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Towards a user preference model for interior lighting Part 1: Concept of the user preference model and experimental method

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The objective and subjective factors influencing human-centric lighting design and their effect on the user of the lighting system are analysed with the aim of developing a user preference model. It is discussed how to apply this user preference model in the Internet of Things network structure of luminaires in order to obtain an 'Internet of Luminaires' for good user acceptance. The method of a visual experiment intended to elucidate these concepts and contribute to the user preference model is described. In the experiment, subjects assessed scene brightness, visual clarity, colour preference and scene preference in a real room. Modelling equations of these attributes will be shown and discussed in Part 2 of this work.

1. Introduction

After the invention of the incandescent lamp by Edison, the history of lighting engineering involved three main phases with not very clearly defined time boundaries. In the first phase, from the end of the 19th Century or the beginning of the 20th Century until the beginning of the 1990s, several stages of the industrial revolution took place in mechanical and electrical engineering. This led to the development of thermal radiators and discharge lamps as light sources. In this period, the main purpose of visual lighting engineering research concerned *visual performance*[1–3] to ensure that what needed to be seen to perform visual tasks could be seen easily and quickly without discomfort thus (also) being able to avoid work accidents.

Between 1994 and 2017, due to the appearance of coloured semiconductor LEDs and white phosphor-converted LEDs, energy-efficient and reliable LED lighting systems with long lifetimes, one fixed spectrum and fixed correlated colour temperature (CCT) were developed. During this development period, the first human-centric lighting (HCL) systems were designed around the year 2012. We refer to the concept of HCL in the sense as defined and explained in detail in our previous work.[4] To apply HCL design principles, visual lighting engineering research defined a series of new colorimetric[5,6] and non-visual (melanopic)[7,8] descriptor quantities and analysed the (immediate) emotional effect of different lighting conditions.[9–12]

The onset of the third phase occurred in 2013–2015 when the first serious HCL

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concepts with dynamic lighting came into existence optimising visual performance, immediate emotional aspects and longer-term non-visual aspects like sleep quality, work creativity, concentration ability, well-being and alertness.[13] At the same time, discussions began about the development of intelligent luminaires with microcontrollers, sensors and communication systems (e.g. DALI, KNX, LON etc.) and their decentralised or centralised networking (so-called connectivity) via different internet platforms, e.g. the cloud, different server structures or the Internet of Things (IoT).

The two concepts, HCL and connectivity, are intrinsically interwoven in modern lighting engineering: a perfect HCL system is only feasible if the luminaires are driven and controlled intelligently being connected with each other via a ubiquitous control system. Vice versa, there is no use in connecting and driving the luminaires without appropriate lighting engineering knowledge that applies the HCL principles to the driving and control system. Therefore, for successful intelligent lighting system design, the HCL concepts of lighting engineering (Figure 1) and the concepts of IoT network structures applied to luminaires (i.e. the 'Internet of Luminaires', see Figure 2) should be combined.

To interpret Figure 1, it should be mentioned that every human user of a lighting system is an individual who has a special personal life path and life experience resulting from the factors age, gender, region of origin, cultural background, personality, recent sleep quality, current state of mind, like or dislike of the current weather, interests, education and profession. This individual works in a certain life phase in a certain region in a building that represents a certain lighting application or lighting context with a specific work content (e.g. office, industrial facility, hospital, school, university or nursing home). This individual has certain expectations concerning work and private life and communicates every day with colleagues, friends and family members. The individual carries out a specific activity (work, relaxing, social, creative, concentrated; with or without using an

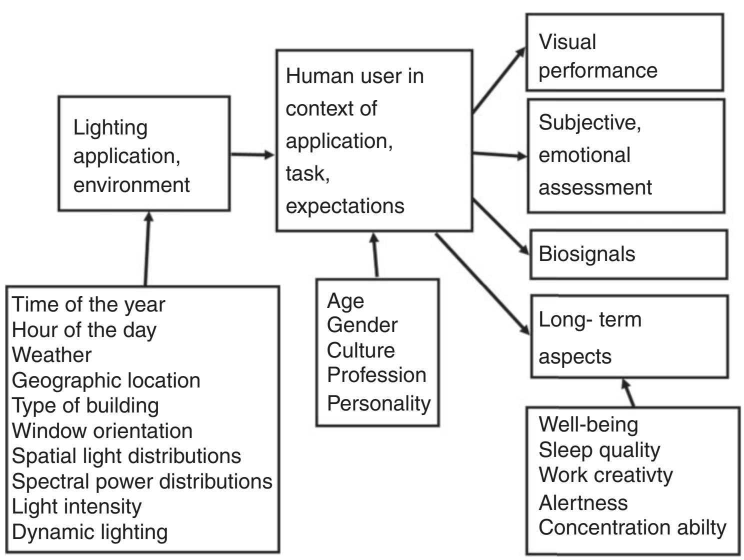

Figure 1 Influencing factors of human-centric lighting design (left: objective factors; middle: subjective factors) and their effect on the human user (right)

