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Investigation into biological effects of light in offices under different lighting scenarios and at varying conditions

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Abstract:

This study investigates the influence of each type of light from the DDL concept (daylight, direct, diffuse and combination of direct and diffuse) on the biological effects of light in offices. Additionally, the season, window orientation, sky condition and time of the day were looked into as potential variables, which can have an impact on biological effects of light. This investigation includes three experiments of different types of light, which are used in the DDL concept. In order to understand the contribution and impact on biological effects, each type of light was investigated separately. First, daylight is assessed, followed by a test of electric lighting with direct and diffuse light, and lastly, two lighting scenarios from previous DDL studies, which were reportedly favoured by participants are examined. The evaluation of biological effects of light was done with a use of a new and prospective programme ALFA, which allows lighting designers to simulate lighting within a space and have an insight into the biological effects of light through an equivalent melanopic lux (EML) value. This research provides an overview of impact of four variables (window orientation, sky condition, season and time of the day), which may be used as a guideline in basic understanding of how biological effects of light in offices are affected by those various conditions.

ABSTRACT

The following study investigates the impact of daylight, direct light, diffused light and two Double Dynamic Lighting (DDL) scenarios on biological effects of light in offices with different window orientations, under various sky conditions, seasons and times of the day. The approach taken in this study, seeks to find how different light distributions and directionalities of DDL concept affect biological effects of light in offices with different window orientation, time of the day, season and sky condition. This is done by number of simulations conducted in ALFA, a programme that reports the value of Equivalent melanopic lux, which is used for evaluation of biological effects of light. Results from different lighting scenarios are compared and analysed resulting in findings that daylight input in the summer is sufficient at providing required EML value for all investigated cases. Direct lighting performed slightly higher values of EML than diffuse light. Both DDL scenarios reported high values of EML in majority of investigated cases. This confirms that DDL scenarios, which were favoured by participants also fulfill biological needs. The results from the study point out the complexity of designing office lighting with a holistic approach. Further studies are necessary in order to investigate missing parameters such as: room and window size, age of office workers, daylight control system etc.

CONTENTS

Glossary

Abbreviation	**Phrase**
CCT	Correlated colour temperature
DDL	Double Dynamic Lighting
EML	Equivalent melanopic lux
ipRGC	Intrinsically photosensitive retinal ganglion cells
LED	Light-emitting diode
N/N	Neutral/neutral
NIF	Non-image forming
SCN	Suprachiasmatic nucleus
W/C	Warm/cold

1 Introduction

The aim of this study is to investigate influence of daylight and electric light, with different distribution and directionality, on biological effects of light in the offices with consideration of different seasons, window orientations, sky conditions and times of the day. In this introduction, the background and motivation for the project are outlined, and the scope and limitations of the project are briefly discussed. Finally, the structure of the report is outlined.

1.1 Project background

For hundreds of years, daylight was used as an indicator for people's daily rhythm (Panda et al., 2002; Stevens & Zhu, 2015). The rising sun was a signal for waking up and sunset a sign for ending the day (Pauley, 2004). It was intuitive for people to follow daylight, which later created a natural 24-hour rhythm that people started to follow. Additionally, light not only provides us with the ability to see but also a feeling of safety, and it is therefore an integral part of our everyday life (Painter, 1994).

Before 1879, people could only rely on daylight and candlelight to help them see. However, Thomas Edison's invention of incandescent light quickly changed people's perception of the night and it became an indispensable part of our lives (Nye, 2019). Since then, our days started to become longer and longer thanks to electric lighting. The darkness of the night was no longer an indicator for people to go to sleep. Electric lighting caused a disturbance in our natural inner clock through the use of inadequate intensity and spectral power distribution during the day and night (Stevens, 2009a, 2009b).

Nowadays people spend around 90% of their waking time indoors, where a large part of their time is spent at work (Klepeis et al., 2001). Office workers spend the majority of the day inside the office, therefore environment in which they are has a significant influence on their performance and productivity (Kamarulzaman et al., 2011). Our modern lifestyle is shifting significantly from the active life during the day and rest during the night. Society is trying to extend the days for as long as possible by introducing the night shifts, stores that are open 24/7, or street lighting (Grogan & Sadanand, 2013; Kreitzman, 1999). All of that contributed to a loss of darkness, especially in big metropolitan cities where seeing stars in the sky has become a luxury, due to the excessive use of light at night (Longcore & Rich, 2004). Moreover, we are constantly exposed to all kinds of screens. At work, we are in close contact with computer screens and smart phones, which we constantly carry with us. Additionally, office workers are exposed to mainly static electric lighting within an office despite the outdoor weather conditions (Begemann et al., 1997; Heil & Mathis, 2002). Such constant exposure, if not controlled, can have serious effects on our circadian rhythm, mood, and cognitive performance (Cajochen et al., 2011; Chang et al., 2015; Sroykham & Wongsawat, 2013). That is why control over the light exposure should be designed in a way that provides lighting for alertness when needed and limits exposure to the rich in blue wavelengths in the evening (Lockley et al., 2003, 2006).

1.2 Motivation and vision

The rapid change over the last few decades regarding the evolution of electric lighting from the gentle incandescent light into more intense LED light undoubtedly provided us with numerous new possibilities. However, such a quick and intense change in technology comes at a price, with several unwanted effects. Currently, lighting designers are faced with new problems and challenges such as the impact of lighting on human health (Boyce, 2010). The numerous research conducted on LED's suggests that there is a possibility to design light in a way that improves our health, circadian rhythm, alertness, and well-being (Boyce, 2010; Küller & Wetterberg, 1993; Partonen & Lönnqvist, 2000). However, there are also many effects of light that can contribute to serious health issues such as blue hazard if light is not designed in a proper way (Ham et al., 1976; Van Norren & Vos, 2016).

Nevertheless, improvements in light design that are beneficial to our health will not happen by just a change of a lightbulb in our office or home, which many companies are now trying to sell under the names of Human Centric Lighting (Houser et al., 2021). Since the subject of biological needs is still a fairly new domain, there is a lack of clear guidelines and tools that can help with the evaluation of lighting from the biological aspect (CIE, 2021; Zeng et al., 2021). With the current focus on meeting the requirements of visual needs, not much attention is paid to biological ones (Smolders et al., 2012, 2013).

The goal of this study is to point out the complexity of designing with consideration of the biological, visual and biological effects of daylight and electric light, and to emphasise the need for new tools and guidelines to meet this holistic approach to lighting. Despite the number of research conducted within this field, there are still many unknowns that have to be resolved to fully understand and grasp the scope of the topic of the biological effects of light and their relation with other effects (Bellia et al., 2020; Figueiro et al., 2018).

The approach taken in this study, seeks to find how different light distributions and directionalities of Double Dynamic Lighting (DDL) concept (daylight, direct, diffuse and combination of direct and diffuse lighting) affect biological effects of light in offices with consideration of different window orientations, times of the day, seasons and sky conditions.

The attention needs to be drawn to how challenging it is to design office lighting with a use of daylight and electric light, that benefits both our circadian rhythm and visual needs, and at the same time has a positive influence on perception of the space by office workers. By testing several factors, which can influence the human's physiology, this study investigates which features of light have the greatest impact focusing on directionality, distribution of light and spectral power distribution with the use of the Double Dynamic Light approach. This approach has proved to have a positive effect on workers satisfaction and created a space that has been perceived as comfortable (Hansen et al., 2020).

Based on the knowledge gathered above, the following initial problem statement will be investigated:

Imagine if lighting in the office, involving daylight and electric light, could have a positive influence on our alertness and general well-being, and could support our visual needs during a time spend in the office and at the same time be perceived as a desired and comfortable space to be in.

1.3 Scope of research

The subject of biological effects of light is a broad and still fresh topic to discuss. This thesis will focus on evaluation of how each type of the DDL concept (daylight, direct, diffuse and combination of direct and diffuse light) is affecting biological effects of light in the office. Furthermore, it will test the lighting scenarios that had been examined in a study in the DDL project and proved to bring beneficial influence on office workers (Hansen et al., 2020). The scenarios that received positive feedback will be evaluated from a biological and visual point of view. All scenarios will be tested in a fixed location in Copenhagen, Denmark.

1.4 Limitations

The Covid-19 pandemic caused limitations regarding the access to the physical building, which made it impossible to measure the material's reflectance in the Double Dynamic Lighting lab at AAU with a spectrometer. Additionally, build-in materials from the software ALFA had to be used decreasing the reality of the simulation. The dynamism of daylight had to be limited to three types of the sky, since ALFA offers only a limited choice of sky conditions.

The limitations of access to Aalborg University Campus also took away the possibility of comparing the ALFA results with on-site measurements conducted within a space with a spectrometer, as well as conducting psychological analysis with participants within the space, and testing different scenarios. That is the reason psychological effects will be based on the research conducted earlier within this space.

1.5 Report structure

The following report consists of eight sections starting with literature review in which current state of the research regarding biological effects of light within office environment is summed up. Following with methodology describing the details regarding the methods which are implemented. Next section contains of three research questions and objectives. Then analysis and results of three experiments are presented. Subsequently, the discussion summing up the results of the study is demonstrated followed by a summary and future work, expressing the potential of further studies and investigation of the presented approach.

2 Literature Review

In this section, the existing literature around the biological effects of light on humans will be discussed. The purpose of this section is to provide insight into the fundamentals of the influence of light on people, as well as the importance of adequate light in office spaces. The DDL concept is introduced in this section, which is the theoretical framework for this study.

2.1 Visual, psychological and biological effects of light

Researchers mainly discuss lighting from the visual point of view with a focus on intensity and contrast, which can be observed by the bare eye. The visual effects of light have been studied for many years, resulting in specific standards regarding light levels to perform different tasks (van Bommel & van den Beld, 2004).

However, light can also change the perception of the space. It can create a certain atmosphere or give an impression of a private, spacious, or pleasant environment (Countryman, 1992; Durak et al., 2007). For daylight, under clear sky conditions, we perceive the light as cold-white, but as soon as the sky changes into overcast, daylight is perceived as more natural white (Knoop et al., 2020). Furthermore, another change occurs during transition hours, with a warm appearance of light caused by scattering of light and low position of the sun over the horizon (Cuttle, 2015). The ability to change the perception of the space via light, is mainly referred to as psychological effects of light.

However, the rapid growth of knowledge within the lighting design industry, resulted in the discovery of new photoreceptors. Research shows that these photoreceptors not only affect humans in a visual way, but also non-visual, commonly called biological effects of light (Berson et al., 2002).

In recent years, the aspect of biological effects of light has been studied intensely, and it has been proved that light besides the visual and psychological effects, can also influence people's alertness, circadian rhythm, heart rate, etc. (Brainard et al., 2001; Scheer et al., 2004).

However, it has been stated that, psychological and biological effects are not independent and they tend to overlap. The connection occurs when higher stimulus is achieved with higher illuminance and higher density of wavelengths, within a short wavelength part of the spectrum. It is a similar way of increasing the alertness and manipulating the biological effects (Kuijsters et al., 2015).

