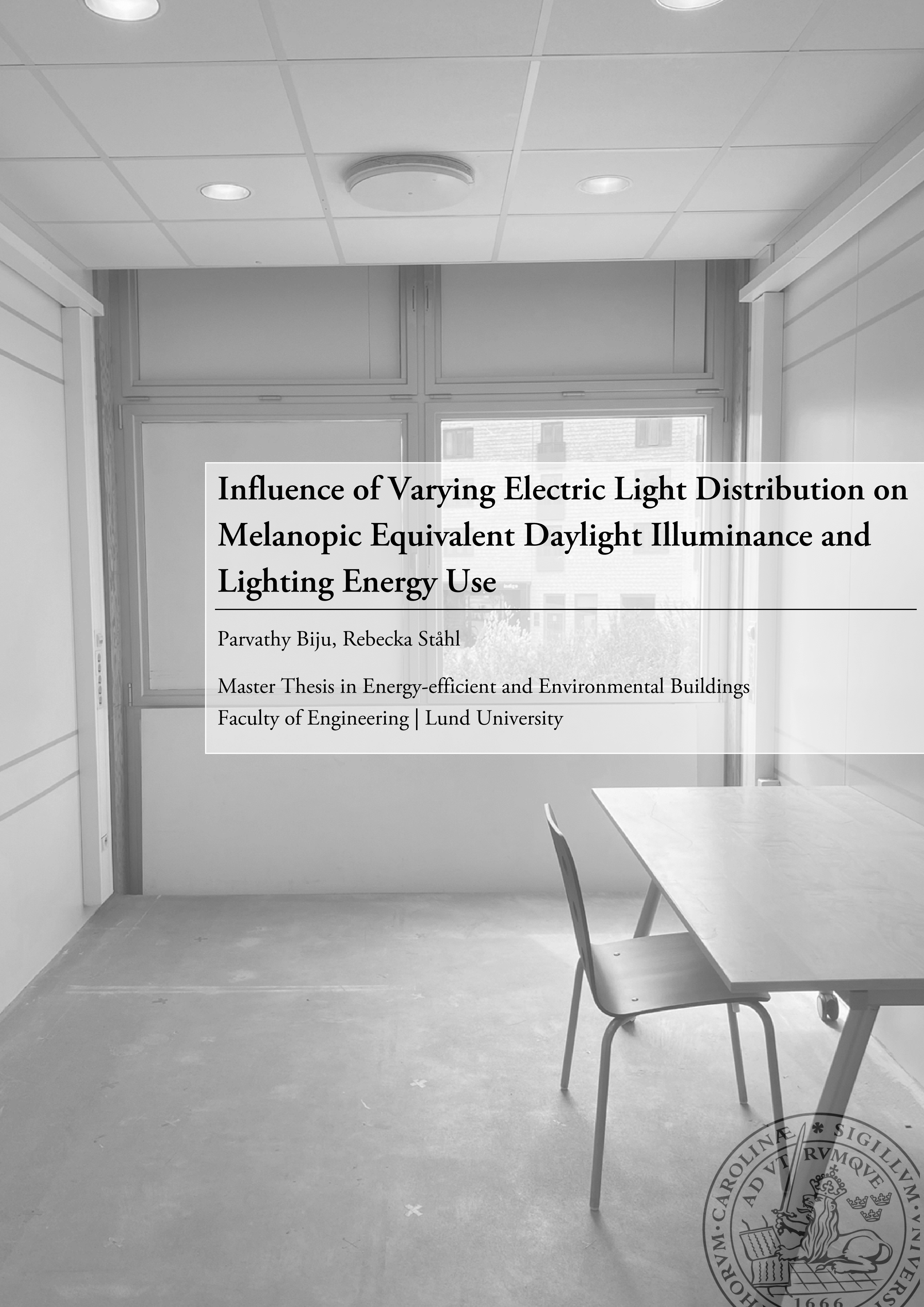

Influence of Varying Electric Light Distribution on Melanopic Equivalent Daylight Illuminance and Lighting Energy Use

Parvathy Biju, Rebecka Ståhl

Master Thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1 666 and has today a total staff of 6 000 employees and 47 000 students attending 280-degree programs and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

Human beings in modern society spend more than 90% of their time indoors to live, work, and socialize. To improve health, quality of life and task performance, integrative lighting is designed to give the right light at the right time at the eye to stimulate circadian entrainment. Current designs for integrative lighting consider rooms as black boxes, overlooking the contribution of daylight to the non-visual stimuli. To meet recommended values of circadian illumination on the vertical, the luminous power output must be three times higher than that needed to meet visual requirements, making it critical to implement daylight to save energy.

This study investigated the impact of direct and direct-indirect distributions of electric light combined with daylight on horizontal illuminance, vertical illuminance, melanopic equivalent daylight illuminance, and energy use in a mock-up office in Lund, Sweden. On-site technical measurements, observer-based tests and simulations were carried out to collect data. The on-site measurements were used to calibrate the Rhinoceros 3D and Grasshopper model. Field tests with subjects were carried out to understand whether different lighting scenarios could ensure similar visual performance. Further lighting scenarios with different CCTs and view directions were tested using LARK 2.0 to determine which of the scenarios could reach the visual and non-visual requirements in the most energy-efficient way.

The results showed that both direct and direct-indirect electric lighting perform similarly in terms of visual perception, alertness/sleepiness, and cognitive performance. Average horizontal illuminance exceeds visual requirements for all the lighting scenarios, but the non-visual requirements were never achieved with only electric light. Most of the circadian illumination on the vertical is provided by daylight as melanopic equivalent daylight illuminance exceeds non-visual requirements under a clear sky for most of the year. Overall, simulated results for direct electric lighting yielded a higher activation state in people for all the lighting scenarios.

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This research paper had given us the opportunity to venture into new realms in-lieu of software unexplored earlier and new methodologies, with which we had gained knowledge and confidence for our future ventures.

Abbreviations and Nomenclature

CCT	Correlated Colour Temperature
CIE	International Commission on Illumination.
DF	Daylight Factor
DHI	Diffuse Horizontal Irradiance
DSST	Digit Symbol Substitution Test
$\bar{E}_{amb}$	Mean Ambient Illuminance
E_h	Horizontal Illuminance
EML	Equivalent Melanopic Lux
E_v	Vertical Illuminance
GHI	Global Horizontal Irradiance
ipRGCs	Intrinsically Photosensitive Retinal Ganglion Cells
IWBI	International WELL Building Institute
KSS	Karolinska Sleepiness Scale
LENI	Lighting Energy Numeric Indicator
mEDI	Melanopic Equivalent Daylight Illuminance
OBEA	Observer-Based Environmental Assessment
PILQ	Perceived Indoor Lighting Quality
RHT	Retinohypothalamic Tract
SAD	Seasonal Affective Disorder
SCN	Suprachiasmatic Nuclei
SPD	Spectral Power Distribution
TEA	Technical Environmental Assessments
TLMs	Temporal Light Modulations
T_{vis}	Visible Transmittance of a glazing
WAIS	Wechsler Adult Intelligence Scale
WWR	Window-to-Wall Ratio

Glossary

Correlated Colour Temperature (CCT)

The temperature of a Planckian radiator having chromaticity similar to that associated with a given spectral distribution on a modified 1976 UCS diagram. It is expressed in kelvin [K] (CIE, 2023).

Daylight Factor (DF)

The quotient of the illuminance at a point on a given plane due to the light received directly and indirectly from a sky of assumed or known luminance distribution and the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, where the contribution of direct sunlight to both illuminances is excluded. It is expressed in % (CIE, 2023).

Diffuse Horizontal Irradiance (DHI)

Irradiance produced by diffuse solar radiation on a horizontal surface on the Earth. It is expressed in watt per square meter [W/m^2] (CIE, 2023).

Mean Ambient Illuminance ($\bar{E}_{amb}$)

The average illuminance on the walls and ceiling, as defined by SS-EN 12464-1:2021. It is expressed in lux.

Horizontal Illuminance (E_h)

Illuminance on a horizontal plane. It is expressed in lux (CIE, 2023).

Equivalent Melanopic Lux (EML)

The light of a given light source experienced by the circadian system as an equivalent of photopic lux. It is expressed in units of melanopic lux [lux] (Lucas et al., 2014).

Vertical Illuminance (E_v)

Illuminance on a vertical plane. It is expressed in lux (CIE, 2023).

Global Horizontal Irradiance (GHI)

Irradiance produced by global solar radiation on a horizontal surface on the Earth. It is expressed in watt per square meter [W/m^2] (CIE, 2023).

Lighting Energy Numeric Indicator (LENI)

Annual energy required for lighting in a building normalized to the unit area, as defined by SS-EN 15193-1:2017. It is expressed in kilowatt-hours per square meter per year [$kWh/m^2/year$].

Melanopic Equivalent Daylight Illuminance (mEDI)

The amount of daylight (D65) illuminance needed to achieve a circadian response similar to a given light source. It is expressed in units of melanopic lux [lux] (Brown et al., 2022).

Perceived Indoor Lighting Quality (PILQ)

Tool containing 16 bipolar adjectives to rate the perceived lighting quality of indoor environments on a seven-point scale (Dubois, et al., 2019).

Spectral Power Distribution (SPD)

The intensity of any radiometric or photometric quantity [e.g., irradiance transmittance, reflectance etc.] as a function of wavelength. It is expressed in units of power per unit area per unit wavelength [e.g., $W/m^2/nm$] (McCluney, 1994).

Window-to-Wall Ratio (WWR)

The proportion of exterior wall surface area that is glazed (Troup et al., 2019).

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1 Introduction

Human beings in modern society spend more than 90% of their time indoors to live, work, and socialize (Cincinelli and Martellini, 2017), and they are often underexposed to daylight. Indeed, the advent of air conditioning and cheap fluorescent lighting in the 1930s led to the popularization of artificially illuminated and conditioned deep-plan buildings, known as the 'post-fluorescent' era (Lechner, 2015). Lack of daylight and prolonged exposure to artificial illumination can impact on people's health and quality of life; bad lighting can also reduce task performance. This is especially problematic in the Scandinavian countries, at high latitudes, with extreme variability of daylight from summer to winter. Winter in Skåne, southern Sweden is characterized by overcast skies and the absence of thick snow cover with high albedo. The intense gloom during winter further lessens retinal exposure to daylight (of short wavelength) which can disrupt the human circadian rhythm, leading to fatigue and sleepiness (Haines, 1991). Low exterior light levels during winters in Skåne cause vitamin D deficiency and may even result in seasonal affective disorder (SAD) within the population (Dubois, et al., 2019). This generated an interest in circadian controls– officially named 'integrative lighting' by the International Commission on Illumination (CIE, 2023)– over LED lighting in recent years within the Scandinavian population, especially in Sweden. These types of control regulate the spectrum of electric lighting and its intensity to meet the non-visual or "circadian" requirements vertically at the eye of the occupant. However, to meet the non-visual requirements, the luminous power output can be three times higher than standard lighting design criteria when designing only for lighting fulfilling "visual" requirements, which are generally based on horizontal illumination on the desk. This poses a challenge with regards to building energy use (Altomonte et al., 2021a).

Office spaces are commonly provided with side vertical openings. As daylight is the ideal *zeitgeiber* (time-giver), it is of interest to study (1) whether daylight alone can fulfil the visual and non-visual requirements during most of the working hours and (2) when not, whether different distributions of electric lighting could help fulfil the requirements in an energy-efficient way.

To this end, this study investigates two different electric lighting distributions combined with daylight in a mock-up office. Field tests with subjects were carried out to understand whether different lighting scenarios could ensure similar visual perception and visual task performance. Further lighting scenarios were tested using lighting simulations to determine which of the scenarios could reach the visual and non-visual requirements in the most energy-efficient way.

1.1 Background

1.1.1 The Effect of Light on Humans

Daylight influences individual's physiology via (1) visual perception, (2) visual acuity, (3) direct skin absorbance of ultraviolet light, and (4) non-visual ocular actions (Münch et al., 2017). In daylighting design of buildings, concerns are limited to a visual– including perception and acuity– and a non-visual pathway– including the effects of light on circadian rhythms.

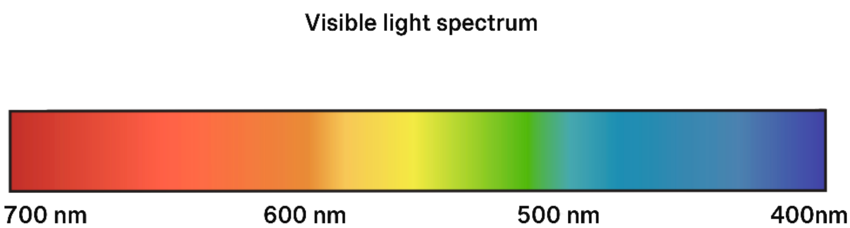

Figure 1: Visible light spectrum (Adapted from Ronan, 2007).

1.1.1.1 Visual Effects of Light

The primary function of light is to support human vision. Photons are detected by the retina– a layer of photoreceptors (rods and cones) located at the back of the eye. The photoreceptors contain proteins with opsins (light sensitive photopigments) which absorb light and start the electrophysiological chain of events stimulating the visual system to see. High-quality images can be produced on the retina with adequate light quality and quantity (Münch et al., 2017). Cones respond to luminance levels of more than 5 cd/m^2 for photopic (diurnal) vision, whereas rods (containing rhodopsin) respond to luminance levels of less than 0.005 cd/m^2 for scotopic (nocturnal) vision with a lack of colour perception (CIE, 2023).

Existing lighting design criteria focuses on designing for adequate horizontal illumination (E_h) to meet the visual requirements on the horizontal work plane and areas around that surface in paper-based offices, with little to no consideration for non-visual (circadian) requirements. For offices, the horizontal work plane is generally 0.80 m above the floor in which a visual task lies. As per the SS-EN 12461-1:2021 standard, E_h should be equal or > 500 lux to meet the requirements of visual acuity in paper-based offices.

The SS-EN 12464-1:2021 standard also specifies target values for the mean ambient illuminance ($\bar{E}_{amb}$), which takes into account the average illuminance on the walls and ceiling. The $\bar{E}_{amb}$ must be maintained within 200 lux and 500 lux.

1.1.1.2 Non-Visual Effects of Light

Melanopsin in the intrinsically photosensitive retinal ganglion cells (ipRGCs) are primarily responsible for circadian entrainment by converting photic signals from rods and cones into electrical signals transmitted via the retinohypothalamic tract (RHT) to the suprachiasmatic nuclei (SCN) (Figueiro, Nagare and Price, 2018). The biological clock located in the SCN of the brain's hypothalamus is synchronised with the day-night cycle due to light-dark patterns incident on the retina. The local day-night cycle regulates the timing for circadian entrainment of alertness and other bodily functions. The human biological clock has adapted to the 24-hour light-dark patterns incident on the retina and oscillates with a duration of approximately 24.2 hours in the absence of temporal cues (Figueiro, Nagare and Price, 2018).

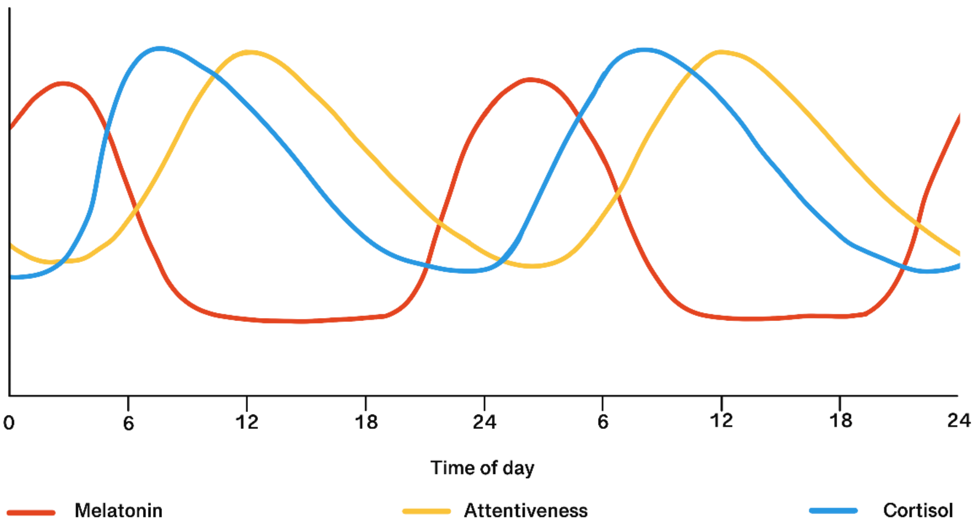

Figure 2: Day-night cycle for circadian entrainment (Adapted from TRILUX, 2022).

The variation of daylight in level and spectral composition throughout the day influences the activation state of people– production of cortisol for daytime alertness and melatonin for night-time sleepiness (Dubois et al. 2019). This is because the human circadian system is a blue light detector as the "blue versus yellow" (b-y) bipolar neurons within S-cones (containing cyanopsin responsive to 460 nm "blue" region) provide photic input to the SCN in addition to ipRGC's response (Gall & Bieske, 2004). Moreover, amacrine cells only allow "blue" signals from the b-y bipolar cells to the ipRGCs. This is in contrast with the L-cone's and M-cone's (containing chloropsin and erythropsin) spectral sensitivity for visual perception and visual acuity under photopic conditions (CIE V(λ) curve) which peaks at 555 nm "yellow-green" region (Figueiro, Nagare and Price, 2018). The spectral sensitivity of the ipRGCs and the visual system are shown in Figure 3.

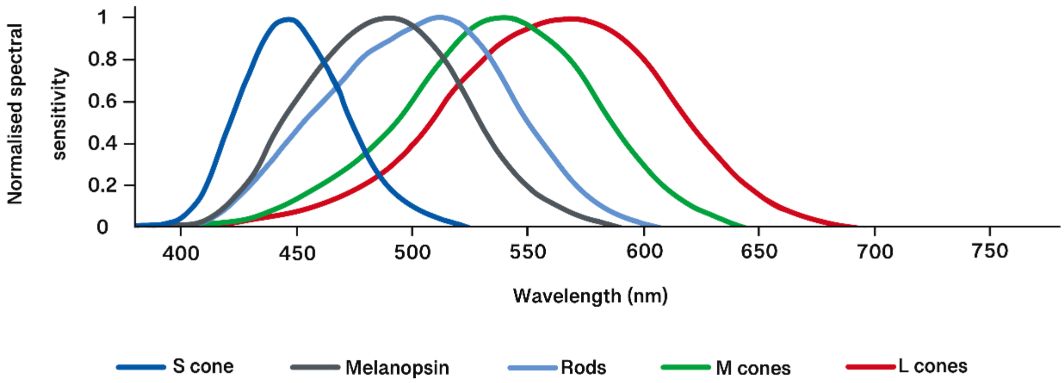

Figure 3: Normalized spectral sensitivity (Adapted from Blume, Garbazza and Spitschan, 2019).

As non-visual effects of light are subjective, they would not only depend on light quality and quantity (timing, pattern, wavelengths, intensity, and duration), but also an individual's characteristics and state, as well as their work conditions and living circumstances (Lockley, 2009). Cajochen, Chellappa and Schmidt (2010) realised that just 40 lux of blue shifted light suppresses melatonin secretion at night and can significantly affect sleep. Andersen, Mardaljevic and Lockley (2012) proposed three distinct times of light exposure to induce the natural wake-sleep cycle over the 24-hour day. Sufficient daylight exposure during 06:00–10:00 hours (early to mid-morning) can advance the circadian rhythm in most people. Exposure to daylight of high illuminance levels with a strong short wavelength component during 10:00–18:00 hours (mid-morning to early evening) can boost alertness without disrupting the biological clock. Exposure to daylight must be avoided during 18:00–06:00 hours (night-time). In their study, Sahin and Figueiro (2013) also found that L-cones with 48-minute exposure to long-wavelength (red) light of 40 lux increases cortisol levels and alertness during post-lunch dip hours more than blue light. These studies show that darkness in the evening is as important as light in the morning to regulate the timing for circadian entrainment.

To investigate a light source's effectiveness at stimulating an individual's melatonin levels, the spectral response of the five photoreceptors (S-cones, M-cones, L-cones, rods, and ipRGCs) to the light source would be assessed. This can be operationalized by calculating the equivalent melanopic lux (EML) introduced by Lucas et al. (2014) or the melanopic equivalent daylight illuminance (mEDI) proposed recently by CIE, with this study focusing on mEDI.

mEDI is the International System compliant metric and it describes the amount of daylight (D65) illuminance needed to achieve a circadian response similar to a given light source and is expressed in units of melanopic lux [lux]. mEDI is assessed using the CIE α-optic Toolbox v1.049a, a Microsoft Excel calculator published under the International Standard CIE S 026 (CIE, 2020). The toolbox needs measurements of irradiance at 1 or 5 nm steps, or the photopic illuminance and spectral power distribution (SPD) of the light source to calculate mEDI. Measurements are taken at a height of 0.46 m above the work-plane representing the eye of an observer in sitting position (Altomonte et al., 2021b). As per WELL Building Standard v2, mEDI of ≥250 lux must be achieved for at least four hours to meet non-visual requirements. This target was adopted from Brown et al. (2022). As the standard focuses on non-residential buildings, maximum levels of mEDI during evenings and nights are not provided (IWBI, 2022). For residential spaces, Brown et al. (2022) recommends mEDI of ≤10 lux for at least 3 hours before bedtime and ≤1 lux at the time of sleep.

1.1.2 Natural and Electric Lighting

Daylight is the combination of direct and indirect solar radiation, sunlight, and skylight. It has a continuous spectral power distribution covering the full visible light spectrum. It is dynamic and varies during the day and over the year by shifting in colour, direction, intensity, and diffuseness (Knoop et al., 2019). Conversely, traditional electric lighting is non-dynamic and may exhibit rapid temporal light modulations (TLMs), normally unperceivable with the naked eye, which is sensed by the brain causing eye strain, migraines, fatigue etc.

Since most office activities occur during daytime, daylight can potentially be the primary source of illumination indoors, if well designed. According to Reinhart and Wienold (2011) good daylighting is a '*Space that is primarily lit with natural light and that combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating, and cooling. It is a compromise between optimizing the annual daylight availability within a space while making sure that the space is energy-efficient and provides high occupant satisfaction*'. Due to the increasing acknowledgement of its positive impact on an individual's physiology, daylighting is being incorporated in modern building design via side vertical openings (i.e., windows). A window will not only provide daylight into the room, but can also filter natural light, control quantity of solar radiation, and provide a view outdoors. The provision of daylight through windows ensures high vertical surface illuminances, which lowers the sense of gloominess contrasted to ceiling-mounted electric lighting with a horizontal illumination component (Haines, 1991).

Furthermore, adequate daylight access is important due to its potential for energy savings (Baker, A., & K., 1993). A significant amount of energy consumption by present-day buildings is attributed to electric lighting systems, albeit currently available LEDs have high luminous efficacies of approximately 200 lm/W. Daylight, with luminous efficacies of approximately 100-150 lm/W, is a cheap and zero-energy source of illumination (Dubois, et al., 2019). Therefore, electric lighting should act as a complement to daylight, particularly during periods of very low daylight availability to fulfil lighting needs.