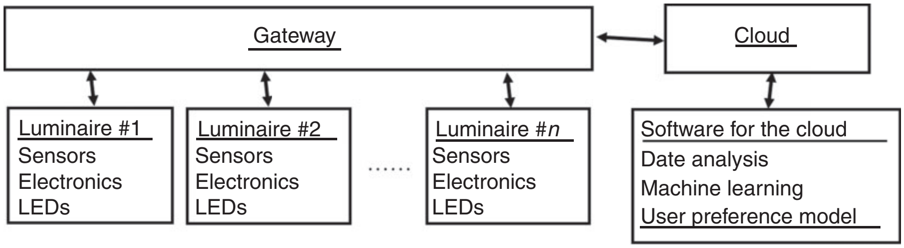

Figure 2 Concept of the Internet of Things network structure applied to luminaires ('Internet of Luminaires'). Luminaire #1 can be located e.g. in a school in Europe and Luminaire #2 e.g. in an office in Asia

information display) at a particular pace associated with a certain level of pressure to perform the task and has a certain emotional relationship with the other persons in the same interior that influences feelings and judgements.

The building stands at a certain geographic location in a specific climate zone and has a certain geometry, window orientation, architecture, furnishing style, table cloths, window sills, shutters, wall and ceiling colours, flowers, coloured books, paintings, decorations, and possibly coloured fruits and other food on the table. The building and its human users are subject to the changes of weather (with more or less daylight of different type according to the presence/absence/type of clouds, temperature and humidity according to the season), time of the year and time of the day as well as the noise level. The building not only contains lighting systems but also heating, warm water, air conditioning, window control, curtains and communication systems. These systems should interact with the lighting control system in order to increase the work performance and the well-being of the users and to ensure a smooth workflow.

Concerning the lighting systems that illuminate the rooms and the individual workplaces, their lighting characteristics can be varied in terms of four basic physical properties:

1) Spectral power distribution (related quantities are white tone chromaticity, correlated colour temperature or CCT: warm white, neutral white, cool white; the relative power in certain important wavelength ranges in the spectrum, e.g. the wavelength range around 480 nm for more or less circadian stimulation; or the wavelength range between 600 nm and 660 nm to provide red or orange objects in the room with more or less saturation to enhance the colour quality of the objects and the faces of the persons in the room);
2) Intensity (related quantities are luminance, illuminance, luminous flux; they are closely related to the perceptual attributes of scene brightness[14,15] and visual clarity[16–18]);
3) Spatial light distributions (e.g. the illuminance distributions on the walls and on the working surfaces, e.g. wall washing, artificial sky, other ceiling lighting; general diffuse lighting and focused task lighting; it is important to avoid glare both from daylight and from artificial lighting)
4) Temporal changes of lighting (e.g. the changes of natural daylight entering the room; or dynamic artificial lighting;[13,19] e.g. continuous light level control according to a pre-programmed daily control schedule during the working day for office lighting; if pulse width modulation (PWM) is used then it is important to avoid flicker and the stroboscopic effect).

The user of the lighting system reacts (see the right-hand side of Figure 1) to the objective and subjective conditions of the lighting application and to the task to be executed (see the left and middle parts of Figure 1) with a certain level of visual performance related to the task, assesses the lit environment subjectively (e.g. its brightness and visual clarity), expresses emotions evoked by the environment (and a judgement about the preference of the entire lit scene including the preference of the colour appearance of the objects under the current illumination) and also generates different, measureable bio-signals (e.g. electroencephalogram, EEG; electrocardiogram, ECG; blood pressure, skin conductance and heart rate). Lighting characteristics also influence long-term (non-visual) aspects like the abovementioned long-term sleep quality, work creativity, concentration ability, well-being and alertness.

From the point of view of defining and structuring the 'Internet of Luminaires', the intelligent luminaires of a building can be either (1) connected in a decentralised manner as a building-specific unit or (2) connected in a centralised manner (see Figure 2) with all other luminaires (in any building of a country, a region or the world) within a Cloud structure.

At the beginning, the 'Cloud' (depicted on the right-hand side of Figure 2) is a data structure containing the parameters of the sensors, the electronics and the LEDs of the luminaires (#1 to #*n*) that can be addressed individually. The users' visual performance, subjective and emotional assessments, long-term reactions and in some cases possibly also their biosignals (see the right column of Figure 1) shall be collected by questionnaires or by monitoring their own settings or their biosignals over a long time period by the use of the Cloud, for a large set of luminaires under a wide range of different conditions (including the variations of season, weather and geographical location and with users of different age, professions and tasks; see the left and middle columns of Figure 1).

This dataset shall be analysed extensively possibly by artificial intelligence (e.g. machine learning, deep learning, neural network) methods. Then, a user preference model shall be created that predicts the optimum driving values for each luminaire at any time; with different driving values at every time of the day to obtain so-called optimum daily control schedules. The user preference model will evolve continuously from the data being accumulated. The combination of Figures 1 and 2 is important for lighting design: the knowledge implemented in the software, i.e. the expert system to be established with machine learning can be used to design the lighting system and integrate it with all other systems like intrusion prevention, window blinds, air conditioning and heating.