All in all, the power of the light and light features can not only impact our perception of spaces that surround us or our visual comfort for task performance, but also our mood and alertness. Summary of the different effects of light is presented in Figure 1.

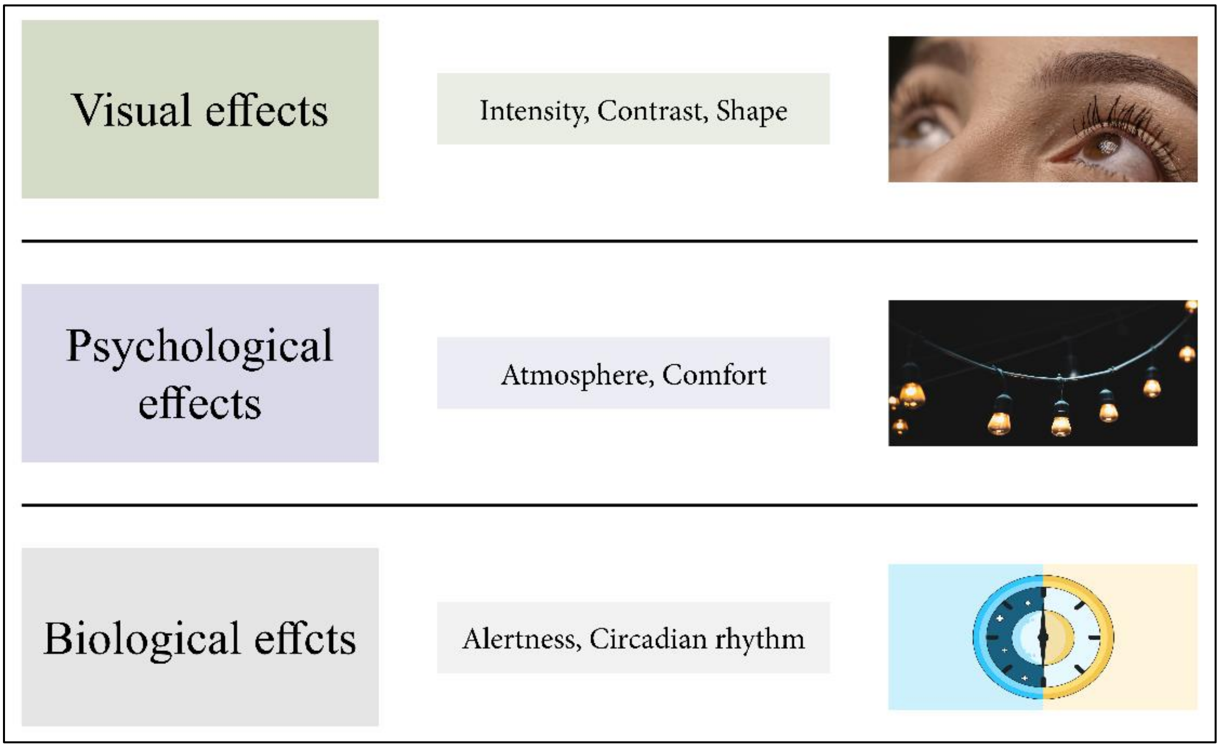

Figure 1. Schematic showing the visual, psychological and biological effects on humans. Images taken from A) (Pexels, 2021b) *B)* (Pexels, 2021c), *C)* (TechExplorist, 2020).

2.2 Biological effects of light

From a biological perspective, light affects humans' circadian rhythm and alertness. These two effects will be explored further here. This section seeks to explain the impact of light on human health as well as provide a basic understanding of how light causes changes in human physiology.

2.2.1 Circadian rhythm

Following the cycle of the sun, many organisms developed a 24-hour cycle (Rea et al., 2002; Reiter et al., 2001). The circadian rhythm plays a vital role in human health, and since light triggers the changes in melatonin production it has a major influence on people's well-being (Prayag et al., 2019). The idea of lighting supporting people's circadian rhythm exists under the circadian lighting term. Circadian lighting, is a concept in which electric light follows human's sleep-wake cycle and supports our natural 24-hour internal clock. Electric light is used to support human health by limiting the negative effects of electric light on circadian rhythm

(Ashdown, 2019). However, in recent years, electricity and the constant availability of light changed our natural rhythm. That is why it is crucial to create lighting environments that follow our day and night cycle. With bright light in the morning and low-level lighting in the evening (Figueiro et al., 2018).

When the electric light was introduced, people's circadian rhythm was not significantly disturbed, since only incandescence light was primarily used. The spectral power distribution of incandescent light is rich in the red part of the spectrum, and includes less powerful blue wavelengths to which ipRGC cells are most sensitive (Bailes & Lucas, 2013). However, with the current global trend with energy-efficient lighting, the world leans towards the more blue-enriched LED lights, that provide much higher energy efficiency than incandescent lights. Nevertheless, the transition to less energy consuming LED lights means that circadian rhythm, as well as sleep, might be negatively affected (Bauer et al., 2018).

Changes such as the invention of electric lighting, the introduction of night shifts, and an increase in traveling between different time zones, caused disturbances in our circadian rhythm (Boulos et al., 2002; Jet et al., 1995). Those changes, may look at first glance as positive, but can cause serious disorders like melatonin production, metabolic and sleep disorder or psychiatric illnesses (Anothaisintawee et al., 2016; Depner et al., 2014; Figueiro et al., 2009).

2.2.2 Influence of daylight on circadian rhythm

Firstly, when working with biological effects of light it is important to include daylight input. Under clear sky, daylight illuminance can reach a level from 25 000 to even 100 000 lux with direct sunlight (Wikipedia, 2021). The most vital aspect of daylight is not the illuminance itself, but its broadband spectral power distribution (Blume et al., 2019). Nevertheless, the daylight access strongly depends on the location and season, which vary significantly in the Nordic countries (Piotrowska & Borchert, 2017). Daylight is considered as an ideal light source in terms of providing a suitable amount of light as well as ideal spectrum for people (Acosta et al., 2019). Therefore, the presence of daylight in the office environment is crucial.

Moreover, studies proved that daylight has a positive impact on occupants in the spaces as well as on the reduction of energy consumption (Edwards & Torcellini, 2002). The presence of natural light within the space increases worker's satisfaction, physiological health benefits, and increases productivity (Edwards & Torcellini, 2002; Heschong, 2002). Additionally, studies confirmed that people prefer dynamic changes of illuminance levels based on sky condition and season (Begemann et al., 1997; Nicol et al., 2006). There is proof of the connection between daylight, view, satisfaction, and health and is strongly associated with full spectrum of light from daylight, which has an impact on human's psychology and physiology (Boyce et al., 2003). Office workers from daylit offices continue to report an increase in general well-being, as well as make fewer mistakes in comparison to fluorescent-lit offices (Wells, 1965).

Daylight access has also a positive influence on decreasing seasonal affective disorder, which is a major issue in Nordic countries (Edwards & Torcellini, 2002; Rashid & Zimring, 2008). Moreover, daylight has the ability to reduce stress and eye-straining (Heerwagen et al., 1998). The possibility to look out, has been stated as the most vital aspect of working near the window (Christoffersen & Johnsen, 2000). Additionally, lack of connection with the outside has been stated to be the main source of dissatisfaction among office workers, due to the lack of natural dynamism of light, which daylight provides throughout the whole day (De Carli et al., 2008). In conjunction with office workers preference towards daylit office, natural light has also been connected to increase of productivity (Veitch et al., 2008).

2.2.3 Alertness

Human sensitivity to short-wavelength light affects alertness. The biologicall effects of light can have a great impact on our alertness, mood, and well-being. Noguchi et al. (2004) found out that the use of bright light in the office (2500 lux), used for 2 hours in the morning and one hour in the afternoon, increased participants alertness in comparison to 750 lux. The brighter light later caused a decrease in body temperature at night and improved the quality of sleep (Noguchi et al., 2004).

The discovery of Intrinsically Retinal Ganglion Cells (ipRGC) cells two decades ago in mice's retina, started a discussion regarding existence of cells in human's eyes that can have a different effect on people than visual (Berson et al., 2002; Hattar et al., 2002). The ipRGC cells are much more sensitive to short wavelengths due to the presence of the melanopsin pigment, which is responsible for so-called non-image-forming effects. Those cells communicate with a brain area called suprachiasmatic nucleus (SCN) (Hattar et al., 2003). The signal is later passed to the pineal gland, which is responsible for melatonin production (Brainard et al., 1985), sleep regulation (Lupi et al., 2008), alertness (Chang et al., 2013; Rahman et al., 2014), body temperature (Badia et al., 1991), mood and cognitive function (Legates et al., 2014).

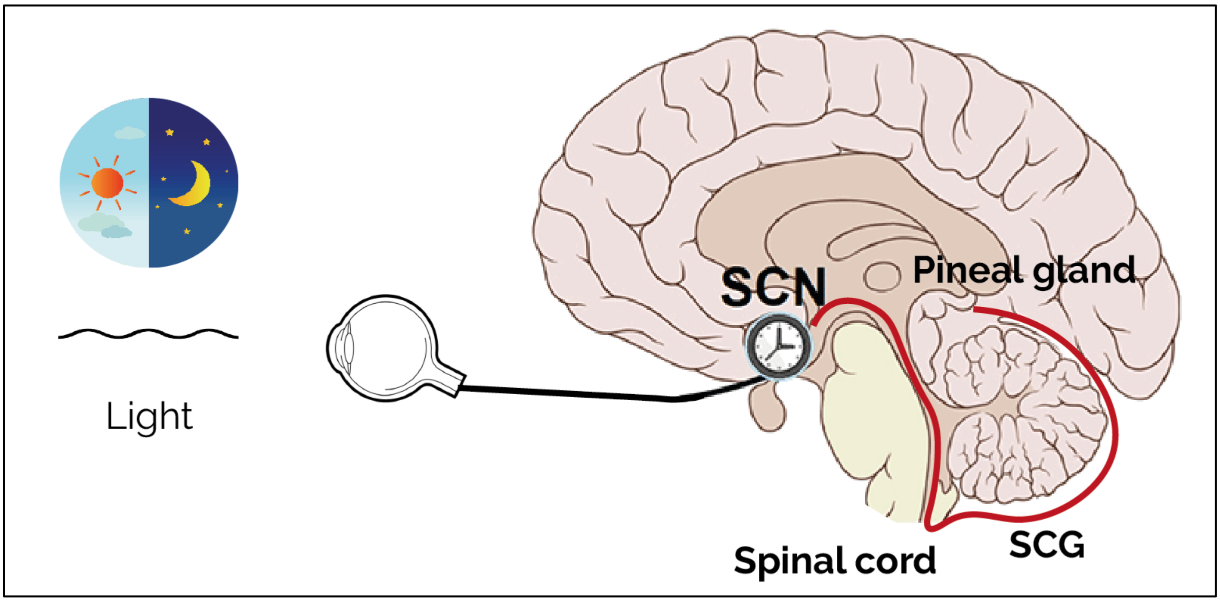

Figure 2. Light path through the brain causing suppression/production of melatonin (Cao, 2019).

