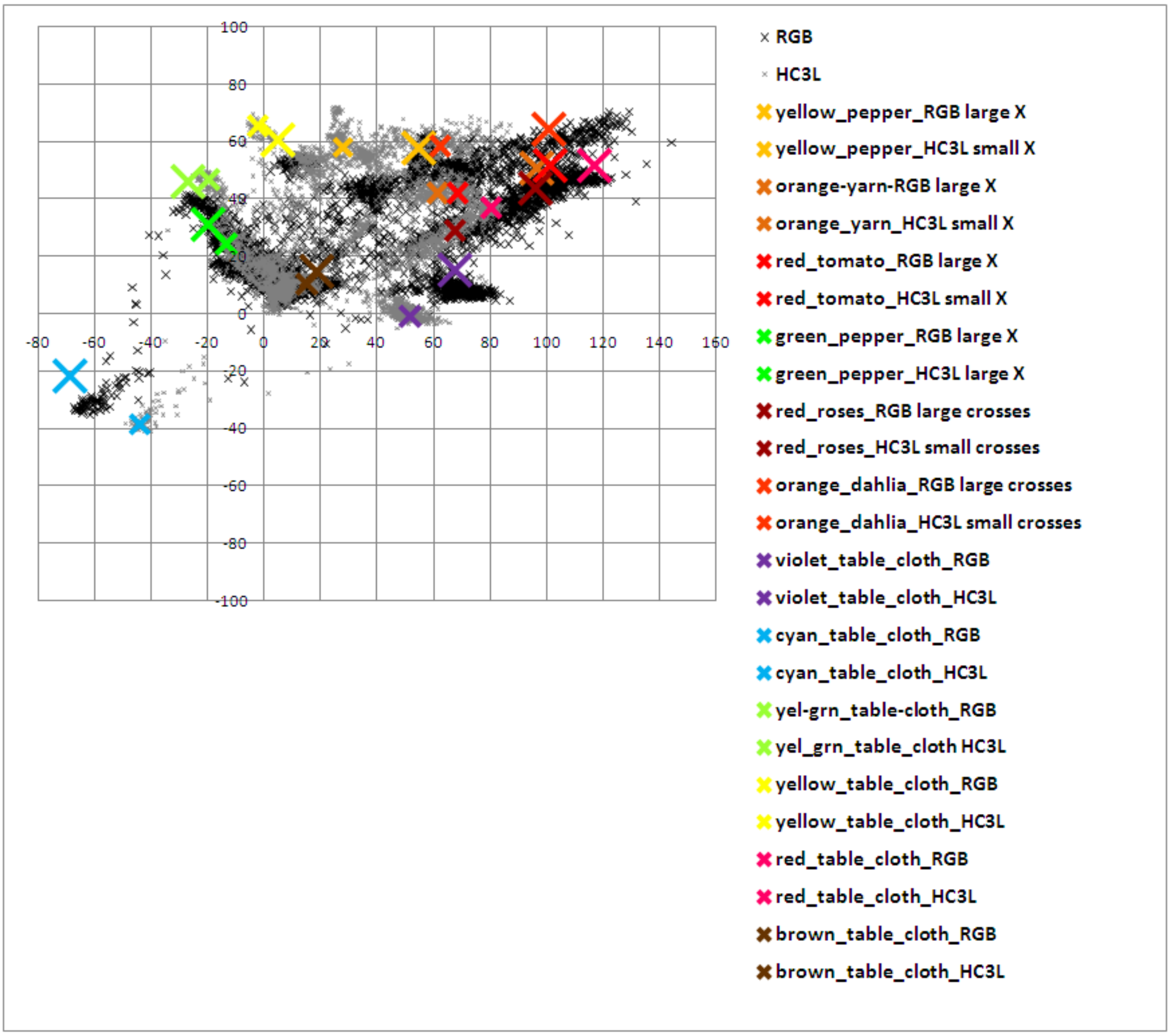

Figure 3. *Colour distributions ("colour signatures") of the objects in the CIECAM02 a_C-b_C diagram, illuminated by HC3L (small grey crosses) and by RGB (large black crosses) of the 1st still life (SL1). Small (large) coloured crosses show the mean a_C-b_C values of these objects under HC3L (RGB)*

As can be seen from the CIECAM02 a_C-b_C diagram of Figure 3, if the light sources change then the colour distributions of the objects also change. The colour distribution (i.e. the sum of the colour signatures of the textures of the objects [5]) under RGB LED is distorted compared to HC3L. This makes the four "colour constancy related" dimensions (F, H, A, V1) break down in the 1st still life experiment for RGB compared to HC3L, see Figure 4 where the mean visual scale values and their 95% confidence intervals are shown for four observers. However, note that RGB brightness (B) and RGB gamut (V2) are improved compared to HC3L.