The time-dependent optimum driving values of the LED channels of each luminaire that result from the user preference model should be sent from the Cloud via the Gateway towards each (individually addressable) luminaire. The aim is to achieve an optimum spectral, spatial and temporal light distribution for every user in every building according to the current local weather, time, sun position, user and task composition in the given building. At fast data exchange rates, a control loop considering the current temperature and the ageing of the LEDs is also imaginable. With the aid of motion sensors, energy consumption can be reduced. Furthermore, the internet of luminaires can also be connected (as mentioned earlier) with other device networks via the IoT, for example those controlling the amount of daylight in the room, heating and intrusion detectors. According to the above considerations, one of the important future research subjects of lighting engineering should be the development of a general user preference model based on HCL principles (Figure 1). This user preference model should be implemented in the Cloud via the internet of (intelligent) luminaires (Figure 2).

The present paper deals with four selected aspects of the user preference model for interior lighting related to visual performance and the subjective, emotional assessment of the lit environment: (1) scene brightness, (2) visual clarity, (3) colour preference and (4) general scene preference. The present authors consider these aspects as important visual attributes that might help us to make a start in the process of establishing the user preference model. The attribute brightness is defined in the CIE e-ILV as the '*attribute of a visual perception according to which an area appears to emit, or reflect, more or less light*'.[20] Although brightness has '*at least three aspects*',[21] the present article deals only with the 'scene brightness' aspect, the perception of '*the overall amount of light reaching the observer's eyes*'.[21] The concept of scene brightness is important in many areas of lighting engineering including the design of the lit interior space in which brightness should be generally high enough in order '*to make seeing easy*',[22] i.e. for good visual performance. Spatial brightness distributions of interior lighting should be well-balanced for good visual comfort and good (i.e. three-dimensional) space perception or perceived spaciousness.[22,23] The concept of scene brightness (or spatial brightness) refers to the brightness of spatially extended scenes and not of small light sources or small individual objects.[14,15]

In several previous studies,[24–26] it has been found that scene preference, i.e. the general subjective judgement about lighting quality in a lit interior, tends to increase with illuminance level. Illuminance levels in the range between 700 lx and 3000 lx were necessary to achieve a pleasant and lively impression of the room.[24,25] A possible explanation[27] of these relatively high illuminance levels is that, for good lighting quality, good visual clarity (in the sense of '*clear visibility of continuous colour transitions, fine colour shadings on the object surfaces and clearly visible contrasts between the different coloured objects*'[27]) is essential. Indeed, Boyce and Cuttle[26] found that increasing the illuminance made a room appear '*more pleasant, more comfortable, clearer, more stimulating, brighter, more colourful, more natural, more friendly, more warm and more uniform*' and also '*less hazy, less oppressive, less dim and less hostile*.' According to this, in shop lighting often light levels higher than 1000 lx are used and, in order to attract the customers' attention, illuminance levels of more than 1500 lx are applied.

Reading the literature on the preferred illuminances at workplaces, we find conspicuously high (horizontal) levels, between 1300 lx and 2250 lx.[28–31] In another study in office rooms with windows,[32] subjects added an illuminance of the artificial lighting of 800 lx to the daylight coming from the windows so that, altogether, a preferred illuminance range between 854 lx and 1430 lx was obtained (depending on season and the time of the day). In a field study,[33] 67% of the subjects found a preferred horizontal workplace illuminance of 966 lx on average. This latter value depended on the season, with a higher mean preferred horizontal illuminance in the spring (1046 lx) than in the summer (927 lx), in the autumn (875 lx) and in the winter (787 lx). Furthermore, in an industrial assembly workplace equipped with fluorescent luminaires (4000 K), preferred illuminance levels at about 1350 lx were found.[34] It should also be mentioned that other studies in which subjects in offices were given control of their lighting resulted in subjects choosing to work at illuminances below 500 lx contradicting the above-mentioned higher illuminance values.[35,36]

In 1969 Aston and Bellchambers' subjects had to adjust the level of illumination of two cabinets to get equal '*overall clarity*' which was defined as '*the satisfaction gained by you personally, discounting as far as possible any obvious difference in colour and brightness*'.[16] It was mentioned that '*the attractiveness (of interiors) is not due to the quality of the colour* *rendering of individual hues alone, but that some additional factor, variously referred to as colour or visual 'clarity', added to the attractiveness of the interior*.' Later, Thornton and Chen[17] defined the visual clarity of an object scene under a given light source as the visibility of small visual details. Visual clarity correlated well with the perceived spatial brightness of the observed scene.[17] As a further aspect, Hashimoto and Nayatani[18] stated that '*visual clarity is caused by the feeling of contrast between (the) coloured objects under (the given) illumination*' and this was predicted by the gamut area made by the component colours of a four-colour combination.