However, electric lighting systems cannot stimulate the circadian rhythm in most people like natural daylight does. Integrative electric lighting– a development of traditional electric lighting– provides both visual and non-visual benefits (CIE, 2023). The effect integrative lighting will have on circadian entrainment depends on corneal illumination, timing, duration, SPD, and prior lighting exposure history, i.e., the right light needs to be received at the eye at the right time (Cai et al., 2018). Increasing the power of a luminaire till corneal illuminance is high enough for circadian entrainment would adversely impact the energy use (Dai et al., 2018). It must be noted that the overall corneal illuminance depends on two parts– direct corneal illuminance, and indirect corneal illuminance. Direct corneal illuminance is light that arrives directly at the eye from the light source and indirect corneal illuminance is inter-reflected light that gets reflected at least once in the room before reaching the eye (Cai et al., 2018). As lighting designs commonly focus on visual requirements (Vetter et al., 2021), they typically direct light towards the work plane (Dai et al., 2018). Altomonte et al. (2021a) states that it is difficult to meet non-visual targets without increasing the luminous power output three times more than that needed for visual requirements.

The current designs for integrative lighting do not consider the contribution of daylight to the non-visual stimuli, which leads to oversized electric lighting systems and can cause energy rebounds. Rather than considering rooms as black boxes, integrative lighting needs not only sensible daylight provision, but also efficient electric lighting sources and rightfully installed controls to help reduce lighting energy use (Gentile *et al.*, 2022). Integrative lighting can be designed in an energy-efficient way by:

- homogenously distributing light between the vertical and horizontal plane using indirect lighting systems to reduce the risk of discomfort glare (Cai et al., 2018),
- including daylighting,

- increasing the blue component in light with a correlated colour temperature (CCT) between 4000K and 6500K,
- applying highly reflective but diffusive room surfaces to increase indirect light to the eye (Dai *et al.*, 2018).

1.2 Objective and Research Questions

This research aims to fill in the gaps in existing research by examining how electric lighting can be distributed to improve energy efficiency without compromising daylight within buildings in Swedish winter. To meet an individual's non-visual (circadian) requirements, integrative lighting needs to provide the right light at the right time at the eye. Moreover, currently available daylight harvesting systems, which are advertised to offer high energy-savings, are not easily accessible due to their high costs and difficulties with installation.

To this end, the objective of this study is to test direct (e.g., downwards light) and direct-indirect (e.g., diffuse) distributions of electric lighting in combination with daylight to meet both visual and non-visual targets in an energy-efficient way.

This would result in the four lighting conditions of:

- direct (downward) only electric lighting,
- direct-indirect (diffuse) only electric lighting,
- high daylight illuminance + direct electric lighting,
- high daylight illuminance + direct-indirect electric lighting.

The objective is realised by using on-site technical measurements, simulations, and observer-based assessments of the lighting conditions in the daylighting rooms of Lund University's Energy and Building Design laboratories at Lund, Sweden. On-site technical measurements are used to confirm whether both visual and non-visual targets are met and to calibrate the model for simulations. Observer-based responses are used to support the technical data.

The hypothesis of this study is that traditional luminaires designed to spread light along the vertical plane (walls) combined with daylight may boost circadian entrainment and lower the energy use. It is also expected that the diffuse electric lighting scenario would also result in better visual performance and in comparatively better perceived quality of lighting. A second hypothesis is that daylight from windows alone can provide enough illumination to meet the non-visual requirements.

The specific research questions this study intends to answer is which electric light distribution in addition to daylight meets an individual's visual and non-visual requirements, while also achieving minimal building energy use.

The secondary research questions are as follows:

- Which electric light distribution in addition to daylight complies with SS-EN 15193-1:2017 and achieves minimal building energy use.
- Which electric light distribution in addition to daylight offers high-quality visual performance i.e., visual perception and task performance.
- Which electric light distribution in addition to daylight influences the activation state of people.

2 Methodology

This study follows the workflow presented in Figure 4.

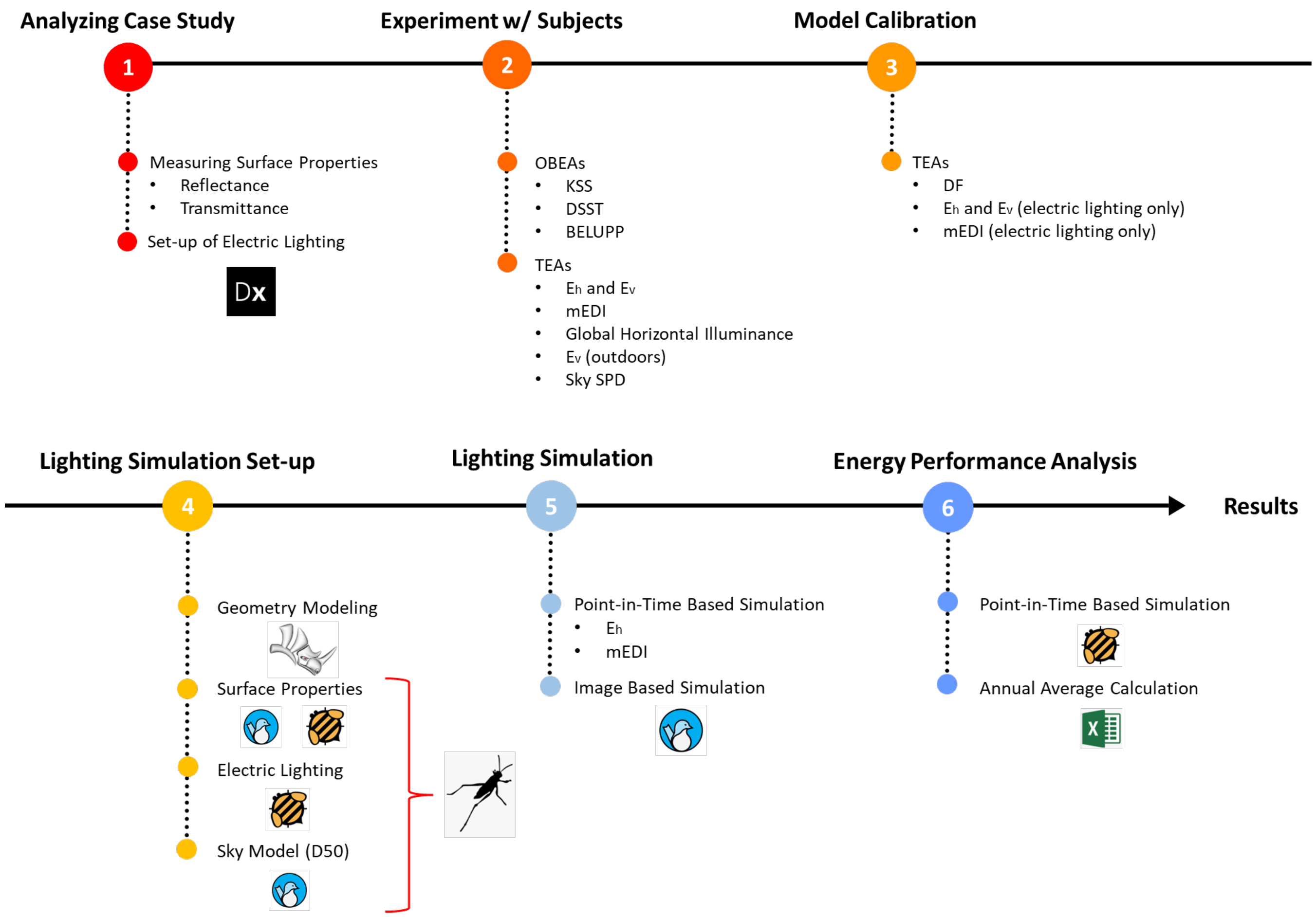

Figure 4: Workflow of the methods used in this study.

2.1 Case Study

Two office-like looking test rooms in the Energy and Building Design Laboratory were chosen for an in-depth analysis on the influence of varying daylighting and electric lighting distribution on mEDI and lighting energy use. The Energy and Building Design Laboratory is located at Sölvegatan in Lund, Sweden (55.71 N, 13.21 E). The test rooms occupied an area of 10.80 m^2 (2.70 m × 4.00 m) and a height of 3.10 m.

Figure 5: Energy and Building Design Laboratory at Lund University.

The daylight admitting surfaces in the room are the four double-glazed windows facing the south direction. The total glazing area is 4.16 m^2, of which two windows are 117.40 cm × 113.70 cm and the other two are 65.50 cm × 113.70 cm (Figure 6). A fixed Window-to-Wall Ratio (WWR) of 0.32 was maintained in both test rooms by covering three of the four windows with panels of semi-matte white paint finish.

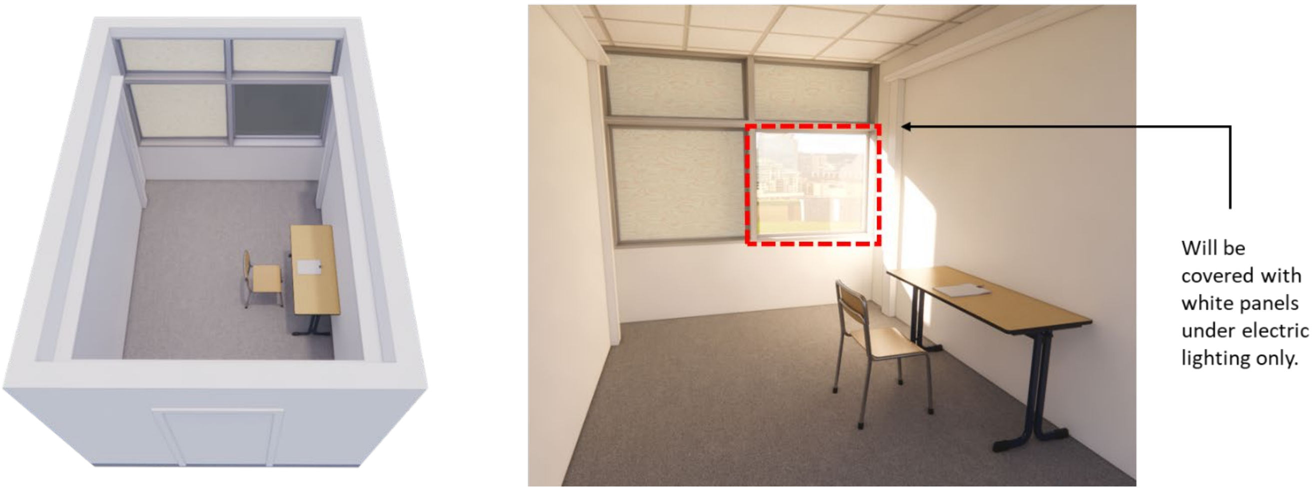

Figure 6: 3D Revit model of the office mock-ups at Energy and Building Design Laboratory.

2.1.1 Surface Properties

2.1.1.1 Measuring Reflectance

The V(λ) reflectance was measured with a Hagner S4 photometer (luminance meter) and a totally diffuse, reference plate with a known reflectance (R_{plate}) of 94.10 % (Figure 7). Reflectance was measured for the main Lambertian surfaces i.e., diffusely reflecting surfaces such as the walls, the ceiling, the floor and the white panels. The luminance meter was aimed perpendicularly to the measured surface, and the reference plate was placed in front of the luminance meter and on to the surface. After the luminance was measured for the plate (L_{plate}), it was removed to take the luminance for the surface at the same spot ($L_{surface}$). This process was repeated five times and an average value of the reflectance for each surface ($R_{surface}$) was then calculated using the formula:

$$R_{surface} = \frac{L_{surface} \times R_{plate}}{L_{plate}} \quad [\%]$$

where;

$L_{surface}$ is the measured luminance for the surface,

R_{plate} is the known reflectance of the reference plate,

L_{plate} is the measured luminance for the reference plate.

1) Hagner E4-X lux meter
2) KONICA MINOLTA CRI Illuminance Meter CL-70F
3) Hagner S4 photometer
4) Reflectance plate

Figure 7: Instruments used for Technical Environmental Assessments (TEAs).

To find the reflectance for spectral surfaces, the Spectral Material Database was used. Table 1 presents the reflectance for different surfaces in the room.

Table 1: V(λ) reflectance [%] for different surfaces in the room.

Surface	V(λ) Reflectance ($R_{surface}$) [%]
Internal Wall (Light Gray)	78.13%
Ceiling (White)	91.90%
Floor (Gray Concrete)	37.92%
Panels (Semi-Matte White Paint)	98.71%
Window Frame (Aluminum)	51.54%
Table (Light Brown Wood)	31.88%
Cable Trunking (White)	87.56%
External Wall (Matte Black Paint)	5.07%
Ground (Dirty Asphalt)	8.44%

2.1.1.2 Measuring Transmittance

The Hagner S4 photometer (illuminance meter) and Hagner E4-X lux meter were used to measure transmittance of the glazing (T_{vis}). Both sensors were facing outside but one was on the inside of the window, and one was on the outside. The illuminance measurements were made five times and an average value of the transmittance was then calculated to be 82.43% for the windows using the formula:

$$T_{vis} = \frac{Illuminance\ inside\ of\ the\ window}{Illuminance\ outside\ of\ the\ window} \quad [\%]$$

2.1.2 Electric Lighting

The electric lighting design in the two rooms differed mainly in relation to the spatial distribution of lighting. One office mock-up was equipped with direct lighting via spotlights, while the other was equipped with direct-indirect pendants providing a more diffuse lighting distribution. Both light sources are provided with the same 4000K LED chips. The luminaires used in this study are the 77447 Pleiad Evo (spotlights) and 29475-402 DTI LED Type 2 (pendants) from Fagerhult.

The electric lighting installations were designed in DIALux Evo so that visual targets are met. EVO files of the luminaires were taken from the manufacturer's website. DIALux renderings of the lighting distribution with spotlights and pendants are shown in Figure 8 and Figure 9 respectively.

Figure 8: DIALux rendering of 77447 Pleiad Evo's light distribution in the test room.

Figure 9: DIALux rendering of 29475-402 DTI LED Type 2's light distribution in the test room.

As per SS-EN 12464-1:2021, the $\bar{E}_{amb}$ was maintained within 200 lux and 500 lux calculated using the formula below, along with a work plane illuminance equal to or > 500 lux.

$$\bar{E}_{amb} = \frac{\bar{E}_{v\,wall1} + \bar{E}_{v\,wall2} + \bar{E}_{v\,wall3} + \bar{E}_{v\,wall4} + \bar{E}_{ceiling}}{5} \quad [lux]$$

Figure 10 presents the layout of luminaires in the test rooms. It must be noted that the spotlights are ceiling recessed and pendants are suspended 0.50 m from the ceiling. Also, two of the six spotlights are dimmed at 50% to increase the difference for $\bar{E}_{amb}$ in the two test rooms. Table 2 details the resulting average illuminance on the main room surfaces.

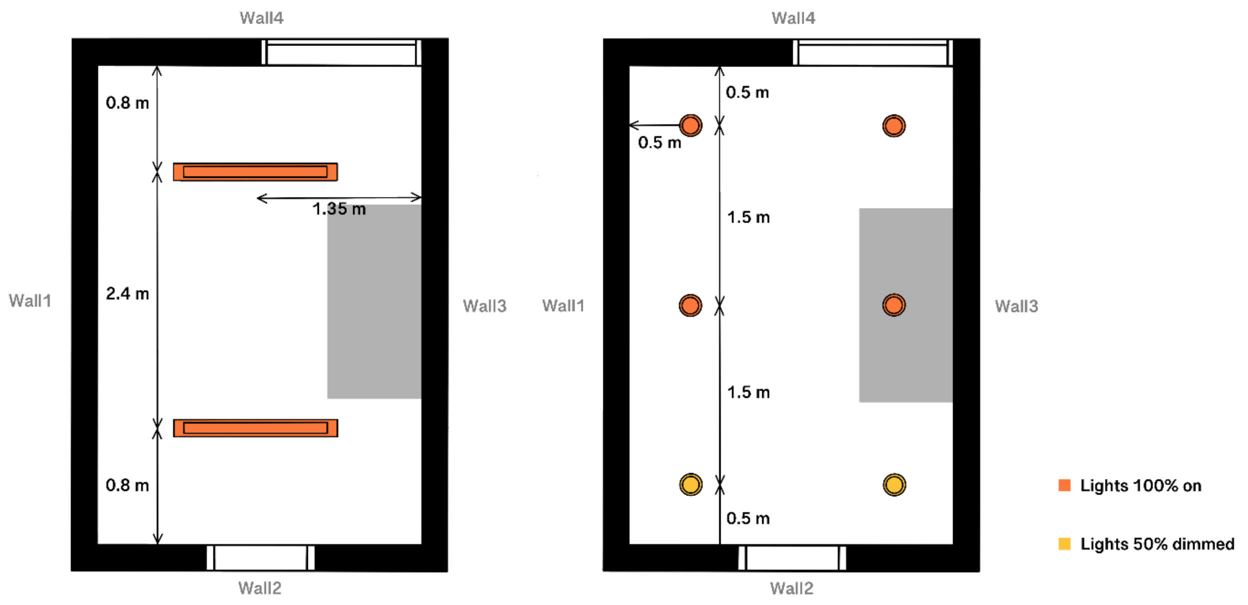

Figure 10: Layout of spotlights (left) and pendants (right) in the test rooms.

Table 2: Average illuminance [lux] on the main room surfaces and the resultant mean ambient illuminance [lux] in the test rooms.

	Average Illuminance [lux]	
	Test room w/ Spotlights	**Test room w/ Pendants**
$\bar{E}_{v\ wall1}$	396	390
$\bar{E}_{v\ wall2}$	350	413
$\bar{E}_{v\ wall3}$	384	376
$\bar{E}_{v\ wall4}$	444	413
$\bar{E}_{ceiling}$	294	649
$\bar{E}_{work\ plane}$	662	654
$\bar{E}_{amb}$	374	448

2.1.3 Technical Environmental Assessment (TEA)

2.1.3.1 Daylight Factor (DF)

DF measurements were carried out on an overcast day with no electric lighting. The overcast sky is a condition where the sky is completely covered with clouds (>95%) to exclude the contribution of direct sunlight. To verify the sky condition is overcast on a certain day, a pyranometer with a shadow ring was used to measure the diffuse horizontal irradiance (DHI) and a pyranometer without a shadow ring was used to measure the global horizontal irradiance (GHI). The pyranometers were mounted horizontally on the roof of the Energy and Building Design Laboratory to prevent shadowing. When the GHI was similar to the DHI, the sky condition was considered to be overcast as there is little to no direct radiation reaching the pyranometer.

The illuminance was measured at 18 points in the room at 0.715 m from the floor to have the values at desk (work plane) height. As per SS-EN 12464-1:2021, the grid points were created 0.50 m from the walls and the measurement devices were allocated in a grid of 0.85 m × 0.60 m spacing distance. The illuminances were simultaneously measured with two lux meters, one that was placed at the different points in the room (Ei) and one that was outside (Eo) in an unshaded place. The measurements were repeated three times at every point and an average value of the DF was then calculated using the formula:

$$DF = \frac{Ei}{Eo} \times 100 \quad [\%]$$

where;

Ei is the illuminance inside the room,

Eo is the illuminance outside.

The measured DF for the grid points in both test rooms is presented in Figure 11. As the inconsistencies between results of DF are within an acceptable margin of error i.e., ±30%, the test rooms were considered to be identical. The discrepancies could be due to the sky condition not being constantly overcast over the duration of the DF measurement or due to minor errors by the authors.

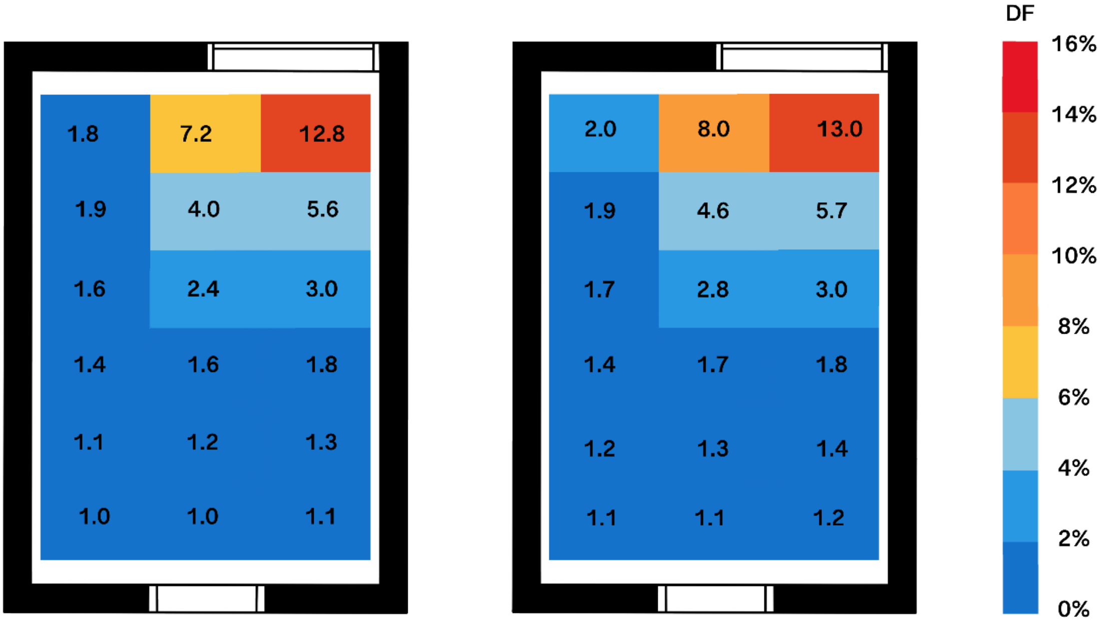

Figure 11: Measured DF [%] for grid points in the test room with spotlights (left) and with pendants (right).

2.1.3.2 Horizontal and vertical Illuminance

E_h was measured at 15 points formed in a 0.375 m × 0.350 m grid on the desks starting 0.05 m from the edge. The measurement was performed under only electric lighting to confirm that the requirement of at least 500 lux was achieved on average for the work plane. E_v was measured 0.46 m above the work plane aimed toward the wall representing the eye position of a sitting person. Figure 12 illustrates the measuring points for E_h, E_v, and mEDI in the test room.

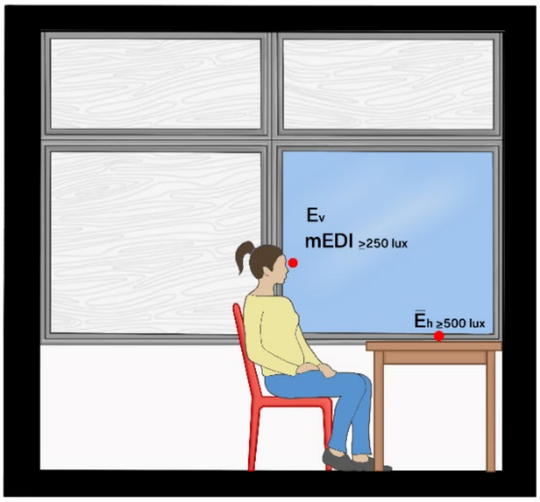

Figure 12: Room illustration with measuring points for E_h, E_v, and mEDI.

The E_h measured for the grid points on the desk in both test rooms is presented in Figure 13. E_v of 264 lux was measured in the test room with spotlights and 351 lux with pendants. As pendants provide 33% more illuminance than spotlights, the pendants can be dimmed proportionally for potential energy savings.

