Department of Electrical Engineering and Automation

User acceptance studies for LED office lighting: light spectrum and correlated colour temperature

Mohammad Shahidul Islam

Aalto University

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Abstract

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Abstract

During the last decade, lighting technology based on light-emitting diodes (LEDs) has advanced rapidly and is paving the way for the application of LED lighting in offices. Two experiments were carried out to study user preference for different LED light spectra and correlated colour temperature (CCT), and to determine user acceptance for LED office lighting.

In a lighting booth experiment, twenty one different LED spectral power distributions (SPDs) were realised considering colour quality scale (CQS) gamut area scale Qg, CQS Colour preference scale Qp, feeling of contrast index (FCI) along with the CIE colour rendering index (CRI) at the CCTs of 2700K, 4000K, and 6500K. The observers evaluated the lit scenes under different light spectra at 500 lux for different factors such as brightness, visual comfort, and pleasantness. The observers preferred the LED SPDs which had higher values of a reference-based metric (Qp) or higher values of an area-based metric (Qg). The chromaticity difference (Duv) values also influenced the user preference of the light spectra. The observer preferred the CCT of 4000K and 6500K to the CCT of 2700K at 500 lux.

The findings of the lighting booth experiment were used as the base line for the office room experiment where six different LED SPDs were realised at the CCTs of 4000K and 6500K considering Qp, Qg, and FCI. The observers evaluated the lit environments under different SPDs for brightness, visual comfort, glare, and pleasantness of colour of light along with other lighting aspects at illuminance levels of 300 lux and 500 lux. At 4000K, the observers preferred the LED light spectra which had higher values of Qp and Qg to the fluorescent lamps in the office environment at 500 lux. The preferred LED SPDs had negative Duv values, whereas the fluorescent lamp had positive Duv values. The observers preferred the CCT of 4000K to 6500K, under which the observers felt more comfortable and found the colour of light more pleasant than under 6500K at 500 lux. It was also found that the lit environment should be able to provide good quality lighting for visibility and the observers should feel visually comfortable in that lit environment if the illuminance level is varied.

The results indicate the need to develop LED light spectra for office lighting considering Qp and Qg with negative Duv values within the recommended limit. As the Duv values affected the observers' preferences, colour of white light should be characterised not only by CCT but also by Duv values.

Keywords light emitting diode, spectra, office lighting, colour rendering, correlated colour temperature, preference, acceptance

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Espoo, February 2015
Mohammad Shahidul Islam

Contents

List of Abbreviations and Symbols

ANOVA	Analysis of variance
CT	Colour temperature
CCT	Correlated colour temperature
CFL	Compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage
CQS	Colour quality scale
CRI	Colour rendering index
D_{uv}	Chromaticity difference measured in the CIE 1976 u´v´ chromaticity diagram.
ECG	Electronic control gear
FCI	Feeling of contrast index
FL	Fluorescent lamp
GAI	Gamut area index
LED	Light emitting diode
MCC	Macbeth Colour Checker chart
MCRI	Memory colour rendering index
NIST	National Institute of Standards and Technology
p-value	The probability of statistical significance test
PSU	Power supply unit
Q_a	General colour quality scale
Q_g	Gamut area scale, a CQS supplementary metric
Q_p	Colour preference scale, a CQS supplementary metric
R_a	CIE general colour rendering index
R_i	Special colour rendering index

RCRI	Rank order based colour rendering index
SPD	Spectral power distribution
SPSS	Statistical package for the social sciences
UCS	Uniform chromaticity scale
ΔE_i	The colour difference between the reference and test source of i^{th} colour sample

List of Publications

This doctoral dissertation consists of a summary of the following publications which are referred to in the text by their numerals

I. Islam, M; Dangol, R; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2013. Investigation of user preferences for LED lighting in terms of light spectrum. *Lighting Research and Technology*, volume 45, issue 6, pages 641-665.

II. Dangol, R; Islam, M; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. 2013. Subjective preferences and colour quality metrics of LED light sources. *Lighting Research and Technology*, volume 45, issue 6, pages 666-688.

III. Islam, M; Dangol, R; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. User acceptance studies for LED office lighting: lamp spectrum, spatial brightness and illuminance level. *Lighting Research and Technology,* first published on December 17, 2013 as DOI: 10.1177/1477153513514425.

IV. Dangol, R; Islam, M; Hyvärinen, M; Bhusal, P; Puolakka, M; Halonen, L. User acceptance studies for LED office lighting: Preference, naturalness and colourfulness. *Lighting Research and Technology,* first published on December 6, 2013 as DOI: 10.1177/1477153513514424.

The Author played a major role in all the phases of the work presented in this thesis. He was the main author of Publications I and III and was responsible for the data analysis of Publications I and III. He contributed to the measurements, subjective data collection and was responsible for the development of the questionnaire for the experiment described in Publications I and II. He contributed to the planning of the experiment and measurements and took part in simulating the spectra and questionnaire development as well as in collecting the data in the experiment for Publications III and IV.

1. Introduction

1.1 Background

Lighting accounts for 30% - 40% of the total energy consumption in office buildings and European office buildings use about 50% of their total electricity consumption for lighting [1]. Fluorescent lamps (FLs) are commonly used in office buildings [1], [2]. An energy efficient lighting technology would help to conserve energy in offices. However, users do not necessarily accept a new technology if it fails to meet their expectations and needs. A light source can be energy efficient with reasonable price but may not be accepted by the end users if the colour quality in terms of colour rendering is not acceptable [3].

Though the compact fluorescent lamps (CFLs) were more energy efficient than the incandescent lamps, they were not well accepted by the end-users for various reasons in the 1980s and 1990s [4]. Bad colour rendering and variations in colour characteristics, particularly colour consistency and correlated colour temperature (CCT) were some of the factors of the end-users dissatisfaction with the CFLs in the early stages and in the 1990s [5]–[7]. Along with other factors, too bluish appearance of light was also a reason why end-users did not accept CFLs well [8]. The visual colour rendering of the CFLs [9] was not good, even when the CIE (International Commission on Illumination) colour rendering index (CRI) of the CFLs was good. With time, more advanced CFL technology has appeared in the market. However, the fluorescent lamp technology (i.e. FL and CFL) can be considered mature and significant improvements in terms of luminous efficacy are not expected in the future.

As an alternative to the existing lighting technologies, lighting technology based on light emitting diodes (LEDs) has emerged bringing with it the potential for significant energy savings [10]. In the last few years, the evolution of this technology has been so rapid that LEDs are competitive alternatives in office lighting [11]. Recently, an LED luminaire with efficacy of 200 lm/W was demonstrated by Cree and the efficacy was two times higher than that of the best linear fluorescent lamp luminaires [12].

One of the advantages of LEDs is the tunability or controllability of the light spectrum [13] realised with them. LED lighting systems can be developed by mixing different types of LEDs [14] to produce tunable white light with varying spectral power distributions (SPDs).

LEDs still have challenges to overcome to be competitive and applicable in general illumination including office lighting. The CIE CRI is not well-suited for white LED light [15]–[17] but is still in use to describe colour rendering of light sources until a new and more suitable metric is developed [10]. The SPDs of LEDs [18], [19] are different from those of lamps of existing technologies. A study [18] showed that optimising LED SPDs to achieve white light may lead differences between the measured and observed (visual) colour rendering properties. The spectra of different light sources are shown in Figure A1 in Appendix A. There is a probability that suboptimal LED products could be developed, potentially wasting energy as the metric is not well-suited [3].

The colour rendering and CCT are two important factors for describing the colour quality of a light source and both factors are encompassed by the SPD of the light source [3]. The colour rendering is defined by the CIE as "*Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance under a reference illuminant*" [20]. According to the CIE colour temperature is defined as "*If the chromaticity lies exactly on the Planckian locus the temperature of the Planckian radiator is the colour temperature (CT) of the test source".* However, if the chromaticity of the test source deviates slightly from a point on the Planckian locus, the expression CCT is used instead of CT. The CIE defines CCT as "*CCT is the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a diagram where the (CIE 1931 standard observer based) u', 2/3v' coordinates of the Planckian locus and the test stimulus are depicted*" [21].

The CIE CRI is calculated by using the CIE Test Sample method approved by CIE in 1974 [20]. The CIE CRI is the average of the first eight special colour rendering indices (R_i). The special colour rendering index (R_i) is calculated for each of the eight samples by equation (1).

$$R_i = 100 - 4.6\Delta E_i, \quad (1)$$

where ΔE_i is the colour difference between the reference and the test source of i^{th} colour sample.

The colour rendering and the CCT are important aspects for user acceptability of a light source [8], [22]. By tuning the LED SPDs both colour rendering and CCTs can be varied to satisfy users' needs [14]. It is thus foreseen that tunable LED lighting would be able to satisfy many of the end-users' expectations and requirements and such systems are expected to enter general lighting applications including office lighting in the near future.

However, the successful implementation of a new technology is determined by correctly matching the technology with the needs of the particular application and by the acceptance of the end-users according to their needs. If LED lighting technology does not fulfil end-user expectations and requirements regarding colour characteristics, it might fail to gain successful market penetration. Therefore, the understanding and assessment of the relevant factors that affect the quality of LED lighting in offices are relevant in the development of LED lighting technology.

For LED lighting in offices, a more diversified description of lamp light quality will be required. Very limited research related to the users' requirements, expectations, and preferences for LED lighting in offices has been done.

Subjective preference studies can often be the only available and relevant method when the success of a new technology such as LED has to be assessed in terms of end-user acceptance [23]. User preference studies and subjective assessment of LED lighting are the means to find out the answers to the above discussed factors. Thus, the user preference and acceptance study of LED lighting is a prerequisite and visual subjective validation is required to know the effects of different LED SPDs on users.

1.2 Aim of the work

The overall objective of the work is to find out the applicability and acceptability of LED lighting with realised SPDs for offices.