In the different definitions of visual clarity, it is common that both local and global contrasts and both achromatic and chromatic contrasts on the object surfaces of the scene play an important role when assessing visual clarity. The importance of visual clarity and the importance of its relation to brightness in the design of a lit environment for high user acceptance was pointed out in Flynn and Spencer's study,[37] in which the adjective pairs 'bright-dim' (brightness) and 'clear-unclear' (visual clarity) correlated well with each other. A similar positive correlation between these two attributes was also suggested by Viénot *et al*.[38] and Fotios and Atli.[15]

In a psychophysical experiment,[39] visual clarity (measured with a comprehensive method comprising several tasks like reading letters, colour vision tests and assessing the visibility of colour transitions on real structured and coloured object surfaces) was significantly influenced by the bluish spectral content of the spectrum: A spectrum with higher CCT, i.e. higher blue content, evoked higher visual clarity and not only by illuminance level. Visual clarity was found to be a monotonically increasing function of illuminance level flattening above a critical illuminance depending on the blue content of the spectrum. For warm white light sources (i.e. those of the smallest visual clarity at a given illuminance level), this critical minimal illuminance required for good visual clarity equalled about 2000 lx.

Concerning colour preference, this attribute is significantly influenced by the type of white tone (e.g. warm white, neutral white, cool white) illuminating the coloured objects and the achromatic surfaces (e.g. white walls or grey furniture) in the scene. The colour appearance of coloured objects was more preferred under a higher CCT (4000 K) than under a lower CCT (2500 K) at the same object chroma enhancement (object saturation) level.[40] This is in accordance with another study,[41] in which the white tone preference in a room at the illuminance level of 2457 lx peaked at a CCT of about 5000 K (cool white) and not at 3100 K (warm white). In another study,[42] observer preference for perceived illumination chromaticity was significantly influenced by correlated colour temperature (2700 K–6500 K), object scene colour type (with red objects, blue objects or mixed objects), cultural background (Chinese or European origin, living in Germany or in China) and gender (men, women). The most general scene with mixed object colours was generally preferred in the 3985 K–6428 K CCT range.

In yet another study,[41] variable CCTs were used to illuminate a scene of coloured objects in a room and these CCTs were systematically combined with varying object saturation levels. Neutral white (4100 K) and cool white (5000 K and 5600 K) tones generally resulted in higher colour preference ratings than a warm white tone at 3100 K. In a similar, more recent study,[4] subjects rated the colour preference of a still life arrangement of coloured objects in a real room illuminated at the illuminance level of 2000 lux by 28 different spectra of a four-channel LED light engine at different object saturation levels and different white points (3200 K, 4200 K, 5000 K and 5600 K). Mean colour preference ratings had a maximum at a moderate chroma enhancement (i.e. object saturation) level. Here again, the lowest CCT (3200 K) exhibited lower preference ratings than the three higher CCTs.

The findings summarised above indicate that lighting, especially modern LED lighting with the broad range of variable illuminance levels, CCTs and object saturation levels, can be '*intentionally designed to reinforce, or even evoke, planned perceptual responses*' and has the potential '*to lift a person's spirit, create relaxing settings, direct attention, and create delight*'.[43] In this respect, a shortcoming of the above-mentioned previous studies is that the most important variables (illuminance level, CCT and object saturation level) were never varied systematically within the same experiment and the above described four important visual attributes were not assessed by the same subjects at the same time. Also, only a few studies investigated higher illuminance levels (higher than 500 lx) and real rooms with immersive viewing. We need a real room experiment (instead of mock-ups) to stimulate the subject to evoke a realistic emotional and cognitive response. According to the above considerations, the present paper investigates the above-mentioned four selected visual attributes of user preference: Brightness, visual clarity, colour quality and scene preference in visual experiments in a real room lit with controllable, reproducible, high-intensity four-channel LED luminaires producing different lighting conditions with different illuminance, correlated colour temperature (CCT) and object chroma enhancement levels.

The aims of the present study are to model the visually scaled (dependent) variables scene brightness (B), visual clarity (VC), colour preference (CP) and scene preference (SP) with the physically measured (independent) variables illuminance, CCT and a descriptor of the chroma enhancement (object oversaturation) level and to validate these equations (except for colour preference because this has already been extensively investigated).[4,39,40,41,44] The hypothesis is that there is an interdependence among the four dependent variables and a further aim is to explore this interdependence, especially the relationship between scene preference (as a general optimisation target, this is the most important variable for the user preference model) and the other three variables, brightness, visual clarity and colour preference. We also would like to point out that the general minimum horizontal work plane illuminance required by the standard[45] for offices (500 lx) only corresponds to a 'moderate' subjective assessment of visual clarity, colour preference and scene preference and, in order to reach the 'good' level of these attributes, we have to provide higher illuminance.

In the present study, only these four selected visual attributes resulting from acute (i.e. short-term) effects of lighting are investigated while the measurement of bio-signals and long-term aspects (see Figure 1) are not dealt with. The spatial and temporal characteristics of the lighting in the room were not varied: the LED luminaires provided homogeneous downwards oriented illumination without indirect components. Also, in the experiment reported here, dynamic lighting was not investigated. The illuminance level and the spectrum were constant within every one of the investigated lighting conditions. Therefore, it should be emphasised that the present paper represents only a small step towards the comprehensive user preference model (Figure 2) of intelligent luminaires.