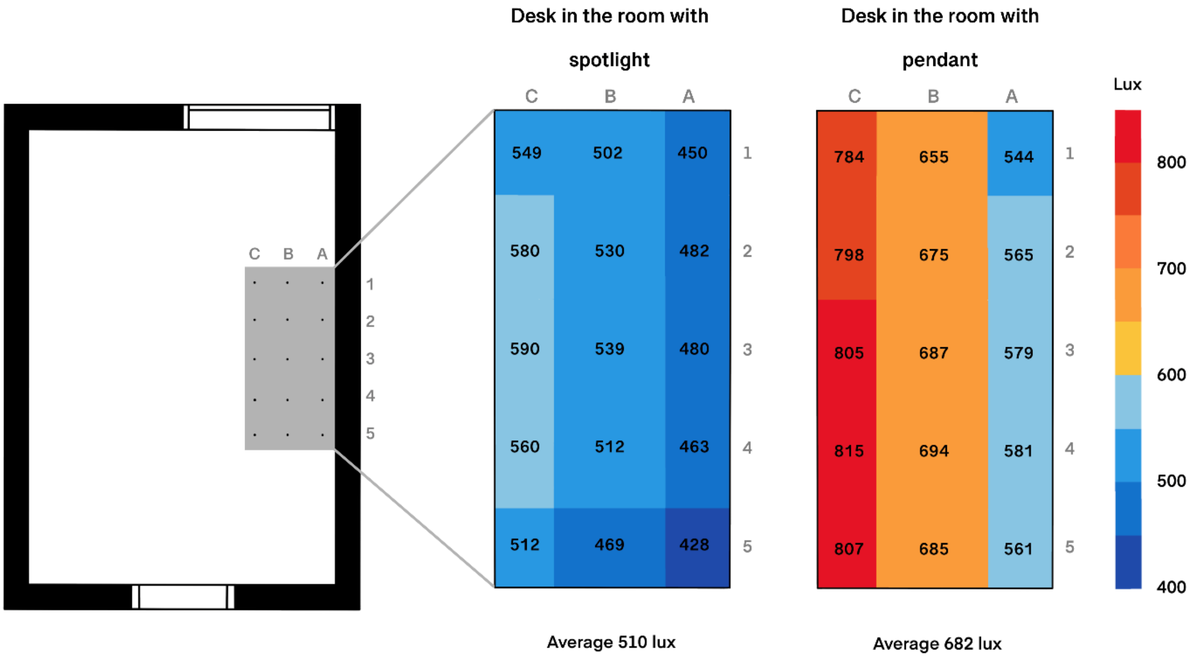

Figure 13: Measured E_h [lux] for grid points on the desk in the test room with spotlights (left) and with pendants (right).

2.2 Observer-Based Environmental Assessment (OBEA)

To quantitatively measure the quality of lighting in the test rooms, an OBEA was conducted. Subjective data was collected from ten participants. The participants were students at Lund University between the ages of 20 and 35 and of mixed genders. Subjective perception of the lighting environment will vary from person to person, nevertheless a group of individuals will have a general perception of the lighting environment with one or two outliers.

The participants were exposed to the following four lighting conditions:

- direct only electric lighting,
- direct-indirect only electric lighting,
- direct electric lighting with high daylight illuminance,
- direct-indirect electric lighting with high daylight illuminance.

The participants took turns in the office mock-ups to experience the four lighting conditions, but they did not all start in the same room. When in pairs, one participant started in either of the office mock-ups whilst the other participant experienced the other office mock-up at the same time. They were brought in on two different occasions– one day to experience only electric lighting and another day to experience electric lighting with daylight from a clear sky. Section 3.1 details the date and time on which the participants took part in the experiments.

To assess the visual perception, alertness/sleepiness, and cognitive performance for the four lighting conditions participants performed the following paper-based tests.

- Karolinska Sleepiness Scale (KSS)
- Digit Symbol Substitution Test (DSST)
- BELUPP Questionnaire

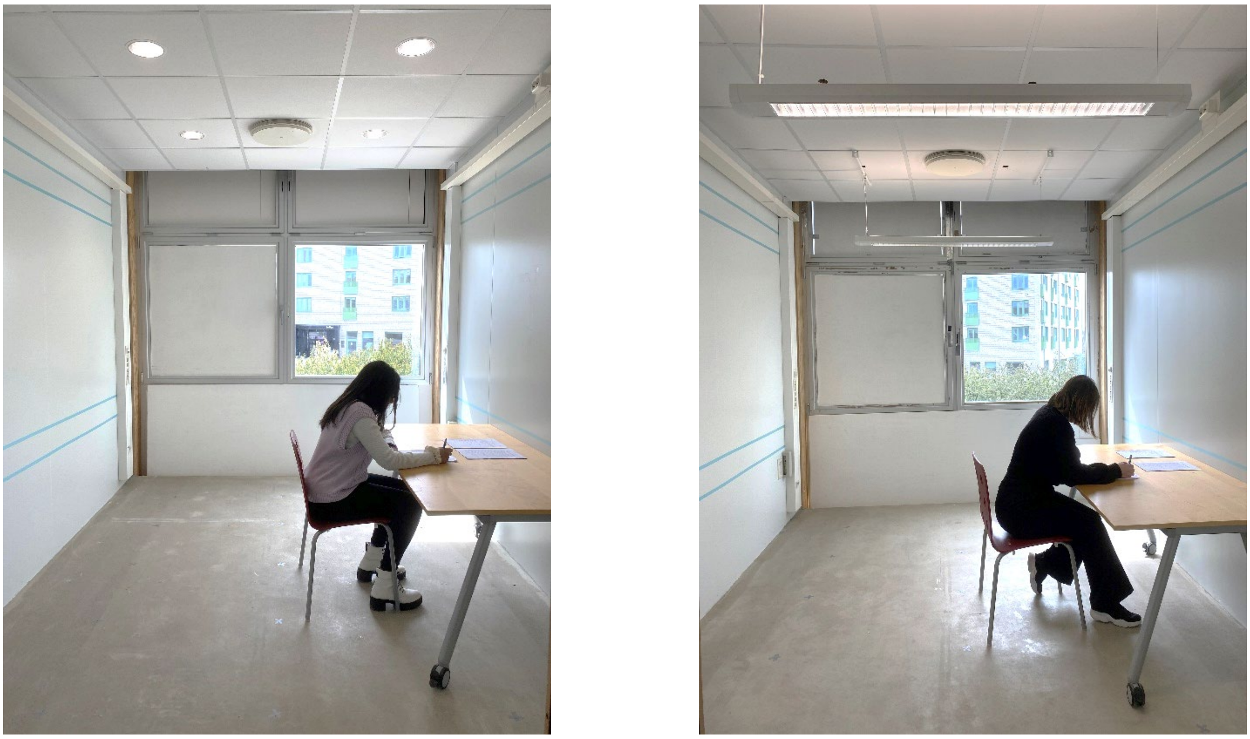

Figure 14: Participants in the test rooms with spotlights (left) and with pendants (right) under electric lighting with daylight from a clear sky.

Before conducting the OBEA, participants were asked to fill in a preliminary questionnaire to collect information about their gender, age, quality of sleep and quality of vision. This was done to ensure the experiment results were reliable. The data from the questionnaires was used to support the experiment results in case any participants have specific vision impairments and/or sleep-wake disorders.

The timeline for the OBEAs and TEAs performed in the scenarios with daylight is presented in Figure 15. It must be noted that the timeline for the only electric lighting scenarios is the same as Experiment 1 and Experiment 2, but the time for TEAs was cut down as not many measurements were taken. Before conducting the OBEA, the participants were handed an instruction sheet detailing the timeline of the experiment (Appendix E).

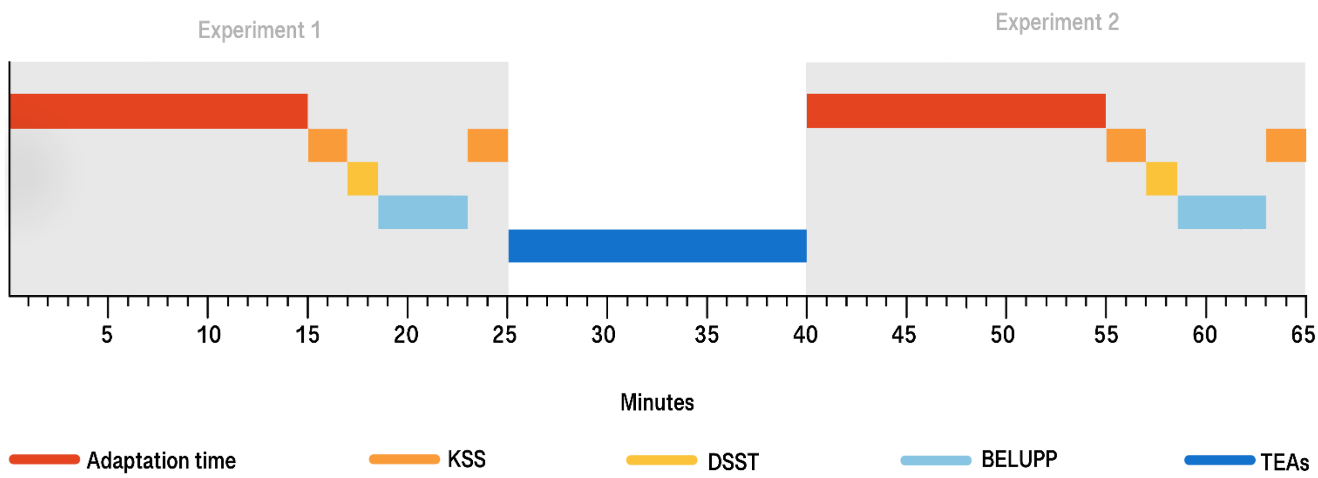

Figure 15: Timeline for OBEAs and TEAs performed in the scenarios with daylight.

TEAs of E_h on the desk (Appendix A) and E_v at eye level were carried out in between each experiment session to monitor the lighting conditions in both rooms. The KONICA MINOLTA CRI Illuminance Meter CL-70F (Figure 7) was used to assess the SPD of the light entering the eye (Appendix B). Moreover, the Global

Horizontal Illuminance and SPD of the sky were measured to keep track of the clear sky conditions during each session (Appendix C and Appendix D).

2.2.1 Karolinska Sleepiness Scale (KSS)

The KSS asks participants to report their subjective level of sleepiness at a particular time during the day (Appendix E). The participants indicate their psycho-physical state in the room using the 9-point rating scale for different levels of alertness/sleepiness i.e.,

1- Extremely alert
2- Very alert
3- Alert
4- Rather alert
5- Neither alert nor sleepy
6- Some signs of sleepiness
7- Sleepy, but no effort to keep awake
8- Sleepy, but some effort to keep awake
9- Very sleepy, great effort to keep awake, fighting sleep

To assess the participant's sleep-wake pattern prior to the experiment, they were asked to fill the KSS form during three times of the day for three days– after waking up (morning), after lunch (afternoon), and before going to bed (evening).

2.2.2 BELUPP Questionnaire

BELUPP is a paper-based questionnaire asking participants to evaluate the visual appearance of light in the test rooms. The questionnaire contained 16 bipolar scales of the Perceived Indoor Lighting Quality (PILQ) tool. As semantic understanding of vocabulary used for the scales is crucial, English and Swedish versions of the questionnaire were made available, along with a sheet of definitions to aid the participants. A BELUPP score sheet was then used to assess the answers (Appendix E).

2.2.3 Digit Symbol Substitution Test (DSST)

The DSST is a standard neuropsychologic test involving a paper-based task. It is a part of the Wechsler Adult Intelligence Scale (WAIS) which measures intelligence and cognitive vitality. In this study, the DSST was simplified by the authors to assess a participant's visual spatial awareness and sustained attention under different lighting conditions.

The DSST had numbers from one through nine paired with a symbol at the top of the page. This was followed by 100 blank boxes with numbers on top, which required participants to copy the symbols that correspond to the number within 90 seconds. The test was scored based on the number of completed items and number of symbols incorrectly copied. The higher the score the better the person's performance (Appendix E).

2.3 Lighting Simulation

The 3D geometry of the laboratory room was modelled in Rhinoceros 3D to carry out dynamic calculations in the parametric simulation tool Grasshopper (with Honeybee, Radiance, and LARK 2.0 plug-ins). The results were used to analyze lighting performance of the room and its potential for circadian entrainment.

2.3.1 Geometry Modelling

Critical surfaces that affect daylighting and electric lighting in the room such as wall, ceiling, and floor were modeled as in reality. The external and internal construction details of the windows were modelled to account for their effect on lighting distribution. They were simplified to reduce the number of surfaces to be simulated and to minimize computational time. Similarly, the table was modeled without legs and the cable trucking was simplified as cuboids. Chairs and other small furnishings were ignored. Figure 16 illustrates the 3D Rhino model of the laboratory room. As the surrounding buildings are at a considerable distance from the room, the context was ignored to shorten simulation time.

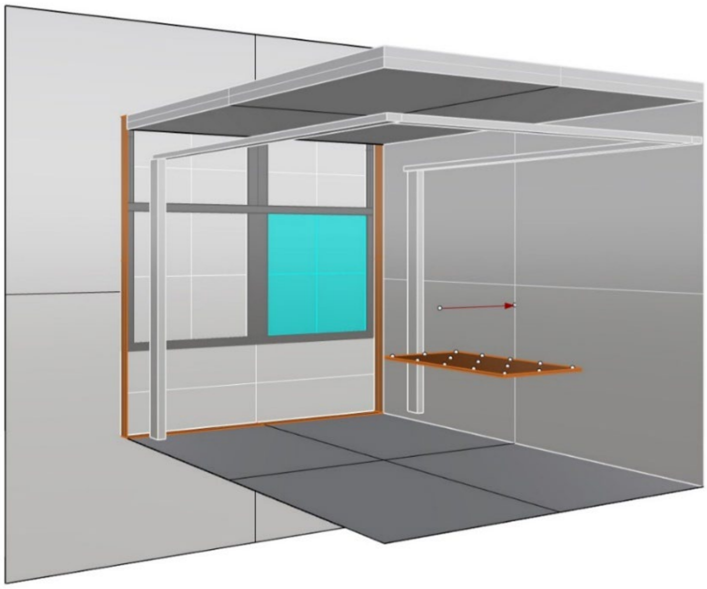

Figure 16: 3D Rhino model[1] of the test room with the original view direction.

2.3.2 Surface Properties

Material properties of the room surfaces were defined in LARK 2.0 as a Radiance (RAD) material with reflectance/transmittance data in 9 channels (red, green, and blue channels). Data about the material's SPD, roughness, and specularity was collected from the Spectral Material Database. The SPD at each wavelength in the visible part of the electromagnetic spectrum was provided as a CSV file.

2.3.3 Electric Lighting

The relative SPD for LEDs with CCT of 4000 K was collected from the EMPIR 15SIB07 PhotoLED database (Jost et al., 2021). IES photometric files illustrating the light distribution from luminaires in the test rooms were taken from the manufacturer's website. This information was used to define a RAD luminaire material in LARK 2.0 with spectral data in 9 channels.

2.3.4 Sky Model

An EPW weather file of Lund (TMYx 2007 - 2021) was used to get the horizontal direct irradiation, horizontal diffuse irradiation, and global illuminance for a meteorological year. According to a study by Sendra et al. (2021), to represent daylight from clear sky and overcast sky entering through south-facing windows, the CIE D50 illuminant was chosen as the sky model. The relative SPD of CIE D50 illuminant was collected from the CIE 15:2004 Technical Report. This information was used to define a RAD sky material in LARK 2.0 with spectral data in 9 channels.

[1] Visibility of the door and some walls were turned off for better visualization of the 3D Rhino model.

2.3.5 Model Calibration

The accuracy of the computational model was calibrated with the following TEAs of the mock-up offices:

- **Daylight Factor (DF)**

The simulated DF values were compared to the measurements and were within an acceptable margin of error i.e., ±30% in both test rooms. The simulated DF values for grid points in the test rooms are presented in Figure 17 alongside those measured on-site (Figure 11).

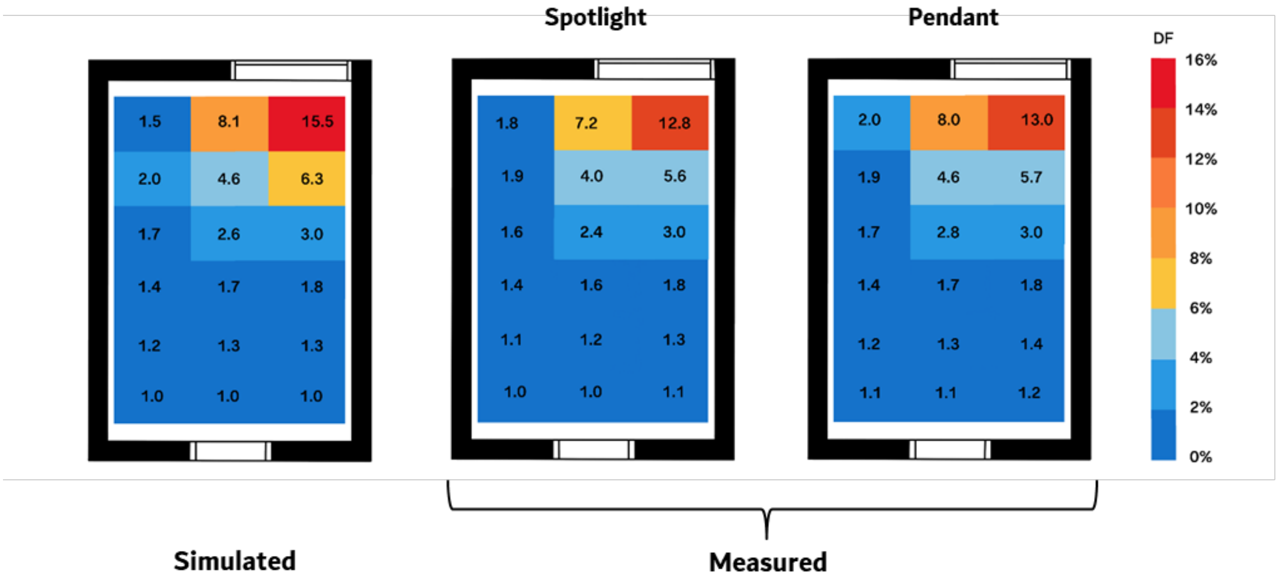

Figure 17: Comparison between simulated DF [%] (left) and measured DF [%] (right) for grid points in the test rooms.

- **Horizontal illuminance (only electric lighting)**

The simulated E_h values on the desk were compared to that of measurements and were within an acceptable margin of error in the room with pendants. However, in the room with spotlights, the measured E_h values on the desk were approx. 30% lower than that simulated in DIALux and Grasshopper. This could be attributable to the depreciation of the lamps over time and/or due to a malfunction of the LED drivers. To match reality, a candela multiplier of 70% was applied to the spotlights.

The simulated E_h values for grid points in the test rooms are presented in Figure 18 alongside those measured on-site (Figure 13).

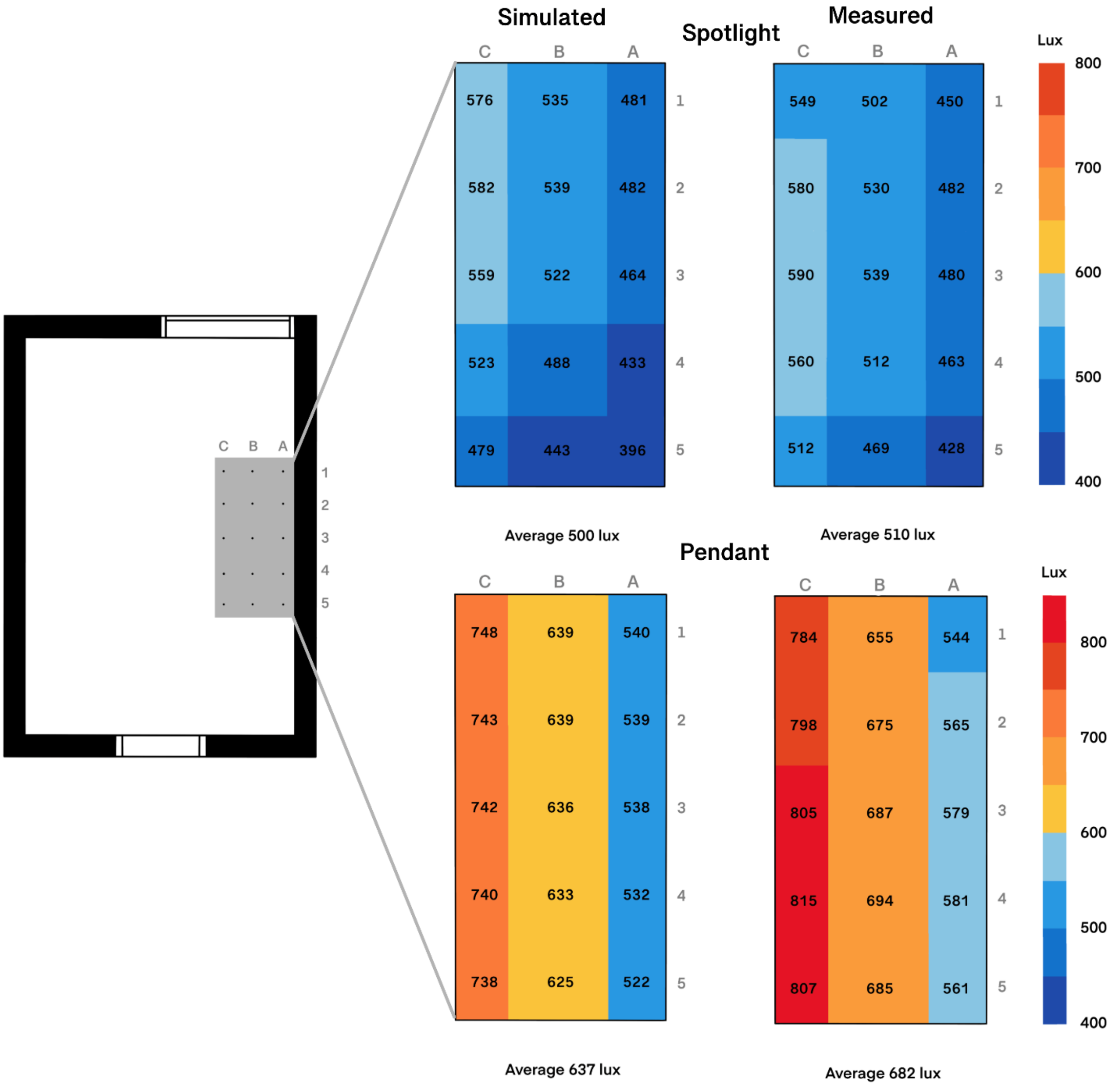

Figure 18: Measured and simulated values of E_h [lux] for grid points on the desk in the test rooms.

- **Vertical illuminance (only electric lighting)**

The simulated E_v values at eye level (0.46 m from the desk) were compared to that of measurements and were within an acceptable margin of error i.e., ±30% in both test rooms (Table 3).

Table 3: Measured and simulated values of E_v [lux] in the test rooms with only electric light.

	Vertical Illuminance E_v [lux]	
	On-site Measurement	Simulation
Test Room w/ Spotlights	264	272
Test Room w/ Pendants	351	269

- **Melanopic Equivalent Daylight Illuminance (mEDI)**

With only electric lighting, the simulated mEDI values at eye level were compared to that of measurements and were within an acceptable margin of error i.e., ±30% in both test rooms (Table 5). When supplemented with daylight however, the simulated E_v values at eye level were lower than measured in both test rooms (Table 4), which may be because of the general sky model and weather file used. This subsequently underestimated the circadian potential of the lighting environments.

Table 4: Measured and simulated values of E_v [lux] in the test rooms under electric lighting with daylight from a clear sky on 6th April (9:10-10:15).

