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Towards a user preference model for interior lighting. Part 2: Experimental results and modelling

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Subjects assessed their visual impressions about scene brightness, visual clarity, colour preference and scene preference in a real room in which the horizontal illuminance, the correlated colour temperature and the level of chroma enhancement of the light source were changed systematically. The aim of the experiment is to contribute to the development of a user preference model. The concept of this model and the experimental method were described in Part 1 of this work. In Part 2, modelling equations of these four visual attributes and their validation are shown. Criterion illuminance levels for 'good' levels of the visual attributes were determined depending on correlated colour temperature.

1. Introduction

Subjects assessed their visual impressions about scene brightness, visual clarity (VC), colour preference (CP) and scene preference (SP) in a real room in which the horizontal illuminance, the correlated colour temperature (CCT) and the level of chroma enhancement of the light source were changed systematically. The aim of the experiment was to contribute to the development of a user preference model. The concept of this model and the experimental method were described in Part 1 of this work.[1] In the present Part 2, the results of this experiment are discussed and modelling equations of these four visual attributes and their validation are shown. Criterion illuminances for 'good' levels of these four visual attributes are also shown, depending on CCT.

2. Results and discussion

2.1. Main experiment

The dataset resulting from the main experiment[1] consisted of 4 (attributes) × 36 (light source spectra, see Table 1 in Khanh *et al.*[1]) × 30 (subjects) = 4320 interval scale numbers. First, the outliers (those data lying outside the whiskers defined by 1.5 times the interquartile range of the boxplot diagram of a given attribute and a given spectrum) were removed; 4%, 5%, 2% and 2% of the data were outliers in case of brightness, VC, CP and SP, respectively. The dataset without outliers will be analysed in this paper. The effect of the variables horizontal illuminance (E_v), CCT and saturation (ΔC^*) on every one of the four scaled attributes (brightness, VC, CP and SP) and their interactions were investigated in four analyses of variance

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Table 1 Statistical significance (p; F-tests) of the effect of the independent variables E_v, CCT and ΔC^* (see Table 1 in Khanh et al.[1]) on the four scaled attributes (brightness, visual clarity, colour preference and scene preference) and their interactions

Variable	CCT	ΔC^*	E_v	CCT×ΔC^*	CCT×E_v	ΔC^*×E_v	CCT×ΔC^*×E_v
Brightness	0.000	0.592	0.000	0.497	0.000	0.001	0.001
Visual clarity	0.000	0.000	0.000	0.002	0.029	0.024	0.002
Colour preference	0.000	0.000	0.000	0.000	0.005	0.009	0.037
Scene preference	0.000	0.000	0.000	0.009	0.076	0.000	0.001

CCT: correlated colour temperature.

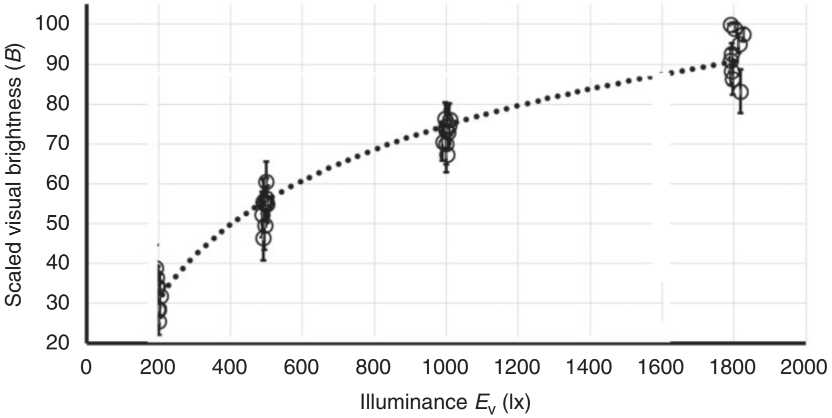

Figure 1 Mean scaled brightness (B) as a function of illuminance E_v for the 36 light source spectra (see Table 1 in Khanh et al.[1]). Intervals are 95% confidence intervals. dotted curve: logarithmic fit with equation (1) ($r^2 = 0.96$)

(ANOVA). Table 1 shows the significance of these effects (F-tests). As can be seen from Table 1, the main effect of the independent variables E_v, CCT and ΔC^* on all attributes is significant at the 5% level except for the effect of saturation level ΔC^* on brightness.

2.1.1. Modelling brightness

The dependence of visually scaled brightness on illuminance is shown in Figure 1.

As can be seen from Figure 1, the logarithmic fit curve of equation (1) ($r^2 = 0.96$; Pearson's correlation coefficients squared) describes the mean tendency with an accuracy of about ±10 visual brightness units

$$B = 27.1945 \ln(E_v) - 113.231 \qquad (1)$$

The error measure E (defined by the square root of the sum of the squared differences between the fit curve and the mean experimental data for every experimental condition) equalled 27.5 in case of equation (1). Involving CCT and ΔC^* related terms in the model produced no improvement. In the next step, we replaced the value of illuminance by the value of equivalent illuminance computed by the Fotios and Levermore SWS lumens model,[2] see equation (2)

$$E_{v,eq} = E_v (S/V)^{0.24} \qquad (2)$$

The concept of the SWS lumens model[2] is that the value of illuminance should be modified because illuminance alone is not enough to predict the impression of brightness. According to equation (2), this modification is incorporated in the $(S/V)^{0.24}$ term representing the relative signal of the short-wavelength sensitive human photoreceptors. The symbol S in equation (2) represents the signal of the short-wavelength sensitive human photoreceptors obtained by weighting the relative spectral power distribution of the light source with the spectral sensitivity of the S-cones and integrating over the visible wavelength range. The quantity V is obtained by weighting the relative spectral power distribution of the light source with the $V(\lambda)$ function and integrating over the visible wavelength range.