2. Method

In a series of experiments, subjects assessed the lighting of different table tops containing a white tablecloth and coloured objects (in one of the arrangements used, there was only a white tablecloth). Typical spectral reflectance curves of such coloured objects can be seen, for example in Figure 3 of reference 44. Although the room (3 m $\times$ 3 m) with its white

Figure 3 Photos of the four different test setups to scale brightness (top left), visual clarity (top right), colour preference (bottom left) and scene preference (bottom right) (available in colour in online version)

walls and office furniture was intended to mimic an office, it is important to point out that observers did not assess the whole room, just the table and the objects on it. The light of the luminaires illuminating the room was directed toward the table providing homogeneous illumination. The spatial distribution of the illumination was not varied, just the illuminance level and the relative spectral power distribution of the light source. In every experiment in the series, the different light source spectra were shown to all the subjects in the same order for each series of assessments but different orders were used for the different series.

2.1 Main experiment

The main experiment was carried out in a dedicated experimental room in March and April. It consisted of four different tests to scale the four different visual attributes: Brightness, visual clarity, colour preference and scene preference, in distinct experimental sessions. Every one of the four tests had a different dedicated test setup (Figure 3). We used different test setups in order to foster the recognition of the different concepts of the four different attributes. Discerning between the different attributes was further supported by the use of detailed written definitions of every attribute in the questionnaires (see below). This was further emphasised by the fact that, although every subject took part in all four tests, the individual tests were carried out on different days.

As can be seen from Figure 3, the table was empty for brightness assessment. The aim was to avoid any structure in order to distinguish brightness from visual clarity by assessing just the brightness impression of the tablecloth on which the spectral radiance distribution of the illumination was measured. Concerning visual clarity, this attribute corresponds to the clear visibility of achromatic and coloured texture and fine spatial details. This is the reason why the objects in Figure 3 were chosen: The achromatic test chart with complicated spatial structure, the highly colour-textured pullover, the doll with the conspicuous spatial structure of her hair, the water lily with fine colour shadings, the printed document with letters and the piece of cyan textile. For colour preference, homogeneous coloured surfaces were used including two MacBeth ColorChecker® charts. Finally, to evaluate scene preference, in order to emphasise the perception of three-dimensionality and to be able to judge the more or less appealing appearance of the table top arrangement that resembled a still life, the objects (containing fine spatial structures like the brushstrokes on the painting) were assembled to provide a deep perspective.

Every one of the four test setups in Figure 3 was illuminated by two thermally stable, reproducible and mechanically robust four-channel (red, green, blue and warm white) LED light engines with 36 different spectra. The same 36 spectra were used to illuminate every test setup but in a different randomised order for each setup. The properties of these 36 spectra are listed in Table 1. Horizontal illuminance was measured in the middle of the table by a well-calibrated illuminance meter. The other values were computed from the spectral radiance measured on the white tablecloth in the middle of the table by a well-calibrated tele-spectro-radiometer. Relative spectral radiance distributions are shown in Figure 4.

As can be seen from Table 1, four nominal illuminance levels (200 lx, 500 lx, 1000 lx and 1800 lx), three nominal CCT levels (3000 K, 4100 K and 5600 K) and three saturation levels (measured in terms of the quantity ΔC^*, an object saturation measure[4] computed in CIELAB colour space that corresponds to the mean value of the individual ΔC^* values of the 15 CQS test colour samples VS1–VS15[47]) were generated. (In future work, an improved colour appearance model such as CAM02-UCS could be used instead of CIELAB). The three saturation levels included (1) one level between $\Delta C^* = -0.1$ and 1.0 with a high R_a value; (2) one

Table 1 Properties of the 36 spectra used to illuminate the four test setups in the main experiment

i	E_v	CCT	ΔC^*	R_a	i	E_v	CCT	ΔC^*	R_a	i	E_v	CCT	ΔC^*	R_a
33	197	2980	0.0	94	14	489	4077	-0.1	92	12	1009	5504	0.7	95
9	198	2992	1.9	91	22	491	4082	2.6	87	7	1000	5570	4.1	79
34	204	2995	10.7	21	4	502	4110	12.0	26	2	1005	5616	11.6	34
20	199	4082	0.5	96	11	495	5580	0.8	95	31	1791	2982	0.2	94
24	193	4068	2.4	88	16	496	5584	4.3	79	18	1796	2983	1.7	93
21	199	4101	11.8	27	30	499	5612	11.4	35	1	1818	2995	11.2	22
3	196	5545	0.7	95	35	997	2979	0.0	94	17	1793	4090	0.1	93
25	192	5602	4.4	78	26	999	2988	1.7	93	6	1791	4083	2.5	88
23	201	5587	11.5	35	8	1001	2991	11.2	22	27	1814	4107	12.2	25
15	491	2975	0.2	94	10	1000	4077	0.0	92	29	1789	5606	1.0	95
28	496	2988	1.9	92	19	990	4069	2.5	88	5	1801	5586	4.2	79
32	500	2996	11.3	21	13	1006	4110	11.8	27	36	1825	5617	11.6	34

i: Order of the spectrum in the brightness test (different orders were used in the other three tests); E_v: horizontal illuminance in lux measured in the middle of the table; CCT: correlated colour temperature (K); ΔC^*: object saturation measure,[46] mean of the individual ΔC^* values of the 15 CQS test colour samples VS1–VS15[48]; *R*a: the CIE general colour rendering index