The first objective is to find out users' preference and acceptance of LED lighting in offices considering lighting factors related to visual perception. The second objective is to find out which CCT users prefer for office lighting when realised LED SPDs along with fluorescent lamps were used. The subjective assessment was based on questions regarding visual perception, which mainly included lighting factors related to visual comfort, brightness, and pleasantness of colour of light.

2. State of the art

2.1 Introduction

The SPD of light sources is one of the important determining factors of the colour characteristics of light in a lit space. Two properties, CCT and colour rendering index [1], describe the colour of a light source, both of which are determined by the light source SPD. Different SPDs will make a lit space appear different [24] and can influence the visual perception of the lit environment [25]–[28]. Visual perception and subjective responses to lighting may change under different SPDs at the same illuminance level [29]. Subjective responses may also be influenced by the chromaticity difference[1] (D_{uv}) values [30], [I-II] of the SPDs.

The light source SPD may affect the brightness perception of lit spaces [31]–[34] and visual comfort [28], [35] as well. Visual comfort [36] is a matter of subjective feelings and perceptions in a lit environment. Visual comfort is a very important factor that has effects on good lighting quality [36], [37]. Visual comfort is affected by brightness of the task, glare, and other factors [36]. Hence, for the assessment of user acceptance of LED lighting in offices, brightness perception and visual comfort are important to consider.

The quality of light has been found to be correlated with the CCT of the light source [38]. The CCT of the light source affects the visual perception of a lit environment by influencing factors such as brightness, pleasantness, and visual comfort [28], [34], [39]–[41]. It has also been found that CCT may not have an effect on brightness [32], [42], while colour rendering properties may have a major effect on brightness [42].

Light source SPDs may have effects on the pleasantness of a lit environment [43]. Both visual comfort and pleasantness may have effects on mood and well-being of the users of a lit space [34]. Therefore, it is important to provide visual comfort and pleasantness in an office environment.

[1] The chromaticity of a white light source can be specified by CCT and chromaticity differences (D_{uv}). The D_{uv} measures the distance from the Planckian locus in the CIE 1976 chromaticity diagram i.e. CIE 1976 uniform chromaticity scale (UCS), also known as CIE (u', v'). Positive and negative D_{uv} values are located above and below the black body locus, respectively. [49]

2.2 LED SPDs realisation and LEDs in office lighting

In the beginning of the 2000's, experiments [9], [24], [44]–[48] were conducted to study subjective assessment of LED lighting in terms of the colour rendering property based on different criteria. The studies were done with light spectra realised by mixing RGB (red, green, and blue) LEDs. The LED light spectra were used as test sources and conventional light sources (fluorescent lamps, CFL or incandescent lamps) were used as reference sources. Some of the studies [9], [44]–[48] showed that CIE CRI did not describe visual colour rendering of LED light spectra well. Shakir & Narendran [24] investigated the acceptability of LED lighting and visual appearance of lit scenes at the illuminance of 25-35 lux. They found that lighting under the RGB LED spectrum was equal to or better than that under the reference lamp. Narendran & Deng [48] conducted a subjective study with different LED clusters at the illuminance of 200 lux and found that the observers preferred lighting under RGB LED clusters in terms of colour preference and reading tasks to that under reference source.

However, some [9], [44]–[47] of the above mentioned studies were done with a small number of observers (8-15). In some of the studies, the CCT difference between the reference and test lamp was large. There should be no difference [48] or the difference should be small [49] because the perceivable colour appearance difference [50] among the light sources of same CCT might affect the subjective evaluations. In some cases, the difference was about 615K at 4000K in the study done by Sándor & Schanda [47] and it was 1200K at 6500K in the studies done by Sándor *et al.* [46] and by Sándor & Schanda [47]. The difference was 1400K to 2800K in the studies done by Shakir & Narendran [24] and by Narendran & Deng [48]. None of the studies discussed D_{uv} values of the light spectra except the study by Schanda [45] but the D_{uv} values were outside of the allowed limit (±0.0054) [20].

On the other hand, challenges regarding RGB LED lighting were also stated. Studies done by Szabó *et al.* [51] and Viénot *et al.* [52] showed that RGB LED light spectra performed the worst compared to other light sources. The study by Szabó *et al.* [51] was conducted with different LED clusters to investigate the colour quality in terms of colour discrimination, colour rendering, colour preference, and colour harmony. According to nine observers' evaluations, the RGB LED cluster yielded the worst results. The RGB cluster had the lowest CIE CRI (R_a=38) values compared to the others (R_a=72-98). The study by Viénot *et al.* [52] was conducted with different LED clusters realised with different LEDs (Red, green, blue, amber, and cool white LEDs). It was recommended that RGB LED lighting should be avoided because the RGB LED clusters yielded poor colour discrimination compared to reference lamps. The RGB LED SPDs introduced deprivation of radiant energy in parts of the spectrum. Other LED clusters (D_{uv} values of two LED clusters were outside of the allowed limit) also impaired colour discrimination. All the LED clusters had much lower CIE CRI values and R_{a14} values than those of the reference lamp.

Improvement was made in realising LED SPDs by adding more LEDs to supplement missing parts of radiant energy in the spectrum. Studies by Mahler *et al.* [27] and Viénot *et al.* [53] showed that LED clusters, which included warm and cool white LEDs and other colour LEDs (red, green, blue, and amber), would render colours well. It was suggested [53] that by using a correct combination of the LEDs, it would be possible to achieve satisfactory performance in terms of the colour discrimination and colour appearance of the LED SPDs and thus to provide much more satisfactory lighting.

Viénot *et al.* [34], [54] conducted experiments with LED SPDs realised for very high CIE CRI values (R_a>90). Colour appearance (hue and brightness) and subjective feelings (such as brightness, visual comfort, and pleasantness etc.) were evaluated at the CCTs of 2700K, 4000K, and 6500K under different illuminance levels. It was found that pleasantness and visual comfort increased as the CCT decreased and brightness increased as the CCT increased at a given illuminance. However, the effects of LED SPDs and D_{uv} values of the LED SPDs were not discussed.

LED lighting was found to be quite positive in some visual subjective studies conducted in light booths. Studies by Boissard & Fontoynont [15] and Jost-Boissard *et al.* [16], [55] were conducted using different LED clusters realised as various combinations by mixing red, green, cyan, amber, and white (cool and warm) LEDs for different CIE CRI values. The LED SPDs including red, green, and white (warm or cool) LEDs were often preferred to fluorescent lamps in terms of colour rendering in the study by Jost-Boissard *et al.* [55]. It was possible to develop LED SPDs to provide a lit environment similar to fluorescent lamps. The LED SPDs were often preferred to fluorescent lamps and were well accepted in the study by Boissard & Fontoynont [15]. It was postulated in the study by Jost-Boissard *et al.* [16] that LEDs could be viable alternative to fluorescent lamps when the LED SPDs are realised correctly to provide white light. Thus, these positive outcomes could be considered as the base lines for the further studies in mock-up or real environments with LED lighting.

Yun *et al.* [29], [35] carried out experiments in a mock-up room with two LED SPDs at different illuminance levels to investigate the effects of SPDs on subjective appraisals of lighting. The subjective appraisals were done considering lighting aspects such as visual comfort, preference, brightness, and light colour along with other aspects. The SPDs played an important role in investigating subjective evaluation of lighting perception and the observers showed preference to the red-colour emphasizing SPD over the blue-colour emphasizing SPD. The effect of illuminance on the subjective appraisals of lighting was found to be dependent on the SPD of LED lighting. However, the colorimetric properties (CRI, CCT, and D_{uv} values etc.) of the SPDs were not discussed.

Few studies concerning LED lighting had been conducted in office environments and showed contradictory results about the subjective impression of LED lighting. Yi *et al.* [56] conducted a study in a university meeting room by replacing fluorescent lamps (4000K, R_a=85) with LED lamps (5300K, R_a=75). The observers were satisfied with the lit environment even though the illuminance of the LED lighting was 30% less than that of FL lighting. Yi *et al.* [56] also conducted a user preference study in laboratory conditions to compare lit scenes under LEDs and FL lamps in terms of visual comfort and reading activities. Though the lit environment under fluorescent lamps was preferred, skin and dress looked better in the lit environment under LED lighting. Regarding reading activities, LED lighting was acceptable. It was postulated that LED lighting might be acceptable in an office space. Studies by Thompson *et al.* [57], [58] were conducted with thirteen observers at 300 lux in an office environment in the lab by replacing FL lighting (3000K) with LED lighting (5000K). The LED SPDs were realised for the different CIE CRI values by tuning different LEDs. The LED lighting was found to be positive in terms of visual perception and office activities for the application of office lighting [57]. However, the collected data of these studies were not large (320) compared to the queries (1365).

A case study by Ryckaert *et al.* [59] was conducted in a small office room by replacing FL lamps with phosphor converted LED lamps. The visual appearance of the lit environment was assessed in terms of attractiveness, naturalness of skins and coloured objects as well as visual comfort, brightness, and attractiveness in the whole room. The LED replacement lamps had the CCT of 3400K (R_a=88), 4200K (R_a=90), 4700K (R_a=65) and the fluorescent lamps (R_a=84) had the CCT of 4100K. The illuminance levels under the fluorescent lamps were about 80% higher than those under the LEDs lamps. The lighting under the LED lamps was not quite compatible and well accepted for office lighting.

None of these studies (done in office or mock-up rooms) discussed the D_{uv} values of the spectra. Only the CIE CRI was either considered for realisation of the LED SPD or used as the colour rendering metric for the LED light sources used in the experiments.

2.3 Use of different colour rendering metrics

Ryckaert *et al.* [59] assessed user evaluation in a small office room considering the colour quality scale (CQS) and Memory Colour Rendering Index (MCRI) values of lamps. However, CQS or MCRI values did not show consistency with the subjective evaluations. The studies by Boissard & Fontoynont [15] and Jost-Boissard *et al.* [16] assessed user evaluations considering the CQS and/or gamut area index (GAI) values for different SPDs. The GAI [16] described the observers' judgment for objects' colour appearance well. On the other hand, it seemed that the CQS was better than the CIE CRI in expressing the colour quality of LED SPDs [15].