	Vertical Illuminance E_v [lux]	
	On-site Measurement	Simulation
Test Room w/ Spotlights	1267	1000
Test Room w/ Pendants	1223	1013

Table 5: Measured and simulated values of mEDI [lux] in the test rooms with only electric lighting.

	mEDI [lux]	
	On-site Measurement	Simulation
Test Room w/ Spotlights	137	155
Test Room w/ Pendants	185	148

2.4 Circadian Potential

Acknowledging the underestimation of simulated photopic illuminance and mEDI values at eye level under electric lighting with daylight, scenarios with spotlights and pendants having CCTs of 4000 K, 2700 K and 6500 K were tested and compared. To further analyze the influence of diffuse daylight on E_v and mEDI at eye level, the desk and viewpoint were positioned as shown in Figure 19, such that the new view direction faces the wall opposite to the original view.

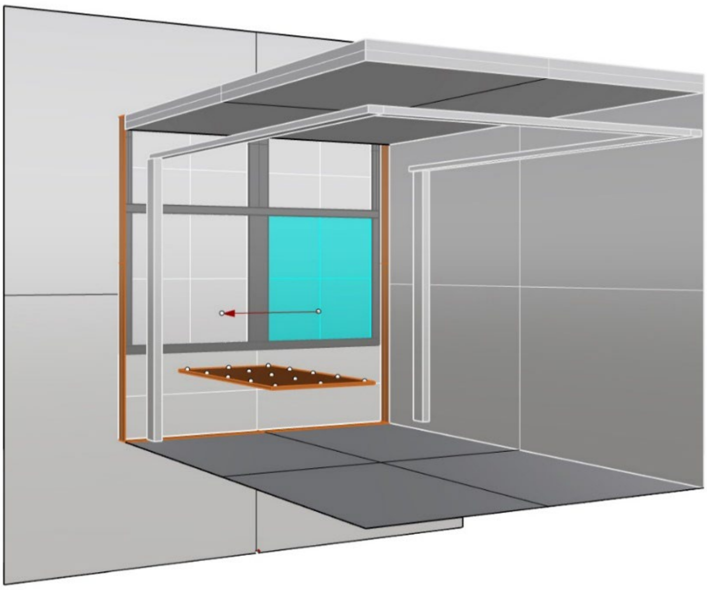

Figure 19: 3D Rhino model[2] of the test room with the new desk position and view direction.

Table 6 summarizes the lighting scenarios participants were exposed to in the experiments and those that were simulated.

[2] Visibility of the door and some walls were turned off for better visualization of the 3D Rhino model.

Table 6: Summary of the lighting scenarios studied using experiments and simulations.

Lighting Scenarios	Experiment w/ Subjects	Simulation
4000K Pendant Only	✓	✓
4000K Pendant + New View Direction		✓
4000K Pendant + Daylight	✓	✓
4000K Pendant + Daylight + New View Direction		✓
4000K Spotlight Only	✓	✓
4000K Spotlight + New View Direction		✓
4000K Spotlight + Daylight	✓	✓
4000K Spotlight + Daylight + New View Direction		✓
2700K Pendant Only		✓
2700K Pendant + New View Direction		✓
2700K Pendant + Daylight		✓
2700K Pendant + Daylight + New View Direction		✓
2700K Spotlight Only		✓
2700K Spotlight + New View Direction		✓
2700K Spotlight + Daylight		✓
2700K Spotlight + Daylight + New View Direction		✓
6500K Pendant Only		✓
6500K Pendant + New View Direction		✓
6500K Pendant + Daylight		✓
6500K Pendant + Daylight + New View Direction		✓
6500K Spotlight Only		✓
6500K Spotlight + New View Direction		✓
6500K Spotlight + Daylight		✓
6500K Spotlight + Daylight + New View Direction		✓

2.4.1 Point-in-Time Based Simulation

To assess the impact of daylight and electric light on the activation state of people and energy efficiency, the different lighting scenarios were simulated for the 21st of March, June, September, and December at 9:00, 12:00 and 15:00. This analysis period was chosen to represent the maximum (summer solstice), equinox (vernal and autumnal equinox), and minimum (winter solstice) of daylight availability throughout the year under clear sky and overcast sky conditions.

2.4.2 Image Based Simulation

As paper-based tasks would be carried out in the test rooms, a critical viewpoint was chosen for a qualitative analysis of the room's lighting conditions. Based on point-in-time results, fisheye views of WX False Colour images of the best-case and worst-case scenarios were produced to predict the occurrence of high luminance contrasts between surfaces in the visual field.

2.5 Energy Performance Analysis

Energy calculations for different lighting scenarios were carried out on a point-in-time basis for the 21st of March, June, September, and December at 9:00, 12:00 and 15:00. The point on the desk with the least daylight illuminance under different sky conditions was determined, and a simulation was done under only electric lighting with no dimming at that point. The amount of electric lighting needed in addition to daylight to meet the target E_h of 500 lux was calculated to predict the dimming of luminaires at each point-in-time.

The annual electric lighting energy use was estimated using the point-in-time simulation results for the 21st of March, June, September, and December at 9:00, 12:00 and 15:00 under overcast and clear sky. The point-in-time simulation results were extrapolated to represent an 8:00 to 17:00 day with the assumption that 8:00 to 11:00 is the same as 9:00, 11:00 to 14:00 is the same as 12:00, and 14:00 to 17:00 is the same as 15:00. A similar simplification was used to calculate the monthly electric lighting energy use, where February to April is the same as March, May to July is the same as June, August to October is the same as September, and November to January is the same as December. The electric lighting energy use results for the 21st of March, June, September, and December were multiplied with the number of days in each month to estimate monthly energy use. To account for daylight variations under different sky conditions, average monthly percentages of overcast and clear sky in Lund were used in the calculations (Table 7).

Table 7: Average monthly percentages of overcast and clear sky in Lund (WeatherSpark, no date).

Sky Condition	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Overcast	70%	66%	62%	56%	48%	45%	44%	47%	50%	58%	68%	71%
Clear	30%	34%	38%	44%	52%	55%	56%	53%	50%	42%	32%	29%

As per standard SS-EN 15193-1:2017, the default standby energy density for controls of 1.5 kWh/m^2/year was added to the normalized yearly output value to give the Lighting Energy Numeric Indicator (LENI) for both test rooms. The LENI values of direct and direct-indirect electric lighting with manual ON/OFF switches and with daylight-linked control were compared to LENI of a hypothetical energy-efficient LED fixture having a lighting power density of 4 W/m^2 to assess the efficiency of the lighting system (Gentile & Dubois, 2017). Annual operating hours of 3 285 h (9 h × 365 days) were used instead of 2 250 h stated in SS-EN 15193-2:2017 for the calculations, which can lead to an overestimation of LENI.

3 Results

3.1 User Perspective

The quantitative results from the TEAs for different participants in the test rooms under only electric lighting and under electric lighting with daylight from a clear sky are presented in Table 8 and Table 9 respectively.

Table 8: TEAs for different participants in the test rooms under only electric light.

Participant	Gender	Age	Date and Time	$\bar{E}_h$ [lux]		E_v [lux]		mEDI [lux]	
				Spotlights	Pendants	Spotlights	Pendants	Spotlights	Pendants
#1	Female	34	4th April 13:00-13:50	510	682	264	351	137	185
#2	Male	26	4th April 13:00-13:50	510	682	264	351	137	185
#3	Male	26	31st March 13:00-13:50	510	682	264	351	137	185
#4	Male	25	31st March 13:00-13:50	510	682	264	351	137	185
#5	Male	29	31st March 10:00-10:50	510	682	264	351	137	185
#6	Female	24	17th April 13:20-14:10	510	682	264	351	137	185
#7	Female	24	31st March 10:00-10:50	510	682	264	351	137	185
#8	Male	27	30th March 16:00-16:50	510	682	264	351	137	185
#9	Female	32	28th March 10:00-10:50	510	682	264	351	137	185
#10	Female	24	28th March 10:00-10:50	510	682	264	351	137	185

Table 9: TEAs for different participants in the test rooms under electric light with daylight from a clear sky.

Participant	Gender	Age	Date and Time	$\bar{E}_h$ [lux]		E_v [lux]		mEDI [lux]	
				Spotlights	Pendants	Spotlights	Pendants	Spotlights	Pendants
#1	Female	34	4th April 10:45-11:50	2926	2963	2130	2230	1598	1667
#2	Male	26	4th April 10:45-11:50	2926	2963	2130	2230	1598	1667
#3	Male	26	6th April 9:10-10:15	1401	1574	1267	1223	962	895
#4	Male	25	6th April 9:10-10:15	1401	1574	1267	1223	962	895
#5	Male	29	6th April 11.05-12:10	2310	2432	1850	1843	1400	1381

#6	Female	24	17th April 12:15-13:20	2324	2415	1430	1510	1076	1110
#7	Female	24	21st April 10:30-11:35	1999	2118	1530	1690	1170	1287
#8	Male	27	28th April 11:00-12:05	2286	2427	1590	1850	1153	1345
#9	Female	32	28th April 13:30-14:35	1984	2002	909	1310	651	920
#10	Female	24	28th April 13:30-14:35	1984	2002	909	1310	651	920

The qualitative results from the OBEA are presented. The KSS scale, DSST test, and BELUPP questionnaire were filled-in under four lighting conditions– direct electric lighting with spotlights, direct-indirect electric lighting with pendants, direct electric lighting with daylight from a clear sky, and direct-indirect electric lighting with daylight from a clear sky. No statistical tests were performed due to the small sample size.

3.1.1 Karolinska Sleepiness Scale (KSS) Scale

The results from the KSS questionnaire are presented in Figure 20 and Figure 21[3]. To quantitatively measure and compare participant's psycho-physical state under the above-mentioned lighting conditions, a score of 1 was assigned to a participant's vote for 'very sleepy, great effort to keep awake, fighting sleep' up to a score of 9 for 'Extremely alert'.

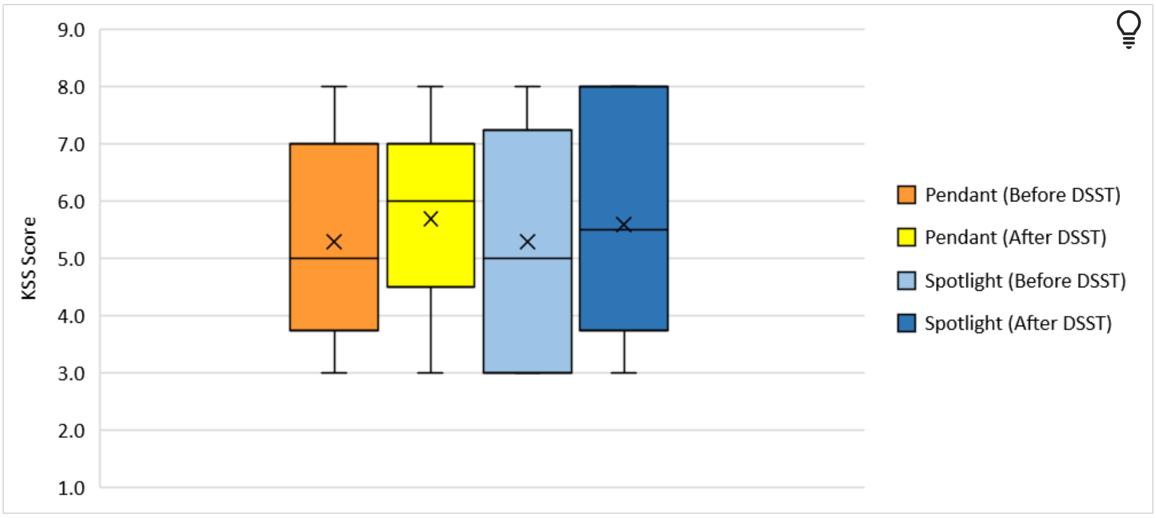

Figure 20: KSS results of participant's alertness under direct and direct-indirect electric lighting.

[3] indicates only electric lighting conditions.
indicates clear sky conditions.
indicates overcast sky conditions.

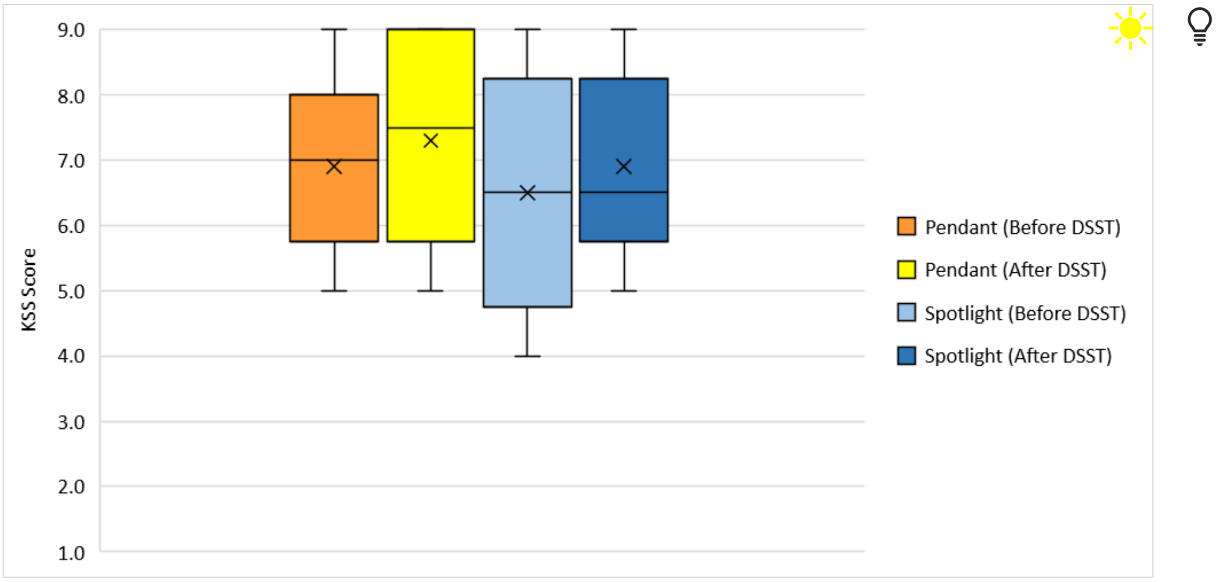

Figure 21: KSS results of participant's alertness under direct and direct-indirect electric lighting with daylight from a clear sky.

Figure 20 shows that under only electric lighting alertness increased by 5.66% in the test room with spotlights and by 9.62% in the room with pendants before and after the DSST test. The number of participants having a psycho-physical state of alertness i.e., 'Rather alert', 'Alert', 'Very Alert' and 'Extremely alert' before the DSST test increased from 40% to 50% in the room with spotlights and to 60% in the room with pendants after the DSST test.

Figure 21 shows that under daylight from a clear sky alertness increased by 7.81% in the test room with spotlights and by 5.80% in the room with pendants before and after the DSST test. The number of participants having a psycho-physical state of alertness i.e., 'Rather alert', 'Alert', 'Very Alert' and 'Extremely alert' before the DSST test increased from 60% to 80% after the DSST test in the room with spotlights. 80% of participants in the room with pendants indicated alertness before and after the DSST test, however their level of alertness increased after the test.

3.1.2 BELUPP Questionnaire

The results from the BELUPP questionnaire are presented in boxplots in Figure 22 and Figure 23.

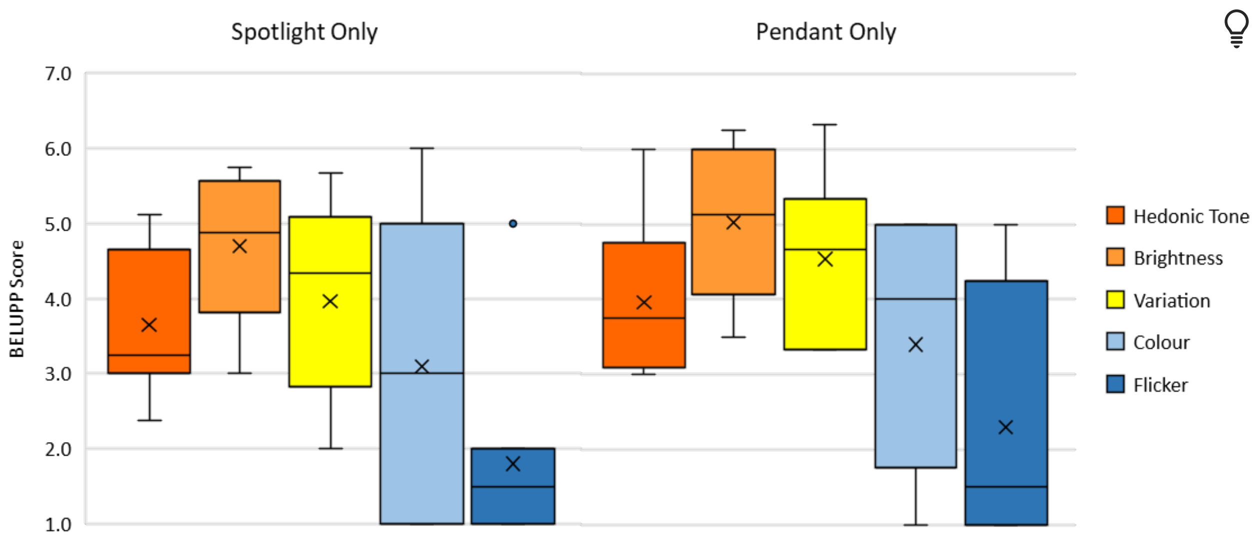

Figure 22: BELUPP results of participant's perception of direct and direct-indirect electric lighting.

Figure 22 shows that under only electric lighting the participants scored the test room with pendants a higher value for hedonic tone, brightness, and flicker compared to the room with spotlights. One participant expressed discomfort due to flicker when in the room with pendants. Both electric lighting conditions showed similarities for variation which was unexpected as spotlights distribute light in a downward direction, while pendants distribute light uniformly in all directions. Both electric lighting conditions also showed similarities in colour with one participant stating that the 4000K (white) spotlights seemed akin to a hospital.

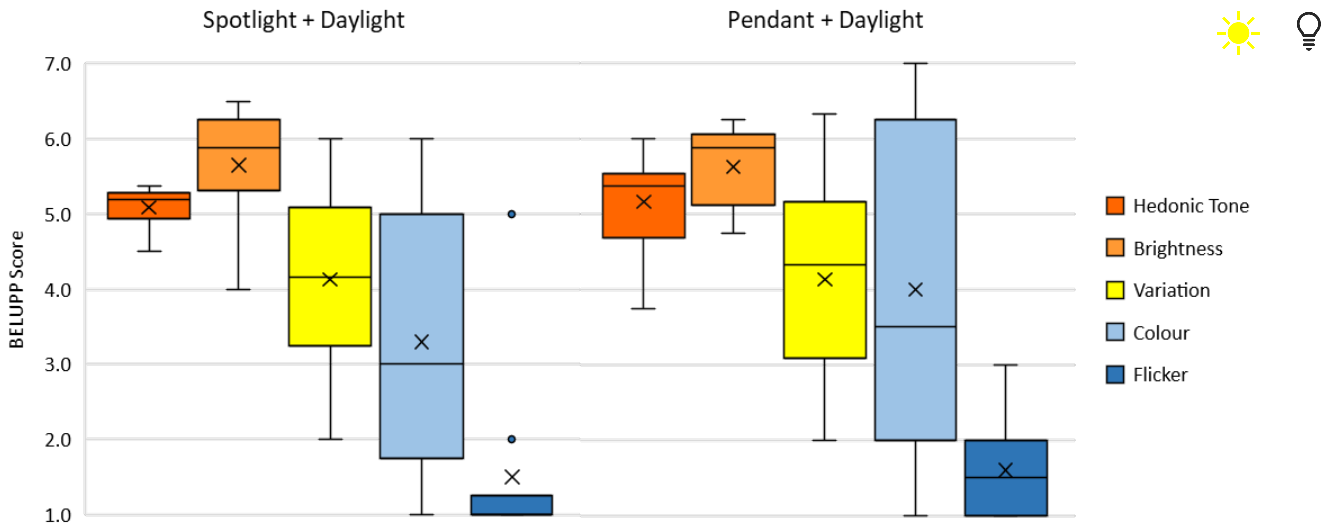

Figure 23: BELUPP results of participant's perception of direct and direct-indirect electric lighting with daylight from a clear sky.

Figure 23 shows that under daylight from a clear sky the participants scored the room with pendants a higher value for colour compared to the room with spotlights. Both mock-ups showed similarities for hedonic tone, brightness, variation, and flicker which was expected as daylight contributes largely to the rooms' lighting environment under a clear sky. However, two participants stated that they preferred the room with spotlights as it had a better view outdoors though the rooms are adjacent to each other. This demonstrated that TEA results are not always the only indicator of lighting optimization, and the user experience of the space should also be considered.

3.1.3 Digit Symbol Substitution Test (DSST)

The results from the DSST test were inconclusive as the number of samples correctly completed by the participants improved with each round of testing regardless of the lighting condition. But interestingly, it was observed that participants made more mistakes in the room with spotlights. In the room with spotlights the number of samples incorrectly completed was 300% higher than the room with pendants under only electric lighting. Similarly, the number of samples incorrectly completed was 400% higher in the room with spotlights compared to the room with pendants under electric light and daylight.

3.2 Circadian Potential

The data collected from Grasshopper simulation software presents visual and non-visual performance of four different lighting conditions– direct electric lighting (spotlight) with daylight from a clear sky, direct-indirect artificial lighting (pendant) with daylight from a clear sky, direct electric lighting (spotlight) with daylight from an overcast sky, and direct-indirect electric lighting (pendant) with daylight from an overcast sky. The results of mEDI at eye level are summarized in Figure 24 and Figure 25.

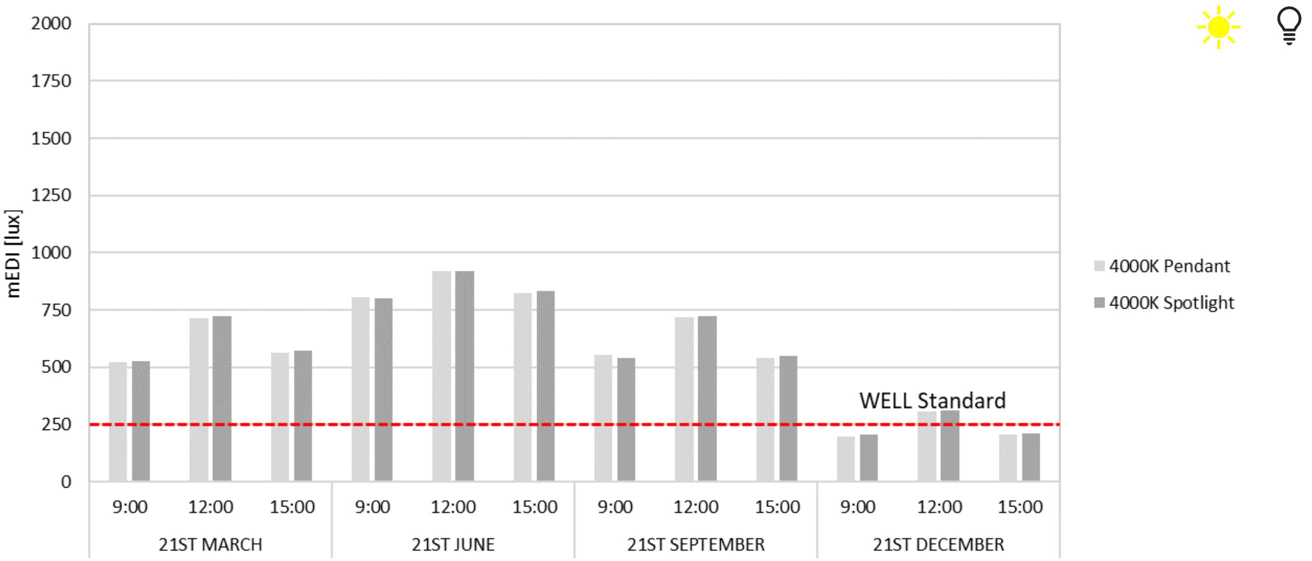

Figure 24: Simulated mEDI [lux] values over a year for 4000K electric lighting under a clear sky.