An alternative, more comprehensive model[3] computes a weighted sum (the weighting depends on illuminance level) of the $V(\lambda)$ function, the $S(\lambda)$ function (spectral sensitivity of the S-cones) and the spectral sensitivity function of the intrinsically photosensitive retinal ganglion cells (ipRGCs) to obtain the so-called $B_2(\lambda)$ function. We weighted every one of the 36 spectra of the main experiment and every one of the 25 spectra of the validation experiment by the $B_2(\lambda)$ function (at the appropriate illuminance level) and integrated in the visible spectral range. Then, we compared these resulting B_2-integral values with the corresponding $E_{v,eq}$ values (equation (2)) for every spectrum. We obtained for the 36 spectra of the main experiment $r^2 = 0.98$ and for the 25 spectra of the validation experiment $r^2 = 0.96$, i.e. excellent positive correlation.

The quantity $(S/V)^{0.24}$ can be predicted (at least in case of the present 36 spectra) from CCT (in K) by equation (3) with $r^2 = 0.99$. The prediction of equation (3) can be applied in practice if the value of $(S/V)^{0.24}$ is not available but the value of CCT is known

$$(S/V)^{0.24} = -0.0138(\mathrm{CCT}/1000)^2 + 0.1769(\mathrm{CCT}/1000) + 0.2859 \quad (3)$$

The logarithmic fit curve of equation (4) with $E_{v,eq}$ ($r^2 = 0.97$) describes the mean tendency with less scatter (see Figure 2) than equation (1) (Figure 1) in the vicinity of the highest investigated illuminance. The error measure E equalled 25.3 in the case of equation (4)

$$B = 27.058 \ln\left(E_{v,eq}\right) - 105.25 \quad (4)$$

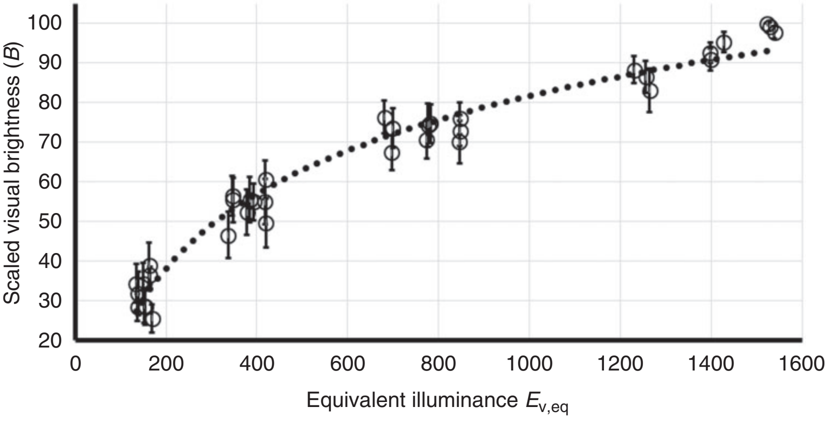

Figure 2 Mean visually scaled brightness (B) as a function of equivalent illuminance $E_{v,eq}$ for the 36 light source spectra (see Table 1 in Khanh et al.[1]). Intervals are 95% confidence intervals. Dot curve: logarithmic fit of equation (4) with $r^2 = 0.97$

2.1.2. Modelling VC

The mean VC values could be predicted by the value of the illuminance E_{v} according to equation (5) with $r^2 = 0.82$ (see Figure 3, upper) and the error measure value of $E = 46.5$

$$\mathrm{VC} = 19.804 \ln(E_{\mathrm{v}}) - 60.496 \qquad (5)$$

To reduce the fitting error of equation (5), we modelled VC with the aid of equivalent illuminance (equation (2)) with equation (6) in the next step

$$\mathrm{VC} = 19.877 \ln\left(E_{\mathrm{v,eq}}\right) - 55.75 \qquad (6)$$

Equation (6) resulted in $r^2 = 0.84$ and $E = 43.9$. In the last (third) step of modelling, we modified equation (6) by a ΔC^* (i.e. object saturation) dependent term (see equation (7)) and this resulted in $r^2 = 0.92$ and $E = 30.5$. This improved fit is depicted in Figure 3(lower). Equation (7) was set up to be valid for positive or zero ΔC^* values ($\Delta C^* \geq 0$) only. The reason is that negative ΔC^* values are not relevant for practice because de-saturated object colours are not preferred. The ΔC^* term of equation (7)