A study conducted by Ohno & Davis [60] used spectrally tuned LED SPDs at the illuminance levels of 800 lux (3000K and 4000K). The CQS and the CIE CRI were considered for the SPDs. Eight observers evaluated lit environments in terms of skin colour and appearance of objects in a real sized room which represented an office environment. The general CQS (Q_a) predicted the observers' preference better than the CIE CRI. The CQS supplementary metric Q_p

performed well as a preference metric for the visual evaluation of the lit environment and the supplementary metric Q_g correlated quite well with preference as long as the Q_g values of the LED light spectra were less than 100.

Lit scenes between warm CCTs (2850K, 3030K, and 3500K) and cool CCTs (5930K and 6100K) were compared at the illuminance level of 150 lux in the visual experiment done by Pousset *et al.* [38]. The observers compared the quality (good/not good) of observed colour of different samples under different LED lightings. The Q_a and Q_p did not show consistency with the preference for the quality of LED lighting and thus the CQS did not show satisfactory predictions for quality of LED lighting. The value of Q_g was not considered in the analysis.

Thus, different colour rendering metrics showed different results for LED light spectra regarding subjective preferences.

2.4 Preference of CCTs

The preferences of CCTs are strictly subjective and may also depend on geographical locations and culture along with other factors [61]. In Japanese offices [2] light sources with 5000K are widely used, whereas light sources with 4200K are usually used in U.S. offices [62].

Subjective judgements and preferences for CCTs showed considerable inter-observer variation in the study done by Schröder [63]. The illuminance of 500 lux was found to be significantly more comfortable than the illuminance of 1000 lux at 3000K but there was no significant difference at 6000K. The warm CCT (3000K) was more preferred to the cool CCT (6000K) at both illuminance levels in terms visual comfort. The study done by Hu *et al.* [32] showed that observers would prefer to work under light sources with a lower CCT (3500K) than to work under a higher CCT (6500K). The CCT of 3500K was judged to be more comfortable and satisfying than the CCT of 5000K in the study by Wei *et al.* [41] and the lit environment of an office space (at 500 lux) at 3500K (R_a=82) was rated higher (for preference) than at 6500K (R_a=98) [64]. Shamsul *et al.* [40] found that the CCT of 4000K was most preferred and most comfortable over the CCTs of 3000K and 6500K. Kang *et al.* [28] found that observers preferred the lit environment under the CCT of 4000K for visual comfort over those under the CCTs of 3000K and 6500K. DeLaney *et al.* [65] found that lit environments at 4200K were mostly preferred to those at 3000K. A study done in office space at 3000K, 4000K, 5000K, and 6000K by Park *et al.* [66] showed various results. In an office experiment, 4000K was most preferred, whereas 5000K was chosen to be a suitable CCT for an office space and 3000K was found to be most comfortable. When preference was assessed in terms of comfort and spaciousness, 4000K was preferred to 2700K in the study done by Manav [67]. Cockram *et al.* [68] found that people preferred the CCT of 4300K for office work over the CCT of 6500K. Thus, different studies showed different CCT preferences. These above mentioned studies were done with fluorescent lamps.

The difference in spectral distribution of LEDs compared to fluorescent lamps, might affect not only the visual perception, but also the well-being and performance of people [19]. User preferred CCT may be one of the essential factors for the preference and acceptability of the LED lighting. However, few studies have been conducted in mock-up rooms or offices for the preference of CCT when LED lighting was implemented.

The experiment done by Spaulding *et al.* [69] in an office-like booth used four lighting conditions: LED spectra at 3500K and 4500K with R_a=90, T8 FL 4100K with R_a=85 and T8 FL 4100K combined with an incandescent table lamp. The lit environment under the FL 4100K combined with an incandescent table lamp was rated to be the most comfortable and the FL 4100K was rated to be most pleasant. Huang *et al.* [70] conducted a study with LED lamps (in a class room) with the CCTs 2700K, 4300K, and 6500K at 500 lux. The CCT 4300K was preferred to the CCTs of 2700K and 6500K in terms of working attention.

Lin *et al.* [71] conducted experiments in which eight observers performed four office-like tasks and did visual assessment under LED lightings at the CCTs of 3000K, 4000K, 5000K, and 7000K at 600 lux. The observers preferred the CCT of 4000K and 7000K in terms of brightness and visual comfort. It was suggested that 4000K or the combination of 4000K and 7000K might be the best CCT setting for office workers. Ono *et al.* [2], [72] had eleven observers evaluating LED lighting in an office environment. The observers could choose between illuminance levels and CCT in the illuminance range of 300 lux to 900 lux and CCT range of 2900K to 5700K, respectively. The users preferred the CCT range from 3000K to 5500K. However, colour temperature in the range of 3500K to 4000K was often selected by the users. Thus, the result indicated that there might be a certain range of the preferred colour temperature for office workers.

3. Users' preference studies in lighting booth

3.1 Introduction

The quality of a light source is highly dependent on its colour characteristics and end-users will not accept highly energy efficient light sources with poor colour quality [3]. Therefore, a lighting booth experiment was carried out as the first phase of the user acceptance study to find out user preferences, requirements, and expectations for office lighting with different realised LED SPDs. As the CIE CRI is not well-suited for white LED light spectra [15]–[17], other proposed metrics were also considered in realising the LED light spectra for the experiment. Sixty observers assessed the visual appearance of different lit scenes in a lighting booth in terms of brightness, visual comfort, pleasantness, and interest along with other aspects related to colour quality.

3.2 Experimental set up

A booth with three sections was built in a dark room. The middle section of the booth had a fluorescent luminaire, while the left and right sections of the booth had LED luminaires (Figure 1).

Figure 1. The booth with a different light source in each section: LED luminaires in the left and right, and fluorescent lamp luminaire in the middle

Diffuse grey paint (IN2–NCS-S2500N) was used to coat the inner surfaces of the booth to maintain the reflectance of the inner surfaces at 50%. A chair rail was set up so that a constant distance of 55–60 cm could be maintained between the observer's eyes and the centre of each section of the booth. Two LED luminaires were made with LED panels consisting of twelve LED strings of different types and each string had nine LEDs connected in series. Each LED type was controlled by PC DMX/RDM USB interface software and a 24 channel DMX/RDM compatible power supply unit. The master dim function of the power supply unit was used to control the light output of the LED luminaires. A Plexiglas GS WHO2 diffuser was used beneath the LED panel to provide homogeneous illumination at the base of each section of the booth. The fluorescent lamp (circular fluorescent lamps Osram FC 40W) luminaire was constructed by using electronic ballast (Helvar EL 1X39 SC). The average horizontal illuminance on the base plane of each section of the booth was maintained between 460 lux and 470 lux with the help of DMX control for LED SPDs and a dimmer (Osram HF DIM P MCU) for fluorescent lamps. Under the LED SPDs, the illuminance uniformity was around 0.85 and under the fluorescent lamps it was around 0.80.

3.3 Spectral power distribution of LEDs

Twenty-one different LED spectra (seven spectra at each CCT) were realised for various combinations of the CIE CRI and three proposed colour rendering metrics: Colour Quality Scale (CQS) [73] Gamut Area Scale (Q_g), CQS Colour Preference Scale (Q_p) and Feeling of Contrast Index (FCI) [74]. The criteria (Table 1) for all seven LED SPDs at a particular CCT were kept the same. The CIE CRI was used to realise the LED SPDs despite its limitations as it is the only internationally recognized metric for measuring and specifying the colour rendering properties of light sources. The CQS Q_p rewards light sources that increase the chroma effect and the CQS Q_g is related to increased colourfulness and preference [73]. The metric FCI is also related to gamut area. However, it is claimed that by using the FCI together with the CIE CRI, the colour-rendering capability of a light source can be well-defined and clarified [74]. The perceived chroma of object colour increases under illumination of a light source with a high FCI value, and the brightness sensation should become high [74].

Table 1. Different criteria considered for realisation of LED SPDs at three CCTs; 2700K, 4000K, and 6500K

SPDs	Criteria/properties
SPD 1	Very high value of CRI (> 95)
SPD 2	High Q_g value (115-119) and R_a= 80
SPD 3	High FCI value (135) and R_a= 80
SPD 4	Low FCI value (89-93) and R_a= 80
SPD 5	High Q_p value (around 100) and R_a= 80
SPD 6	Low Q_p value (72-76) and R_a= 80
SPD 7	Mimic to fluorescent lamps regarding Q_p, Q_g, FCI value and CIE CRI

The values of the chromaticity differences (D_{uv}) for different LED SPDs were kept below the recommended value of 0.0054 [20]. The values of metrics Q_p and Q_g of all SPDs were calculated by using Excel-based software version 7.5 (CQS 7.5) provided by the US National Institute of Standards and Technology

(NIST). A new version of CQS (CQS 9.2) was also used to calculate those values. The GAI and FCI values of all SPDs were also calculated. Measurement of spectra was carried out with spectrophotometer Konica-Minolta CS 2000. The display wavelength bandwidth of the spectrophotometer was 1 nm and the spectral bandwidth was 5 nm in the range of 380 to 780 nm. Table A1 in Appendix A [I] shows the measured colorimetric characteristics of eight spectra at 2700K, 4000K, and 6500K.

3.4 Methods

3.4.1 Observers

Altogether 60 observers with normal vision participated in the experiment. There were 20 male and 20 female observers aged 20 to 40 years (average age 25.5 for male and 24.6 for females), and 10 male and 10 female observers aged 50 to 65 years (average age 56.1 for male and 54.9 for females). All the observers were tested for visual acuity (with or without glasses) and colour vision before they took part in the experiment. None of the observers had a background in the lighting field.

3.4.2 Questionnaire

The questionnaire used in the experiment had two parts (see Appendix B [I]): (i) individual evaluation and (ii) comparison evaluation. The individual evaluation referred to viewing a single section of the booth at a time and rating the lit scene in that section. For individual evaluation, the observers expressed their assessment by putting a mark on a continuous line scale in the questionnaire. There were questions related to visual appearance and visual perception of the lit scene in the booth and about the naturalness and colourfulness of the selected objects shown in the booth. Seven different objects were selected to be assessed in terms of naturalness and colourfulness: a coloured picture, a Macbeth Colour Checker (MCC) chart, a sample of wood, a smartphone, a Coke can, a hand (skin), and a printed text. They were selected to represent different objects and colours found in a typical office.