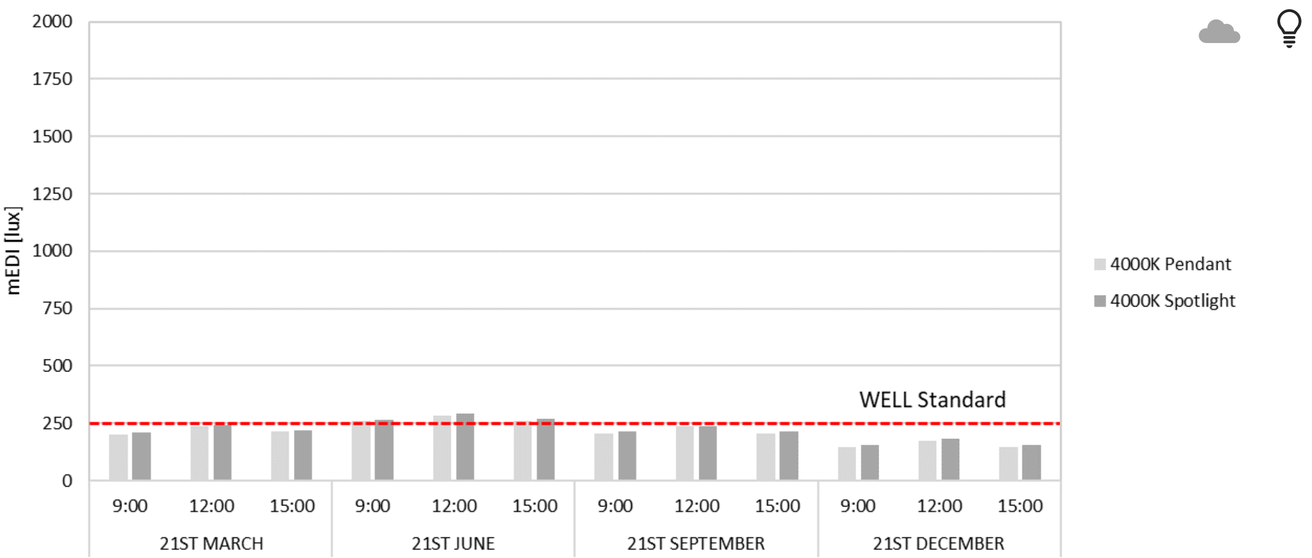

Figure 25: Simulated mEDI [lux] values over a year for 4000K electric lighting under an overcast sky.

Table 10 shows that in the absence of daylight, direct electric lighting provides a mEDI of 155 lux and direct-indirect electric lighting provide a mEDI of 148 lux, which does not meet the non-visual requirements of ≥ 250 lux as per WELL Building Standard v2 (Feature #L03). The mEDI exceeds 250 lux under clear sky throughout the year except for December. Under an overcast sky, the non-visual requirements of ≥ 250 lux is only achieved during June for both pendant and spotlight. Overall, lighting conditions with direct electric lighting demonstrate slightly higher mEDI than direct-indirect electric lighting.

Table 10: Simulated mEDI [lux] and E_h [lux] values for only electric lighting.

	Original View Direction				**New View Direction**			
	mEDI [lux]			**Photopic Illuminance [lux]**	**mEDI [lux]**			**Photopic Illuminance [lux]**
	4000K	**2700K**	**6500K**		**4000K**	**2700K**	**6500K**	
Test Room w/ Pendants	148	84	198	637	147	84	198	639
Test Room w/ Spotlights	155	88	208	523	155	88	209	522

The results of photopic E_h (at the center of the desk) and mEDI (at eye level) under only daylight are summarized in Figure 26 and Figure 27.

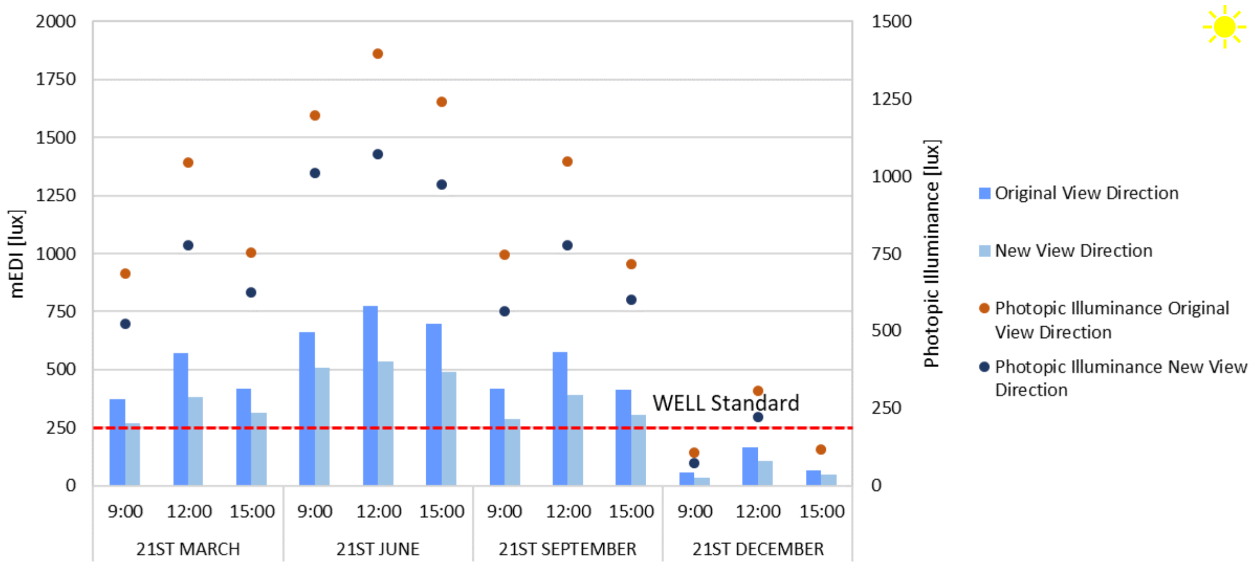

Figure 26: Simulated mEDI [lux] and E_h [lux] values over a year for only daylight under a clear sky.

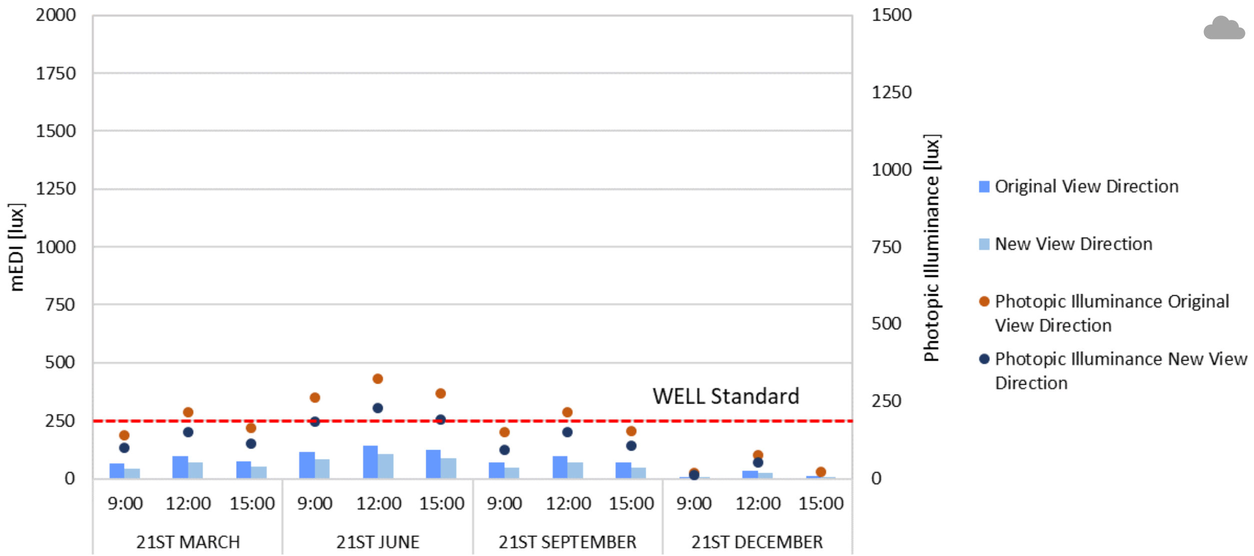

Figure 27: Simulated mEDI [lux] and E_h [lux] values over a year for only daylight under an overcast sky.

Figure 26 shows that with only daylight from a clear sky the mEDI results meet the non-visual requirements of ≥250 lux, and E_h results meet the visual requirements of ≥500 lux throughout the year except for December for both view directions. The visual and non-visual targets are not met under an overcast sky throughout the year for both view directions and would need to be supplemented with electric lighting.

3.2.1 Influence of CCT

The results of photopic E_h (at the center of the desk) and mEDI (at eye level) for electric lighting of different CCTs with daylight are summarized in Figure 28 and Figure 29.

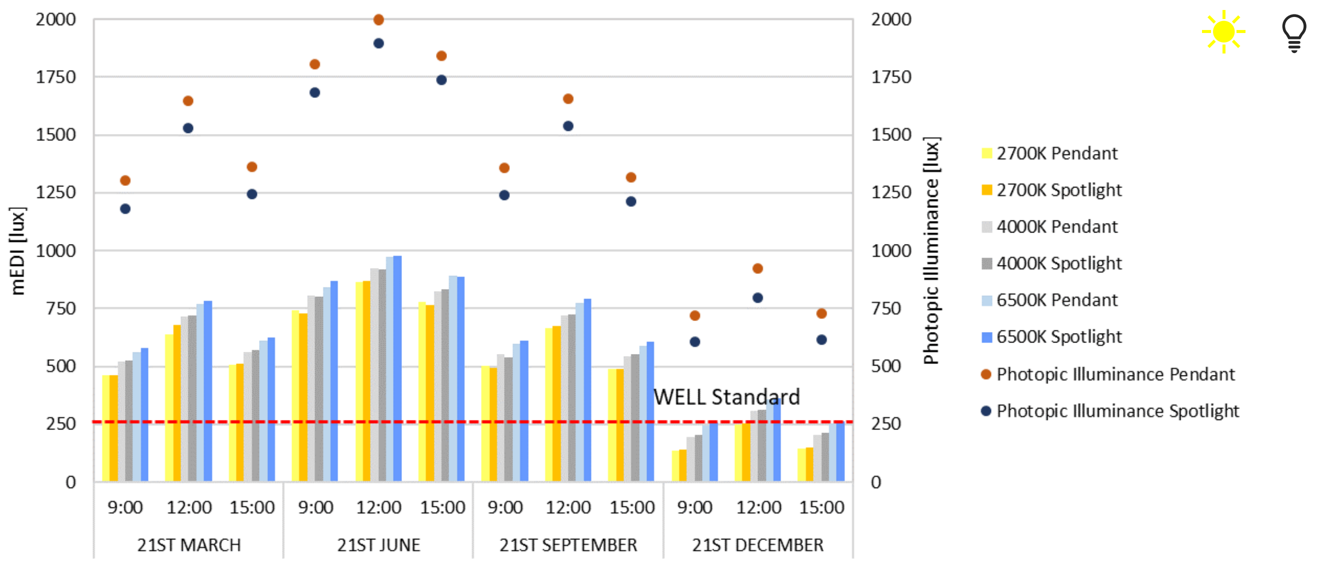

Figure 28: Simulated mEDI [lux] and E_h [lux] values over a year for electric lighting of different CCTs under a clear sky.

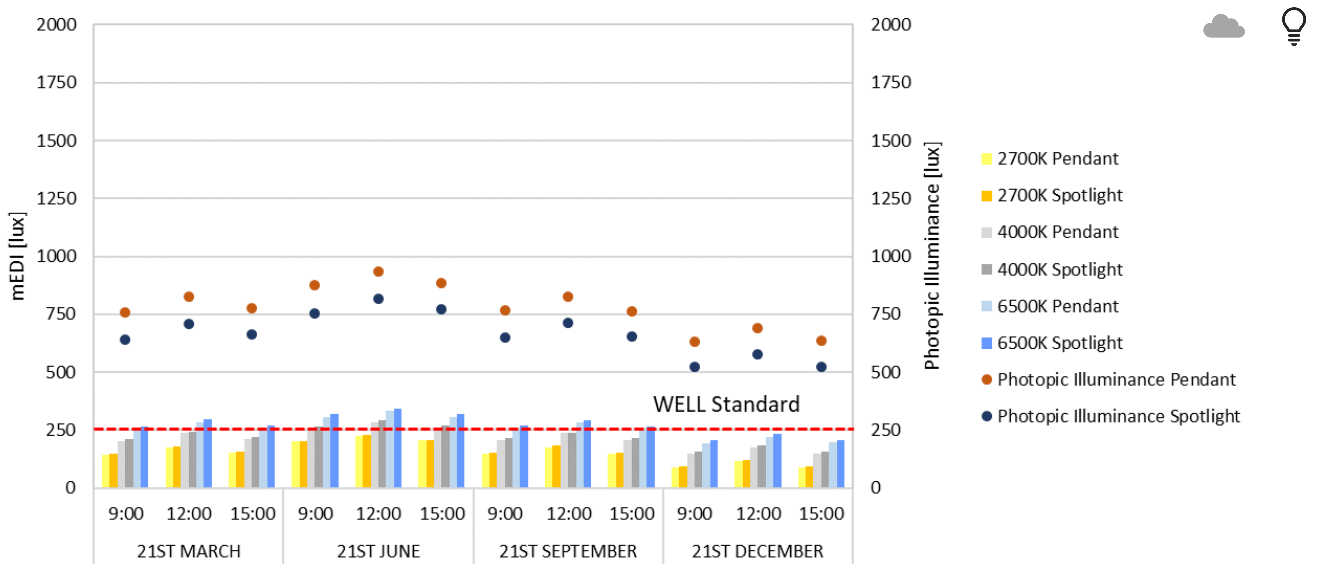

Figure 29: Simulated mEDI [lux] and E_h [lux] values over a year for electric lighting of different CCTs under an overcast sky.

The mEDI values follow a trend similar to that of 4000K electric lighting under clear sky and overcast sky, with expectedly higher values for 6500K electric lighting and lower values for 2700K electric lighting. Table 10 shows that in the absence of daylight, direct electric lighting of 2700K and 6500K CCT provide mEDI of 88 lux and 208 lux, whereas pendants of 2700K and 6500K CCT provide mEDI of 84 lux and 198 lux. These results do not meet the non-visual requirements of ≥250 lux. However, the mEDI exceeds 250 lux under a clear sky throughout the year for both pendant and spotlight of 6500K CCT, mainly due to the contribution of daylight. Under an overcast sky, the non-visual requirement of ≥250 lux is achieved throughout the year except for December for 6500K electric lighting. 2700K electric lighting does not meet the non-visual requirement of ≥250 lux under an overcast sky.

3.2.2 Influence of View Direction

The simulated photopic E_h (at the center of the desk) and mEDI (at eye level) for the second view direction (Figure 19) under electric light with daylight are presented in Figure 30 and Figure 31.

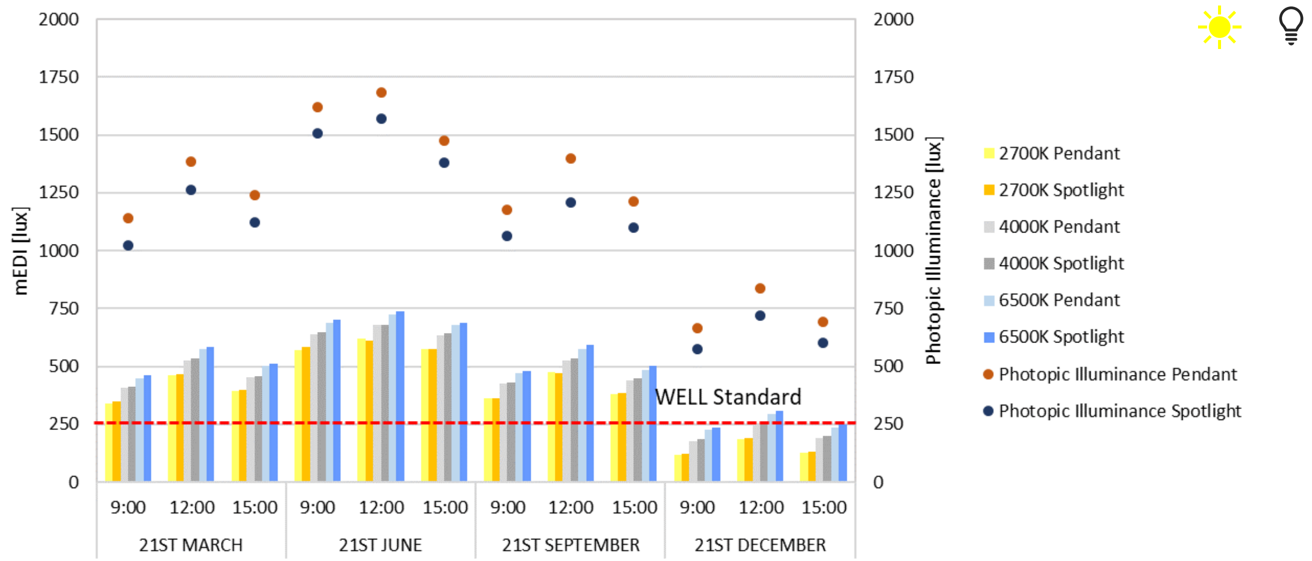

Figure 30: Simulated mEDI [lux] and E_h [lux] values over a year for electric lighting of different CCTs under a clear sky for the new viewing direction.

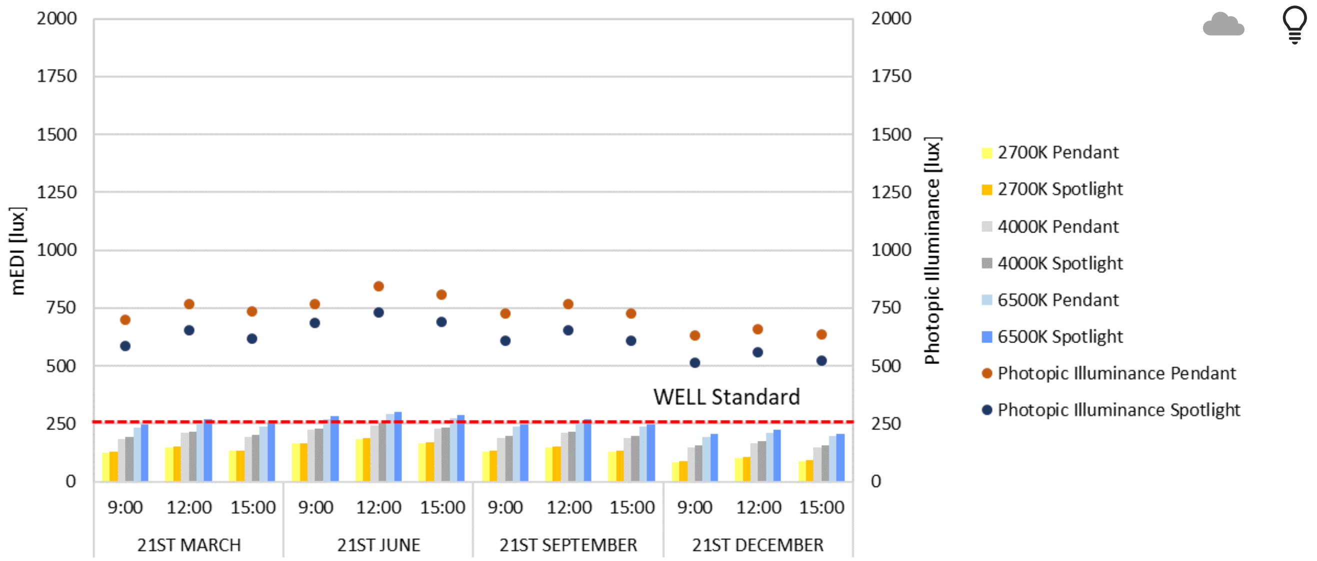

Figure 31: Simulated mEDI [lux] and E_h [lux] values over a year for electric lighting of different CCTs under an overcast sky for the new viewing direction.

The result follows the same trend as the original view but with lower values. The mEDI results meet the non-visual requirements of ≥250 lux for all CCTs under a clear sky throughout the year except for December. This shows that even by having daylight on one's back, the WELL targets are met under a clear sky. Under an overcast sky the WELL Standard is only achieved with 6500K during June for both pendant and spotlight. It can be concluded that most of the circadian illumination on the vertical is provided by daylight.

3.3 Energy Performance Analysis

The energy use of electric lighting employing daylight-linked control at each point-in-time is detailed in Table 11 and Table 12. The yearly energy use of electric lighting with and without daylight-linked control is presented in Table 13.

Table 11: Energy use of direct electric lighting with daylight-linked control on a point-in-time basis.

		Energy Use [W/m^2]			
		Spotlight + Clear Sky	Spotlight + Clear Sky + New View Direction	Spotlight + Overcast Sky	Spotlight + Overcast Sky + New View Direction
21ST MARCH	9:00	0.34	0.95	5.91	5.91
	12:00	0.00	0.00	5.57	5.78
	15:00	0.00	0.00	5.91	5.91
21ST JUNE	9:00	0.00	0.00	5.11	5.62
	12:00	0.00	0.00	4.58	4.86
	15:00	0.00	0.00	5.04	5.55
21ST SEPTEMBER	9:00	0.00	1.23	5.91	5.91
	12:00	0.00	0.00	5.55	5.75
	15:00	0.00	0.00	5.91	5.91
21ST DECEMBER	9:00	5.91	5.91	5.91	5.91
	12:00	4.30	4.62	5.91	5.91
	15:00	5.91	5.91	5.91	5.91

Table 12: Energy use of direct-indirect electric lighting with daylight-linked control on a point-in-time basis.

		Energy Use [W/m^2]			
		Pendant + Clear Sky	Pendant + Clear Sky + New View Direction	Pendant + Overcast Sky	Pendant + Overcast Sky + New View Direction
21ST MARCH	9:00	0.28	0.77	5.06	5.16
	12:00	0.00	0.00	4.53	4.70
	15:00	0.00	0.00	4.89	5.15
21ST JUNE	9:00	0.00	0.00	4.15	4.58
	12:00	0.00	0.00	3.73	3.95
	15:00	0.00	0.00	4.10	4.52
21ST SEPTEMBER	9:00	0.00	1.00	4.97	5.08
	12:00	0.00	0.00	4.51	4.68
	15:00	0.00	0.00	4.97	5.10
21ST DECEMBER	9:00	5.19	5.34	5.97	5.99
	12:00	3.49	3.76	5.54	5.60
	15:00	5.10	5.18	5.94	5.96

Table 13: Yearly electric lighting energy use[4] with and without daylight-linked control systems.