Melatonin is a hormone released at night by the pineal gland, which is responsible for the control of the sleep-wake cycle (Auld et al., 2017). The signal from the ipRGC cells states whether it is a day or a night. Based on that signal, at night melatonin production increases and communicates to the body that it is time to sleep (Paul et al., 2009; Reiter et al., 2011). However, if during night-time we are exposed to high light levels, our melatonin production will be suppressed causing trouble with sleep (Czeisler et al., 1986). It has been proved that long–time exposure to certain blue wavelengths can have an impact on melatonin production (Figueiro et al., 2009). With the current exposure to light in the evening melatonin is suppressed (Lewy et al., 2010), causing disturbance to our circadian rhythm as well as contributing to sleep difficulties (Vetter, 2020). For that reason, ipRGCs cells are known as the main photoreceptors for non-image-forming (NIF) functions.

2.3 Metrics to assess biological and visual effects of light

To properly understand the effects of light on human physiology, it is important to know which factor of light in particular is responsible for those effects. Several studies summed up the peak of the sensitivity at the wavelengths 446 – 488 nm (Brainard et al., 2001; Newman et al., 2003). The action spectra regarding the melatonin suppression has a peak at 464 nm, which varies distinctly from the 555 nm peak sensitivity for photopic vision (Brainard et al., 2001).

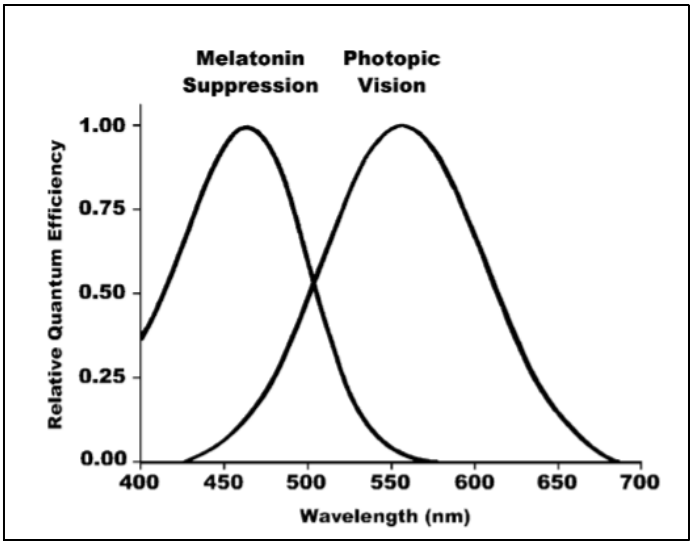

Figure 3. Comparison of action spectra for melanopsin - based circadian photoreceptive system and photopic cone photoreceptors. (Jasser et al., 2006).

Furthermore, when used monochromatically, these short wavelengths at 460 nm are more potent at phase shifting of the circadian pacemaker than 555 nm wavelengths (Lockley et al., 2003). Therefore, measures that are used to evaluate the visual effects of light will not provide any valuable insights into the biological effects of light (Webb, 2006).

2.3.1 Equivalent melanopic lux (EML)

One of the metrics used and implemented by WELL Standard is Equivalent melanopic lux (EML), which is a metric used for measuring biological effects of light on people. It quantifies light effects on the human circadian cycle. It can be calculated at a point in a given direction by multiplying the visual illuminance by the melanopic ratio, which depends on the spectrum of incident light (AmBX, 2020). This metric is weighted to the ipRGC cells instead of the cones. EML is measured vertically at the 1.2 m height above the floor at the workstation (WELL Standard, 2020).

2.3.2 Horizontal illuminance

Illuminance is a metric used to describe the amount of luminous flux per unit area, which refers to amount of light falling on surface area (Tregenza & Loe, 2014). Horizontal illuminance specifically describes the amount of light on the horizontal plane. It is used mainly as a metric to express visual effects of light. The photoreceptors responsible for photopic vision are cones (Imamoto & Shichida, 2014). Horizontal illuminance in the office should meet the standard requirements of 500 lux on the task area (EN Standard, 2011).

2.3.3 Correlated colour temperature vs. Spectral power distribution

In order to specify colour appearance of light a correlated colour temperature is mainly used (CCT). CCT is measured in kelvin (K) and gives the information regarding the colour of the light (LEDsave, 2018). This metric is used to translate the perceived hue of the light source by humans with thermodynamics of black body temperature (Alto, 2018). However, CCT is not the most precise metric to describe the spectrum of the light source, since different spectral power distributions can have the same values of CCT as it is shown in Figure 4 and Figure 5. The spectrum of LED light, which provides 3000 K, is richer in wavelengths from red part of the spectrum with a characteristic peak for LED lights around 460 nm. The fluorescent light, with the same CCT as LED light, provides entirely different spectral power distribution with many peaks for various wavelengths.

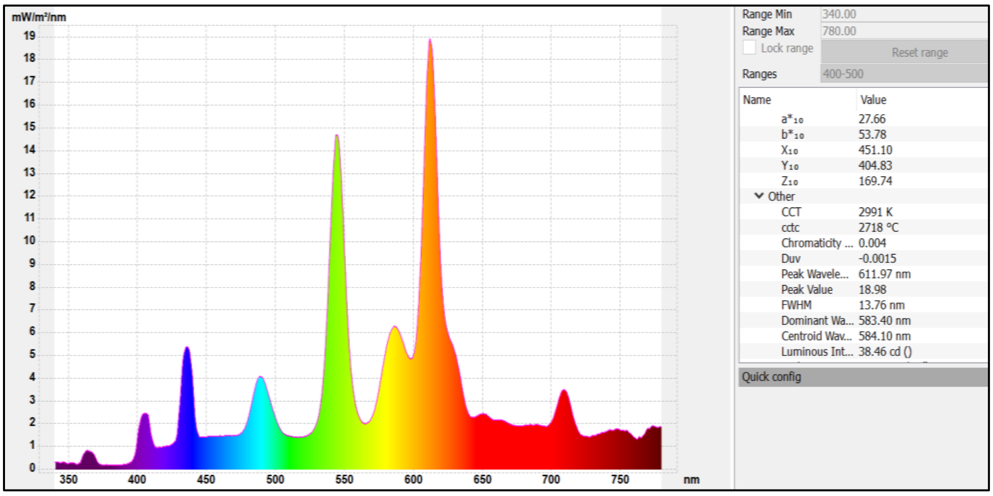

Figure 4. The spectral power distribution of fluorescent light with 3000 K correlated colour temperature.

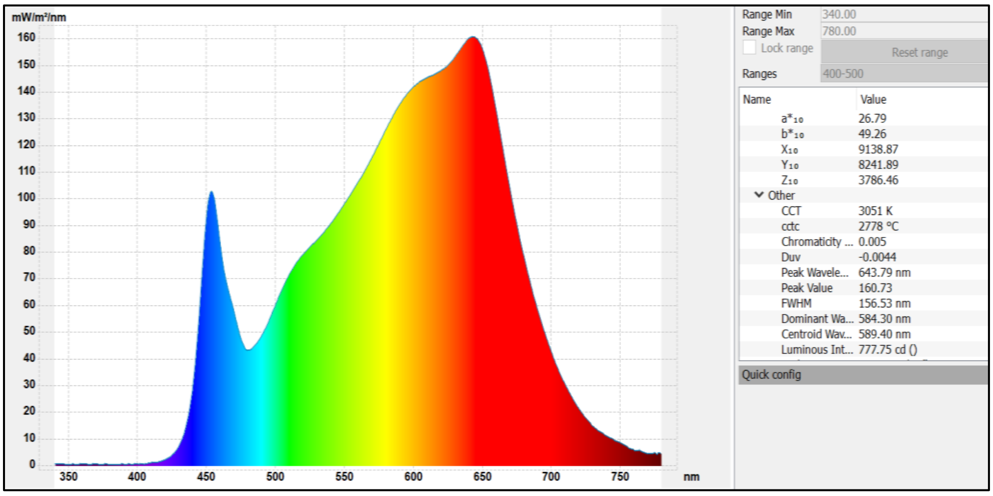

Figure 5. The spectral power distribution of LED light with 3000 K correlated colour temperature.

Since ipRGC cells are more sensitive towards the short wavelengths within the spectrum (Gropp, 2014), the spectral power distribution of implemented electric lighting is necessary to be taken into consideration, when designing with a focus on the biological needs. The information regarding colour apprearnce from CCT does not provide sufficient information in comparison to spectral power distribution (Halper, 2017).

Spectral power distribution has a crucial impact on biological needs, since it was confirmed that melatonin suppression has a peak sensitivity regarding the circadian system between 440-482 nm (Brainard et al., 2001). Polychromatic light rich in blue wavelength part of the spectrum causes a greater suppression of melatonin in comparison with light, which involves less short-wavelength light (Brainard et al., 2015). Kozaki et al. (2016) found out that morning exposure to short wavelengths of light prevented melatonin suppression more effectively, than exposure to light in the morning with a lower amount of blue wavelengths.

The spectrum of daylight coming from the sun is known for its broad spectral power distribution. Generally, it has been proved that circadian efficiency decreases with a spectrum being dominated by long wavelengths (Bellia et al., 2011). There is an implication made by Hartstein et al. (2020) that spectral power distribution may have a significant impact on circadian rhythm. It was also reported that it caused a certain influence on some building occupants (Bellia et al., 2011). Electric light comes with many forms of spectral power distributions, which vary significantly from the one provided by daylight. Even though electric light is perceived as white, the spectrum behind this light is different than daylight. We may perceive different spectral power distributions as the same, but they have different effects on people in terms of the circadian rhythm (Blume et al., 2019).

Several studies confirm that use of light with spectral power distribution rich in blue wavelengths, increases alertness of office workers (Figueiro et al., 2020). With the use of wavelengths from the range of 430 – 480 nm it is possible to increase the melatonin suppression to a higher extend than the light with spectral power distribution involving more red wavelengths (Figueiro & Leggett, 2021). This indicates that the blue-rich spectrum of light can offer vital circadian benefits during the day when the level of melatonin is desired to be low (Lehrl et al., 2007).

Spectral power distribution influences the perception of the space in terms of perceived brightness with higher brightness being reported under short wavelengths spectrum (Ngarambe et al., 2021). Ngarambe et al. (2021) also conducted research connecting spectral power distribution with participant's moods. As a result of this study, no negative aspects of mood intervention have been reported under spectrum with a peak in the lower area of the spectrum. Moreover the researched spectrum reported a higher self-reported productivity level from participants. Light with higher correlated colour temperature has also proved to increase a circadian stimulus up to 5% in comparison to any other light with warmer spectral power distribution (Acosta et al., 2019).