Questions related to visual appearance mainly dealt with brightness (dim/bright), visual comfort (uncomfortable/comfortable), pleasantness (unpleasant/pleasant), and boredom (boring/interesting) of the lit scene in the booth under different SPDs. In the comparison evaluation, the observers compared the naturalness of objects and lit scenes in terms of overall preference under LED SPDs in the right section of the booth and under fluorescent lamps in the middle section of the booth.

3.4.3 Evaluation sessions

Each observer evaluated 24 lit scenes (7 LED SPDs x 3 CCTs and 1 Fluorescent lamp x 3 CCTs). The observers participated in six different sessions (two sessions at each CCT) on six different days. At the beginning of each session, the observers were given five minutes to adapt to the lighting conditions in a single section of the booth.

During the first session, the observers answered different questions presented in the questionnaire and judged four lit scenes under different SPDs for individual evaluation, and performed the side-by-side comparisons between the lit scenes under the LED SPDs and the fluorescent lamp SPD at a particular CCT. Whenever the LED spectrum in the section was changed, the observers were asked to wait four minutes so that the lit scene under the LED spectrum could stabilise and the observer could adapt to the new lit scene. During the time of individual evaluation, other sections of the booth were either covered with black curtain or switched off. During the second session, the same procedure as in the first session was followed at that particular CCT. During the second session at that particular CCT, a reverse comparison (detailed information about the reverse comparison can be found in publications [I, II] was also done between the lit scenes under one of the LED SPDs and under the fluorescent lamp. On average, the observers took about 40 minutes to finish each session. The same procedure was performed for the other two CCTs.

3.5 Results and statistical analysis

For the statistical analysis, the marked ratings in every question were measured and converted into a range of values between -3 and 3. The statistical analysis for the converted data was performed using the Statistical Package for the Social Sciences (SPSS) version 20. For individual data analysis, analysis of variance (ANOVA) was used with a significance level of p=0.05.

3.5.1 Preference of SPDs

For ANOVA analysis, the different SPDs were considered as the independent variables, whereas the ratings of the observers were considered as dependent variables. After one-way ANOVA analysis, *post-hoc* analysis was performed using the Duncan procedure to find out which SPDs the observers preferred. The differences in the observers' mean ratings were statistically significant for all questions about the visual appearance of the lit scene in the lighting booth under all SPDs at 2700K, 4000K, and 6500K. Table 2 shows the mean ratings and the results of the statistical analysis for the questions related to visual appearance of the lit scenes at the three CCTs. Overall, it was found that the observers preferred SPD2, SPD5, and SPD8 in most cases for the visual appearance of the lit scenes, whereas SPD4 and SPD6 were least preferred. The mean ratings under SPD2 were the highest in most cases.

Table 2. The mean observer ratings and *p*-values for different questions related to visual appearance of lit scenes in booth under different SPDs.

CCT K			SPD1	SPD2	SPD3	SPD4	SPD5	SPD6	SPD7	SPD8	*p*-value
2700	Bright/Dim	Mean	0,43	**1,40***	0,65	*-0,16*	0,79	*0,23*	**1,01**	0,76	<0,001
		SD	1,43	1,08	1,41	1,34	1,29	1,32	1,08	1,23	
	Comfortable/ Uncomfortable	Mean	*0,65*	**1,38***	*0,62*	*0,27*	**1,20**	*0,41*	**1,15**	**1,19**	<0,001
		SD	1,46	0,91	1,23	1,37	1,06	1,41	1,25	1,14	
	Pleasant/ Unpleasant	Mean	*0,70*	**1,29***	*0,60*	*0,28*	**1,06**	*0,32*	**1,08**	**1,14**	<0,001
		SD	1,45	0,98	1,35	1,40	1,24	1,39	1,34	1,09	
	Interesting/ Boring	Mean	*0,41*	**1,09***	*0,43*	*0,09*	**0,68**	*0,19*	**0,70**	**0,70**	<0,001
		SD	1,33	1,10	1,22	1,36	1,33	1,33	1,09	1,10	
4000	Bright/Dim	Mean	1,14	**1,65***	*0,87*	*0,55*	**1,53**	*0,69*	*0,72*	**1,52**	<0,001
		SD	1,29	1,02	1,43	1,46	1,00	1,27	1,24	1,00	
	Comfortable/ Uncomfortable	Mean	**1,38**	**1,37**	*0,80*	*0,68*	1,14	*0,95*	*0,93*	**1,51***	0,001
		SD	1,14	1,02	1,24	1,24	1,55	1,26	1,18	1,10	
	Pleasant/ Unpleasant	Mean	**1,28**	**1,38**	*0,77*	*0,52*	**1,12**	0,95	*0,79*	**1,43***	<0,001
		SD	1,24	0,98	1,27	1,42	1,47	1,27	1,20	1,08	
	Interesting/ Boring	Mean	**0,92**	**1,22***	*0,48*	*0,20*	**0,97**	*0,46*	*0,42*	**1,16**	<0,001
		SD	1,32	1,09	1,41	1,36	1,16	1,13	1,35	0,96	
6500	Bright/Dim	Mean	1,23	**1,74***	1,20	*0,65*	**1,63**	*0,65*	*0,91*	**1,48**	<0,001
		SD	1,20	0,97	1,17	1,49	1,02	1,34	1,33	1,10	
	Comfortable/ Uncomfortable	Mean	0,94	0,93	1,02	*0,74*	**1,32**	*0,54*	*0,78*	**1,40***	0,006
		SD	1,44	1,32	1,28	1,40	1,23	1,47	1,23	1,15	
	Pleasant/ Unpleasant	Mean	**1,02**	**0,89**	**1,06**	*0,62*	**1,28**	*0,25*	*0,67*	**1,41***	<0,001
		SD	1,25	1,35	1,26	1,43	1,24	1,53	1,31	1,09	
	Interesting/ Boring	Mean	**0,73**	**0,97**	**0,98**	*0,45*	**1,08***	*0,24*	*0,42*	**1,08***	<0,001
		SD	1,31	1,13	1,12	1,32	1,23	1,45	1,18	1,09	

SPD1 to SPD7 are LED spectra and SPD8 is fluorescent lamp SPD
Bold= the mean values for the SPDs which were in the group with the highest mean value in the Duncan test.
Bold*= the mean ratings which were highest among the mean ratings for a particular question.
italic= the mean ratings for the SPDs which were in the group with the lowest mean value in the Duncan test.

3.5.2 Preference of CCTs

For one-way ANOVA analysis, CCT was considered as the independent variable. After ANOVA analysis, *post-hoc* analysis was performed using the Duncan procedure to investigate which CCT the observers preferred. The differences in the means of the observers' ratings were statistically significant (Table 3) at three CCT levels in the case of the visual appearance of the lit scenes in the lighting booth under different SPDs. For the questions bright/dim and interesting/boring about the lit scenes, CCT 2700K was least preferred and in the both cases the mean ratings were the highest at 6500K. For the questions related to visual comfort and pleasantness about the lit scenes, the observers' mean ratings (highest among the observers' ratings) at 4000K were statistically higher than those at CCT 2700K. Overall, CCT 2700K was least preferred among the CCTs.

Table 3. The mean observer ratings and *p*-values for different questions related to visual appearance of lit scene in booth at different CCTs.

Questions		2700K	4000K	6500K	*p*-value
Bright/Dim	Mean	0,64	**1,08**	**1,19***	<0,001
	SD	1,35	1,28	1,27	
Comfortable/ Uncomfortable	Mean	0,86	**1,10***	<u>**0,96**</u>	0,016
	SD	1,29	1,24	1,34	
Pleasant/ Unpleasant	Mean	0,81	**1,03***	<u>**0,90**</u>	0,033
	SD	1,33	1,28	1,35	
Interesting/ Boring	Mean	0,54	**0,73**	**0,74***	0,019
	SD	1,26	1,28	1,26	

Bold= the mean values for the CCTs which were in the group with the highest mean value in the Duncan test.
Bold*= the mean ratings which were highest among the mean ratings for a particular question.
<u>**Bold**</u> = the mean ratings for the CCT which was in the both groups.

3.6 Summary

The statistical analyses showed that overall (considering all three CCTs), the observers preferred the lit scenes under SPD2 (high Q_g value), SPD5 (high Q_p value) and SPD8 (fluorescent lamp) in terms of visual brightness, visual comfort, pleasantness, and boredom (interesting/boring). On the other hand, SPD4 (low FCI value) and SPD6 (low Q_p value) were least preferred. The mean ratings under SPD2 were the highest in most cases. When the preference of CCT was analysed, it was found that overall, CCT 2700K was the least preferred among the CCTs. However, CCT 4000K was found to be more comfortable and more pleasing whereas, 6500K was found to be brighter than the other CCTs.

The findings provided the basis for the second phase of the user acceptance studies conducted in office rooms.

4. User preference studies in office rooms

4.1 Introduction

For the second phase of the user acceptance studies, an experiment was designed in two office rooms, one illuminated with LED luminaires and the other with fluorescent lamp luminaires. The objective of the study was to find out users' preferences and expectations for lighting by investigating the interrelations between SPDs, spatial brightness, and illuminance levels.

In this phase of the study, different LED spectra were optimised at the CCTs of 4000K and 6500K by considering three different proposed colour rendering metrics as well as the CIE CRI. Light source SPD can affect the perception of spatial brightness. The spaces illuminated by different light spectra at the same illuminance might appear differently bright [25], [75]. People prefer a lit environment which looks bright [76], [77]. Thus, subjective assessment of spatial brightness is an important aspect for user acceptance of LED lighting in an office environment. Spatial brightness can be affected by illuminance as well [75]. Reductions in illuminances reduce energy consumption. However, it is important that the observers are able to perform their work in an office environment, feel comfortable and accept the lit environment of the entire room at the specific illuminance level. The subjective evaluation of the lit environments under different light spectra was assessed by considering different lighting aspects such as spatial brightness, glare, spaciousness, visual comfort, and pleasantness of colour of light along with others. This work employed two illuminance levels (500 lux and 300 lux) at two different CCTs. The observers assessed the lit environments while doing different office-related tasks.