Electric Lighting System	Work Position	Annual Energy Use with Daylight-Linked Control [kWh/(m^2.year)]	Annual Energy Use without Daylight-Linked Control [kWh/(m^2.year)]
Spotlight	Original View Direction	13.47	20.91
	New View Direction	13.95	
Pendant	Original View Direction	11.98	22.40
	New View Direction	12.50	

It can be concluded that the energy use for the pendant is lower than spotlight when the sensor is installed. If the work position were changed to face the opposite wall, the new viewing direction would increase the energy use by 0.5 kWh/m^2/year.

There is a significant energy-saving potential for installing daylight-linked controls compared to standard manual ON/OFF switches. For direct-indirect electric lighting there is potential to save up to 73.4% and up to 46.5% for direct electric lighting. However, when compared to LENI of 14.64 kWh/(m^2.year) for the hypothetical energy-efficient LED system, the installed electric lighting is not energy-efficient.

3.4 Summary of Results

Figure 32 details the overall visual and non-visual performance of the different lighting scenarios. The lowest E_h case was 2700K spotlights (excluding daylight) with the original and new view direction. The lowest mEDI case was 2700K pendants (excluding daylight) with the original and new view direction. By considering the annual energy use without daylight-linked control for spotlights of 20.91 kWh/(m^2.year) and for pendants of 22.40 kWh/(m^2.year) the best case was 6500K spotlights under daylight with the original view direction. Similarly, the worst case was 2700K pendants (excluding daylight) with the original and new view direction.

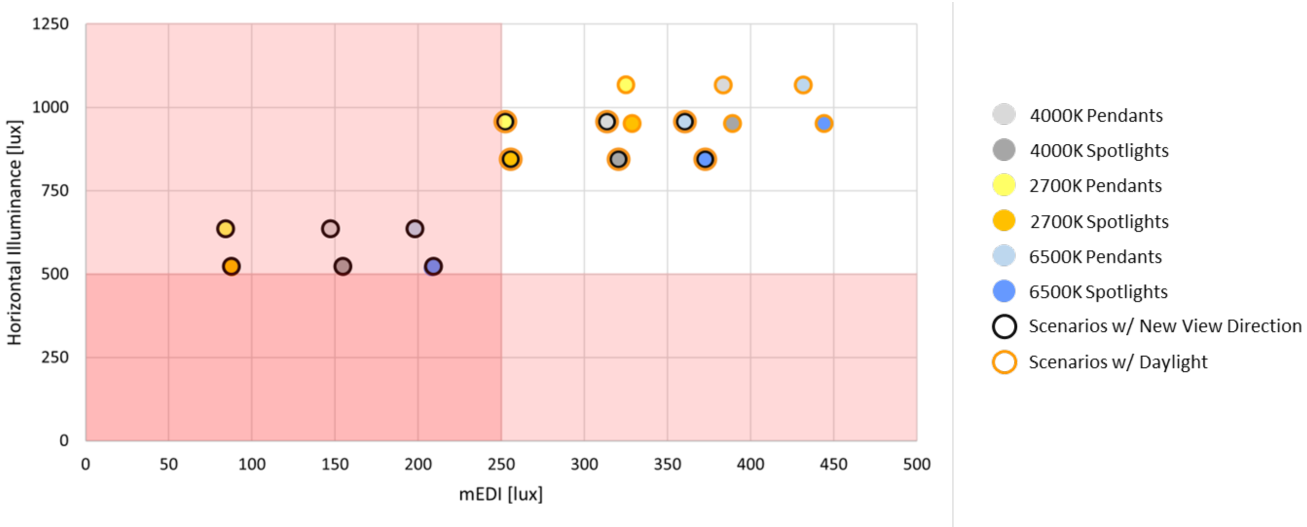

Figure 32: Overall visual and non-visual performance of the different lighting scenarios.

Figure 33 and Figure 34 details the circadian luminance in the best-case and worst-case scenarios. Figure 35 and Figure 36 details the photopic luminance in the best-case and worst-case scenarios. For the best case, WX

[4] The electric lighting systems are over dimensioned as the calculation is based on 3 285 h of usage with lighting always on (and dimmed).

False Colour images were produced for the darkest and brightest day of the year i.e., 9:00 on 21st December with overcast sky and 12:00 on 21st June with clear sky respectively.

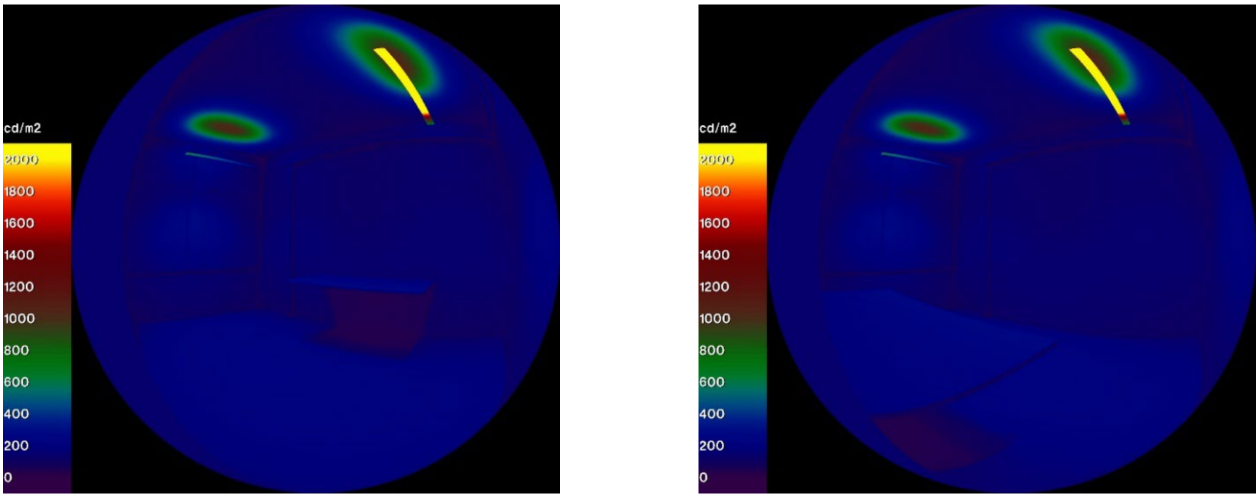

Figure 33: Circadian luminance with 2700K pendants (excluding daylight) in the original (left) and new view direction (right).

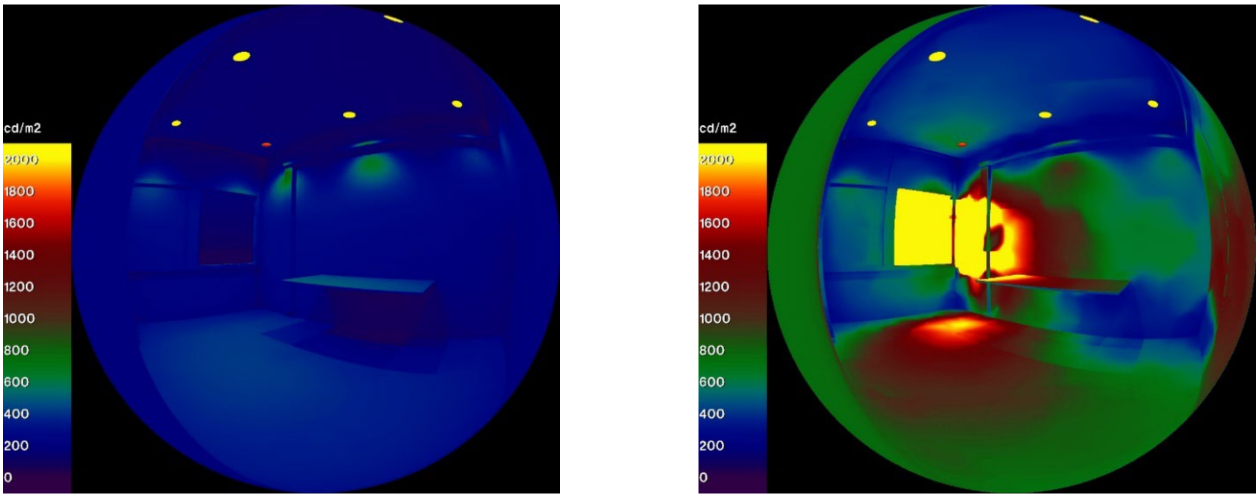

Figure 34: Circadian luminance with 6500K spotlights under overcast (left) and clear (right) sky in the original view direction.

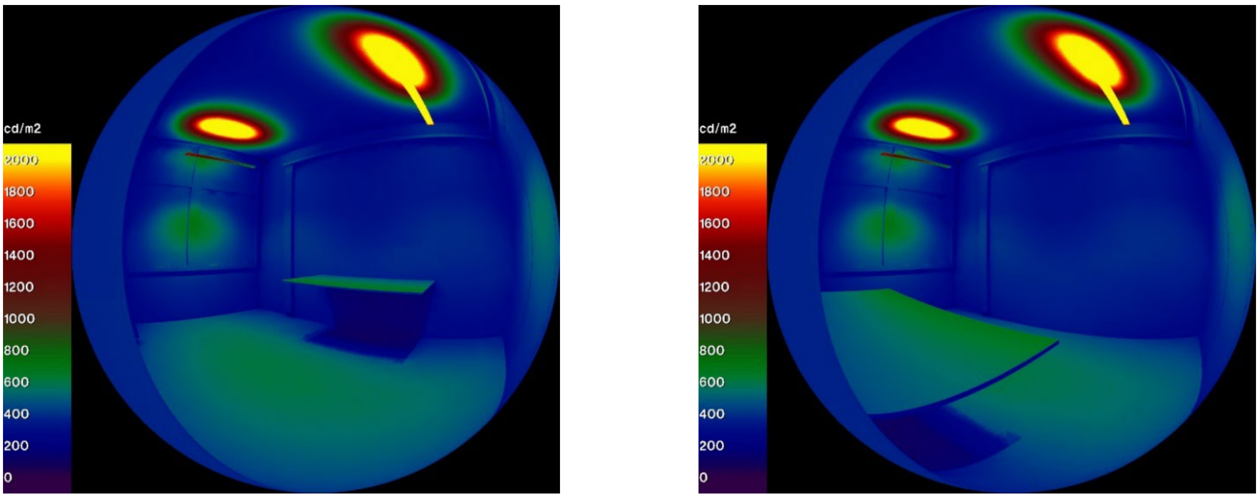

Figure 35: Photopic luminance with 2700K pendants (excluding daylight) in the original (left) and new view direction (right).

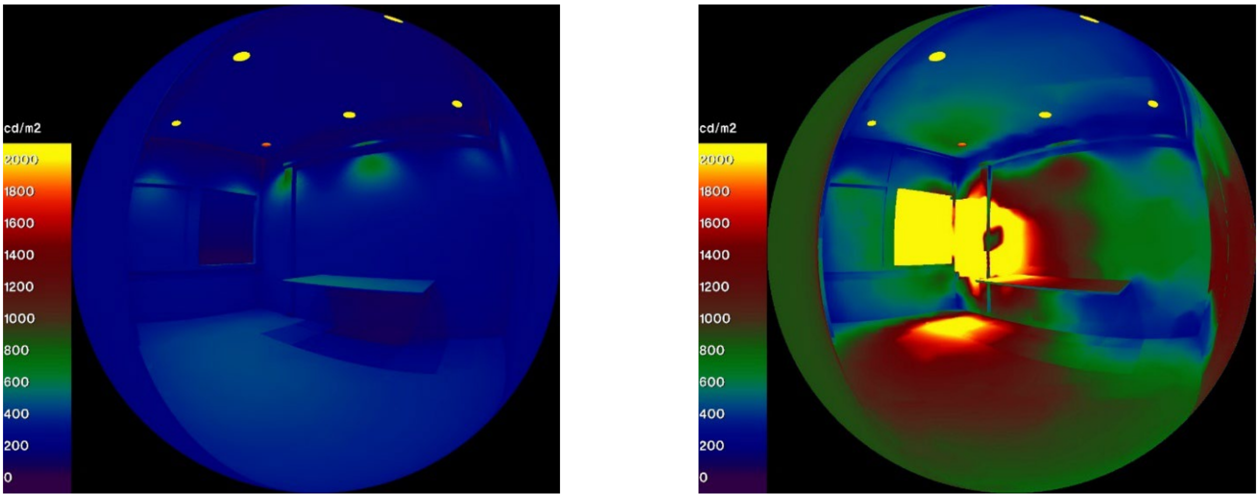

Figure 36: Photopic luminance with 6500K spotlights under overcast (left) and clear (right) sky in the original view direction.

4 Discussion

4.1 User Perspective

Data from the preliminary questionnaire revealed that none of the participants had notable vision impairments and/or sleep-wake disorders. It was noticed that one participant who identified themselves as a 'pronounced evening person' had a generally poor sleep-wake pattern prior to the experiment with 6-7 hours of sleep and bedtimes later than 1:00. When under only electric lighting, this participant showed no changes in alertness/sleepiness and described their psycho-physical state to be 'sleepy, but no effort to keep awake' in both test rooms before and after the DSST test. Another participant who identified themselves as 'to some extent evening person' had a generally good sleep-wake pattern with 7-8 hours of sleep and bedtimes around 22:00. This participant, conversely, showed more alertness under only electric lighting than with daylight from a clear sky. Indicating that the participants behavior, preferences, and prior experience may have greater impact on their alertness than the temporary lighting condition tested. Generally, alertness increased in both test rooms under only electric lighting. The number of participants having a psycho-physical state of alertness i.e., 'Rather alert', 'Alert', 'Very Alert' and 'Extremely alert' before the DSST test increased from 40% to 50% in the room with spotlights and from 40% to 60% in the room with pendants after the DSST test. With daylight from a clear sky, the number of participants having a psycho-physical state of alertness before the DSST test increased from 60% to 80% after the DSST test in the room with spotlights. 80% of participants in the room with pendants indicated alertness before and after the DSST test, however the number of participants having a psycho-physical state of 'Extremely alert' before the DSST test increased from 10% to 30% after the DSST test.

The results from the DSST test were inconclusive as the number of samples correctly completed by the participants improved with each round of testing regardless of the lighting condition. Therefore, no conclusive statements could be made on the impact different lighting scenarios have on a participants' cognitive performance.

When participants were asked to select their preferred lighting condition, the number of participants that favored direct electric lighting with daylight from a clear sky over direct-indirect electric lighting with daylight from a clear sky were divided equally. These reactions aligned with the BELUPP results of the participants which showed that the test room with pendants hardly exhibited a higher value for hedonic tone and brightness compared to the room with spotlights. This goes against the primary hypothesis of this study that direct-indirect electric lighting combined with daylight would result in better perceived quality of lighting.

It must be noted that the KSS, DSST, and BELUPP results can be misleading due to the limited number of participants and do not provide a reliable representation of the entire population. Seeing that there were no significant differences between the office mock-ups, the two electric lighting systems can be concluded to sustain similar visual performance.

4.2 Circadian Potential

On-site measurements of work plane illuminance and SPD at eye level provided an understanding of electric lighting distribution in the test rooms, which aided in calibration of the luminaire files used in the Grasshopper simulation software. The results of work plane illuminance showed higher values in the room with pendants than with spotlights in all the lighting scenarios. It was also noticed that with only electric lighting, the simulated mEDI value at eye level was 12.85% higher than measured in the room with spotlights and 20.27% lower than measured in the room with pendants. These differences can be because spotlights focus light on a downward direction (bottom hemisphere) with much of the emitted light incident on the retina. There is little to no distribution in the top hemisphere. Direct-indirect electric lighting, on the other hand, distributes light uniformly in all directions (top and bottom hemisphere), and much of the emitted light is reflected at least once in the room before reaching the eye. This can affect the SPD of the light incident on a surface as some surfaces reflect more light at certain wavelengths than others. The extent of the change in SPD of the incident light depends on the surface's optical properties such as its reflectance, transmittance, and absorptance. It must be noted that although reflectance of the significant Lambertian surfaces in the room was measured, data about the material's SPD, roughness, and specularity was collected from the Spectral Material Database. Moreover, the data for spectral surfaces and other Lambertian surfaces were approximated. The SPD at each wavelength in the visible part of the electromagnetic spectrum was provided as a CSV file, which may not represent the surface's optical properties as in reality. One participant stated that the internal walls in the mock-ups appeared to have a blue tint, whereas the authors perceived it to be light gray and used spectral data for White Board Partition Wall 1 from the Spectral Material Database.

In the presence of daylight, mEDI results for 4000K electric lighting showed that the non-visual requirements of ≥250 lux is only achieved during June under an overcast sky. Moreover, only small differences can be observed in the point-in-time mEDI results under an overcast sky. This can be connected to how Radiance employs the 10K Lux CIE overcast sky with a fixed zenith illuminance of 10,000 lux (IES, 2021). The constant, low levels of light exposure can disrupt the body's internal clock and lead to feelings of fatigue and lethargy. Electric lighting thus contributes largely to the non-visual circadian effect under an overcast sky. However, the impact of electric lighting on the circadian rhythm may still be less than that of natural light exposure under a clear sky. This is evident seeing that the differences in the point-in-time mEDI results climbed up when under a clear sky. The mEDI exceeds 250 lux under clear sky throughout the year except for December. This could be attributable to the fact that 9:00 and 15:00 are approximately the times of sunrise and sunset in the month of December. December in Lund is characterized by short days and low daylight availability. Therefore, daylight contributes largely to the non-visual circadian effect under a clear sky, which correlates with the secondary hypothesis of this study that daylight from windows alone can provide enough illumination to meet the non-visual requirements.

The mEDI results for simulations of electric lighting with different CCTs followed a trend similar to that of 4000K electric lighting under clear sky and overcast sky, with generally higher values for 6500K electric lighting and lower values for 2700K electric lighting. This was to be expected as the cool-coloured (blue-enriched) lighting from 6500K electric lighting significantly influences the production of cortisol for daytime alertness. However, prolonged exposure to cool-coloured light may cause visual discomfort and must be further studied with subjective tests. Moreover, it was observed that mEDI results peaked at 12:00 in all scenarios. This is possibly related to the room's south orientation resulting in higher photopic illuminances around noon and to the fact that the CCT of daylight varies through the day with mornings and evenings typically characterized by warm-coloured (red-enriched) lighting of lower CCT and cool-coloured lighting of higher CCT at midday.

When comparing mEDI results for the second view direction with the original view, it was observed that the results follow the same trend but with lower values. In the original view, a person is facing the wall adjacent to the window which receives both direct sunlight and diffuse daylight at 9:00 and 12:00 throughout the year. However, in the second view direction the person is facing the wall away from the window which does not receive direct sunlight and mostly diffuse daylight even when the sun is setting on the west at 15:00. The intensity and CCT of daylight can vary depending on the viewer's direction relative to the sun.

Overall, lighting scenarios with direct electric lighting demonstrate slightly higher mEDI than direct-indirect electric lighting. That is, while direct-indirect electric lighting can create uniform, soft illumination, it can lead to lower levels of mEDI. This goes against the primary hypothesis of this study that direct-indirect electric lighting combined with daylight can boost circadian entrainment. However, the uncertainties on the surfaces' optical properties might play a role in the differences between the two settings. In addition, it was noticed that lighting scenarios with mEDI >250 lux have E_h values much higher than 500 lux, which could lead to discomfort glare and must be explored further in future studies.

4.3 Energy Performance Analysis

The annual energy use for electric lighting was calculated using data from point-in-time simulations making the resulting values a simplification and not an exact representation of reality. But since the same calculation method is used for all the lighting scenarios, a comparison between the scenarios can still be made. Direct-indirect electric lighting showed higher potential for energy savings, which could be due to the higher uniformity and illuminance at the work plane than direct electric lighting. It was noticed that under a clear sky, daylight is sufficient to meet the target E_h for a considerable number of working hours and the electric light can be turned off. Under an overcast sky, however, spotlights need to be 100% ON in December as well as at 9:00 and 15:00 during the equinoxes and do not meet the target E_h of 500 lux. This is not favourable as overcast sky is the dominating sky condition in Lund. It is worth considering that there is potential for further energy savings from electric lighting if a larger WWR is used. However, this potentially leads to an increase in the system load during the heating and cooling season. The use of clerestories could allow for uniform ambient lighting while blocking the harsh sun rays in summer. Furthermore, electric lighting with daylight-linked control must be designed to achieve not only the target E_h, but also mEDI values of ≥ 250 lux for circadian entrainment.

5 Conclusion

This study investigated the impact of two different electric lighting distributions on horizontal illuminance, vertical illuminance, mEDI, and energy use in a mock-up office while including the impact of daylight. Field tests with subjects were carried out to understand whether different lighting scenarios could ensure similar alertness/sleepiness and visual task performance. Further lighting scenarios with different CCTs and view directions were tested using lighting simulations to determine which of the scenarios could reach the visual and non-visual requirements in the most energy-efficient way. The results of this study have led to the following conclusions:

- Direct and direct-indirect light distribution perform similar in terms of visual perception, alertness/sleepiness, and cognitive performance as no significant differences were observed in the KSS, DSST, and BELUPP results between the office mock-ups.
- The visual requirement of average E_h ≥500 lux on the desk was achieved for all the lighting scenarios, with higher values in the room with pendants than in the room with spotlights.
- Non-visual requirements are challenging to meet. The non-visual requirement of mEDI ≥250 lux at eye level was never achieved with only electric light. The simulated mEDI value was higher than measured in the room with spotlights and lower in the room with pendants.
- Most of the circadian illumination on the vertical is provided by daylight and is required to reach mEDI ≥250 lux. Only after including daylight from a clear sky was the non-visual requirement achieved for most of the year.
- 6500K direct electric lighting under daylight with the original view direction performs the best in terms of visual and non-visual performance however, prolonged exposure to cool-coloured light may cause visual discomfort.
- Simulated results for spotlights showed a slightly higher mEDI for all the lighting scenarios, possibly yielding a higher activation state in people.
- Without daylight-linked control, spotlights have a lower energy consumption than pendants. With dimming controls there is potential to save up to 46.5% for direct electric lighting and up to 73.4% for direct-indirect electric lighting.

The information presented in this study will hopefully encourage the design of energy-efficient integrative lighting systems while including the impact of daylight on non-visual stimuli. However, it would be interesting to run simulations to obtain results for mEDI with daylight-linked control that maintains work plane illuminance of 500 lux. Furthermore, daylight-linked control must be designed to achieve not only the visual requirement, but also non-visual requirement for circadian entrainment. More studies including all the different types of lighting distributions and window placements are required to make clear conclusions on how they impact horizontal illuminance, vertical illuminance, mEDI, and energy use.

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Appendix A- Horizontal Illuminance

Below are the horizontal illuminances measured on the desk during the experiments. The measurement spots are as presented in Figure 13 and Figure 18.