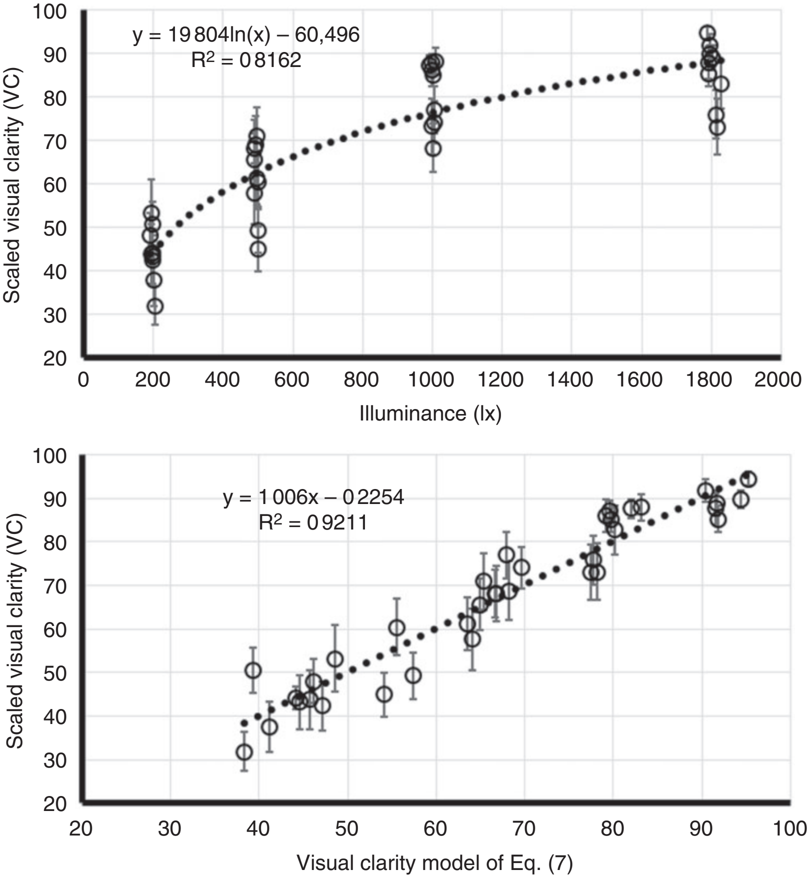

Figure 3 Mean visually scaled visual clarity (VC) as a function of illuminance (upper) and the model equation of equation (7) (lower) for the 36 light source spectra (see Table 1 in Khanh et al.[1]). Intervals are 95% confidence intervals

decreases with increasing object saturation. The reason is that the oversaturation of the object colours tends to destroy the rendering of fine colour shadings on their surfaces[4] if these surfaces are illuminated by a highly oversaturating light source (e.g. with $\Delta C^* = 11$). In this case, the colour discrimination capability (between adjacent colours of a surface structure) is reduced[5] and VC diminishes. Adding further terms to equation (7) did not improve its performance

$$\mathrm{VC} = \left[19.804\ln\left(E_{\mathrm{v,eq}}\right) - 60.496\right] \cdot \left[-0.0004\Delta C^{*2} - 0.011\Delta C^* + 1.0708\right] \tag{7}$$

2.1.3. *Modelling CP*

We repeated the above modelling procedure of VC (equations (5) to (7)) for the CP dataset. Equations (8) to (10) show the results

$$\mathrm{CP} = 13.578\ln(E_{\mathrm{v}}) - 25.782$$
$$(\text{with } r^2 = 0.59 \text{ and } E = 55.8\text{; see Figure 4, upper}) \tag{8}$$

$$\mathrm{CP} = 14.089\ln\left(E_{\mathrm{v,eq}}\right) - 25.397 \quad (\text{with } r^2 = 0.65 \text{ and } E = 51.9) \tag{9}$$

$$\mathrm{CP} = \left(14.089\ln\left(E_{\mathrm{v,eq}}\right) - 25.397\right) \cdot \left[-0.003\Delta C^{*2} + 0.0252\Delta C^* + 1.0192\right] \quad (\text{with } r^2 = 0.74 \text{ and } E = 44.9) \tag{10}$$

The ΔC^* dependent term in the square brackets of equation (10) has a maximum at $\Delta C^* = 4.2$. This tendency is somewhat similar to a previously obtained tendency.[6] But in the previous study,[6] less saturation (about $\Delta C^* = 1$) was required for warm white to achieve optimum CP. The mean visually scaled CP is depicted as a function of the model equation of equation (10) in Figure 4(lower).

As can be seen from Figure 4, the model of equation (10) did not perform well in case of some light sources. In Figure 4, two conspicuous points are marked. Both of them were warm white (3000 K) spectra at a high oversaturation level ($\Delta C^* > 11$). This causes less CP than predicted by equation (10) according to the above mentioned previous finding.[6] To account for this, we added a $(S/V)^{0.24}$ dependent correction term to equation (10), see equation (11). This correction term has negative values for warm white light sources. The mean visually scaled CP is depicted as a function of the model equation of equation (11) in Figure 5

$$\mathrm{CP} = \left(14.089\ln\left(E_{\mathrm{v,eq}}\right) - 25.397\right) \cdot \left[-0.003\Delta C*^2 + 0.0252\Delta C * +1.0192\right] + \left[-518.554((S/V)^{0.24})^2 + 864.872(S/V)^{0.24} - 356.578\right] \quad (\text{with } r^2 = 0.84 \text{ and } E = 35.1) \tag{11}$$

2.1.4. *Modelling SP*

The dependence of mean visually scaled SP on illuminance (lx) is depicted in Figure 6(left). To refine the model of the mean visual SP results, we carried out a similar analysis as in case of CP. The result is shown in equation (12) which has similar terms to equation (11), i.e. a chroma enhancement (ΔC^*) dependence and a dependence on the bluish content of the spectrum ($(S/V)^{0.24}$). In the case of equation (12), the ΔC^* dependent term ($-0.1325\,\Delta C^{*2} + 0.2797\,\Delta C^*$) is additive and not multiplicative as for equation (11). The latter term has its maximum at $\Delta C^* = 1.1$, i.e. for a relatively small level of object oversaturation