2.4 Office lighting

Despite increasing understanding of the biological effects of light, current buildings are still designed mainly with a focus on visual effects of light (Smolders et al., 2012, 2013). The current approach of designing office lighting contributes to lack of implementation of the knowledge regarding biological effects in practice. This contributes to negligence of the knowledge regarding worker's health and well-being which can be improved by regulating sleep, mood and alertness (Papatsimpa & Linnartz, 2020). The research shows that office workers who were exposed to high circadian stimulation in the morning claimed a better quality of sleep, as well as fewer symptoms of depression in comparison to those, who were exposed to low circadian stimulation (Figueiro et al., 2019).

The encouragement to limit our exposure to light and screens is already widely spread. However, the benefits of working in an environment, that provides a suitable level of stimulation during the workday are still overlooked. Nevertheless, light during our work time continues to have a significant impact on our productivity and comfort (Papatsimpa & Linnartz, 2020).

The discouragement regarding the implementation of biological effects in design of office lighting, can be caused by the lack of clear metrics and guidelines to follow. CIE released the CIE Toolbox Kit, which consists of metrics such as Equivalent Daylight Illuminance, Daylight efficacy ratio etc. However, none of these parameters have a clear guideline regarding the desired and applicable values, other than high values should be in the morning and lower in the evening (CIE, 2020). On the other hand, WELL Standard created a guideline using an Equivalent melanopic lux as a parameter. The standard for work area recommends:

"a. At 75% or more of workstations, at least 200 equivalent melanopic lux is present, measured on the vertical plane facing forward, 1.2 m [4 ft] above finished floor (to simulate the view of the occupant). This light level may incorporate daylight, and is present for at least the hours between 9:00 AM and 1:00 PM for every day of the year.

b. For all workstations, electric lights provide maintained illuminance on the vertical plane facing forward (to simulate the view of the occupant) of 150 equivalent melanopic lux or greater (WELL Standard, 2020)"

2.5 Factors affecting biological effects of light

In an office space, there are many variables that affect human circadian rhythm and alertness. These include, but are not limited to, the season, window orientation, sky condition and time of day.

2.5.1 Season

Electric lighting should always be designed based on the daylight availability. There is a need to investigate the daylight access within the space throughout the whole year since in country like Denmark there are four distinct seasons. It is important to include and test different seasons in terms of sunlight access and daylight influence, since there is a considerable change in the light exposure in various geographic locations throughout the year (Cole et al., 1995; Guillemette et al., 1998).

Many studies are confirming the seasonal variation in human physiology and behaviour (Dam et al., 1998; Okawa et al., 1996; Park et al., 2007). In Tromsø, Norway, during winter time 17% of women and 9% of men reported insomnia and sleep problems causing a delayed circadian rhythm (Arendt, 2012). Similar patterns can be noticed for areas and groups with limited access to daylight. The changes of seasons affect humans significantly, according to study conducted in Sweden, during winter time 53.2% of participants experienced seasonal variation in mood and energy and for almost 20% of participants, these changes influenced their daily life (Rastad et al., 2005). With a significant difference in the length of a day and daylight availability, which differs at a different times of the year in countries located further north from the equator, light can be an important factor in optimizing the differences (Adamsson et al., 2018).

The seasonal variations of the mood have been investigated, with a result of higher ratings regarding the mood during summer months than during winter. For higher latitude countries of the northern hemisphere the diversity of daylight between seasons causes, that during winter months the exposure to bright daylight is extremely limited, with people spending on average 10 minutes per day under daylight (Adamsson et al., 2018). From middle to high latitudes the hours with sun vary significantly, depending on the time of the year, which can be associated with human's circadian rhythm and melatonin production and melatonin being produced for a shorter time during summer months and for a longer time during winter (Reiter, 1991). Limited light exposure may even worsen during winter time with a short length of the day (Jean-Louis et al., 2000) and additionally, lower temperature encourages staying indoor (Cole et al., 1995).

2.5.2 Window orientation

The importance and benefits of windows within office spaces are a subject that has been studied for many years, with a focus on human health, well-being as well as satisfaction, and comfort (Boyce et al., 2003). With a rising interest in the benefits of daylighting in educational as well as office environments parameters such as wall to window ratio, window size and orientation are becoming vital elements for not only architects, but also lighting designers (Sedaghatnia et al., 2021).

Windows are an inseparable part of the building design. Additionally, they positively influence occupant's health and well-being. Moreover, they provide space with daylight and view (Aries et al., 2010). However, can also affect energy consumption (Bodart & De Herde, 2002). The issue usually arises when both parameters: the amount of daylight and energy consumption needs to be balanced. Larger windows are preferable to provide better access of daylight, however smaller windows are recommended regarding the aspect of energy consumption.

Windows can contribute to heat gain of a space and glare (Chaiyapinunt et al., 2005; Chauvel et al., 1982). There is an evidence that occupants have a higher tolerance to glare if the view outside the window is pleasant (Chauvel et al., 1982). Window orientation has a significant influence on daylight performance within a room for all four orientations. Particular attention is drawn towards West facing spaces by Saha et al. (2017) since West facing window did not cause glare issues or heat gain. However, according to Zeng et al. (2021), an East facing office proved to be most beneficial in terms of human circadian system.

During a clear or partly cloudy sky condition, each space with different window orientation provides a different character, colour, directionality of light as well as varies significantly in illuminance levels. For North and South facing spaces, the distinction can be especially noticeable with more diffuse and dim light for North facing spaces and direct sunlight with high illuminance values, as well as heat gain, if there is no daylight control, for South window orientation (Day et al., 2012). Following the office window recommendation, TH National Institute of Building Sciences Executive Order 13423 (FedCenter, 2015) in terms of daylight orientation North-facing spaces are a prime choice with South facing spaces on the second place, however only with control over direct sunlight (Lausanne, 1997).

The deliberate choice of window orientation for office spaces is now a solution to the reduction of electricity usage by electric light. As it was proved by Kaminska (2020), South-East facing spaces have a possibility to limit the usage of electric light frequent than North facing spaces.

Nevertheless, when investigating window orientation it is also important to state building's location. Window orientation impact on the room varies between Nordic countries like Denmark and sunny Italy where, the difference between summer and winter daylight input in three offices was not significant (Bellia et al., 2014b). The most recent study focusing on climatic changes across Europe is by Goia (2016) and presents an analysis in Oslo. The results showed that South facing façade is significantly different from other three orientations. However, within the South facing spaces light can disturb visual comfort (Piccolo & Simone, 2009).

It is important to point out that not all above studies has been carried out within a North European climate and location and there has been a limited number of studies regarding window orientation with consideration of biological effects of light.

2.5.3 Sky condition

Different locations around the globe are characterized by sky domes, with various sky radiance and brightness. With a clear sky type, we have a peak sky radiance distribution around the sun, which weakens with the sky distance. With an overcast sky, the clouds are causing a homogenous radiance (Lou et al., 2019). It has been proved that sky conditions, among the other factors, have a remarkable influence on the biological effects of light (Bellia et al., 2014a, 2014b). Under clear sky conditions there has been variation between EML values for different window orientations and for the overcast sky, the values were similar for all four orientations, which may be caused by the scattering of daylight by clouds (Zeng et al., 2021).

There is still a lack of research regarding the dynamics of daylight within an office environment, especially under various sky conditions. Only a few studies explored the influence of daylight on the biological effects of light (Borisuit et al., 2015; Boubekri et al., 2013; Kaida et al., 2006).

Daylight dependents on the position of the sun and major changes regarding the spectral irradiance can be noticed throughout a day (Morsink, 2018). Daylight illumination is dynamic and temporal and is influenced by the geographical location of the building (Bodart et al., 2008).

The consideration of the location of the building is found useful, however the daylight solutions should be applied with cautiousness. Meaning that for country light Denmark, where there is a high frequency of overcast sky (around 56% days of the year (MERRA-2, 2021)), lighting solution should be taken into consideration and designed based on that (Munoz et al., 2014).

Since in Denmark majority of the days throughout a year has an overcast type of sky, it is vital to consider that as well as, see how much light space receives when the direct sunlight is behind the clouds. It should be investigated if we can compensate for the significantly limited amount of daylight with electric light. According to the Weather Spark website, the cloud coverage varies notably throughout the whole year (MERRA-2, 2021). Based on that three different sky conditions were chosen to investigate: clear sky, partly cloudy, and overcast.

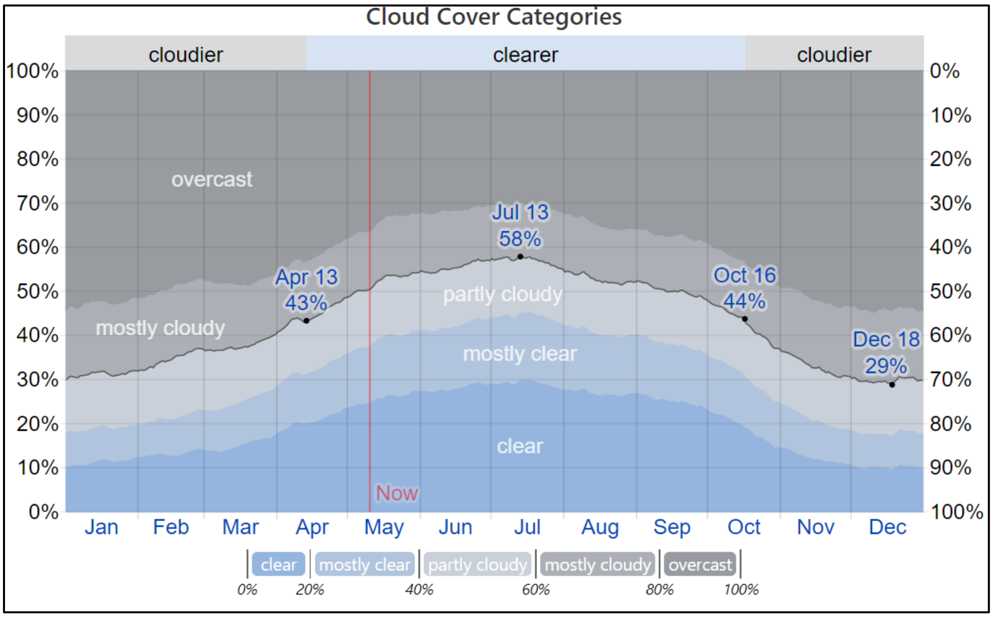

Figure 6. Percentage of cloud coverage throughout a year in Copenhagen, Denmark (MERRA-2, 2021).

2.5.4 Time of the day

Many studies reported that time of exposure to light is vital in terms of the biological effects of light. The main findings suggest that morning exposure has a significant influence on the circadian phase (Galán et al., 1991; Verlag et al., 1987). One of the effects of light, is the ability to shift the circadian phase by the timing of light exposure. Generally, morning exposure causes advance in the clock, and evening light causes delay (Blume et al., 2019). There is evidence that even short exposure to bright light for a short time can influence the human circadian system and shift our circadian phase (Kronauer et al., 2000).