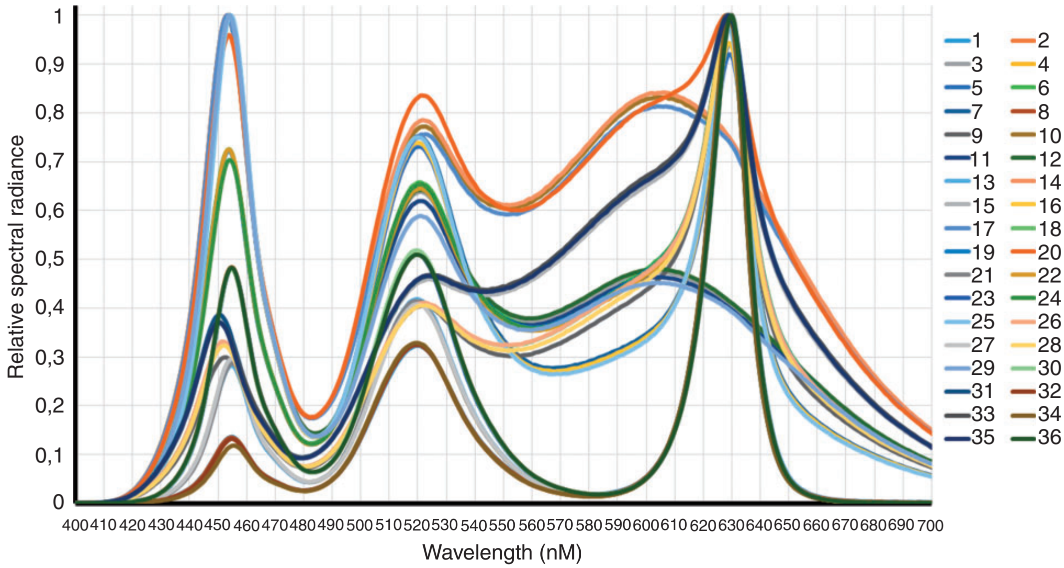

Figure 4 Relative spectral radiance distributions of the 36 spectra numbered in the same order in the legend as in Table 1 ($i = 1$–36) (available in colour in online version)

intermediate level between $\Delta C^* = 1.7$ and 4.4 for best colour preference (depending on CCT) according to previous work[4] and (3) a high-object saturation level between $\Delta C^* = 10.7$ and 12.2 providing a strong oversaturation of the coloured objects in the test setups.

As can be seen from Figure 4, light sources of higher (lower) CCT exhibit higher (lower) blue channel maxima (at about 455 nm) of the four-channel LED light engine. In the case of the spectra with higher object saturation measure values ($\Delta C^* > 10$), the peaks of the red, green and blue LED channels are high. These spectra exhibit only a small amount of radiation between the peaks and this causes a higher chroma impression at the surfaces of the illuminated coloured objects.

Thirty observers (14 men, 16 women) with normal colour vision (tested by the Standard Pseudoisochromatic Plates for Acquired Color Vision Defects[46]) and good or corrected visual acuity between the age of 19 and 32 years (mean: 25.8 years; standard deviation: 3.3 years) took part in the experiment. Every observer carried out every one of the four tests only once (i.e. without repetitions) on different days in groups of two to four in the following order: brightness, visual clarity, colour preference, scene preference. Concerning their cultural background, all observers had lived for at least one year in Germany before the study. Nineteen observers (university students) were Chinese, one observer (university student) came from the Middle East, eight observers were Europeans (university students) and two observers were Vietnamese (one university student and one research fellow). Observers were not allowed to communicate during the experiment. There was a training phase using the same questionnaire for each attribute as in the main experiment (see below) with eight spectra always containing two extreme (anchor) stimuli (very bright – very dark; very low visual clarity expected – very high visual clarity expected; low illuminance, low CCT, high oversaturation; high illuminance, high CCT, low oversaturation). For the brightness scaling, this training was also intended to avoid the so-called initial illuminance bias: The variable scene to be assessed by the subjects was set to both high and low levels before the main trial.[47] In the main experimental phase, after the training phase, a specific questionnaire was used for every attribute.