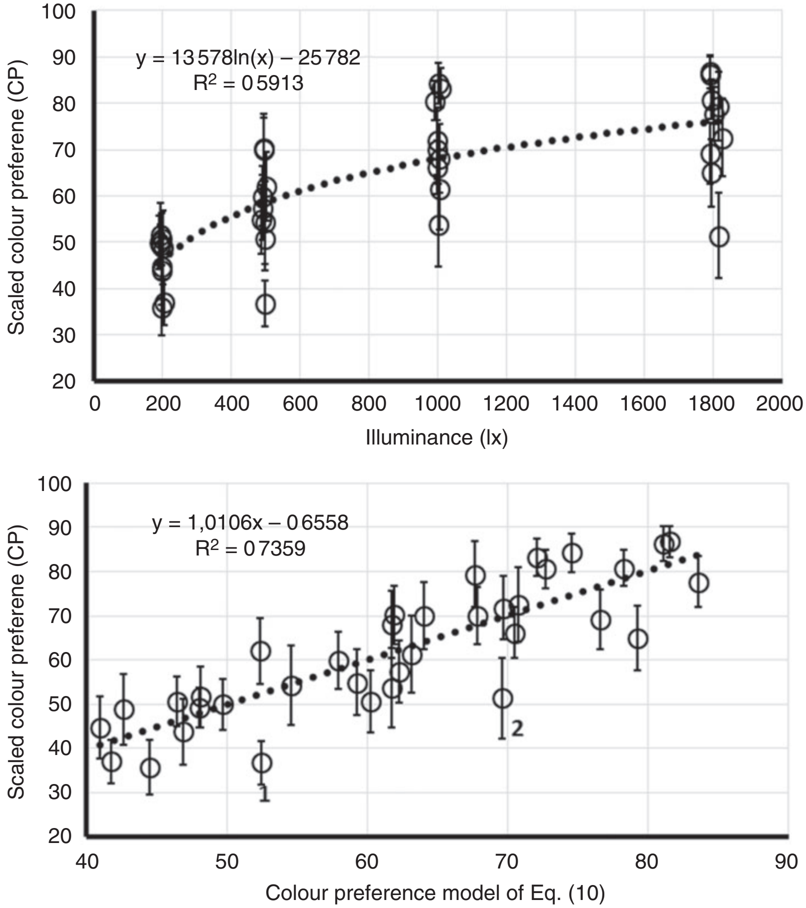

Figure 4 Mean visually scaled colour preference (CP) as a function of illuminance (upper) and the model equation of equation (10) (lower) for the 36 light source spectra (see Table 1 in Khanh et al.[1]). Intervals are 95% confidence intervals. Marked data points: 1–3000 K, 500 lx, $\Delta C^* = 11.3$; 2–3000 K, 1800 lx, $\Delta C^* = 11.2$

$$\begin{aligned} SP = {} & 17.127 \ln(E_{v,eq}) - 41.844 - 0.1325 \Delta C*^2 \\ & + 0.2797 \Delta C* + [-622.378((S/V)^{0.24})^2 \\ & + 980.843(S/V)^{0.24} - 382.535] \\ & (\text{with } r^2 = 0.89 \text{ and } E = 33.9) \end{aligned} \tag{12}$$

The mean visually scaled SP is depicted as a function of the model equation of equation (12) in Figure 6(right).

2.2. Validation experiment

The dataset of the validation experiment[1] consisted of 3 (attributes: brightness, VC and SP) × 25 (light source spectra, see Table 2 in Khanh *et al.*[1]) × 28 or 21 (subjects) = $2 \times 25 \times 28 + 1 \times 25 \times 21 = 1400 + 525 = 1925$ interval scale numbers. First, the outliers (those data lying outside the whiskers defined by 1.5 times the interquartile range of the boxplot diagram of a given attribute and a given spectrum) were removed; 2%, 3% and

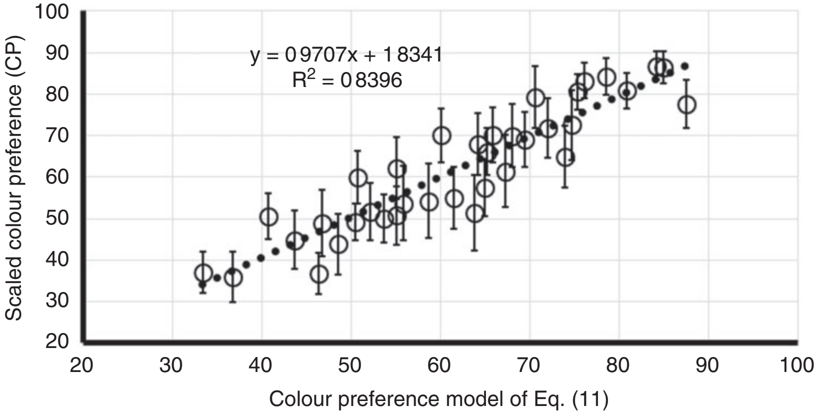

Figure 5 Mean visually scaled colour preference (CP) as a function of the model equation of equation (11) for the 36 light source spectra (see Table 1 in Khanh *et al.*[1]). Intervals are 95% confidence intervals

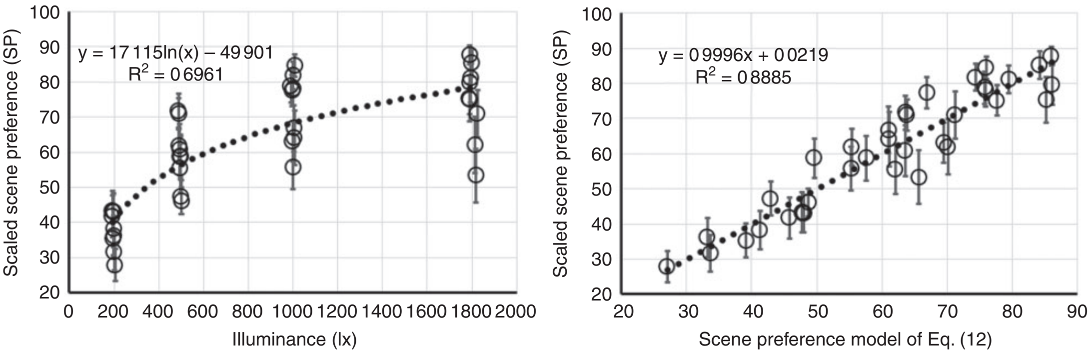

Figure 6 Mean visually scaled scene preference (SP) as a function of illuminance (left) and the model equation of equation 12 (right) for the 36 light source spectra (see Table 1 in Khanh *et al.*[1]). Intervals are 95% confidence intervals

Table 2 Pearson's correlation coefficients squared (r^2) among the mean dependent (i.e. visually scaled) variables in the validation experiment

Variables	B → VC	B → CP	B → SP	VC → CP	VC → SP	CP → SP
r^2	0.97	–	0.94	–	0.93	–

B: brightness; VC: visual clarity; CP: colour preference; SP: scene preference.