Mistimed exposure to light can desynchronize circadian rhythm causing negative effects on human health (Bedrosian & Nelson, 2017). For that reason, exposure to light should be appropriately planned and designed. Following the WELL Standard recommendation, alerting exposure should be provided between 9 am and 1 pm. It is supported by many research, which suggests that bright light exposure in the morning especially during dark winter months successfully suppresses melatonin secretion and re-syncs our inner clock (Crowley & Eastman, 2015; Glickman et al., 2006). Studies confirmed that at high latitudes where people experience constant exposure to daylight during a certain period of time reported an increase in suicides (Björkstén et al., 2005). That indicated that the timing of light exposure is crucial for human health as well as circadian function and mood. Shortage or excess of light can cause notable changes in one’s health and mood.

The results show that bright blue-enriched light exposure in the morning can balance the circadian phase and can work as an effective strategy during the day when there is not sufficient light or, when the exposure is mistimed (Münch et al., 2017). Additionally, Watson (2000) stated in his book "Mood and Temperament" that:

"Although different people reach their acrophase [peak time of time at which the peak of a rhythm occurs] at different times and show somewhat different curves over the course of the day, our analysis have demonstrated that basic circadian rhythm – that is, low Positive Affect at the beginning and end of the day, with a peak occurring somewhere in the middle – is remarkably robust and generalizable across individuals" (p.116). (Watson, 2000)

2.6 Double Dynamic Lighting

Double dynamic lighting is a concept developed by The Lighting Design Research Group at Aalborg University in Copenhagen. It takes into account sky condition, as well as daylight input, providing dynamic electric lighting solution based on the outdoor condition. The aim is not only to deliver a required illuminance to meet standard requirements, but also to provide a combined daylight and electric lighting environment, which can create diversity in the perception of the space (Hansen & Pajuste, 2021). Studies confirmed that people prefer changeable light, which varies throughout the day, just like daylight changes from direct sunlight under the clear sky to diffuse daylight during an overcast day (Wilson & Tregenza, 2011). The dynamics of electric lighting, which are considered in the DDL concept, are: intensity, colour temperature, directionality as well as distribution of light.

The mixture of direct and indirect electric light in an office environment has been studied by many researchers. At first, the ratio between diffuse and direct lighting was investigated with illuminance on the work plane with a result, that 75% of direct light was judged as the most cheerful. It was pointed out that the addition of direct light had a major energizing influence on office workers (Fleischer et al., 2001). Apart from that, the subjective impression of diffuse and direct light has also been investigated. As a result, in terms of ratio the 60% of indirect light contribution to the horizontal illuminance was stated to be favoured (Houser et al., 2002). Another study concerning direct and indirect lighting was conducted by Boyce et al. (2006). The main finding of that study was that direct/indirect systems were reported to be more comfortable than only direct systems (Boyce et al., 2006). The experiment carried out by Stokkermans et al. (2018), who looked into the effects of diffuse daylight on a space which had no view, stressed the prospective and the need of direct light with a combination of diffuse light to re-create an environment similar to daylit spaces. To conclude the above findings, the main preference is towards the combination of direct and indirect lighting in the office spaces over the direct or just diffuse.

Additionally to the directionality of light, the spectral power distribution has been tested in terms of perception of the space with 3000 K CCT being perceived as warm, 3000-5000 K as neutral, and above 5000 K as cold (Cuttle, 2015). However, the perception and preference towards the electric lighting within a space strongly depends on the weather conditions as well as features of the daylight (Fleischer, 2001).

DDL focuses on directionality of light by examining direct and diffuse light, which are coming from different light sources. The combination of direct and diffuse light, with certain spectral power distribution and directionality, can complement the dynamism of daylight inflow that is preferred by users (Shrum, 2017). A number of studies confirms that the combination of direct and diffuse light is favoured by users in comparison to only direct or diffuse lighting (Boyce et al., 2006; Houser et al., 2002; Veitch & Newsham, 2000).

The unique approach of DDL is that it combines daylight and electric light, into one cohesive concept. The view on the directionality of light is distinctive with the direct light coming from a spotlight, recreating the input of daylight from the side window and diffuse panels providing general ambient lighting mimicking the skylight.

A literature study presented by Hansen & Mathiasen (2019). shows that there has been a great interest in biological effects of light impacting people's health and well-being. Ru et al. (2019) found out that higher satisfaction was reported with dynamic lighting concept than the static one. Another study, which investigated the subjective alertness in relation to time of the day, proved that office workers preferred the dynamic change of the light and not always favoured the healthy lighting (de Bakker et al., 2021). Houser et al. (2021) defined four factors of light: temporal pattern, light spectrum, light level, and spatial patterns. The aim of that study was to integrate all four elements in a way, that responds to the dynamism of daylight and propose a design concept, which later can be used not only for visual effects, but also for biological effects of light (Houser et al., 2021).

3 Research question and objectives

This study aims to determine to what extent different light directionalities and distributions of DDL influence the biological effects of light. It seeks to discover the contribution of daylight in offices with different window orientations, seasons, times of the day and sky conditions. Additionally, further experiments aim at establishing whether or not the DDL concept, which is reported to be favoured by the participants from a previous study (Hansen et al., 2020), performs better in terms of meeting humans biological needs than direct or diffuse light within the office space.

3.1 Research questions

This study aims to answer the following three questions:

1) How are biological effects of light affected by daylight in offices with different window orientations, under various sky conditions, times of the day and seasons?

2) Is direct or diffuse electric lighting superior at supporting biological effects of light within offices with different window orientations, sky conditions, times of the day and seasons, with Double Dynamic Lighting directionality of light?

3) Can the combination of direct and diffuse light with ratio of 40/60 and Double Dynamic Lighting directionality of light, provide sufficient amount of light to meet the horizontal illuminance as well as WELL Standard requirements, with consideration of office's window orientations, sky conditions, times of the day and seasons?

3.2 Research objectives

To answer RQ1, the objectives of this work are to:

- conduct ALFA simulations for office model during three seasons, for four window orientations, under three different sky conditions at two different times of the day.

To answer RQ2, the objectives of this work are to:

- based on the daylight simulation results assess, which cases need additional electric lighting to meet horizontal illuminance and WELL standard requirements

- conduct ALFA simulations for office space in which electric lighting is needed to meet visual and biological needs during different seasons, for four window orientations, under three different sky conditions at two different times of the day with daylight inflow and direct electric light, which follows the directionality of direct light presented in DDL concept.
- conduct ALFA simulations for office space during three seasons, for four window orientations, under three different sky conditions at two different times of the day with daylight inflow and diffuse electric lighting

To answer RQ3, the objectives of this work are to:

- conduct ALFA simulations for office space during three seasons, for four window orientations, under three different sky conditions at two different times of the day with a use of two lighting scenarios which were preferred by participants from DDL study by Hansen et al. (2020).

4 Methodology

As the field of biological effects of light is still quite a new domain, research conducted in this area is still in progress. There is a need to investigate and create methodology as well as guidelines on how to design with consideration of biological needs. Based on the findings from the literature review, experiments on season, window orientation, time of the day and sky condition were chosen to be evaluated in terms of biological effects of light using ALFA, which is a new tool for simulating the impact of light on human's physiology.

4.1 Literature review

The literature review is a fundamental part of the study, since it provides the basics on which further investigation within the subject can be developed. The literature review was conducted to develop understanding of the challenges in the field of designing light with consideration of biological effects of light. It provided background information of the current state of knowledge about biological effects of light within an office environment. It aimed at finding out which variables have proved to have a potential to influence biological effects of light. Existing knowledge was combined and four factors, which this study investigates were chosen. The selected factors are season, window orientation, sky condition and time of the day, which were investigated from the aspect of biological effects of light. The selection of those four factors is supported by a number of research in the literature review section. The review of the current research provides a comprehension of what is still missing, and which area should be investigated further. Literature review was also used in the evaluation of the results and provided a better understanding of the simulation outcomes.

4.2 Model and scenario simulations in ALFA

In this section, the methods used in creating the model and simulating the various scenarios will be described. A model of the office was created in Rhinoceros 6 and different scenarios were assessed using the plug-in ALFA.

4.2.1 ALFA software

ALFA (Adaptive Lighting for Alertness) is a new circadian lighting design programme developed by Solemma. It allows architects and lighting designers to predict and control the biological effects of light as well as create more suitable environment for people to work in. ALFA is a plug-in for Rhinoceros 3D versions 6 and 7. Since biological effects of light are more sensitive to blue wavelengths, ALFA uses an extended Radiance lighting engine to render the world in high-resolution with 81-colour spectra. This approach allows it to estimate the amount of light absorbed by an observer's physiological photoreceptors with consideration of a person's location and direction of view (ALFA — Solemma LLC, 2021). Since ipRGC receptors absorb light via pigment called melanopsin, the quantity is referred to as equivalent melanopic lux. This metric is recognized by the international building certification system WELL Building Standard.

Within the building interior, the value of melanopic lux strongly depends on the light emitted by a luminaire and the sky. ALFA is equipped with a library of high-resolution source spectra, which has been taken from physical measurements of the luminaires. ALFA allows to insert a chosen luminaire as an IES file in the library (ALFA — Solemma LLC, 2021).

Regarding the sky type, which plays a major role in the biological effects of light, ALFA offers four sky types: clear, hazy, overcast, and heavy rain clouds for any location on the Earth. The sky option is limited causing major drawbacks in terms of the reality of the simulated conditions.

To ensure realistic results ALFA is equipped with a library of over 500 measured spectral materials, which are based on spectrophotometric measurements of real architectural objects. However, there is also a possibility of creating original materials by importing measured material reflectance.

As a result, ALFA gives back equivalent melanopic lux values and M/P ratio. Apart from the parameters connected to biological effects of light, ALFA provides also data regarding the visual needs with values of horizontal and vertical illuminance (WELL Standard, 2020).

4.2.2 Room model

Since ALFA is a plug-in for Rhinoceros at first, a model of an office was created in Rhinoceros 6 mimicking the DDL lab features. The room dimensions were set to 6.2 x 4.3 x 2.6 m. The space consists of four workstations (four desks and chairs). Desks were created in Rhinoceros 6 with dimensions 1.2 x 0.76 m. The chairs were imported from free3d.com as an obj. extension and rescaled to match the dimensions of the model. The room was equipped with two side windows with a size of 1.35 x 0.85 m. The following layout is presented in Figure 7.