4.2 Experimental set up

4.2.1 Experimental rooms

Two identically furnished office rooms (Figure 2) were prepared for conducting the studies. Both rooms had a floor area of 14.5 m^2 and the height of the ceiling was 2.45 m. The walls of the room were painted white and the surface reflectance was 82%. The reflectance values of the ceiling and floor were 85% and 28%, respectively. The temperature inside the rooms was kept at 22-23˚C with the help of a ceiling-mounted air-conditioning unit in both rooms. Black plastic films were used in the windows to block any daylight from entering the rooms. These black plastic films were covered by venetian blinds in the windows of both rooms. The two rooms were furnished identically with different objects (Figure 2) found in a typical office room.

a) b)

Figure 2. Views of the experimental room in different directions a) view from the door and b) view towards the door

4.2.2 Luminaires

One of the experimental rooms was equipped with six ceiling-mounted LED luminaires and the other with six ceiling-mounted fluorescent lamp luminaires. Eight T5 fluorescent lamps were installed in each fluorescent lamp luminaire: four LUMILUX T5 HO 24 W/840 (4000K) lamps and four LUMILUX T5 HO 24 W/865 (6500K) lamps. The lamps of a particular CCT were driven by one Electronic Control Gear (ECG). Each LED luminaire was built with the help of an LED-based SPD simulator system (LED Simulator). The LED simulator had three main components:

- LED Panels-20-channel LED Panels (LightingMetrics Kft.)
- Interface-PC DMX/RDM USB Interface (Dezelectric Kft.)
- Power Supply Unit (PSU)-24-Channel DMX/RDM Compatible PSU

The LED panel of the LED Simulator had 20 different LED types (with 20 different peak wavelengths) and 24 LEDs per LED type (with the same peak wavelength). The LED panels in the LED luminaires and the lamps in the fluorescent luminaire were concealed by Plexiglas GS WHO2 diffusers in order to get homogeneous illumination in the room. All six LED luminaires were controlled by PC DMX/RDM USB Interface software from a computer placed in the driver cabinet.

Different lighting environments were designed for two illuminance levels (500 lux and 300 lux) under each SPD at the CCTs of 4000K and 6500K. The room with the fluorescent lamp luminaires had four lighting environments [(1 fluorescent lamp SPD x 2 CCTs) x 2 light levels]. The room with LED luminaires had twelve lighting environments [(3 LED SPDs x 2 CCTs) x 2 light levels]. The illuminance uniformity was around 0.80 under LED lighting and around 0.85 under fluorescent lamp lighting at both illuminance levels.

4.2.3 SPDs of LEDs and fluorescent lamps

Six different LED spectra (three spectra at each CCT) and two fluorescent lamp SPDs (one spectrum at each CCT) were used in the experiment. The LED spectra were realised based on the findings of the light booth experiments. The LED spectra were optimised for various combinations of the CIE CRI and the proposed colour rendering metrics: the CQS Q_g, the FCI, and the CQS Q_p.

SPD1 was realised for high Q_p and high Q_g values and it had negative D_{uv} value. SPD2 was realised for high Q_p and high Q_g values and it had positive D_{uv} value. SPD3 was realised to have the similar colour characteristics of SPD1 in terms of R_a, Q_a, Q_p, and Q_g values. SPD1 was realised with eleven LED types. SPD3 was simplified using only three types of LEDs and had negative D_{uv} value. This simplified SPD (SPD3) was realised by using red, mint white and blue LEDs with peak wavelengths of 658 nm, 639 nm, and 448 nm, respectively. These SPDs were realised at 4000K.

SPD4 was realised at 6500K for high Q_p and high Q_g values. SPD5 was realised for medium FCI value, and comparatively lower Q_p and lower Q_g values than those of other SPDs at 6500K. SPD6 was realised for medium FCI, high Q_p and high Q_g values. The LED SPDs at 6500K were realised with negative D_{uv} values.

The measured colorimetric characteristics of the eight spectra (SPD1 to SPD6 are LED spectra and SPD7 and SPD8 are fluorescent lamp SPDs) can be found in publications [III, IV]. The value of chromaticity difference (D_{uv}) for all LED SPDs was kept within the recommended value of ± 0.0054 [20].

4.3 Methods

4.3.1 Observers

Forty observers with normal vision took part in the experiment. There were ten male and ten female observers aged 20 to 30 years (average age 22 for male and 25.8 for females), and ten male and ten female observers aged 50 to 60 years (average age 57 for male and 54.9 for females). All the observers were tested for visual acuity (with or without glasses) and colour vision. The observers were either students or employees of Aalto University, and none of them had a background in the field of lighting.

4.3.2 Questionnaire

The questionnaire used in the experiment was adapted from questions of previous studies [78]–[81] and from the first phase [I] of the user acceptance studies. The questionnaire was developed to investigate various aspects of office lighting such as spatial brightness, colourfulness and naturalness of selected objects, and glare at a working desk and at a meeting table. There were also questions related to overall room evaluation such as overall pleasantness, overall visual comfort, spaciousness, attractiveness, acceptance as well as overall preferences for the lighting. The response scale of the questions in the questionnaire was a seven-point rating scale.

In this work, four questions [III] were considered for evaluating the lighting after a computer task and a reading task at the working desk as well as the reading task at the meeting table. They were related to spatial brightness (dim/bright), the amount of light (more-light/less-light), glare (glare/no-glare) and the difficulty (difficult/easy) of the computer/reading task under a lighting condition. Four questions were considered for evaluating the overall lighting environment in the entire room. They were related to pleasantness of colour of light, overall comfort, spaciousness and overall acceptance.

4.3.3 Evaluation sessions

Each observer evaluated altogether sixteen lighting environments [(3 LED SPDs x 2 CCTs) x 2 light levels) and (1 fluorescent lamp SPD x 2 CCTs) x 2 light levels] in sixteen sessions. One session consisted of one lighting environment.

a) b)

Figure 3. Observers performing the reading task, a) at the desk, b) at the meeting table

At the start of the session, the observers adapted to the lighting environment for five minutes by sitting at the meeting table. After the adaptation, the observer performed a computer task for about five minutes. The task was to compare two columns of random numerical codes consisting of five numbers, and to find and select the adjacent numerical codes with unequal numbers. After finishing the task the observer filled in the questionnaire about the lighting conditions during the computer task.

The reading task at the desk (Figure 3a) was to read a Times New Roman text of font size 12 point on an A4-sized paper (one page). The observers were given about four minutes to read the text, find the mistakes, and underline them. After completing the reading task, the observers filled in the questionnaire about the lighting condition during the reading task. After this they were asked to read one line of Times New Roman text of font size 6 point and to respond whether they could read it or not. After this, the lighting environment at the desk was evaluated for visual appearance.

The observers then moved to the meeting table (Figure 3b) and were asked to read an article in a magazine for four minutes. After reading the magazine, the observers filled in the questionnaire about the lighting condition they experienced during this reading task. They then evaluated the lighting environment at the meeting table for visual appearance. At the end of the session, the observers rated the overall lighting environment while sitting at the meeting table. The session ended by writing comments (if they had any) about the lighting environment. The same procedure was followed for the rest of the sessions. The duration of one session was about thirty minutes. The first lighting environment as well as the subsequent ones for each observer was chosen randomly.

4.4 Results and statistical analysis

The observers' ratings were converted into numerical values on a seven-point scale between -3 and 3. For data analysis, ANOVA (SPSS IBM version 21) was used with a significance level of 0.05.

4.4.1 Statistical analysis for different SPDs and illuminances

A two-way ANOVA was performed by considering the SPD and illuminance as the independent variables and the mean rating as the dependent variable. The two-way ANOVA showed that there was no significant interaction between the illuminances and the SPDs. Therefore, ANOVAs were performed for the main factors, SPD and illuminance level. A *post-hoc* analysis was performed using the Duncan procedure to investigate under which SPDs the observer mean ratings were significantly different, and thus to find out the most preferred lighting environment.

4.4.1.1 Statistical analysis for different SPDs at 4000K

The results of the statistical analysis (Two-way ANOVA) for different SPDs are presented in Table 4. The mean ratings for different lighting environments under SPD1 and SPD3 were statistically significantly higher than those under SPD7 regarding the questions related to spatial brightness for the reading task at the desk and at the meeting table. The mean ratings under SPD1, SPD2, and SPD3 were statistically significantly higher than those under SPD7 for the question related to the spaciousness of the entire room. As the mean ratings for different questions under SPD1 were the highest among the mean ratings (in most cases) under all LED SPDs and the lowest under SPD7 (Table 4), an ANOVA was performed to investigate the statistical difference in the mean ratings of lighting environments under SPD1 and SPD7.

For the reading tasks at the desk and meeting table, the mean ratings under SPD1 were statistically significantly higher than those under SPD7 regarding the questions dim/bright and difficult/easy. The same was found for the questions related to the overall spaciousness and overall acceptance of the lighting environment in the entire room.

Table 4. The mean observer ratings and *p*-values found in two-way ANOVA for different questions and different SPDs at 4000K.