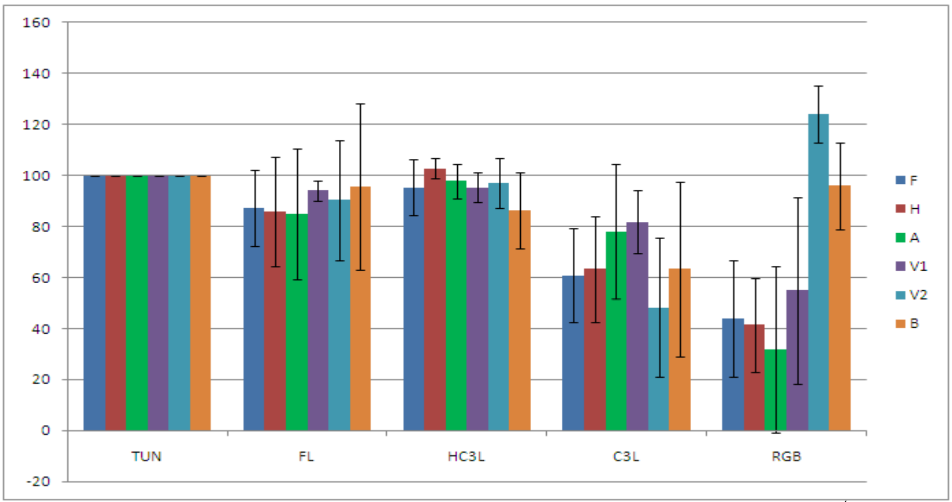

Figure 4. *Mean visual scale values and their 95% confidence intervals of the four observers of the 1st still life experiment. Colour quality scales F, H, A, V1, V2 and B (see Method)*

As can be seen from Figure 4, the reference value of 100 (TUN) is exceeded only by the mean colour harmony rating of HC3L and the mean colour gamut rating of RGB. Generally, RGB obtained the least mean visual scales except for gamut and brightness. The mean values of the visual colour quality ratings of a given light source depend on the particular dimension of colour quality - especially for C3L and RGB. Note that the incandescent lamp (TUN) was forced to obtain 100 as a reference lamp. Correlations among the different dimensions are shown in Figure 5. Figure 5 shows the mean visual scale values minus 100, for H, A, V1, V2 and B, as functions of (F-100). Trend lines are 3rd order polynomials.

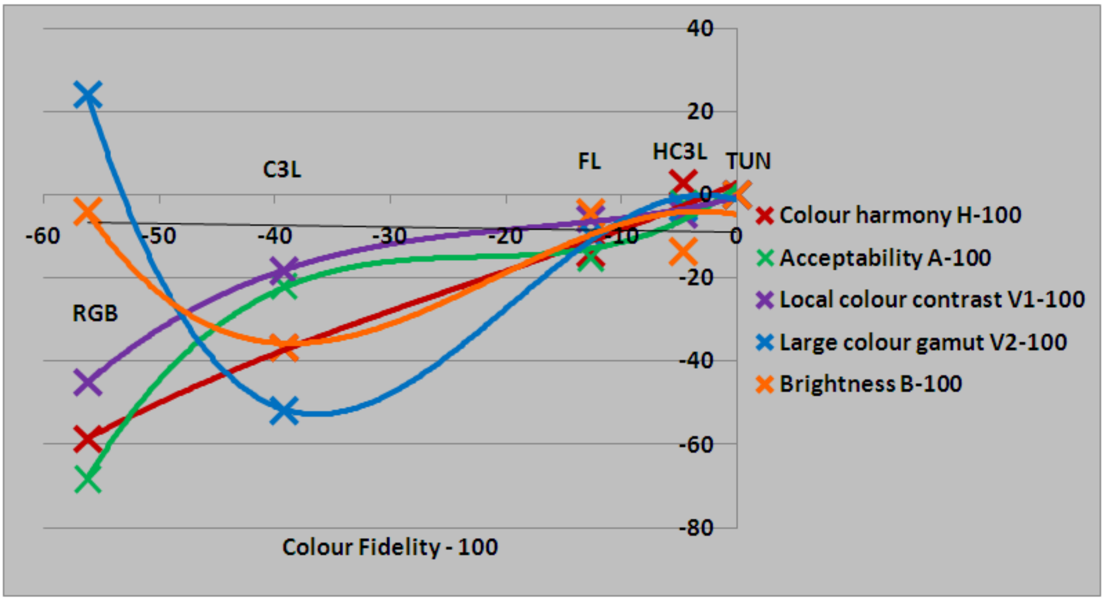

Figure 5. *Mean visual scale values minus 100, for H, A, V1, V2 and B (ordinate), as functions of F-100 (abscissa)*