4% of the data were outliers in the case of brightness, VC and SP, respectively. In Figures 7–9, the mean visually scaled values of brightness, visual clarity and scene preference are depicted as a function of the predicting quantities B, VS and SP (resulting from the fit to the main experiment's results) of equations (4), (7) and (12), respectively.

As can be seen from Figures 7–9, the correlation between the predictor quantities resulting from the main experiment and the mean visually scaled values resulting from the validation experiment is high ($r^2 > 0.91$). In Figure 9, two light sources with significantly lower (confidence intervals do not overlap with the prediction line) observed mean SP values than the prediction are

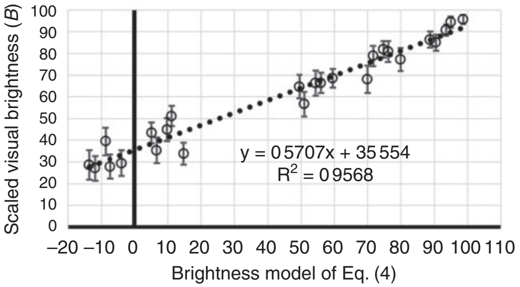

Figure 7 Mean visually scaled brightness (B) of the validation experiment as a function of the predicting quantity B (resulting from the fit to the main experiment's results) of equation (4). Intervals are 95% confidence intervals

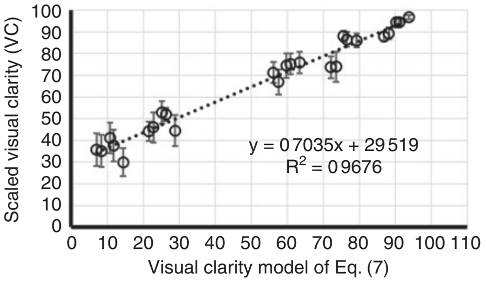

Figure 8 Mean visually scaled visual clarity (VC) of the validation experiment as a function of the predicting quantity VC (resulting from the fit to the main experiment's results) of equation (7). Intervals are 95% confidence intervals

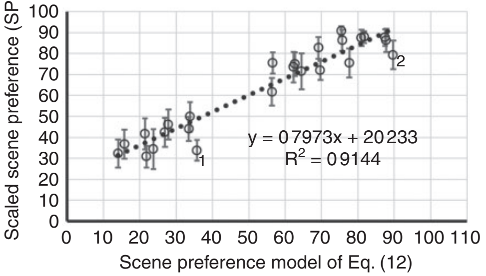

Figure 9 Mean visually scaled scene preference (SP) of the validation experiment as a function of the predicting quantity SP (resulting from the fit to the main experiment's results) of equation (12). Intervals are 95% confidence intervals. 1: 90 lx, 10 000 K; 2: 2000 lx, 10 000 K

marked. Both light sources have a CCT of 10,000 K. This means that such a high CCT (10,000 K) tends to reduce SP. As such a very cold white tone (10,000 K) is not applied in interior lighting practice, this effect was not included in the model equation.

2.3. Correlations among the variables

Tables 2 and 3 show the values of Pearson's correlation coefficients squared (r^2) among the mean dependent (visually scaled) variables in the two experiments. As can be seen from Table 2 (rows of the validation experiment), the correlation coefficients among the dependent variables are high ($r^2 > 0.93$) in the validation experiment in which there was only a little variation of object chroma enhancement ($0.0 \leq \Delta C^* \leq 1.4$).

Due to the influence of changing the chroma enhancement level (or oversaturation level) in a broad range ($0.0 \leq \Delta C^* \leq 12.2$) in the main experiment, here we obtained smaller correlation coefficient values (between 0.61 and 0.85, see Table 3). The lowest r^2 value ($r^2 = 0.61$) occurs in case of B and CP implying that these variables correspond to two (to some extent) independent factors. This finding motivated a subsequent factor analysis. In this factor analysis (with PCA, Varimax rotation and Kaiser normalisation), a CP-related factor (F_1) and a brightness-related factor (F_2) were identified (Figure 10).

As can be seen from Figure 10, both factors (F_1, CP and F_2, brightness) are needed in order to achieve good VC and good SP. Although VC and SP are close neighbours, they have somewhat different weights: we

Table 3 Pearson's correlation coefficients squared (r^2) among the mean dependent (i.e. visually scaled) variables in the main experiment

Variables	B → VC	B → CP	B → SP	VC → CP	VC → SP	CP → SP
r^2	0.80	0.61	0.68	0.78	0.85	0.72

B: brightness; VC: visual clarity, CP: colour preference; SP: scene preference.

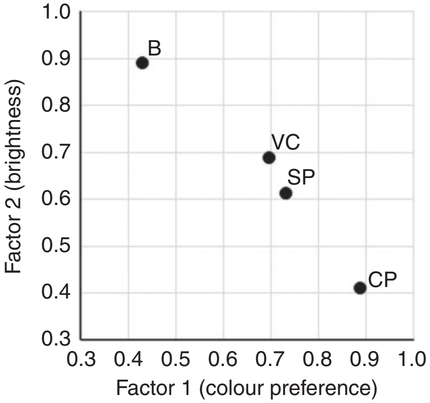

Figure 10 Weights of the variables brightness (B), visual clarity (VC), colour preference (CP) and scene preference (SP) in the diagram of the two factors, colour preference and brightness

need somewhat less brightness (F_2) and more CP (F_1) for SP than for VC, possibly because F_2 is associated with concentrated work while F_1 is related to affective appraisal of the environment and we need a balance between these two aspects to achieve optimum SP. VC should not be the primary optimisation target of the user preference model: it should only be applied if the user would like to concentrate on a task while doing manual work (which is unusual in an office). More often, a self-luminous display is used and it is the background luminance, character size and contrast of the display that determine the user's visual performance. For the display's user, it is more important to provide an appealing environment in the office in order to evoke better subjective, emotional assessments that result in optimum SP when looking around in the room and talking to other people. For special applications, e.g. museum lighting for coloured paintings, CP might be the aim of lighting design.