Place of evaluation	Terms used in questions		SPD7	SPD1	SPD2	SPD3	*p*-value
Computer task at desk	Dim/bright	Mean	0.69	0.90	0.94	0.92	0.685
		SD	1.48	1.47	1.53	1.5	
	Light amount	Mean	-0.35	-0.29	-0.36	-0.34	0.938
		SD	0.93	0.71	0.78	0.75	
	Glare/no-glare	Mean	1.60	1.63	1.58	1.66	0.985
		SD	1.42	1.5	1.55	1.45	
	Difficult/easy	Mean	1.10	1.52	1.46	1.49	0.256
		SD	1.47	1.41	1.38	1.30	
Reading task at desk	Dim/bright **	Mean	*0.33*	**0.83**	0.65	**1.04***	0.016
		SD	1.57	1.59	1.60	1.42	
	Amount of light	Mean	*-0.66*	-0.41	-0.62	-0.35	0.054
		SD	0.83	0.93	0.79	0.80	
	Glare/no-glare	Mean	1.54	1.94	1.65	1.83	0.283
		SD	1.53	1.32	1.49	1.30	
	Difficult/easy	Mean	1.00	1.49	1.34	1.38	0.202
		SD	1.52	1.57	1.49	1.56	
Reading task at table	Dim/bright **	Mean	*0.69*	**1. 32***	0.91	**1.23**	0.015
		SD	1.58	1.43	1.58	1.32	
	Amount of light	Mean	-0.51	-0.39	-0.48	-0.31	0.345
		SD	0.87	0.76	0.83	0.79	
	Glare/no-glare	Mean	1.35	1.48	0.91	1.19	0.061
		SD	1.51	1.46	1.71	1.66	
	Difficult/easy	Mean	1.20	1.64	1.31	1.38	0.278
		SD	1.58	1.40	1.47	1.56	
Overall room	Light colour pleasantness	Mean	0.64	1.21	0.98	1.10	0.100
		SD	1.67	1.68	1.56	1.44	
	Comfort	Mean	0.83	1.20	1.05	1.13	0.342
		SD	1.47	1.40	1.51	1.33	
	spaciousness **	Mean	*0.31*	**0.98***	**0.91**	**0.93**	0.007
		SD	1.29	1.49	1.23	1.26	
	Acceptance	Mean	0.27	0.80	0.55	0.71	0.110
		SD	1.61	1.41	1.39	1.45	

SPD1, SPD2 and SPD3 are LED spectra and SPD7 is fluorescent lamp SPD

** The differences of mean ratings were statistically significant (at 0.05 significance level) for different SPDs.
Bold= the mean values for the SPDs which were in the group with the highest mean value in the Duncan test.
Italic= the mean ratings for the SPDs which were in the group with the lowest mean value in the Duncan test.
Underline= the mean ratings for the SPDs which were in both groups.

Though the mean ratings for SPD3 and SPD1 (Table 4) were in the same group after the Duncan procedure, the mean ratings under SPD1 were higher in most cases. It was also found that the lighting environments under SPD3 were preferred to those under SPD7. Thus, it can be inferred that in terms of the aspects/questions discussed above the observers preferred the lighting environment under SPD1 the most and lighting environments under SPD7 the least at the CCT of 4000K.

4.4.1.2 Statistical analysis for different SPDs at 6500K

According to the ANOVA, there were no statistically significant differences in the mean ratings for any of the questions under different SPDs at 6500K. However, small differences were observed between the ratings.

4.4.1.3 Statistical analysis for different illuminances at 4000K

The mean ratings at 500 lux were statistically significantly higher (Table C3 in Appendix C [III]) than those at 300 lux for the question more-light/less-light for the computer task. For the reading task at the desk and the meeting table, the mean ratings at 500 lux were statistically significantly higher than those at 300 lux for the questions regarding dim/bright, more-light/less-light, and easy/difficult. The mean ratings at 500 lux were statistically significantly higher than those at 300 lux for the questions related to overall comfort, spaciousness, and overall acceptance of lighting environment in the entire room. Thus, the illuminance of 500 lux was preferred to 300 lux at 4000K.

4.4.1.4 Statistical analysis for different illuminances at 6500K

The mean ratings at 500 lux were statistically significantly higher (Table C3 in Appendix C in the publication [III]) than those at 300 lux for the questions regarding dim/bright, more-light/less-light, and easy/difficult for the computer and reading tasks. The mean ratings at 500 lux were statistically significantly higher than those at 300 lux for questions related to overall comfort, spaciousness and overall acceptance of the lighting environment of the entire room. Thus, the observers preferred the lighting environments at 500 lux to 300 lux at 6500K.

4.4.2 Statistical analysis for different CCTs

As the two-way ANOVA showed that there was no significant interaction between the CCT and SPDs, all SPDs (of the same CCT) were considered together for the analysis of CCT. A one-way ANOVA was performed to investigate the statistical significance of the observer's mean ratings for a particular question, considering CCT as independent variable irrespective of the SPD at illuminances of 500 lux and 300 lux.

4.4.2.1 Statistical analysis for illuminance of 500 lux

After the ANOVA analysis, it was found (Table 5) that the mean ratings under CCT of 4000K were statistically significantly higher than those under CCT of 6500K regarding the pleasantness of light colour, overall comfort, and overall acceptance of lighting in the entire room. The trend in the mean ratings for questions related to spatial brightness, amount of light and overall room spaciousness was that the means were higher at 6500K than those at 4000K under illuminance level of 500 lux for the computer and reading tasks. However, these differences were not statistically significant. It can be inferred that the observers' preferred the CCT 4000K over 6500K at 500 lux in terms of the lighting environment assessment in the entire room.

Table 5. The observer mean ratings for different questions and different SPDs at two CCTs (4000K and 6500K)

Place of evaluation	Terms used in questions		4000K	6500K
Computer task at desk	Brightness	Mean	0.97	<u>1.09</u>
		SD	1.50	1.53
	Amount of light	Mean	-0.24	<u>-0.09</u>
		SD	0.80	0.90
	Glare/no-glare	Mean	***1.64***	1.49
		SD	1.47	1.67
Reading task at desk	Brightness	Mean	1.27	<u>1.44</u>
		SD	1.38	1.40
	Amount of light	Mean	-0.24	<u>-0.12</u>
		SD	0.76	0.88
	Glare/no-glare	Mean	***1.69***	1.51
		SD	1.45	1.41
Reading task at table	Brightness	Mean	1.56	<u>1.65</u>
		SD	1.26	1.32
	Amount of light	Mean	-0.18	<u>-0.17</u>
		SD	0.67	0.86
	Glare/no-glare	Mean	***1.23***	0.93
		SD	1.55	1.78
Overall room	colour of light	Mean	**1.42***	1.03
		SD	1.40	1.64
	comfort	Mean	**1.46***	0.95
		SD	1.29	1.64
	Spaciousness	Mean	1.11	<u>1.23</u>
		SD	1.25	1.27
	Acceptance	Mean	**1.23***	0.71
		SD	1.48	1.84

Bold* mean values are statistically significantly higher at 4000K than the mean values at 6500K (at 0.05 significance level)
Bold Italic mean values are higher at 4000K than the mean values at 6500K
<u>Underline</u>= the mean ratings are higher at 6500K than the mean values at 4000K

4.4.2.2 Statistical analysis for illuminance of 300 lux

No statistically significant differences were found in the ratings between 4000K and 6500K under any of the SPDs at 300 lux. However, in most cases, the mean ratings were slightly higher at 4000K than those at 6500K. On the other hand, the mean ratings were slightly higher at 6500K than those at 4000K for the questions related to brightness and spaciousness.

4.4.3 Reading performance of text with 6 point font size

All the observers were able to read the printed text of Times New Roman font size 6 points in all lighting conditions and thus these lighting environments met the criteria of good quality lighting for visibility at 500 lux and 300 lux.

4.5 Summary

The observers preferred the lit environment under the SPD1 the most in terms of the questions related to spatial brightness and spaciousness at 4000K. On the other hand, they preferred the lit environment under fluorescent lamp (SPD7) the least among all the SPDs at the CCT of 4000K. However, there were no statistically significant differences between the mean ratings of the lighting environments under different SPDs at the CCT of 6500K.

All the observers were able to read the printed text of Times New Roman font size 6 points in all lighting conditions at 500 lux and 300 lux. However, the illuminance of 500 lux was preferred to 300 lux at CCTs of 4000K and 6500K for the questions related to spatial brightness, overall spaciousness, and overall comfort along with other questions.

The CCT of 4000K (neutral white) was preferred to the CCT of 6500K (cool white) in terms of lighting assessment regarding the pleasantness of light colour, overall comfort and overall acceptance of lighting in the entire room at 500 lux. No statistically significant differences were found in the ratings between 4000K and 6500K under any of the SPDs at 300 lux.

Spatial brightness played important role in the preference and acceptance of the light spectra in an office environment.

5. Discussion

5.1 Lighting booth experiment

The observers preferred the SPDs (SPD2, SPD5, and SPD8), under which the lit scenes looked brighter and the lit scenes were more comfortable, more pleasant, and more interesting than those under the other SPDs. The preferred SPDs were florescent lamp SPD (SPD8) and LED SPDs realised for high Q_g (SPD2) or for high Q_p (SPD5) values. On the other hand, LED SPD realised for low FCI (SPD4) or for low Q_p (SPD6) values were the least preferred.

The chroma and the colourfulness values of the objects and colours were the highest [I] in the lit scenes under SPD2 and SPD5 and were the lowest under SPD4 and SPD6. Furthermore, the objects looked more natural and the MCC chart looked more colourful under these SPDs (SPD2 and SPD5) as well [I]. SPD8 had either negative D_{uv} values or the D_{uv} values of SPD8 lay closer to the black body locus than those of the SPD3. The D_{uv} values could be the possible reason why SPD3 was not preferred over SPD8, although the objects and colours had higher chroma and colourfulness values in the lit scenes under SPD3. The other preferred SPDs (SPD2 and SPD5) had either negative D_{uv} values or their D_{uv} values lay very close to the black body locus.

The lit scenes in the booth under the preferred SPDs (SPD2, SPD5, and SPD8) looked brighter to the observers than those under the other SPDs at all three CCTs (Figure 4). This supports the findings of Hashimoto *et al.* [74], which showed that when the perceived chroma of object colours under an illumination increased, the brightness sensation became high. This may indicate that when objects look more natural and colourful [I] in a lit scene under an SPD, that scene would look brighter too. The observers may find that same lit scene more comfortable, pleasant, and interesting as well.