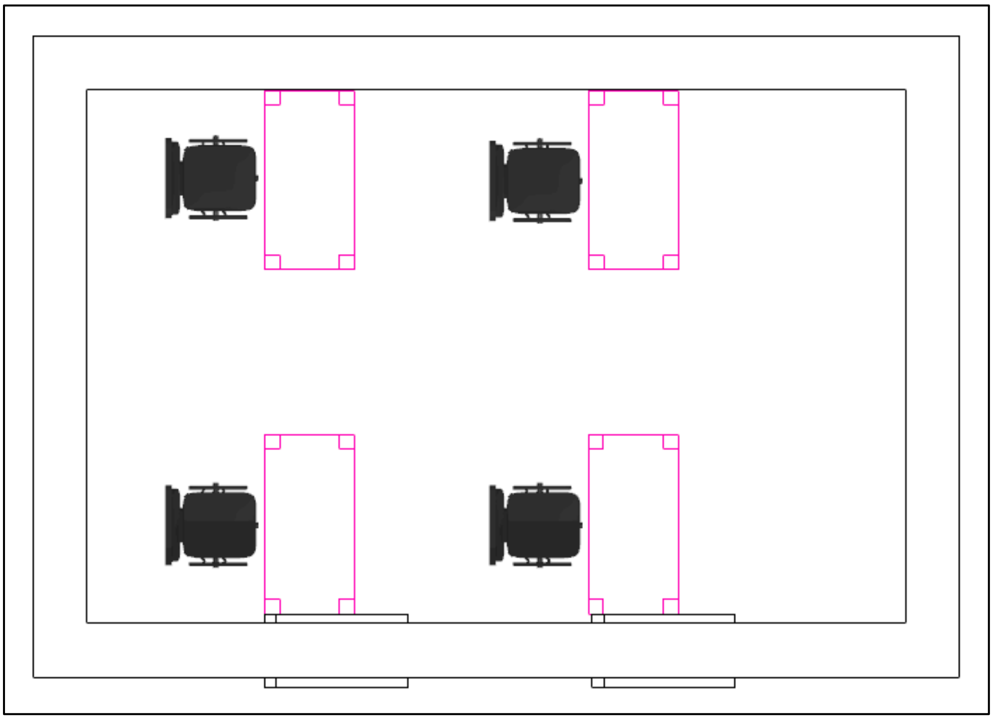

Figure 7. The layout of desks and chairs in a model of the office.

The room dimension and location are the same as the DDL lab, which is located at Aalborg University in Copenhagen. The exact location of Aalborg University in Copenhagen was applied with the following coordinates: 55.6509° N, 12.5419° E.

All the materials were chosen from the installed library in ALFA and were selected to resemble the materials within the DDL room. EN 12 464-1 standard suggest different material for various surfaces within a room.

- Walls (0.5 – 0.8)
- Ceiling (0.7 – 0.8)
- Floor (0.2 - 0.4)

(EN Standard, 2011)

The set materials reflect and follow the standard recommendation with characteristic values of reflectance in the office environment. Selected materials are presented in Table 1 and Table 2.

Table 1. The reflectance of materials used in the model of the office.

	Name	R (photopic)	R (melanopic)	Specularity
Walls	White painted corridor walls	79.8%	75.8%	0.4%
Floor	Interior Flooring	38.1%	38.4%	1.1%
Ceiling	White painted room ceiling	82.2%	77.4%	0.4%
Window frame	Aluminum white railing	78.2%	79.2%	1.7%
Table	Dupont Desaturated blue 119	21.6%	23.4%	0.0%
Chair	Munsell N 6.35	32.3%	32.7%	0.0%

Table 2. The transmittance of materials in the model of the office.

	Name	T (photopic)	T (melanopic)
Windows	Double IGU Clear Tvis 78%	78.5%	77.7%

To conduct a simulation in ALFA, the plane, on which calculations were conducted, had to be selected. To follow the WELL Standard recommendations four planes were applied to the model for each workstation. In Rhino the “Plane” command was used to receive accurate surface for calculation purposes. The four planes were installed with dimensions of 0.55 x 0.28 m. The placement of the measuring planes is presented in Figure 8.

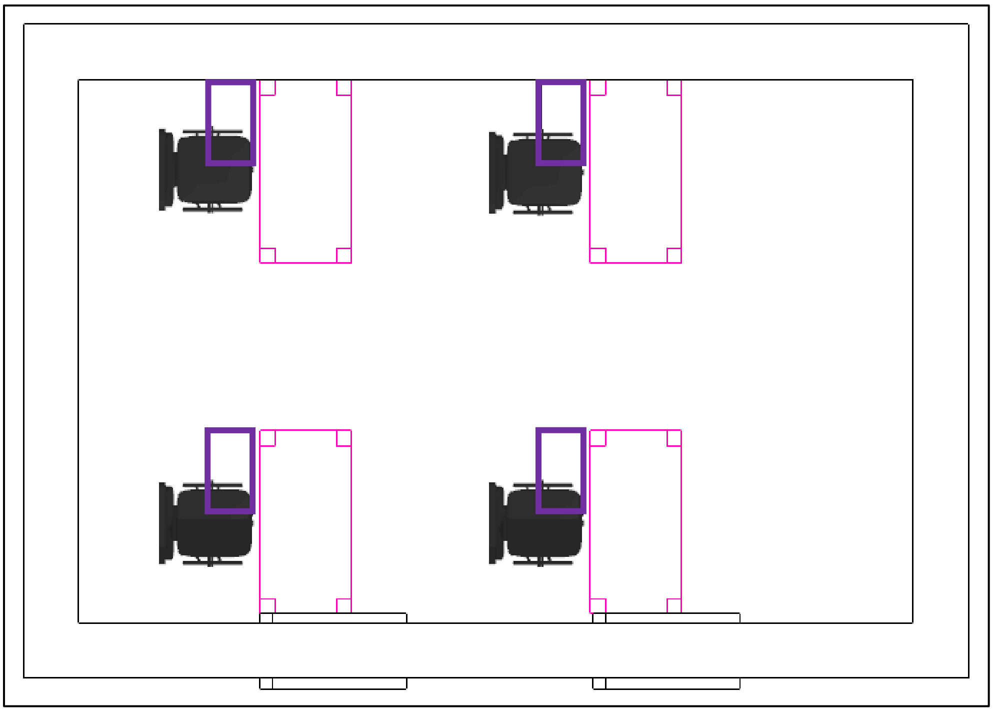

Figure 8. Placement of the measurement planes.

The planes were planted on the floor level for the measurements of horizontal illuminance at 0.76 m level above the plane and vertical measurements of equivalent melanopic lux at 1.2 m. The following results will be referring to the average values from four workstations in each case. The height and placement of measuring points is presented in Figure 9.

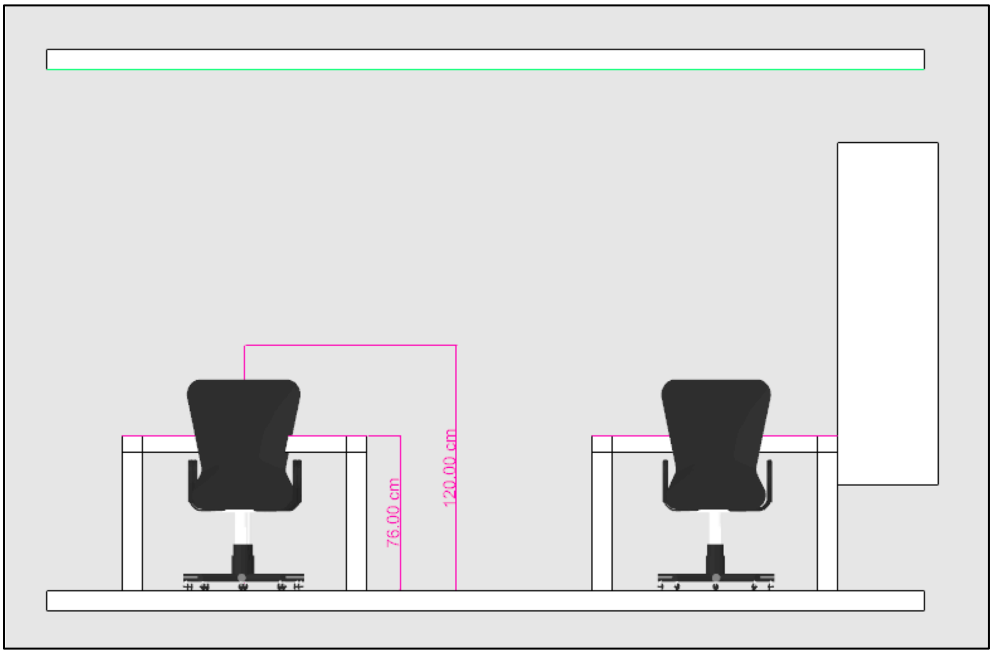

Figure 9. Placement of a horizontal and vertical plane.

The view direction of vertical plane of four measured workstations is presented in Figure 10. Only one view direction in the office was chosen following the placement of the workstation.

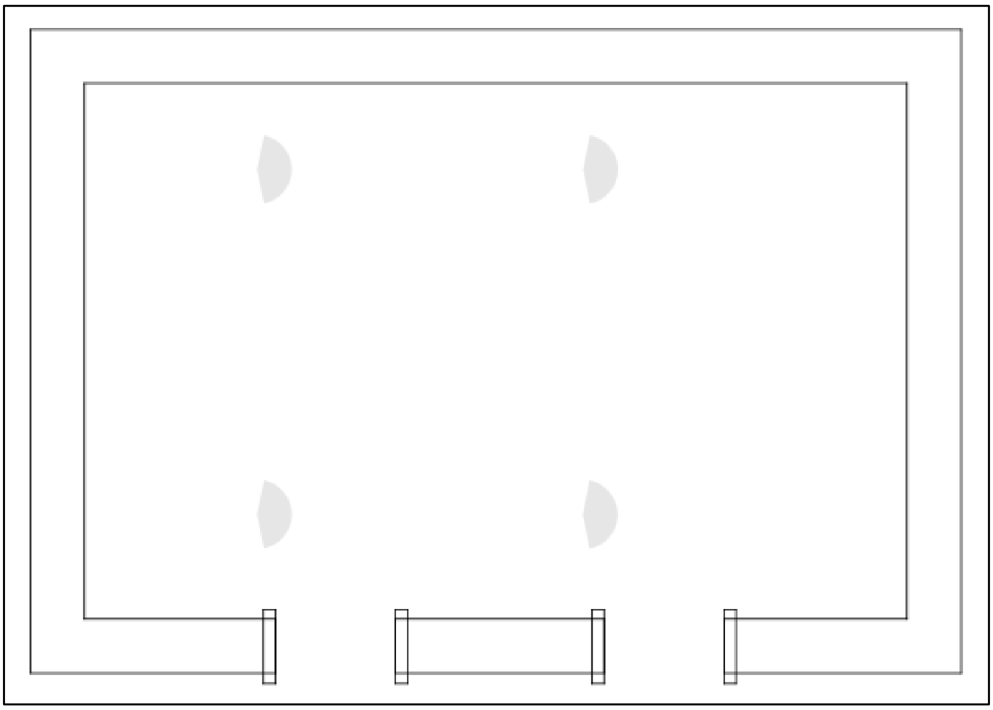

Figure 10. Layout of four measuring points and direction of a view point.

direction was chosen following the placement of the workstations only one view in the office. The view direction was later rotated when the window orientation of the space was changed. The settings of the grid in ALFA are presented in Table 3.