2.4. Minimum illuminance requirements for 'good' assessments

The aim of this section is to derive minimum illuminance requirements for real-life lighting engineering applications with different CCTs in order to ensure at least 'good' VC, CP and SP according to the scale value of 79.6. This corresponds to the 'good' category (see Figure 5 in Khanh *et al.*,[1] right). In the validation experiment, Pearson's correlation coefficients squared (r^2) between brightness (B) and SP equalled 0.94 (Table 2). According to this linear fit (B → SP), the brightness level corresponding to the 'good' SP level (SP = 79.6) equalled B = 78.9 (i.e. in the upper third of the brightness scale, see Figure 5, left, in reference 1). To achieve this value, we need at least a (horizontal) illuminance between 1100 lx (with 5600 K) and 1400 lx (with 2800 K), depending on CCT (Figure 11). Figure 11 depicts the model equation for brightness, equation (4), by substituting equation (3). This range (1100 lx–1400 lx) is higher than the minimum required by the current standard[7] for general office illumination (500 lx). Note that the standard does not say that exactly this illuminance shall be set; this value (500 lx) is just a minimum requirement.

Applying the model equation of VC (equation (7)) to different illuminance and CCT levels at the fixed oversaturation level of $\Delta C^* = 1.1$ (the level of maximum SP), we obtain the following minimum illuminances in order to ensure 'good' VC (VC = 79.6, see Figure 5 in Khanh *et al.*,[1] right): between 1100 lx (with 6500 K) and 1300 lx (with 2800 K) (Figure 12). In lighting practice, if the aim is to achieve at least 'good' VC, then first the CCT shall be selected depending on the engineer's intent and the application, then the chroma enhancement level shall be set to about $\Delta C^* = 1.1$ and, finally, the necessary (horizontal) illuminance level (for 'good' VC) shall be read from Figure 12.

If we apply the model equation of CP (equation (11)) to different illuminance and CCT levels at the fixed oversaturation level of $\Delta C^* = 4.2$ (the level of maximum CP), we obtain the following minimum illuminances to ensure 'good' CP (CP = 79.6, see Figure 5

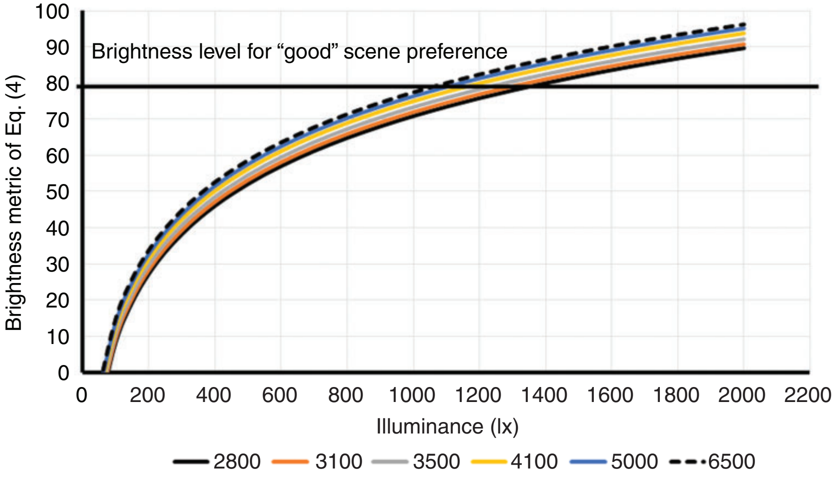

Figure 11 Brightness metric of equation (4) as a function of illuminance (lx) and CCT (K; legend). The brightness level for 'good' scene preference is derived from the validation experiment (available in colour in online version)

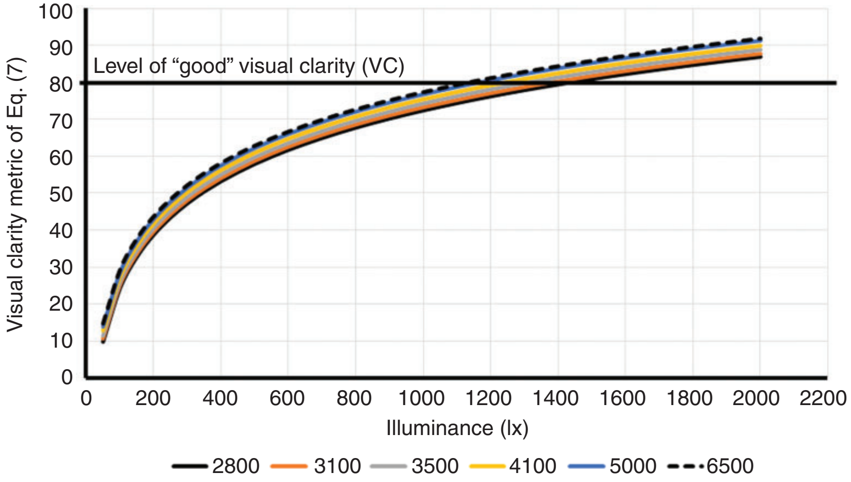

Figure 12 Visual clarity (VC) metric of equation (7) as a function of illuminance (lx) and CCT (K; legend) at the fixed oversaturation level of $\Delta C^* = 1.1$ (the level of maximum scene preference). The level for 'good' VC equals 79.6 (see Figure 5 in Khanh *et al.*,[1] right) (available in colour in online version)

in Khanh *et al.*,[1] right): between 1100 lx (with 6500 K) and 1700 lx (with 3500 K) (Figure 13). For lower CCTs, the 'good' level of CP will be reached only for $E_v > 2000$ lx. This is just an extrapolation because such high illuminance levels were not investigated in the present experiments. In the previous research,[6,8] the 'good' level of CP was not reached at 3100 K–3200 K, neither at 750 lx nor at 2000 lx (see Figure 7 in reference 6), independent of the level of chroma enhancement. In lighting practice, if the aim