The following instructions were formulated on the brightness questionnaire: '*The concept of brightness is used in its well-known, everyday sense. You should assess the brightness of the whole table with the table cloth in comparison to a reference situation. So the question is how bright the table is, compared to the reference situation. The reference situation will be shown in the training phase several times and this corresponds to the brightness value of 100. Complete darkness would correspond to zero. So please evaluate your brightness impression on the table. You can memorise your brightness impression of the reference scene (which corresponds to 100) during the training phase in which this reference will be shown several times. You can put a cross on the brightness scale* (see Figure 5, left). *The scale is open at the top. We will illuminate the table with 8 light sources in the training phase and 36 light sources in the main phase. After a new light source is switched on, first please look at the white table cloth for 80 s. After this adaptation, you can assess brightness. Please do not look at your hand and not at the faces of the other observers. Look only at the table. First please decide in which third of the scale* (see Figure 5, left) *the current situation is (top, middle, bottom) and then please put the cross on the scale within this third according to your brightness impression. The reference will be shown before every light source for 5 s.*'

Figure 5 Brightness scale (left) and the scale used to evaluate visual clarity, colour preference and scene preference (right; labelled by the categories 'excellent' 97.9; 'very good' 91.6; 'good' 79.6; 'moderate' 52.9; 'poor' 41.2; 'bad' 26.5; and 'very bad' 12.8). The non-uniform spacing of the category labels (right) is based on a previous study[48]

The following instructions were formulated on the visual clarity questionnaire: '*Visual clarity is defined as follows: the clear visibility of continuous colour transitions, fine colour shadings on the object surfaces and the clear visibility of the contrasts between the colours of the different coloured objects. Thus, visual clarity corresponds to the clear visibility of the details and the structure (e.g. the single hairs of the doll) and the clear visibility of texture (e.g. the coloured textile patterns of the pullover) and also the clear visibility of the colour transitions and coloured structures on the surfaces of the coloured objects (e.g. the coloured structure in the inside of the water lily or the lines or letters on the black and white test chart). So please assess the visual clarity of the objects on the table. You should look at the objects one after the other and then, also, all objects at the same time. Please make your judgement according to your general impression of visual clarity for all objects in the scene. You can express your judgment by putting a cross on the visual clarity scale* (see Figure 5, right). *By doing so, you should consider the* *categories of the scale (e.g. bad, moderate, good, very good). You can also put your cross to any place between two adjacent categories. You should consider all above characteristics of visual clarity and consider all objects at the same time. There will be 8 light sources in the training phase and 36 light sources in the main phase. After a new light source is switched on, first please look at the white table cloth for 80 s. After this adaptation, you can assess the visual clarity of the whole scene.*' The use of the continuous interval scale with categories (Figure 5, right) turned out to be beneficial in previous studies.[4,39,40,41,44]

The following instructions were formulated on the colour preference questionnaire: '*In this experiment, you will assess the colour appearance of the two MacBeth ColorChecker® charts and the coloured books on the table. These two coloured test charts and the coloured books will be illuminated by 36 different light sources and this will give rise to different colour appearances. Please consider the following: Do you like the colour appearance of the coloured patches of the MacBeth ColorChecker® charts and the books? You should consider all colours at the same time and assess your overall impression. The value of 100 corresponds to your maximum assessment i.e. if the charts and the books appear as you would like to see their colour appearance from the point of view of your colour preference. You can express your judgment by putting a cross on the colour preference scale* (see Figure 5, right). *By doing so, you should consider the categories of the scale (e.g. bad, moderate, good, very good). You can also put your cross to any place between two adjacent categories. There will be 8 light sources in the training phase and 36 light sources in the main phase. After a new light source is switched on, first please look at the white table cloth for 80 s. After this adaptation, you can assess the colour appearance of the charts and the books.*'

The following instructions were formulated on the scene preference questionnaire: '*In this experiment, you will assess the general preference of the whole scene on the table and also the faces of the other observers. You should consider your scene preference impression about all objects and faces at the same time. The scene on the table is intended to mimic the decorations of a prestigiously designed modern office. The scene will be illuminated by different light sources and this will give rise to different lighting situations. To make your judgment, please consider the following points: 1. Is the appearance of the whole scene including the objects and the faces pleasant, attractive, harmonic? 2. Does the scene evoke positive emotions in yourself? 3. Can you well perceive three-dimensionality? 4. Is the visual effect of looking at the scene appealing? The value of 100 corresponds to your maximum assessment if you look at the whole scene from the point of view of all above aspects of scene preference. You can express your judgment by putting a cross on the scene preference scale* (see Figure 5, right). *By doing so, you should consider the categories of the scale (e.g. bad, moderate, good, very good). You can also put your cross to any place between two adjacent categories. There will be 8 light sources in the training phase and 36 light sources in the main phase. After a new light source is switched on, first please look at the white table cloth for 80 s. After this adaptation, you can assess the scene preference of the whole scene*'.

2.2 Validation experiment

The validation experiment (carried out in November and December) consisted of two test setups: one common setup for brightness and visual clarity and another setup for scene preference, see Figure 6. The validation experiment was carried out in the same experimental room using the same two LED light engines as in the main experiment.