As can be seen from Figure 5, harmony (H), acceptability (A), and local colour contrast (V1) exhibit significant positive correlations with fidelity ($r^2_{H,F}$=0.98; $r^2_{A,F}$=0.86; $r^2_{V1,F}$=0.91), and also among each other: $r^2_{H,A}$=0.90; $r^2_{H,V1}$=0.92; $r^2_{A,V1}$=0.97. Latter value ($r^2_{A,V1}$=0.97) indicates that the presence of well perceptible fine colour shadings (V1) increases acceptability (A). As can be seen from Figure 5, fidelity (F) does not correlate with gamut ($r^2_{V2,F}$=0,00) or with brightness ($r^2_{B,F}$=0,10). However, there is significant positive correlation between gamut (V2) and brightness (B): $r^2_{V2,B}$ =0.73; possibly because if the colour gamut is large then there are bright and saturated colours in the scene (saturated colours cause a more intensive Helmholtz-Kohlrausch effect). To explore the above correlations more in detail, further experiments with more observers are currently underway by using the 2nd still life.

Figure 6 summarizes the current result of the visual assessment of the 2nd still life by five observers. The visual ratings were re-scaled to range between 1 and 3 in the following way. The ratings of the three light sources were compared. The light source of the best rating was assigned the value of 3, the light source of medium rating was assigned 2, and finally, the light source of worst rating was assigned 1. Finally, the averages of the five observers were calculated.

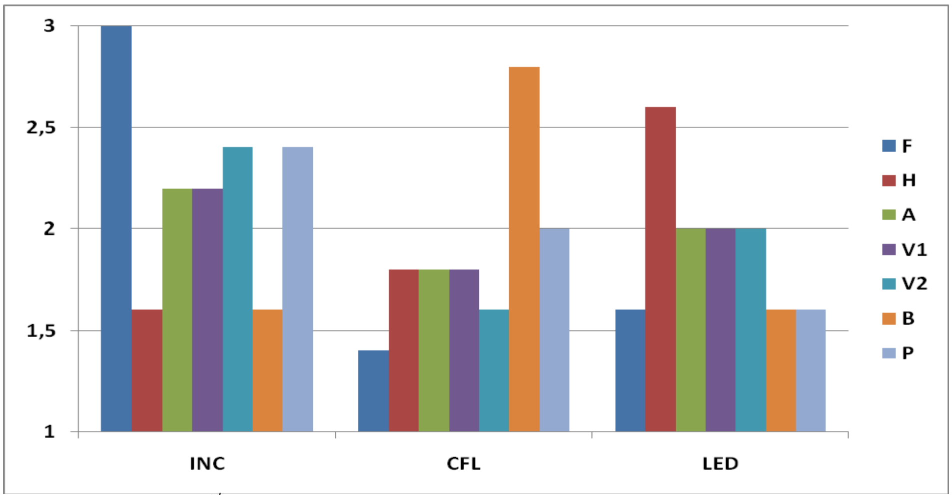

Figure 6. *Result of the 2nd still life experiment. Visual scales were re-scaled to range between 1 (worst) and 3 (best, see text). F: fidelity; H: harmony; A: acceptability; V1: local colour contrast; V2: colour gamut; B: brightness, P: preference of object colour. INC: incandescent lamp; CFL: compact fluorescent lamp; LED: white retrofit phosphor LED lamp*

As can be seen from Figure 6, similar to the 1st still life (SL1) results, mean visual colour quality ratings of a given light source depend on the particular dimension of colour quality. The tungsten halogen reference light source (TUN) obtained the best acceptability (A), local colour contrast (V1), colour gamut (V2) and preference (P) ratings. Fidelity was rated in relation to the incandescent reference (INC). This means that the fidelity dimension of CFL or LED could only be worse or equal to INC. In this respect, LED obtained higher fidelity ratings than CFL but both of them obtained a lower fidelity rating than INC. However, CFL had the best brightness ratings and the white LED had the best harmony (H) ratings. Statistical significance will be analyzed in a subsequent paper after including the results of additional observers.

Conclusions

For the lighting industry, it is important to improve the colour quality of the visual environment by optimizing the spectral power distributions of novel light sources. Colour quality has several visual dimensions. However, in current lighting practice, only colour rendering (i.e. colour fidelity) is evaluated. The present paper showed the importance of quantifying every dimension of colour quality separately. Every dimension needs a separate colour quality index. The user of the light source may apply the most appropriate index for a given application. Two still life experiments with real colourful objects were carried out to scale the different dimensions of colour quality (fidelity, harmony, acceptability, visual clarity, brightness and preference). The ranking among the light sources was found to depend on the particular dimension (aspect) of colour quality which was rated visually.

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