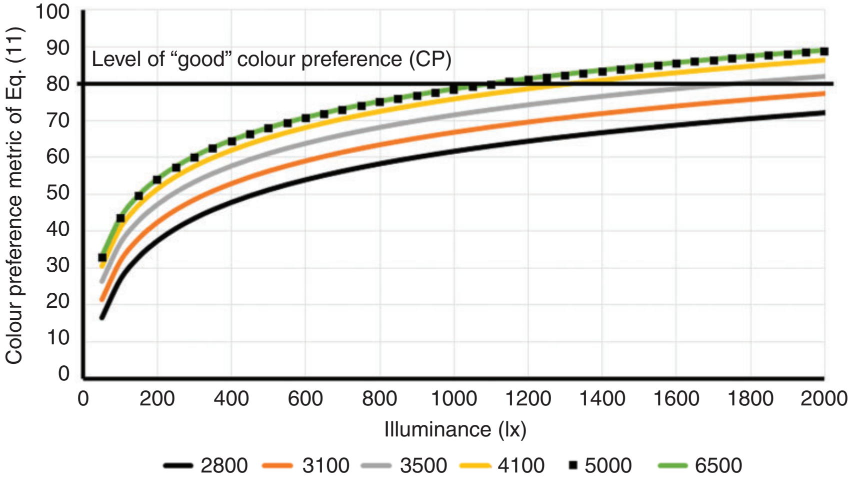

Figure 13 Colour preference (CP) metric of equation (11) as a function of illuminance (lx) and CCT (K; legend) at the fixed oversaturation level of $\Delta C^* = 4.2$ (the level of maximum colour preference). The level for 'good' CP equals 79.6 (see Figure 5 in Khanh *et al.*,[1] right) (available in colour in online version)

is to achieve at least 'good' CP, then first the CCT shall be selected depending on the engineer's intent and the application, then the chroma enhancement level shall be set to about $\Delta C^* = 4.2$ and, finally, the necessary (horizontal) illuminance level shall be read from Figure 13.

Applying the model equation of SP (equation (12)), in turn, to different illuminance and CCT levels at the fixed oversaturation level of $\Delta C^* = 1.1$ (the level of maximum SP), we obtain the following minimum illuminances to ensure 'good' SP (SP = 79.6, see Figure 5 in Khanh *et al.*,[1] right): between 1300 lx (with 6500 K) and 1800 lx (with 3100 K) (Figure 14). For lower CCTs (e.g. 2800 K), the model of equation (12) predicts higher minimum illuminances, e.g. for 2800 K about 2300 lx. The latter value is just an extrapolation because this is out of the range of the illuminance levels investigated in the present paper. In lighting practice, in order to achieve at least 'good' SP (this is the primary goal of the user preference model), first the CCT shall be selected depending on the engineer's intent and the application, then the chroma enhancement level shall be set to about $\Delta C^* = 1.1$ and, finally, the necessary (horizontal) illuminance level shall be read from Figure 14. The minimum (horizontal) illuminance level required by the standard[7] (500 lx) corresponds to an SP value of only SP = 53 (at 2800 K: 'moderate') or SP = 63 (at 6500 K: 'moderate–good'). According to Kruithof's experimental data, the lower limits and the upper limits of comfortable illuminance for general indoor lighting depend on CCT.[9] In particular, lower illuminances are preferred for low CCTs and higher illuminances are preferred for high CCTs. Thus, the present SP result (Figure 14) contradicts the Kruithof rule.

3. Conclusions and outlook

Table 4 summarises the properties and performance of the model equations derived from the main experiment and validated by the validation experiment.

As can be seen from Table 4, the model equations provide a reasonably accurate

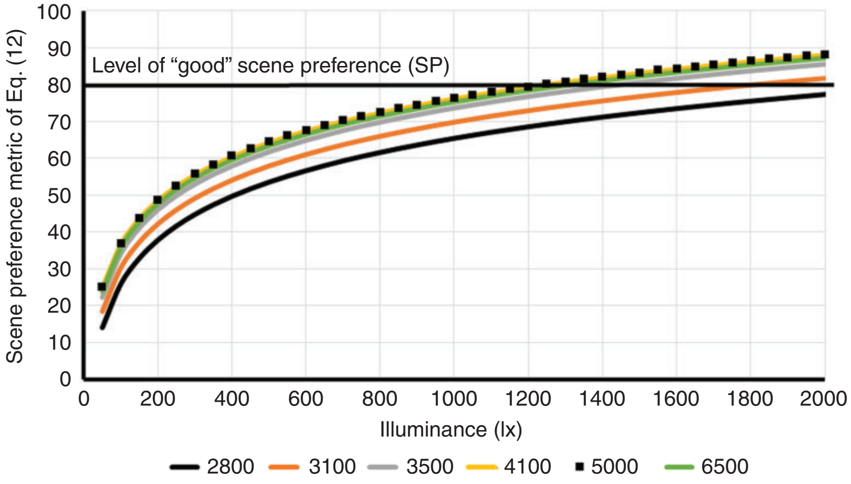

Figure 14 Scene preference (SP) metric of equation (12) as a function of illuminance (lx) and CCT (K; legend) at the fixed oversaturation level of $\Delta C^* = 1.1$ (the level of maximum scene preference). The level for 'good' SP equals 79.6 (see Figure 5 in Khanh *et al.*,[1] right) (available in colour in online version)