SPOTLIGHT — PENDANT

Participant #1 and #2 (4th April 10:45-11:50)

SPOTLIGHT

	1	2	3	4	5
A	6157	2970	2300	2060	1837
B	5253	2960	2407	2153	1900
C	4370	2940	2487	2180	1920

PENDANT

	1	2	3	4	5
A	6147	3023	2387	2053	1813
B	5040	3020	2453	2123	1913
C	4473	3093	2570	2250	2083

Participant #3 and #4 (6th April 9:10-10:15)

SPOTLIGHT

	1	2	3	4	5
A	1643	1407	1257	1140	1030
B	1770	1510	1350	1223	1120
C	1960	1647	1460	1317	1180

PENDANT

	1	2	3	4	5
A	1744	1495	1343	1257	1165
B	1972	1670	1510	1411	1319
C	2180	1862	1676	1541	1457

Participant #5 (6th April 11.05-12:10)

SPOTLIGHT

	1	2	3	4	5
A	3520	2280	1933	1720	1530
B	3803	2430	2060	1827	1640
C	3540	2550	2190	1920	1713

PENDANT

	1	2	3	4	5
A	3513	2363	2017	1817	1667
B	3943	2580	2177	1987	1827
C	3563	2653	2327	2100	1943

Participant #6 (17th April 12:15-13:20)

SPOTLIGHT

	1	2	3	4	5
A	3217	2460	2060	1797	1573
B	3363	2607	2180	1897	1673
C	3427	2670	2227	1967	1750

PENDANT

	1	2	3	4	5
A	2930	2363	2053	1847	1693
B	3307	2630	2267	2033	1860
C	3663	2897	2477	2200	2007

Participant #7 (21st April 10:30-11:35)

SPOTLIGHT

	1	2	3	4	5
A	2550	2067	1793	1590	1420
B	2667	2180	1900	1690	1520
C	2817	2317	2030	1797	1650

PENDANT

	1	2	3	4	5
A	2640	2120	1850	1680	1550
B	2823	2297	2020	1843	1703
C	2880	2430	2147	1960	1830

Participant #8 (28th April 11:00-12:05)

SPOTLIGHT

	1	2	3	4	5
A	3497	2283	1933	1983	1490
B	3230	2220	1763	1453	1317
C	3423	3063	2590	2137	1910

PENDANT

	1	2	3	4	5
A	3667	2910	2197	1623	1257
B	3190	2430	2083	1857	1463
C	4087	2970	2353	2260	2060

Participant #9 and 10 (28th April 13:30-14:35)

SPOTLIGHT

	1	2	3	4	5
A	2473	1943	1537	1460	1253
B	2877	2283	1863	1633	1450
C	3267	2487	2020	1710	1507

PENDANT

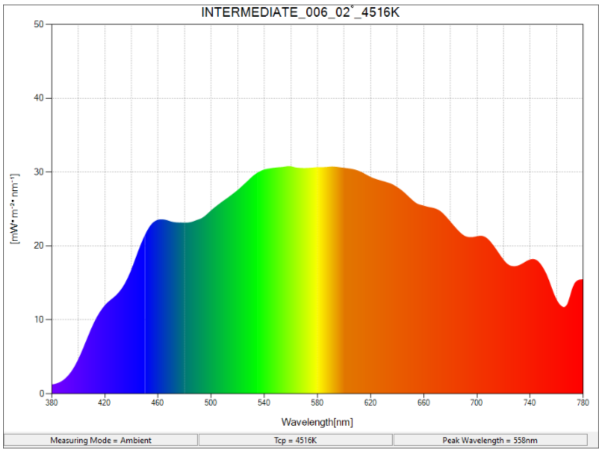
	1	2	3	4	5
A	2317	1760	1553	1463	1380
B	2573	2113	1873	1703	1547
C	3427	2600	2150	1880	1697

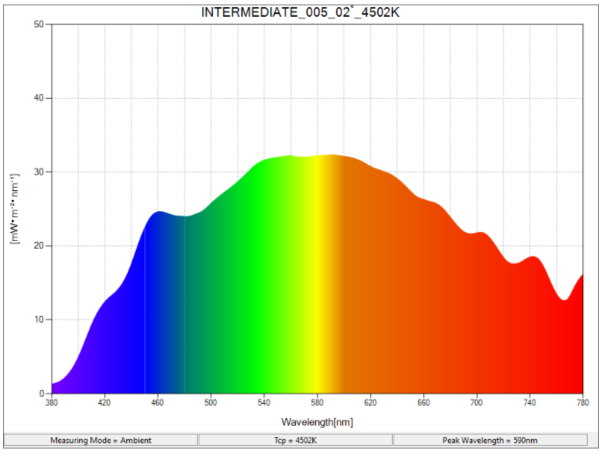
Appendix B- Spectral Power Distribution at Eye

Below are the SPDs measured in the office mock-ups at 0.46 m above the work plane in the original view direction using the KONICA MINOLTA CRI Illuminance Meter.

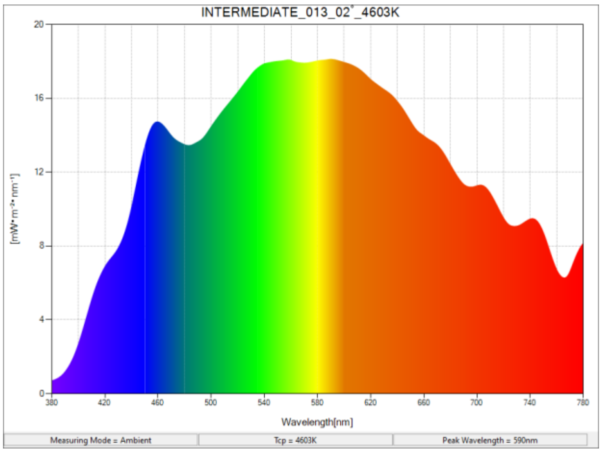
SPOTLIGHT PENDANT

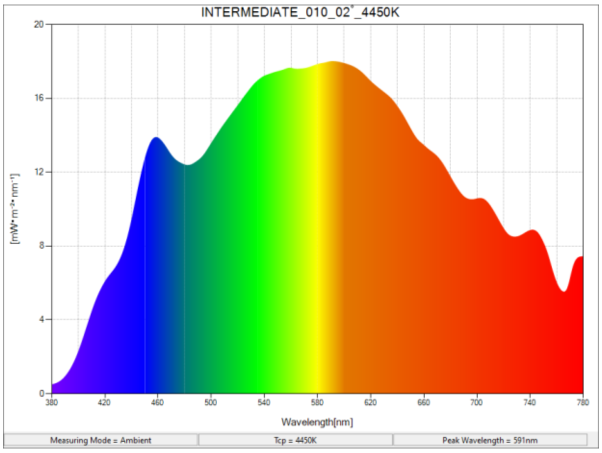
Participant #1 and #2 (4th April 10:45-11:50)



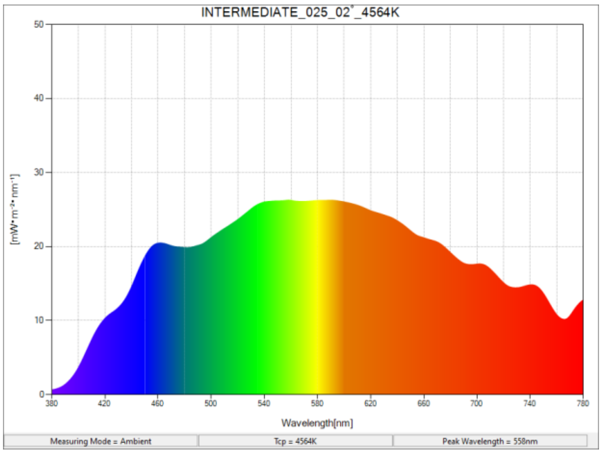


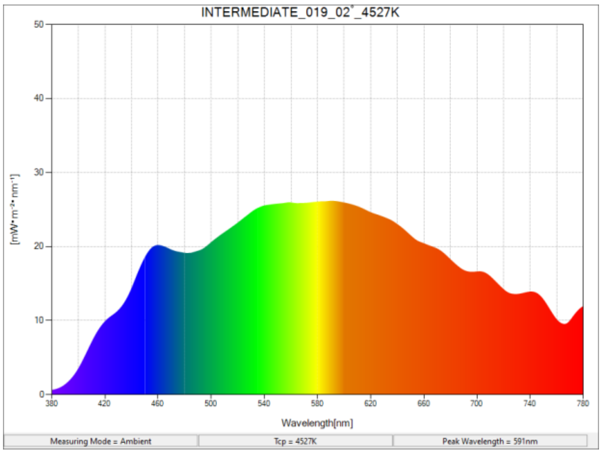
Participant #3 and #4 (6th April 9:10-10:15)



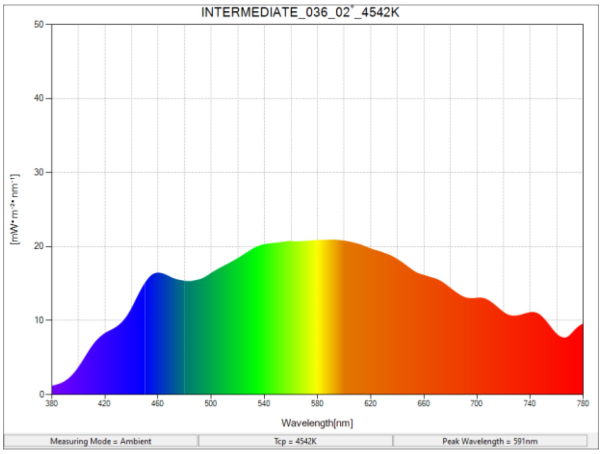


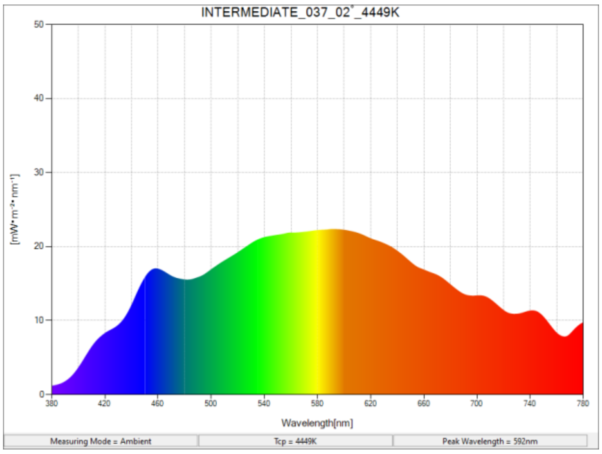
Participant #5 (6th April 11.05-12:10)



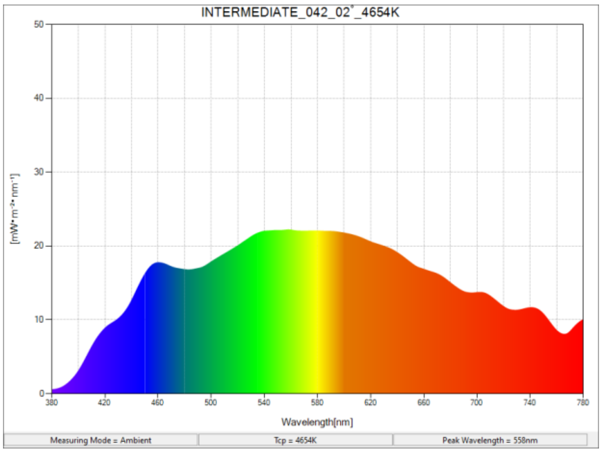


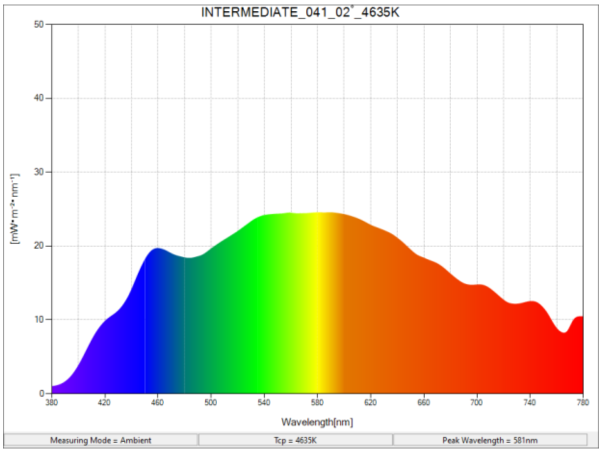
Participant #6 (17th April 12:15-13:20)



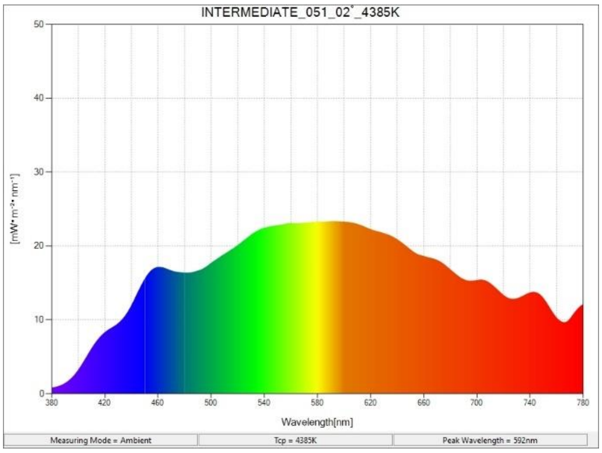


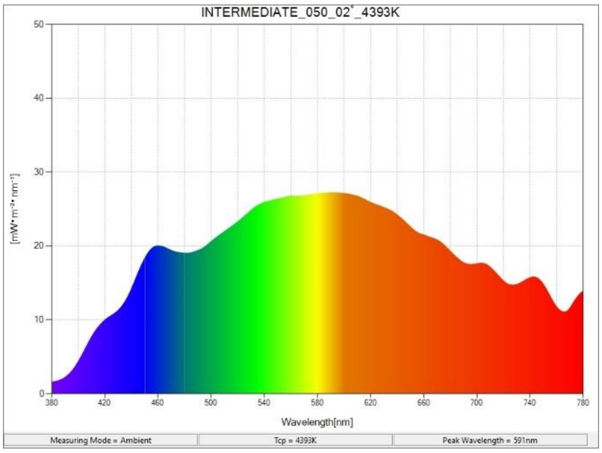
Participant #7 (21st April 10:30-11:35)



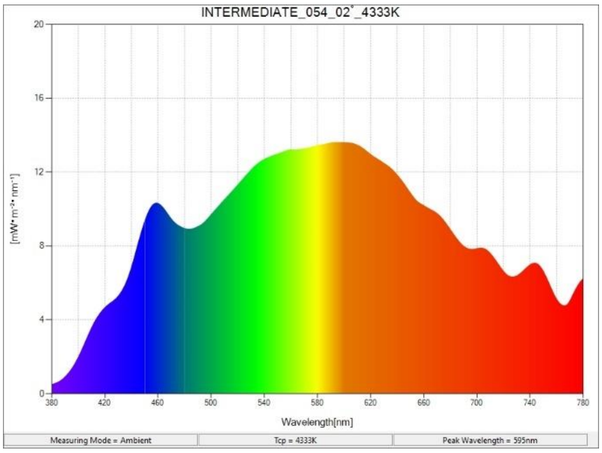


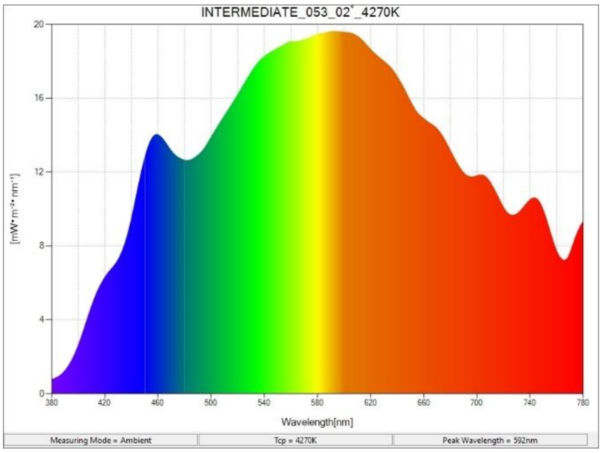
Participant #8 (28th April 11:00-12:05)





Participant #9 and #10 (28th April 13:30-14:35)

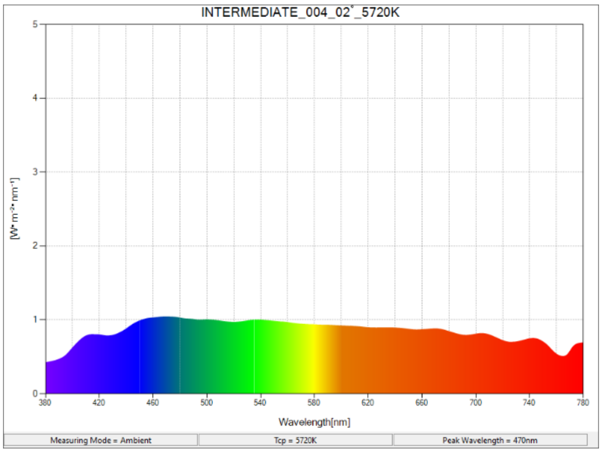




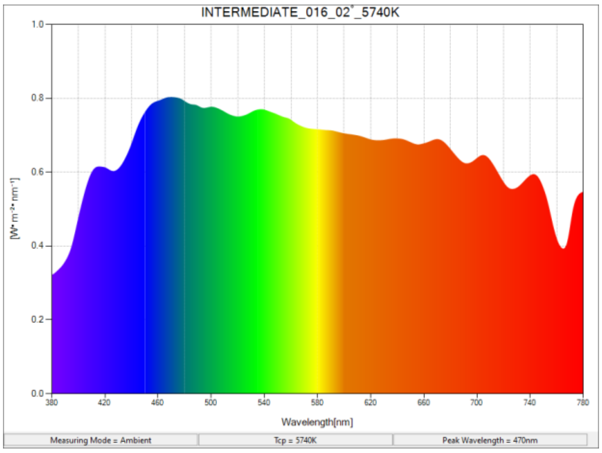
Appendix C- Spectral Power Distribution of the Sky

Below are the SPDs of the sky measured from the roof of the Energy and Building Design Laboratory with the KONICA MINOLTA CRI Illuminance Meter.

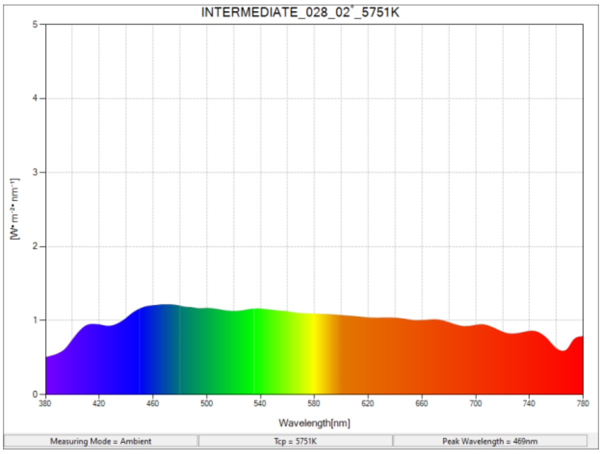
Participant #1 and #2 (4th April 10:45-11:50)



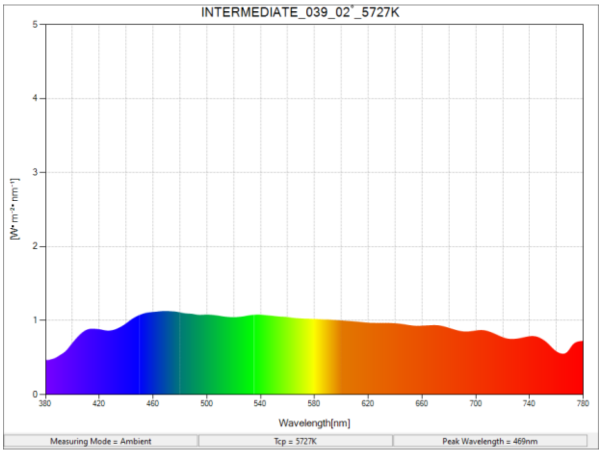
Participant #3 and #4 (6th April 9:10-10:15)



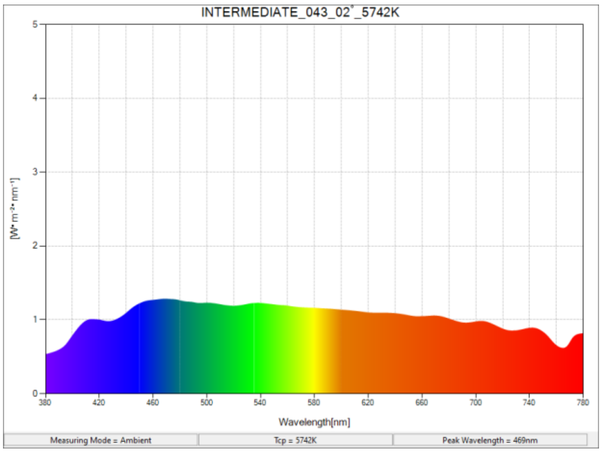
Participant #5 (6th April 11.05-12:10)



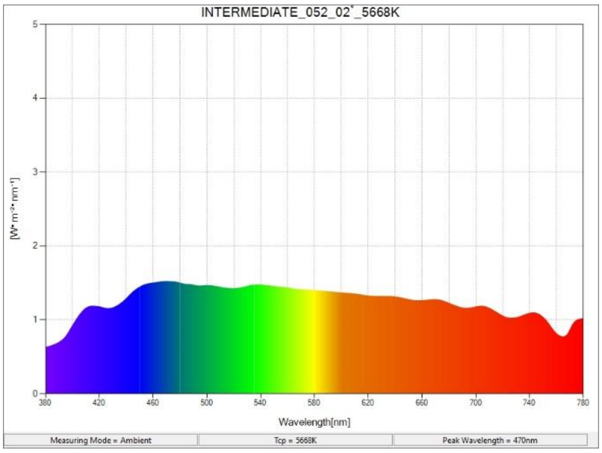
Participant #6 (17th April 12:15-13:20)



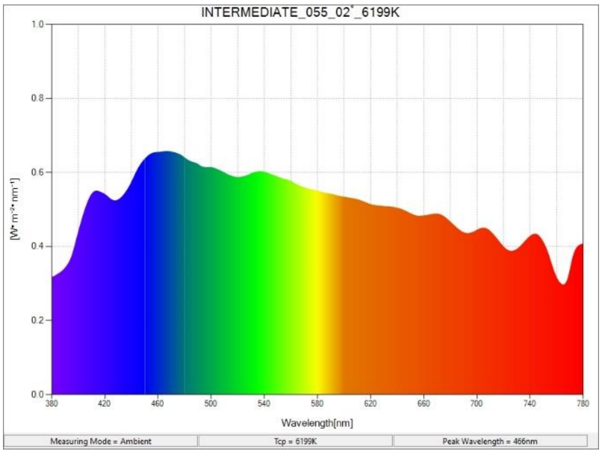
Participant #7 (21st April 10:30-11:35)



Participant #8 (28th April 11:00-12:05)



Participant #9 and #10 (28th April 13:30-14:35)



Appendix D- Sky Condition

Below are the global horizontal illuminances measured from the roof of the Energy and Building Design Laboratory with the KONICA MINOLTA CRI Illuminance Meter. E_v outdoors was measured and collected continuously during the experiments with a Campbell Scientific CR1000 data logger.

Participant #1 and #2 (4th April 10:45-11:50)

Global horizontal illuminance: 70 000 lux

Average E_v outdoors: 68 035 lux

Participant #3 and #4 (6th April 9:10-10:15)

Global horizontal illuminance: 53 833 lux

Average E_v outdoors: 43 473 lux

Participant #5 (6th April 11.05-12:10)

Global horizontal illuminance: 79 367 lux

Average E_v outdoors: 71 851 lux

Participant #6 (17th April 12:15-13:20)

Global horizontal illuminance: 77 533 lux

Average E_v outdoors: 71 881 lux

Participant #7 (21st April 10:30-11:35)

Global horizontal illuminance: 86 000 lux

Average E_v outdoors: 59 399 lux

Participant #8 (28th April 11:00-12:05)

Global horizontal illuminance: 103 000 lux

Average E_v outdoors: 68 241 lux

Participant #9 and #10 (28th April 13:30-14:35)

Global horizontal illuminance: 41 600 lux

Average E_v outdoors: 33 436 lux

Appendix E- Observer-Based Environmental Assessment

INSTRUKTIONER (SVENSKA)

Välkommen till Energy and Building Design Lab!