As can be seen from Figure 6, the same objects were used to test brightness and visual clarity in a different arrangement as in

Figure 6 Photos of the two different test setups of the validation experiment: a common setup to scale brightness and visual clarity (left) and the other test setup for scene preference (right). Colour preference was not tested in the validation experiment (available in colour in online version)

Table 2 Properties of the 25 spectra used to illuminate the two test setups in the validation experiment

i	E_v	CCT	ΔC^*	R_a	i	E_v	CCT	ΔC^*	R_a	i	E_v	CCT	ΔC^*	R_a
1	1020	2693	0.6	95	10	2006	5007	1.1	95	18	91	5010	0.6	95
2	470	3096	0.1	96	11	44	3104	0.0	92	19	1018	9994	1.2	96
3	91	10012	1.2	96	12	43	2698	0.2	92	20	469	5006	1.0	95
4	89	3107	0.4	96	13	44	10021	1.4	95	21	471	9995	1.3	96
5	44	5008	0.8	95	14	2016	10003	1.3	96	22	1018	3099	0.4	96
6	2027	2705	0.5	95	15	44	4097	0.6	95	23	471	4100	0.8	96
7	90	2693	0.5	95	16	2029	4092	0.8	96	24	1013	4109	0.8	96
8	476	2691	0.6	95	17	2032	3103	0.5	96	25	1012	5006	1.1	95
9	89	4100	0.7	96										

i: Order of the spectrum (different randomised orders were used in the two tests); E_v: horizontal illuminance in lux measured in the middle of the table; CCT: correlated colour temperature (K); ΔC^*: object saturation measure[47] (see Table 1); R_a: CIE general colour rendering index

the visual clarity test of the main experiment. For scene preference, different objects (different from the main experiment) were used. Colour preference was not tested in the validation experiment. The test method and the questionnaires were the same as in the main experiment except that 25 different spectra were used (see Table 2, compare with Table 1). The brightness and visual clarity tests were carried out on the same day after each other in groups of two to four. The scene preference test was carried out on a separate day also in groups of two to four.

As can be seen from Table 2, five nominal illuminance levels (45 lx, 90 lx, 470 lx, 1000 lx and 2000 lx) and five nominal CCT levels (2700 K, 3100 K, 4100 K, 5000 K and 10000 K) were used. All of them were at the same high CRI ($92 \leq R_a \leq 96$) level which corresponds to a low oversaturation level ($0.0 \leq \Delta C^* \leq 1.4$).

As can be seen from Figure 7, light sources of higher (lower) CCT exhibit higher (lower)

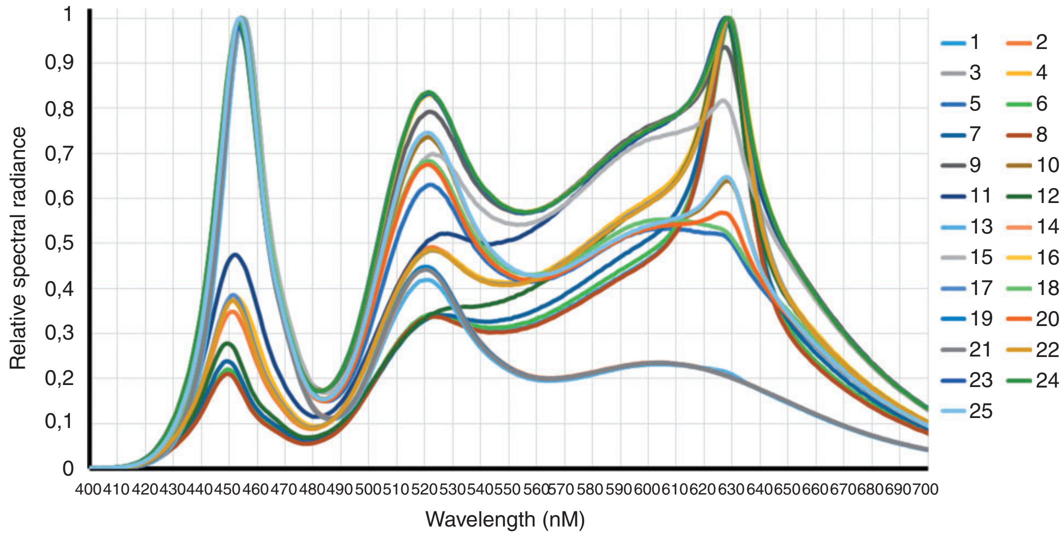

Figure 7 Relative spectral radiance distributions of the 25 spectra numbered in the same order in the legend as in Table 2 ($i = 1$–25) (available in colour in online version)

blue channel maxima (at about 455 nm) of the four-channel LED light engine, similar to Figure 4. Spectra with outstanding red, green and blue LED channel maxima are missing in this case (unlike Figure 4) because every one of these 25 spectra was optimised to have a high CRI ($92 \leq R_a \leq 96$) level corresponding to a low oversaturation level ($0.0 \leq \Delta C^* \leq 1.4$).

Twenty-eight observers with normal colour vision (tested by the Standard Pseudoisochromatic Plates for Acquired Color Vision Defects[46]) and good or corrected visual acuity took place in the brightness and visual clarity test (10 men, 18 women; aged between 20 and 47 years of age, mean: 25.2; 12 Europeans, 14 Chinese, 1 Vietnamese and 1 from the Near East) and 21 observers took place in the scene preference test (7 men, 14 women; a subset of the previous set; between 20 and 47 years of age, mean: 25.2; 6 Europeans, 13 Chinese, 1 Vietnamese and 1 from the Near East). Most of them were university students except one observer who was a research fellow.

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