Table 3. ALFA settings - simulation and grid.

Spacing	119.5
Direction	1
Rotation	Depanding on window orientation • 0 - South • 90 - East • 180 - North • 270 - West
Radius	23.2
Viewplane offset	120 cm
Workplane offset	76 cm

4.2.3 Experiment 1 – daylight

In Denmark, four distinctive seasons vary significantly in terms of the number of sun hours, the height of the sun over the horizon, etc. That being a case, three-season cases were implemented:

Winter (December), Summer (June), Spring/Autumn (March). Simulations were conducted on the 21st day of December, June, and March to receive results from the most crucial days in the year like summer and winter solstice as well as the spring equinox.

At first winter season was tested with clear sky conditions, facing North at 9 am. Than time of the day was changed to 1 pm. By checking the values at 9 am and 1 pm there is a guarantee that the values of equivalent melanopic lux in between those times are fulfilled, since the two most extreme cases are investigated.

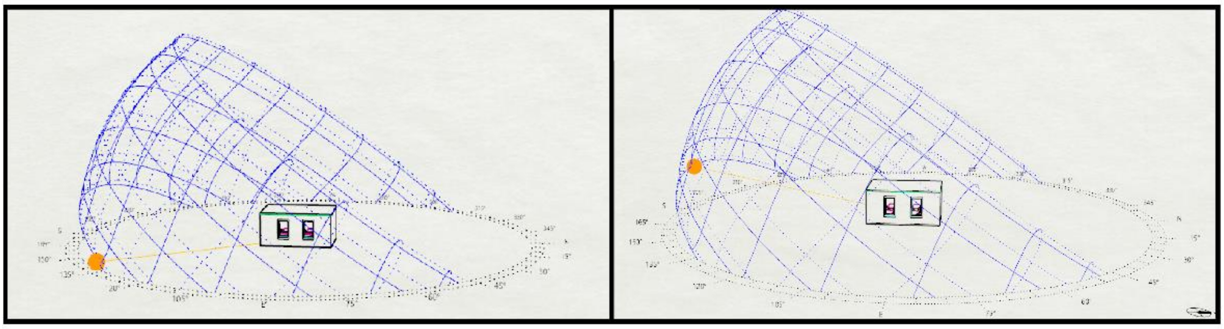

Figure 11. Simulation presenting sun position at 9 AM and 1 PM on the 21st December.

When both times were tested, sky conditions were changed to partly cloudy and overcast. ALFA offers four sky types: clear sky, hazy, overcast, and heavy rain cloud. The chosen sky conditions were the clear sky, hazy and heavy rain cloud, which later will be referred as clear sky, partly cloudy and overcast.

Figure 12. Three sky types implemented in the experiment. Images taken from A) (Pexels, 2021a) *B),* (Jooinn, 2021) *C)* (Freepik, 2021).

After that the model of the room was rotated changing the window orientations from North to West and the same scheme was repeated. In ALFA the window orientation was changed by a rotation of the whole model. Since Rhino reads orientation with North – South on a Y – axis and East – West on the X – axis the changes of window orientation have been done following that pattern.

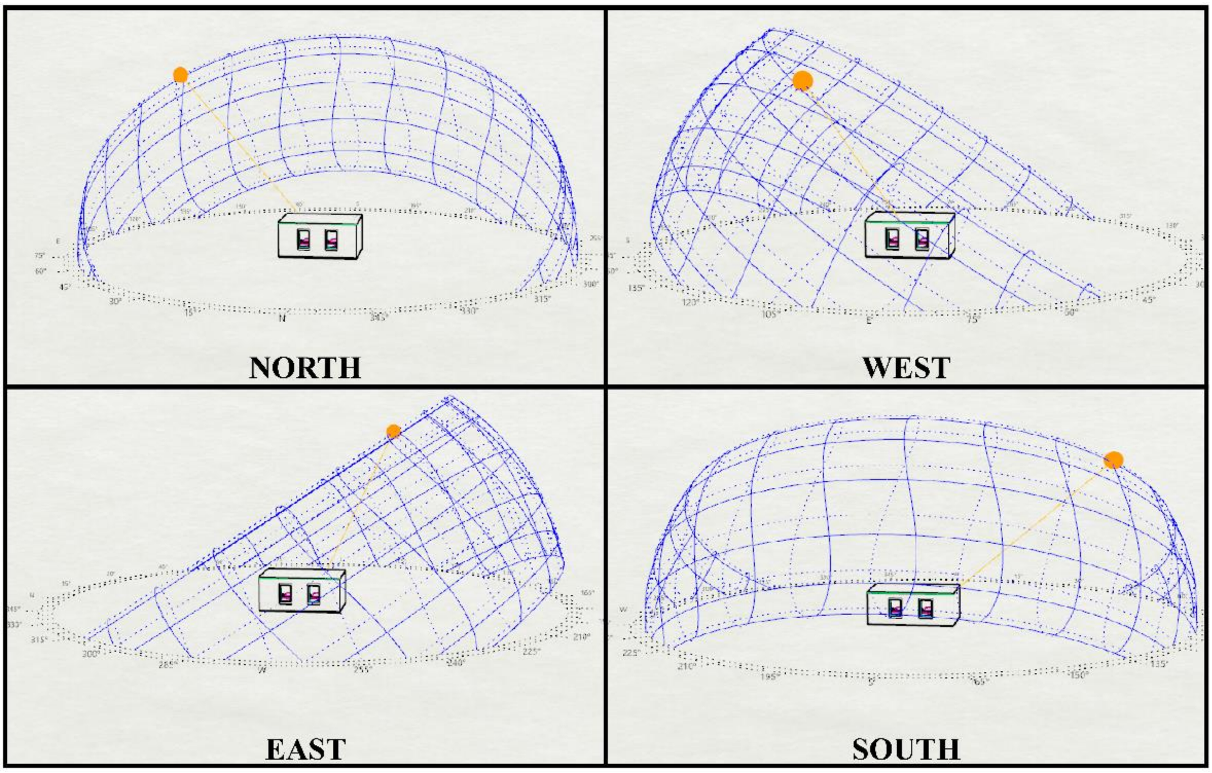

Figure 13. Sun path for four different window orientations in Copenhagen, Denmark.

After simulating all cases during winter season, the steps were repeated for spring/autumn an summer season. After daylight simulation the results of daylight were analysed and cases in which WELL Standard and horizontal illuminance were not met, electric lighting was tested.

4.2.4 Experiment 2 – direct and diffuse light

Primarily in the experiment, the direct light was installed in a form of a spotlight, which provided light on the workstation. The light intensity was set to the maximum and the spectral power distribution set to 4000 K.

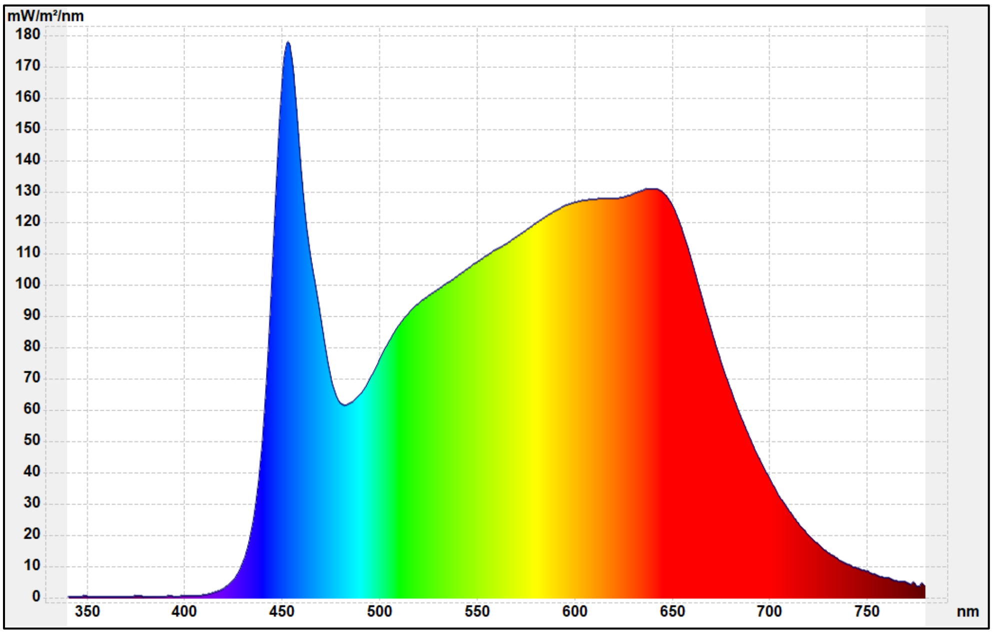

Figure 14. Spectral power distribution of Fagerhult Multilume Flat Delta panel with 4000 K correlated colour temperature.

The spectral power distribution used in the simulations was measured by a spectrometer GL Spectis Touch 1.0. However, the measure spectral power distribution comes from a different luminaire than used in the simulation. The measured spectral power distribution comes from a luminaire, which is installed in the DDL lab at Aalborg University. The light used in the space for diffuse light comes from Fagerhult Multi Flat Delta panels. The measured spectral power distributions were used to increase the reality of the ALFA simulations by providing real-time more accurate data.

The chosen luminaire for a spotlight was a Zumtobel Arcos 3, which is the same luminaire that is installed in DDL lab with a light curve presented in Figure 15.

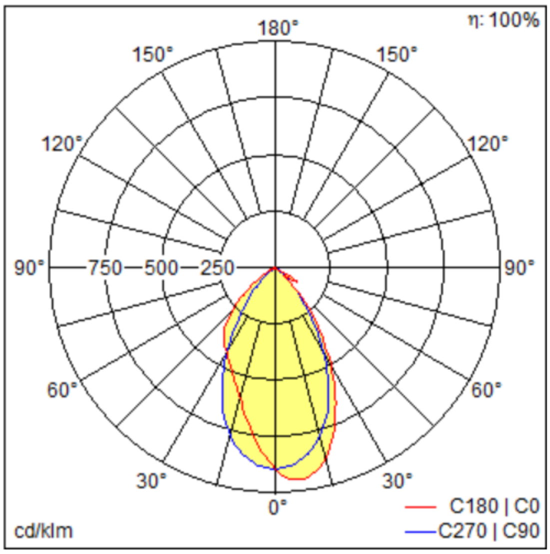

Figure 15. Light distribution curve of spotlight Zumtobel Arcos 3 (Zumtobel, 2021).

The specifications regarding the spotlight are presented in Table 4.

Table 4. Zumtobel Arcos 3 spotlight specification (Zumtobel, 2021).