Din tid här idag kommer att bidra till vår magisteruppsats där vi bedömer inverkan varierande elektriska ljusfördelning har på *melanopic equivalent daylight illuminance* och energianvändning. Du förväntas utföra en uppgift och fylla i frågeformulär under fyra olika ljusscenarier:

- dagsljus + nedåtriktad elektrisk belysning
- dagsljus + diffuse elektrisk belysning
- bara nedåtriktad elektrisk belysning
- bara diffuse elektrisk belysning

STEG ATT FÖLJA

Nedan hittar du stegen du ska följa när du är i experimentrummet:

STEG 1

Låta ögonen anpassas till ljusmiljön- 15 minuter.

Ett alarm låter.

STEG 2

Fyll i KSS-enkäten- 2 minuter.

Ett alarm låter.

STEG 3

Starta DSST-testet (Digit Symbol Substitution Test) - 90 sekunder.

Ett alarm låter.

STEG 4

Fyll i BELUPP-enkäten.

STEG 5

Fyll i KSS-enkäten.

STEG 6

Lämna rummet.

STEG 7

Upprepa steg 1 to 6.

YTTERLIGGARE INFORMATION

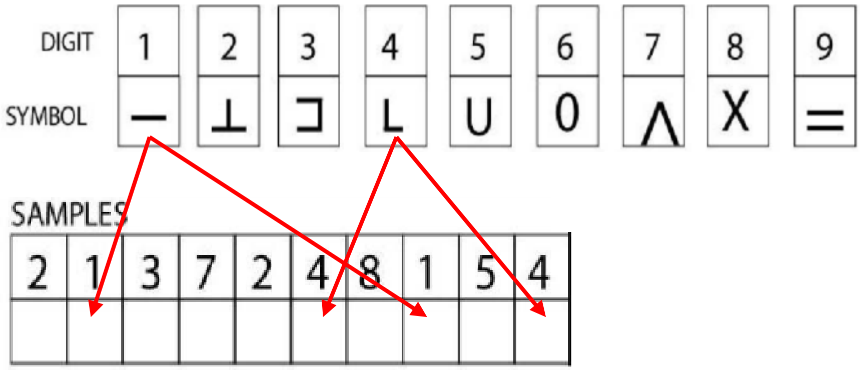
Karolinska Sleepiness Scale (KSS)

Karolinska Sleepiness Scale (KSS) ber deltagarna att rapportera sin subjektiva nivå av sömnighet vid en viss tidpunkt på dagen. Försökspersonerna anger sitt psyko-fysiska tillstånd i rummet med hjälp av betygsskalan.

Digit Symbol Substitution Test (DSST)

DSST är en standard neuropsykologiskt uppgift som involverar en penna och papper. Deltagaren ska kopiera symbolerna till rutan under det rätta numret.

Exempel:



BELUPP Frågeformulär

Det visuella utseendet på ljuset bedöms med ett BELUPP formulär som är utfomat med betygskala. Formuläret är försedd med ett definitionsark för att hjälpa deltagarna.

INSTRUCTIONS (ENGLISH)

Welcome to the Energy and Building Design Lab!

Your time here today will contribute to our Master's Thesis in which we assess the influence of varying electric light distribution on melanopic equivalent daylight illuminance and lighting energy use. You will be expected to complete a task and fill in questionnaires under four different lighting scenarios:

- daylight + downward electric lighting,
- daylight + diffuse electric lighting,
- only downward electric lighting,
- only diffuse electric lighting.

STEPS TO FOLLOW

Below you will find the steps to follow while in the experiment room:

STEP 1

Adapt to the lighting environment - 15 minutes.

An alarm will go off.

STEP 2

Fill out the KSS Questionnaire - 2 minutes.

An alarm will go off.

STEP 3

Start the Digit Symbol Substitution Test (DSST) test - 90 seconds.

An alarm will go off.

STEP 4

Fill out the BELUPP Questionnaire.

STEP 5

Fill out the KSS Questionnaire.

STEP 6

Exit room.

STEP 7

Repeat steps 1 to 6.

ADDITIONAL INFORMATION

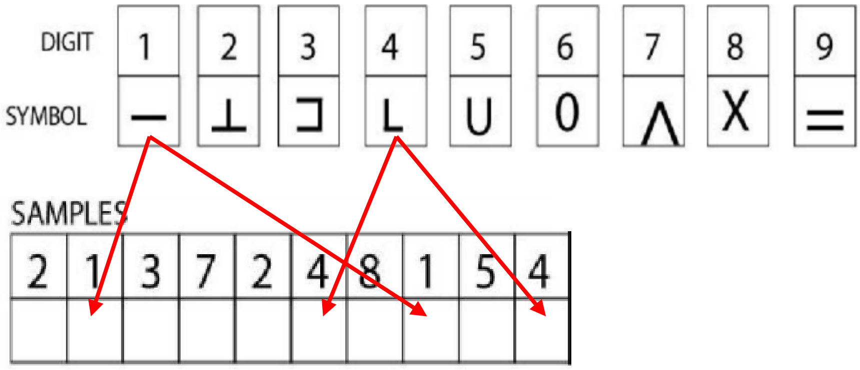
Karolinska Sleepiness Scale (KSS)

The Karolinska Sleepiness Scale (KSS) asks participants to report their subjective level of sleepiness at a particular time during the day. The subjects indicate their psycho-physical state in the room using the rating scale.

Digit Symbol Substitution Test (DSST)

The DSST is a standard neuropsychologic test involving a pencil and paper task. The participant must copy the symbols that correspond to the number.

Sample:



BELUPP Questionnaire

The visual appearance of the light is assessed with BELUPP questionnaire using a rating scale. It is provided with a sheet of definitions to aid the participants.

Preliminär undersökning - Svenska

Data från detta frågeformulär ska användas för att stödja experiment resultaten och visa om någon deltagare har specifika synnedsättningar och/eller sömnsvårigheter.

* Indicates required question

Allmäna frågor

1. Namn *

____

2. Kön *

Mark only one oval.

- Man
- Kvinna
- Föredrar att inte säga

3. Ålder *

____

4. Har du några lässvårigheter? *

Mark only one oval.

- Ja
- Nej
- Vet inte

Sömnkvalitet

5. Välj det alternativ som bäst beskriver dig. *

Mark only one oval.

- Tydlig morgonmänniska
- Till viss del morgonmänniska
- Till viss del kvällsmänniska
- Tydlig kvällsmänniska

6. Hur ofta sover du 5 timmar eller mindre? *

Mark only one oval.

- Aldrig
- Inte ofta
- Ibland
- Ofta
- Alltid

7. Hur ofta sover du 9 timmar eller mer? *

Mark only one oval.

- Aldrig
- Inte ofta
- Ibland
- Ofta
- Alltid

8. Hur tycker du att du sover generellt sett? *

Mark only one oval.

- Väldigt dåligt
- Relativt dåligt
- Varken bra eller dåligt
- Relativt bra
- Väldigt bra

9. I vilken utsträckning utgör störd sömn ett hälsoproblem för dig? *

Mark only one oval.

- Väldigt stort problem
- Relativt stort problem
- Varken ett stort eller litet problem
- Relativt litet problem
- Väldigt litet problem

Kvaliteten på synen

10. Välj det alternativ som bäst beskriver din syn. *

Mark only one oval.

- Närsynt
- Översynt
- Normal syn
- Annat, Vänligen svara frågan nedan

11. Ange andra synfel

____

12. I vilken utsträckning är du ljuskänslig? *

Mark only one oval.

- Extremt känslig
- Väldigt känslig
- Relativt känslig
- Knappt känslig
- Inte känslig

13. Lider du av färgblindhet? *

Mark only one oval.

- Ja
- Nej
- Vet ej

14. Tror du att du har svårt att uppfatta vissa färger? *

Mark only one oval.

- Ja
- Nej
- Vet ej

Preliminary Survey- English Version

The data from this questionnaire would be used to support the experiment results in case any participants have specific vision impairements and/or sleep-wake disorders.

* Indicates required question

General

1. Name *

____

2. Gender *

Mark only one oval.

- Male
- Female
- Other

3. Age *

____

4. Do you have any reading disabilities? *

Mark only one oval.

- Yes
- No
- Don't know

Quality of Sleep

5. Select the option that best describes you. *

Mark only one oval.

- Pronounced morning person
- To some extent morning person
- To some extent evening person
- Pronounced evening person

6. How often do you sleep 5 hours or less? *

Mark only one oval.

- Never
- Rarely
- Sometimes
- Often
- Always

7. How often do you sleep 9 hours or more? *

Mark only one oval.

- Never
- Rarely
- Sometimes
- Often
- Always

8. How do you think you sleep overall? *

Mark only one oval.

- Very bad
- Quite bad
- Neither good nor bad
- Quite good
- Very good

9. To what extent does disturbed sleep constitute a health problem for you? *

Mark only one oval.

- Very big problem
- Quite big problem
- Neither big nor small problem
- Quite small problem
- Very small problem

Quality of Vision

10. Select the option that best describes your eyesight. *

Mark only one oval.

- Myopic (nearsighted)
- Hyperopic (farsighted)
- Normal eyesight
- Other, please answer question below

11. Specify other eyesight problems.

____

12. To what extent are you sensitive to light? *

Mark only one oval.

- Extremely sensitive
- Very sensitive
- Quite sensitive
- Rarely sensitive
- Not sensitive

13. Do you suffer from colour blindness? *

Mark only one oval.

- Yes
- No
- Don't know

14. Do you think you have difficulty perceiving certain colors? *

Mark only one oval.

- Yes
- No
- Don't know

Karolinska Sleepiness Scale (KSS)-Svenska

Karolinska Sleepiness Scale (KSS) ber deltagarna att rapportera sin **subjektiva nivå av sömnighet** vid en viss tidpunkt på dagen. Detta frågeformulär kräver att deltagarna ska ange sitt psyko-fysiska tillstånd **på morgonen** med hjälp av betygsskalan.

* Indicates required question

1. Namn *

2. Tid när du somnade? *

Example: 8:30 AM

3. Hur mycket sömn fick du förgående natt? *

Mark only one oval.

- 5 timmar eller mindre
- 6 timmar
- 7 timmar
- 8 timmar
- 9 timmar eller mer

4. Välj det alternativet som bäst beskriver hur trött du känner dig just nu. *

Mark only one oval.

- Extremt pigg
- Mycket pigg
- Pigg
- Ganska pigg
- Varken pigg eller sömnig
- lätt sömnig
- Sömnig, men ej ansträngande att vara vaken
- Sömnig och ansträngande att vara vaken
- Mycket sömnig, mycket ansträngande att vara vaken, kämpar mot sömnen

Karolinska Sleepiness Scale (KSS)- English Version

The **Karolinska Sleepiness Scale (KSS)** asks participants to report their **subjective level of sleepiness** at a particular time during the day. This questionnaire requires the participants to indicate their psycho-physical state during the **morning** using the rating scale.

* Indicates required question

1. Name *

____

2. Time before you fell asleep (after you turn off the light)? *

____

Example: 8:30 AM

3. How much sleep did you get the previous night? *

Mark only one oval.

- ( ) 5 hours or less
- ( ) 6 hours
- ( ) 7 hours
- ( ) 8 hours
- ( ) 9 hours or more

4. Select the option that best describes how sleepy you feel right now. *

Mark only one oval.

- Extremely alert
- Very alert
- Alert
- Rather alert
- Neither alert nor sleepy
- Some signs of sleepiness
- Sleepy, but no effort to keep awake
- Sleepy, but some effort to keep awake
- Very sleepy, great effort to keep awake, fighting sleep

Karolinska Sleepiness Scale (KSS)-Svenska

Karolinska Sleepiness Scale (KSS) ber deltagarna att rapportera sin **subjektiva nivå av sömnighet** vid en viss tidpunkt på dagen. Detta frågeformulär kräver att deltagarna ska ange sitt psyko-fysiska tillstånd **efter lunchtid** med hjälp av betygsskalan.

* Indicates required question

1. Namn *

____

2. Välj det alternativet som bäst beskriver hur trött du känner dig just nu. *

Mark only one oval.

- ◯ Extremt pigg
- ◯ Mycket pigg
- ◯ Pigg
- ◯ Ganska pigg
- ◯ Varken pigg eller sömnig
- ◯ lätt sömnig
- ◯ Sömnig, men ej ansträngande att vara vaken
- ◯ Sömnig och ansträngande att vara vaken
- ◯ Mycket sömnig, mycket ansträngande att vara vaken, kämpar mot sömnen

Karolinska Sleepiness Scale (KSS)-English Version

The **Karolinska Sleepiness Scale (KSS)** asks participants to report their **subjective level of sleepiness** at a particular time during the day. This questionnaire requires the participants to indicate their psycho-physical state during the **after lunch time** using the rating scale.

* Indicates required question

1. Name *

   ____

2. Select the option that best describes how sleepy you feel right now. *

   Mark only one oval.

   - ◯ Extremely alert
   - ◯ Very alert
   - ◯ Alert
   - ◯ Rather alert
   - ◯ Neither alert nor sleepy
   - ◯ Some signs of sleepiness
   - ◯ Sleepy, but no effort to keep awake
   - ◯ Sleepy, but some effort to keep awake
   - ◯ Very sleepy, great effort to keep awake, fighting sleep

Karolinska Sleepiness Scale (KSS)-Svenska

Karolinska Sleepiness Scale (KSS) ber deltagarna att rapportera sin **subjektiva nivå av sömnighet** vid en viss tidpunkt på dagen. Detta frågeformulär kräver att deltagarna ska ange sitt psyko-fysiska tillstånd **på kvällen** med hjälp av betygsskalan.

* Indicates required question

1. Namn *

____

2. Välj det alternativet som bäst beskriver hur trött du känner dig just nu. *

Mark only one oval.

- ◯ Extremt pigg
- ◯ Mycket pigg
- ◯ Pigg
- ◯ Ganska pigg
- ◯ Varken pigg eller sömnig
- ◯ lätt sömnig
- ◯ Sömnig, men ej ansträngande att vara vaken
- ◯ Sömnig och ansträngande att vara vaken
- ◯ Mycket sömnig, mycket ansträngande att vara vaken, kämpar mot sömnen

Karolinska Sleepiness Scale (KSS)- English Version

The **Karolinska Sleepiness Scale (KSS)** asks participants to report their **subjective level of sleepiness** at a particular time during the day. This questionnaire requires the participants to indicate their psycho-physical state during the **evening** using the rating scale.

* Indicates required question

1. Name *

____

2. Select the option that best describes how sleepy you feel right now. *

Mark only one oval.

- ◯ Extremely alert
- ◯ Very alert
- ◯ Alert
- ◯ Rather alert
- ◯ Neither alert nor sleepy
- ◯ Some signs of sleepiness
- ◯ Sleepy, but no effort to keep awake
- ◯ Sleepy, but some effort to keep awake
- ◯ Very sleepy, great effort to keep awake, fighting sleep

DIGIT SYMBOL SUBSTITUTION TEST (DSST)

1	2	3	4	5	6	7	8	9
ω	o	Ӿ	ɸ	ʌ	–	Ξ	ш	∩

NAME:
SCORE:

7	2	1	4	1	3	8	6	8	9	2	6	1	6	5	9	4	6	5	2	7	3	9	5	1

4	1	3	8	2	5	6	9	6	3	7	4	5	8	2	9	1	6	7	3	8	4	2	7	5

6	9	4	1	7	8	3	5	4	2	7	6	8	1	7	9	2	4	3	2	3	6	5	8	2

4	7	9	3	8	6	7	1	5	3	4	8	3	7	1	2	8	5	2	9	7	9	1	5	6

BELUPP FRÅGOR OCH DEFINATIONER (SVENSKA)

- Mörkt- *det finns lite eller inget ljus*
- Ljust- *det finns tillräckligt med naturligt ljus för att göra saker synliga*
- Behagligt- *ljuset är tillfredställande och ger en känsla av njutning*
- Obehagligt- *ljus som orsakar obehag eller olycka*
- Ofärgat- *ljus utan färg eller neutral färg*
- Färgat- *ljus som har en eller flera färger som inte är svart, vit eller*
- Starkt- *ljus som visar en egenskap i extrem grad*
- Svagt- *minskad ljusstyrka eller briljans*
- Utspritt- *ljus som reflekteras oregelbundet och diffust*
- Koncentrerat- *riktad ljusstråle*
- Varmt- *ljus med röda, orange och gula toner*
- Kallt- *ljus med blå toner*
- Ojämt fördelat- *ljus med varierande kvalitet*
- Jämt fördelat- *ljus oföränderligt i form eller karaktär*
- Hårt- *ljus som ger distinkta skuggor med hårda kanter*
- Mjukt- *ljus som gör att skuggor knappt syns*
- Diffust- *ljus som har ett otydligt och disigt utseende*
- Fokuserat- *ljusstråle*
- Naturligt- *ljus från solen*
- Onaturligt- *ljus från artificiella (elektriska) armaturer*
- Flimrande- *ostadiga ljusrörelser som orsakar snabba variationer i ljusstyrka*
- Flimmerfritt- *stadigt ljus utan variationer*
- Klart- *ljus fritt från grumligheter*
- Murrigt- ljus *som saknar ljusstyrka eller intresse*
- Varierat- *ljusförändring i färg och intensitet*
- Enformigt- *ljus som saknar variation eller intresse*
- Milt- *mjukare ljus med en mer ombonad känsla*
- Skarpt- *skarpare, fräschare ljus*
- Bländande- *ljus som kommer in i ditt öga och hämmar din synprestanda eller orsakar obehag*
- Avbländat- *relativt mörker som skapas av blockering av ljus*
- Dämpat- *inte starkt ljus*
- Lysande- *starkt och intensivt ljus*

BELUPP QUESTIONNAIRE DEFINITIONS (ENGLISH)

- Dark- *with little or no light*
- Light- *having sufficient amount of natural light to make things visible*
- Pleasant- *light giving a sense of happy satisfaction or enjoyment*
- Unpleasant- *light causing discomfort or unhappiness*
- Uncoloured- *light having no colour or neutral in colour*
- Coloured- *light having a colour or colours as opposed to being black, white, or neutral*
- Strong- *light showing a characteristic in extreme degree*
- Weak- *diminishing the strength or brilliance of light*
- Scattered- *light reflecting irregularly and diffusely*
- Concentrated- *pinpointed beam of light*
- Warm- *light with red, orange, and yellow tones*
- Cool- *light with blue tones*
- Uneven distributed- *light varying in quality*
- Even distributed- *light unchanging in form or character*
- Hard- *light making distinct, hard-edged shadows*
- Soft- *light making shadows barely visible*
- Unfocused- *light having an indistinct and hazy appearance*
- Focused- *pinpointed beam of light*
- Natural- *light from the sun*
- Unnatural- *light from artificial (electric) luminaires*
- Flicker- *unsteady movement of light causing rapid variations in brightness*
- No flicker- *steady movement of light with no variations in brightness*
- Clear- *light free from cloudiness*
- Drab- *light lacking brightness or interest*
- Varied- *light changing in colour and intensity*
- Monotonous- *light lacking in variety or interest*
- Mild- *softer light with a more cosy feel*
- Sharp- *crisper, fresher light*
- Glaring- *light that enters your eye and impedes your vision performance or causes discomfort*
- Shaded- *relative darkness produced by the blocking out of light*
- Subdued- *not bright light*
- Brilliant- *bright/intense light*

Miljöpsykologi, LTH, 2000

DITT KODNUMMER: ______________ DATUM: _____________ KLOCKAN: _________

HUR UPPLEVER DU LJUSET I DET HÄR RUMMET?

Markera genom att sätta kryss i nedanstående skalor.

mörkt	☐	☐	☐	☐	☐	☐	☐	ljust
behagligt	☐	☐	☐	☐	☐	☐	☐	obehagligt
ofärgat	☐	☐	☐	☐	☐	☐	☐	färgat
starkt	☐	☐	☐	☐	☐	☐	☐	svagt
utspritt	☐	☐	☐	☐	☐	☐	☐	koncentrerat
varmt	☐	☐	☐	☐	☐	☐	☐	kallt
ojämt fördelat	☐	☐	☐	☐	☐	☐	☐	jämt fördelat
hårt	☐	☐	☐	☐	☐	☐	☐	mjukt
diffust	☐	☐	☐	☐	☐	☐	☐	fokuserat

Vänd blad och fortsätt!

naturligt	☐	☐	☐	☐	☐	☐	☐	onaturligt
flimrande	☐	☐	☐	☐	☐	☐	☐	flimmerfritt
klart	☐	☐	☐	☐	☐	☐	☐	murrigt
varierat	☐	☐	☐	☐	☐	☐	☐	enformigt
milt	☐	☐	☐	☐	☐	☐	☐	skarpt
bländande	☐	☐	☐	☐	☐	☐	☐	avbländat
dämpat	☐	☐	☐	☐	☐	☐	☐	lysande

HUR BRA TYCKER DU DET GÅR ATT SE I DEN HÄR BELYSNINGEN?

mycket dåligt	☐	☐	☐	☐	☐	☐	☐	mycket bra

Miljöpsykologi, LTH, 1995 Datum:______________________

HOW DO YOU PERCEIVE THE LIGHTING CONDITIONS IN THIS ROOM

Mark by ticking the scales below

dark	☐	☐	☐	☐	☐	☐	☐	light
pleasant	☐	☐	☐	☐	☐	☐	☐	unpleasant
uncoloured	☐	☐	☐	☐	☐	☐	☐	coloured
strong	☐	☐	☐	☐	☐	☐	☐	weak
scattered	☐	☐	☐	☐	☐	☐	☐	concentrated
warm	☐	☐	☐	☐	☐	☐	☐	cool
uneven distributed	☐	☐	☐	☐	☐	☐	☐	even distributed
hard	☐	☐	☐	☐	☐	☐	☐	soft
unfocused	☐	☐	☐	☐	☐	☐	☐	focused

Turn page and continue!

natural	☐	☐	☐	☐	☐	☐	☐	unnatural
flicker	☐	☐	☐	☐	☐	☐	☐	no flicker
clear	☐	☐	☐	☐	☐	☐	☐	drab
varied	☐	☐	☐	☐	☐	☐	☐	monotonous
mild	☐	☐	☐	☐	☐	☐	☐	sharp
glaring	☐	☐	☐	☐	☐	☐	☐	shaded
subdued	☐	☐	☐	☐	☐	☐	☐	brilliant

HOW WELL DO YOU THINK YOU COULD SEE IN THESE LIGHTING CONDITIONS?

very bad	☐	☐	☐	☐	☐	☐	☐	very good

PLACE: GENDER:

DATE: AGE:

LIGHTING EXPERIENCE

	Hedonic tone	Brightness	Variation	Colour	Flicker
LIGHT		☐			
UNPLEASANT	8- ☐				
COLOURED				☐	
WEAK		8- ☐			
CONCENTRATED			8- ☐		
COOL	8- ☐				
EVEN DISTRIB.			☐		
SOFT	☐				
FOCUSED			8- ☐		
UNNATURAL	8- ☐				
NO FLICKER					8- ☐
DRAB		8- ☐			
MONOTONOUS	8- ☐				
SHARP	8- ☐				
SHADED	☐				
BRILLIANT		☐			
GOOD	☐				
SUM	:8	:4	:3	:1	:1
MEAN					

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services

Department of Building and Environmental Technology