The observers preferred (Table 3) the higher CCTs (4000K/6500K) over the lower CCT (2700K) at the illuminance of 500 lux. The lit scenes at the CCT of 6500K and at the CCT of 4000K looked significantly brighter than those at the CCT of 2700K and the lit scenes looked slightly brighter at the CCT of 6500 than those at the CCT of 4000K. The observers' mean ratings (with SPD as the independent variable) for the question about brightness of the lit scenes in the booth under all SPDs also indicated the same result (Figure 4). It possibly indicates that a lit scene under higher CCT looks brighter than that of under lower CCT. This supports the findings of the studies done by Harrington [82] and by Juslén [83], in which the higher CCT was found to be brighter than the lower CCT.

The observers' mean ratings were the lowest at 2700K (Table 2) regarding the visual pleasantness and the visual comfort of the lit scenes under the majority of the SPDs. The observers rated the lit scene at 4000K to be the most comfortable and pleasing (Table 3). The findings are in line with the study done by Kruithof [84] according to which the CCT of 2700K should be visually less comfortable and pleasing than the CCT of 4000K at 500 lux.

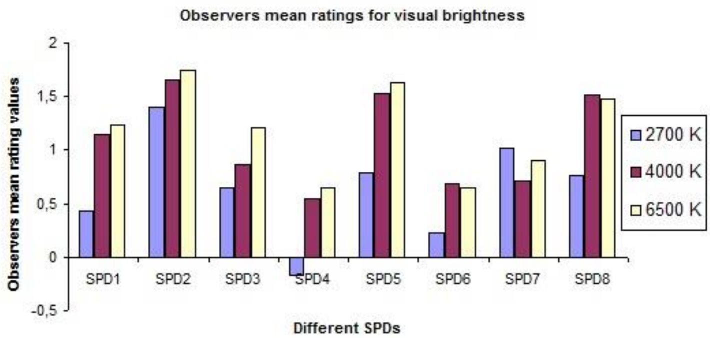

Figure 4. Mean ratings for bright/dim of the visual appearance of the lit scene in the booth at 500 lux for different SPDs at different CCTs with SPDs as an independent variable.

It was possible to develop LED spectra (SPD2 and SPD5) under which lit scenes could be as preferable as under fluorescent lamps (SPD8). Almost all of the mean ratings (Table 2) under the different LED spectra lay on the positive side of the scale (-3 to +3). Thus, none of the LED spectra yielded to low or very low ratings. It was also found that SPD realised for high Q_g value (SPD2) and SPD realised for high Q_p value (SPD5) were preferred over fluorescent lamps in terms of overall preference of the lit scene [II]. The results showed that LED spectra could be developed to be preferred by the users and indicated the high potential of LED lighting to be applicable in offices.

The results indicate [I, II], the CIE CRI alone is not a good indicator of observers' preferences for LED light spectra. This supports the findings of Boissard & Fontoynont [15] and Jost-Boissard *et al.* [16], which showed that CIE CRI was not well-suited for the LED spectra. The metrics Q_p and Q_g (calculated with the CQS version 7.5) were good indicators of users' preference as far as LED SPDs were concerned. The metric Q_g (calculated with the CQS version 9.2) and GAI showed high consistency as preference indicators for both LED light spectra and fluorescent lamp spectra. The graphs showing the performance of the metrics regarding brightness, comfort and pleasantness at 4000K are presented in appendix B.

The findings discussed above were the basis for the realisation of the LED SPDs used in the user acceptance studies conducted in office rooms.

5.2 Office room experiment

At the CCT of 4000K, the observers preferred the lit environment under the light spectrum (SPD1) with the highest values of Q_g, Q_p, and GAI (80 ≤ GAI

≤100) the most in terms of the questions related to spatial brightness and spaciousness. On the other hand, they preferred the lit environment under the SPD (SPD7, fluorescent lamp) with the lowest values of Q_g, Q_p, and GAI the least. The spatial brightness influenced by the SPDs affected observers' preferences. This supports the findings of Flynn *et al.* [76] and Loe *et al.* [77], which state that people prefer a lit environment which looks bright. The graphs showing the performance of the metrics regarding brightness and spaciousness at 4000K are presented in appendix B.

Both of the preferred LED light spectra (SPD1 and SPD3) had negative D_{uv} values, whereas the fluorescent lamp spectrum had a positive D_{uv} value. It was also found that the lighting environments under SPD1 and SPD3 were slightly more preferable to those under SPD2 though all three spectra (SPD1, SPD2, and SPD3) had quite similar Q_p, Q_g, and CRI values. However, SPD1 and SPD3 had negative D_{uv} values, whereas SPD2 had a positive D_{uv} value. This supports the findings of Ohno and Davis [30], which indicated that light sources with negative D_{uv} values are more preferable and acceptable than those with positive D_{uv} values.

There were no statistically significant differences in the mean ratings of the lighting environments under different SPDs at the CCT of 6500K. However, small differences in the mean ratings were observed. In most cases, the observers' mean ratings were the lowest in the lit environment under SPD8 (fluorescent lamp). The possible reason could be that SPD8 had lowest values of Q_g and Q_p and a positive D_{uv} value. The room looked slightly brighter and slightly more spacious under LED light spectra (with negative D_{uv} values) than under fluorescent lamps. As the results at 6500K were not statistically significant, they should be considered as indicative rather than conclusive [III].

The results discussed above (for 4000K and 6500K) showed that lighting an environment with different SPDs affected the perceived spatial brightness differently. It supports the study by Ju *et al.* [75], who concluded that spatial brightness perception could be affected by the SPD of a lighting environment.

At 4000K, the preferred SPDs complied with the criteria of $R_a \geq 80$ and 80 ≤ GAI ≤100, which are claimed by Rea & Freyssinier [85] to be acceptable ranges of the CIE CRI and GAI values for good light sources. The lit environments looked significantly brighter (at the desk and the meeting table) and more spacious (in the entire room) under SPD1 and SPD3 than under SPD7 (GAI=71) at the CCT of 4000K. This might imply that lighting environments under the SPDs with $R_a \geq 80$ and 80 ≤ GAI ≤100 would look brighter and more spacious. This could be a reason for the ratings indicating a need for more light under SPD7 compared to those under the preferred SPDs (SPD1 and SPD3).

According to Boyce & Eklund [37] and Eklund & Boyce [81], good quality office lighting for visibility is such, that people (at least 95% of people) are able to smoothly read printed text of font size 6 points. In this study, all observers could read the printed text of font size 6 points in the lighting conditions at 300 lux and 500 lux. Boyce & Eklund [37] also claimed that at least 70% of people should feel comfortable under a lighting environment to be considered good quality lighting. In this work, none of the lit environments at 300 lux (at the CCTs of 4000K and 6500K) complied with the criterion [37]. On the other hand, lit environments at 500 lux under SPDs at 4000K complied with the criterion. The results showed that the illuminance of 500 lux was preferred to 300 lux at the CCTs of 4000K and 6500K for the questions related to spatial brightness and overall spaciousness along with other factors. Thus, the lit environments under different illuminance levels had affected the perceived spatial brightness differently. This supports the finding in the study by Ju *et al.* [75], in which spatial brightness was affected by different illuminance levels. In this study, the illuminance of 500 lux was preferred and accepted for LED office lighting, which complies with the recommended illuminance level for office lighting [86].

It is also noteworthy that the same spectra (SPD1 and SPD3) were the most preferred, whereas the fluorescent lamp spectrum (SPD7) was the least preferred in terms of colourfulness and preference at 4000K (500 lux) [IV]. At 4000K (500 lux), hands and objects looked more natural in the lit environments under these SPDs than the SPD7. This result may indicate that when objects look more colourful and more natural under one lit environment than under other lit environments, that lit environment may look brighter; the observer may feel more comfortable under that lit environment.

The CCT of 4000K (neutral white light) was preferred to the CCT of 6500K (cool white light) at 500 lux in terms of comfort, pleasantness of light colour, and acceptance of lit environment in the entire room. This supports the findings of Shamsul *et al.* [40], Kang *et al.* [28], Cockram *et al.* [68] and Lin *et al.* [71] that neutral white (about 4000K) light is preferred for office lighting.

SPD3 was a simplification of SPD1. The mean ratings under SPD3 and SPD1 did not differ much. This indicates that the simple SPD3 could offer a lighting environment as good as that under SPD1 at the CCT of 4000K. Hence, it would be a good option to develop simple light spectra while maintaining the preferred criteria for good lighting in an office environment.

5.3 Limitations

In the first phase of the study, a reverse comparison test was done instead of a null condition test, which would have required swapping of the luminaires. Because of the huge size of the LED luminaire, swapping of the luminaires was not possible. However, the lit scenes in the booths were set up in such a way that illuminance uniformity was very close to each other and the average luminance values of the lit scenes under LEDs and fluorescent lamps were kept almost the same. Furthermore, the reverse comparison test verified that the relative positions of the light sources did not affect the judgement of the observers.

The time of the day and the season may have effect [87], [88] on the observers and their lighting preferences. The experiments could not be conducted in the same season and at the same time of the day for all the subjects. They evaluated the lit environment in the office room during a short stay (about 30 min) in the experimental room for short time. Ten subjects also evaluated the lit environment in the office rooms during a stay of two hours and no difference was found between the results obtained from the two hour and 30 min long experiments. However, the evaluations may be different while working in the room for eight hours. Further studies can be done in the same season for eight hours starting at the same time of the day for every observer.

There is always a presence of daylight in real office environments to some extent. However, daylight was blocked from entering the office rooms to provide a similar lighting condition for each observer. Few subjects expressed that they felt suffocated in the room and would not want to work in such an office for a longer time.

Single-item questions were used to represent a factor (e.g comfort or brightness) in the study in order to limit the evaluation time. Studies can be done by asking multiple-item questions to represent different factors and by asking the same questions in several different ways.