Table 4 Model equations, their properties and the minimum illuminance level necessary for a 'good' level of the attribute

	Brightness (B)	Visual clarity (VC)	Colour preference (CP)	Scene preference (SP)
Eq. No.	(4)	(7)	(11)	(12)
Main exp. E	25.3	30.5	35.1	33.9
Main exp. r^2	0.97	0.92	0.84	0.89
Valid Exp. r^2	0.96	0.97	–	0.91
Modelling terms	$\ln(E_{v,eq})$	$\ln(E_{v,eq})$, ΔC^*	$\ln(E_{v,eq})$, ΔC^*, $(S/V)^{0.24}$	$\ln(E_{v,eq})$, ΔC^*, $(S/V)^{0.24}$
ΔC^* for maximum performance	–	0.0	4.2	1.1
Minimum illuminance range for 'good' (lx)	1100–1400[a]	1100–1300	1100–1700	1300–1800

[a] Derived from the validation experiment for 'good' scene preference by considering the linear relationship between brightness and scene preference.

prediction ($r^2 \geq 0.84$) both for the main experiment and the validation experiment. The logarithmic equivalent illuminance terms ($\ln(E_{v,eq})$) correspond to the general signal compression property of the human visual system. Stimulus range bias in case of brightness[10] was avoided by not applying the method of adjustment. Instead, constant stimuli were assessed on continuous scales labelled by categories (except for brightness). These categories, the training phases, the detailed questionnaires and the different scenes in case of the four attributes (see Figure 3 in Khanh *et al.*[1]), helped achieve unbiased judgements and helped subjects distinguish the four attributes.

The chroma enhancement (or object oversaturation) term ΔC^* was considered zero or positive in the present paper according to the general dislike of desaturating spectra. For VC, the ΔC^* term peaks at 0 and then it diminishes more and more rapidly with the increasing object (over-)saturation property of the spectrum. The reason is that highly oversaturating spectra visually destroy the perception of fine colour structures on object surfaces. For CP (SP), the ΔC^* term has its maximum at 4.2 (1.1): we need somewhat more (but still only a relatively small amount of) object chroma enhancement for CP than for general SP. In the case of CP and SP, we also need the $(S/V)^{0.24}$ term expressing the lower preference of scenes at lower CCTs. It is important to accentuate that to achieve 'good' SP, we need a more complex, comprehensive model derived from the influencing parameters: it is neither the illuminance nor a descriptor of colour quality (e.g. ΔC^*, a measure of chroma enhancement), nor a descriptor of the type of white tone (CCT or $(S/V)^{0.24}$) that determine SP alone. The point is that we need a combination of these variables to describe the complexity of the perception of real interior scenes.

To achieve the 'good' level of the attributes VC, CP and SP, we generally need illuminance levels between 1100 lx and 1800 lx according to the present results. This range depends on the attribute (VC, CP or SP) and on CCT. The minimum (horizontal) illuminance level required by the current standard[7] (500 lx) corresponds only to 'moderate' or 'moderate–good' SP. For the success of the user preference model in the control procedure of an intelligent and connected lighting system and in lighting design and evaluation (see Figure 2 in Khanh *et al.*[1]), we need to achieve at least the 79.6 ('good') level of SP (SP: this attribute should be the primary aim of lighting design) by applying an appropriate illuminance (depending on CCT, see Figure 14) and the appropriate chroma enhancement level ($\Delta C^* = 1.1$).

As mentioned in the Introduction, only a limited set of lighting parameters were varied in the present experiments. These experiments were carried out without the spatial variation of luminance distributions on the table, on the walls and on the ceiling; also without dynamic lighting or the inclusion or exclusion of daylight or considering the influence of the time of the day, time of the year, weather, geographical location and the user's age, motivation, state of mood, state of health and cultural background. The viewing context mimicked a modern office (see Figures 3 and 5 of reference 1) which is very different from, e.g. a well-furnished classic living room or a restaurant scene in the evening.

Therefore, the value of the present model equations (Table 4) to the development of the user preference model of Figure 2 in Khanh *et al.*[1] is limited. Issues related to white tone chromaticity[11,12] were not dealt with. A small amount of disturbing tint in the white tone resulting from, e.g. the uncompensated aging or temperature change of the LEDs might destroy user preference. These issues shall be investigated in further studies in the framework of Figures 1 and 2 of Khanh *et al.*[1] Experimental data shall be collected systematically for different lighting applications and geographical locations. The effect of different colour gamut shapes generated by the spectrum of the light source and the effect of different object colour selections (e.g. presenting only reddish-orange or only bluish-purple objects in the scene) shall also be included in the user preference model in the future.

Table 4 shows the necessity of a higher illuminance range (1100 lx–1800 lx) than usual in today's general interior lighting practice. This finding was corroborated by several previous studies mentioned in Part 1 of the present work. Apparently, human centric lighting design really needs these higher illuminance levels combined with a suitable spectrum and suitable spatial and temporal light distributions. Facility managers and building managers have to balance the positive effects of a beneficial lighting installation and the cost of more electric energy. They should monitor the effect of the new installation, e.g. record the number of the days in which the workers are ill or examine the productivity of the workers. Note that we can achieve as much as 140–150 lm/W with a modern LED luminaire today. Electric energy can also be saved (in some cases) by motion sensors and the inclusion of daylight. Therefore, we think that discussions on 'wasting electric energy' do not represent a progressive point of view today. Anyway, further visual experiments should be carried out to verify the illuminance levels shown in the last row of Table 4.

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