6. Conclusions and recommendations

This thesis focused on the investigation of observers' preferences in office lighting and on acceptance of LED lighting in office environments. The effect of different LED light spectra optimised with different colour quality metrics on the users' preferences was investigated in a lighting booth and office rooms considering different lighting factors mainly related to visual perception.

In the lighting booth [I], the preferred LED SPDs (SPD2 and SPD5) were optimised for higher values of a metric (Q_g) that is related to gamut area or for higher values of a metric (Q_p) that is related to chroma effect. The LED SPD2 and LED SPD5 provided a better lighting environment than the fluorescent lamp in the booth [II]. The chromaticity difference (D_{uv}) values of the SPDs affected the observers' preference. The chromaticity coordinates (in the CIE 1976 chromaticity diagram) of the preferred LED light spectra lay below the Planckian locus.

In the office room experiments, the observers preferred the LED light spectrum, which had the highest Q_p and Q_g values the most and preferred the light spectrum, which had the lowest Q_p and Q_g values the least among all the light spectra at 4000K. The chromaticity coordinates of the most preferred SPD and the least preferred SPD lay below (negative D_{uv} value) and above of the Planckian locus, respectively. The least preferred lit environment was under the fluorescent lamp and the observers' accepted the lit environment under the fluorescent lamp the least (Table 4 chapter 4).

The results showed that LED light spectra can be developed to be preferred and accepted in office lighting. The LED light spectra should have good colour characteristics as the visual perception of the lit environment is affected by the colour characteristics of the light spectra. Chromaticity difference (D_{uv}) values affected the observers' preferences for a particular SPD in the lighting booth and office room experiments. Therefore, white light emitted from the light sources should be characterised not only by the CCT but also by the chromaticity difference (D_{uv}) values. The results indicate the need to develop LED light spectra with negative D_{uv} values within the recommended limit [20] for a particular CCT.

Based on the observers' evaluation, lit environments at 500 lux were preferred and accepted to those at 300 lux in an office environment. The observers would not necessarily prefer and accept one lighting environment under an illuminance level even when that level can be considered to be good quality lighting for visibility in office environments. If the observers do not feel comfortable under a lit environment which is good quality lighting for visibility, it cannot be considered as a good lighting in an office environment. Therefore, when the illuminance level is varied, it should be able to provide good quality lighting for visibility and visually comfortable lit environment.

In this work, the observers found the lit environments at the CCT of 4000K to be more comfortable and more pleasing than those at the CCTs of 2700K and 6500K at 500 lux. Thus, the observers preferred the CCT of 4000K at the illuminance level of 500 lux. However, the CCT of 6500K was found to be slightly brighter than the CCT of 4000K in the lighting booth and in the office room experiments. The lit scenes in the booth were found to be significantly brighter at the CCT of 6500K than at the CCT of 2700K at 500 lux.

The findings of the study indicated that it is possible to develop LED SPDs that can be preferred and accepted by end-users and thus LED lighting can be a viable option in office environments.

As the findings showed that light spectra affected the brightness, further research can be done in LED office environments where the observers can control illuminance levels. It might be possible to develop LED light spectra that could provide the same level of brightness perception with a lower illuminance level. If a lower illuminance level (e.g 400 lux) than the currently recommended illuminance level [86] could fulfil the criteria, it might be possible to save energy. However, the lighting conditions should be able to provide enough bright lighting so that people feel comfortable and can perform visual tasks.

The CIE CRI alone is not well suited to assess the colour rendering properties of the LED light spectra. A reference-based metric (Q_p) along with an area-based metric (Q_g or GAI) explained overall observers preference well [I-IV]. Therefore, it would be a good option to consider Q_p and Q_g or GAI in developing LED light sources. However, further studies are needed comparing other proposed metrics such as the rank order based Colour Rendering Index (RCRI) [89] and the Memory Colour Rendering Index (MCRI) [90] as well as the Q_g and the Q_p.

The findings indicated that a simple LED spectrum can offer a lit environment which is as preferred as that under a complex LED spectrum. Therefore, it would be a good option to develop a simple SPD while maintaining the criteria of good lighting in the office environment. This would reduce the complexities and the production costs of LED light sources. However, only one simple LED spectrum was realised as the counterpart of a complex LED spectrum. Further studies should be conducted for office lighting by realising more simple LED spectra as the counterparts of complex LED spectra.

7. References

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Appendix A

The spectra of different types of LEDs, incandescent lamp and fluorescent lamp are shown in Figure A1 below.

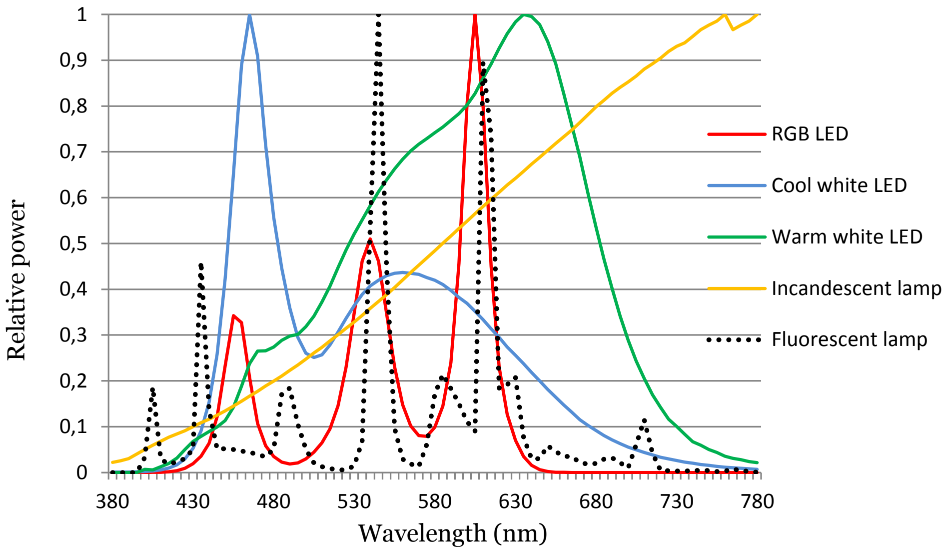

Figure A1. Relative SPDs of different types of LEDs (RGB LED, phosphor converted cool and warm white LEDs), incandescent lamp and fluorescent lamp.

Appendix B

Some example graphs about the performance of the metrics regarding different aspects of lighting are shown below.

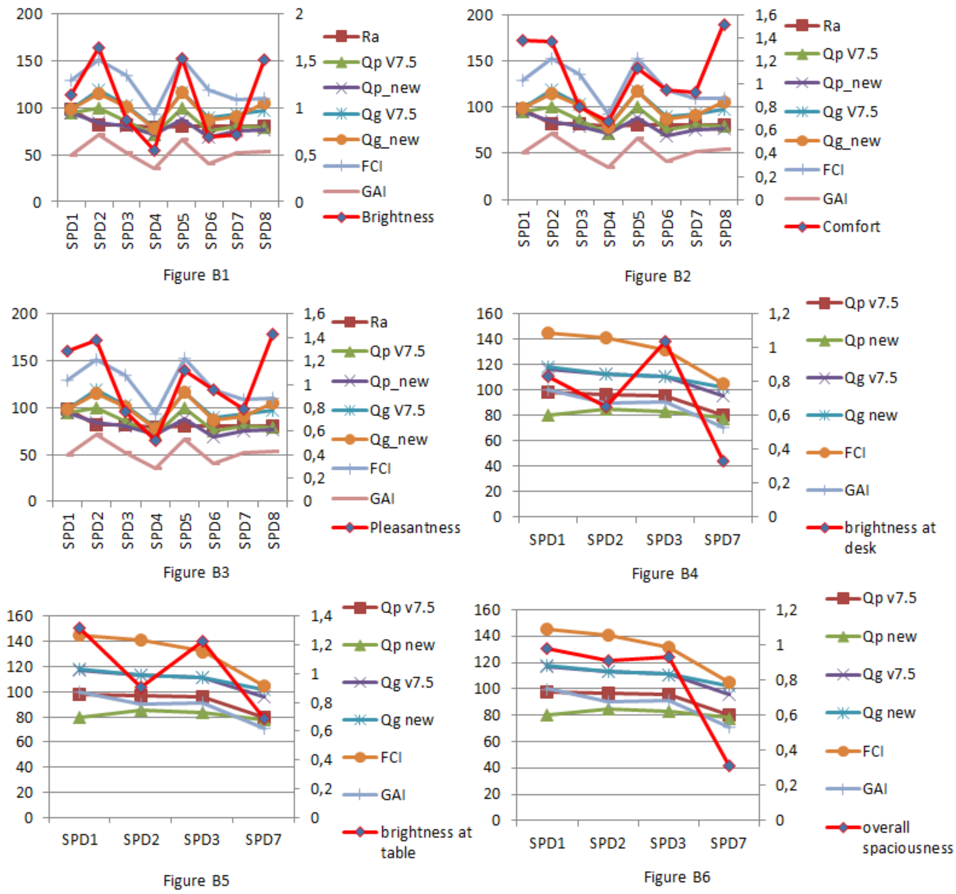

Figure B. The performance of the different metrics in terms of brightness (Figure B1), comfort (Figure B2), and pleasantness (Figure B3) for different SPDs at 4000K in lighting booth experiment and in terms of brightness at desk (Figure B4), brightness at table (Figure 5) and overall spaciousness (Figure B6) for different SPDs at 4000K in office room experiment.

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Due to the rapid development in light emitting diode (LED) technology for the last few years, the LED illumination is expanding in both indoor and outdoor lighting. The measurement techniques developed for the conventional light sources to measure quality and characteristics of light are not always suitable for LEDs. It is also not well-known how end-users would evaluate the LED lighting in offices. The colour rendering properties and the CCT are important aspects for user acceptability of a light source. However, the CIE CRI is not well-suited for white LED light. Therefore, understanding and assessment of the relevant factors that affect the quality of LED lighting in offices are relevant in the development of LED lighting technology.
This thesis considers end-users' evaluation of LED lighting in office environment and thus explores the end-users' preferences and acceptance of a lit environment under different types of LED spectra.

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