Luminaire luminous flux	1400 lm
Colour Rendering Index min.	95
Luminaire efficacy	40 lm/W
Luminaire input power	35 W

Regarding the placement of the luminaires, the direct spotlights were placed in a way that the beam would hit the measuring plane (horizontal illuminance and vertical plane for EML), as accurately as possible. The spotlights were rotated 32° degree to provide the same directionality as in the Hansen et al. research (Hansen et al., 2020). Spotlight beam distribution is illustrated in Figure 16 and Figure 17.

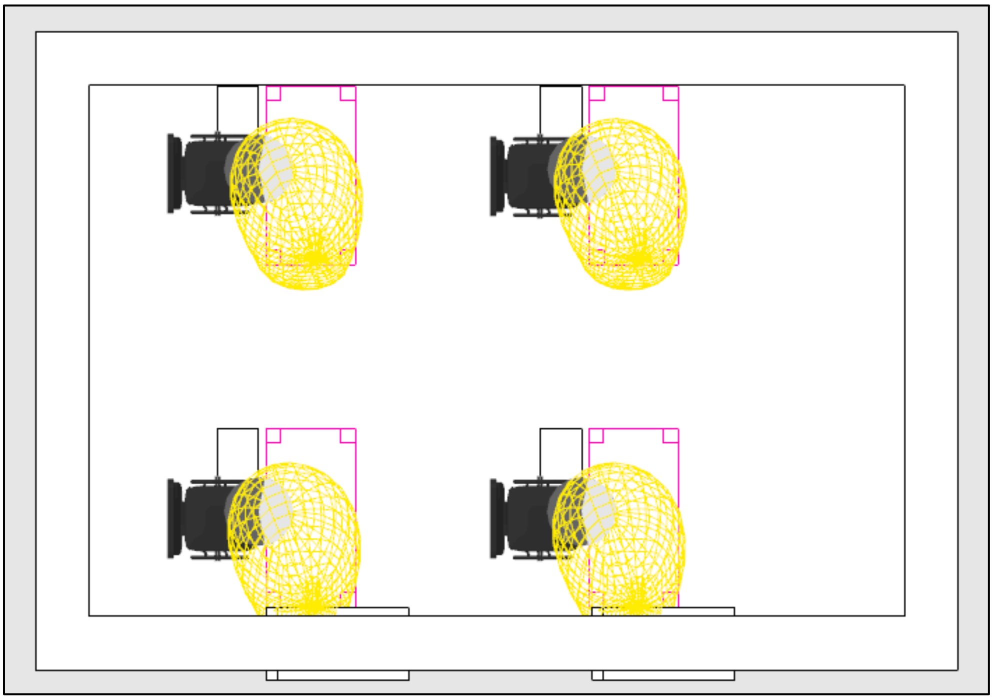

Figure 16. Top view of direct light sources in the office model.

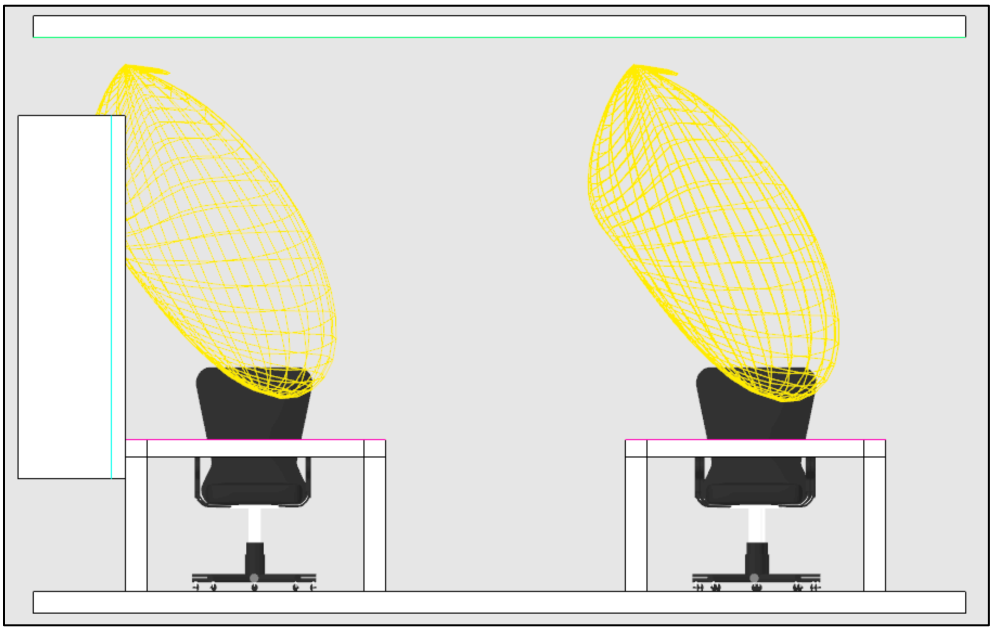

Figure 17. Front view of direct light sources in the office model.

As for diffuse light Notor 65 Indirect from Fagerhult was chosen. The diffuse luminaires were chosen in order to provide ambient lighting. The indirect light source was chosen in order not to interfere with direct lighting scenario.

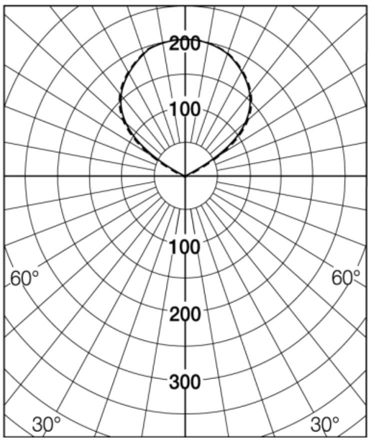

Figure 18. Light distribution curve of diffuse light (Fagerhult International, 2020).

The specification regarding the diffuse light is presented in Table 5.

Table 5. Diffuse light specification (Fagerhult International, 2020).

Luminaire luminous flux	2755 lm
Colour Rendering Index min.	80
Luminaire efficacy	132 lm/W
Luminaire input power	21 W

Diffuse light sources were placed over the desks at 170 cm height from the floor level. The indirect panels provide diffuse light in a similar way as diffuse ceiling panels installed in DDL lab which were used in Hansen et al. (2020). The placement of the luminaires is illustrated in Figure 18 and Figure 19.

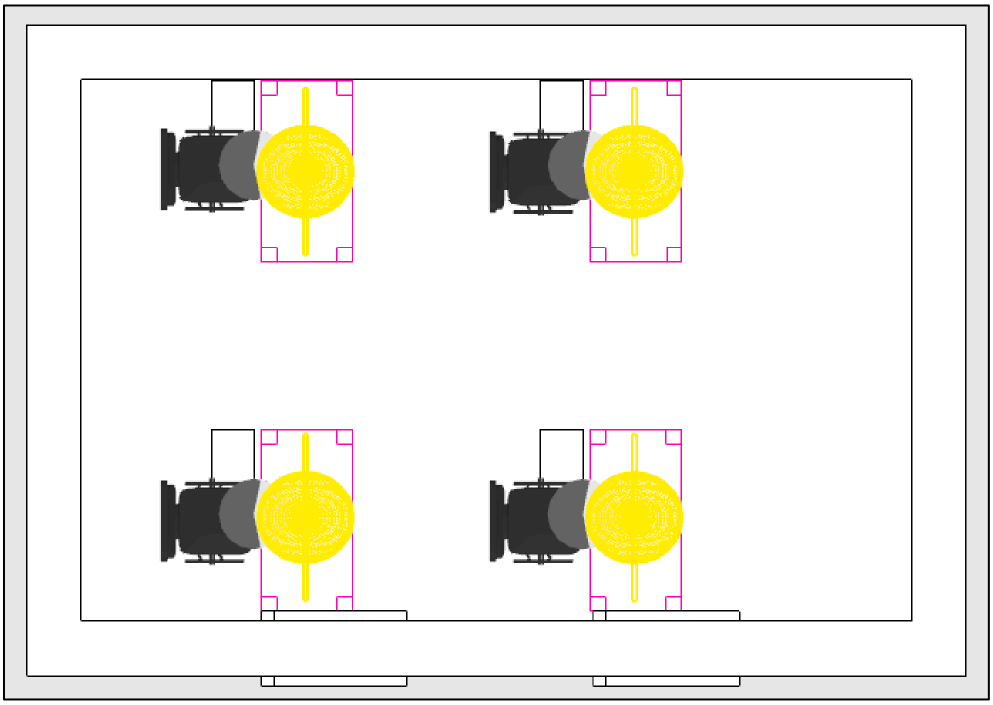

Figure 19. Top view of diffuse light sources in the office model.

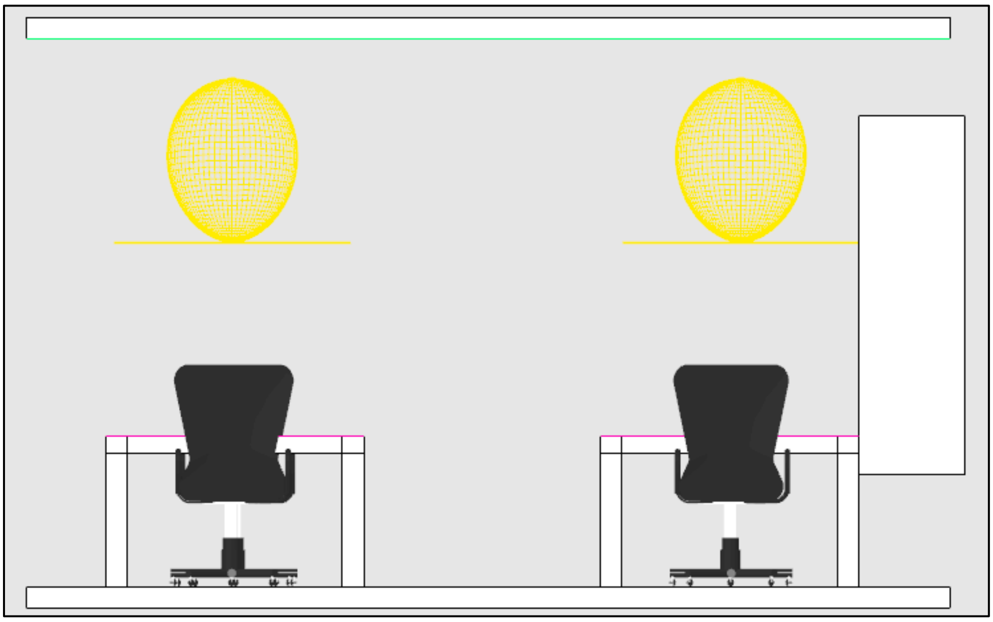

Figure 20. Front view of diffuse light in the office space model.

The spectral power distribution used for both direct and diffuse light in experiment 2 is presented in Figure 21. Implemented spectral distribution has a peak around 460 nm typical for LED lights.

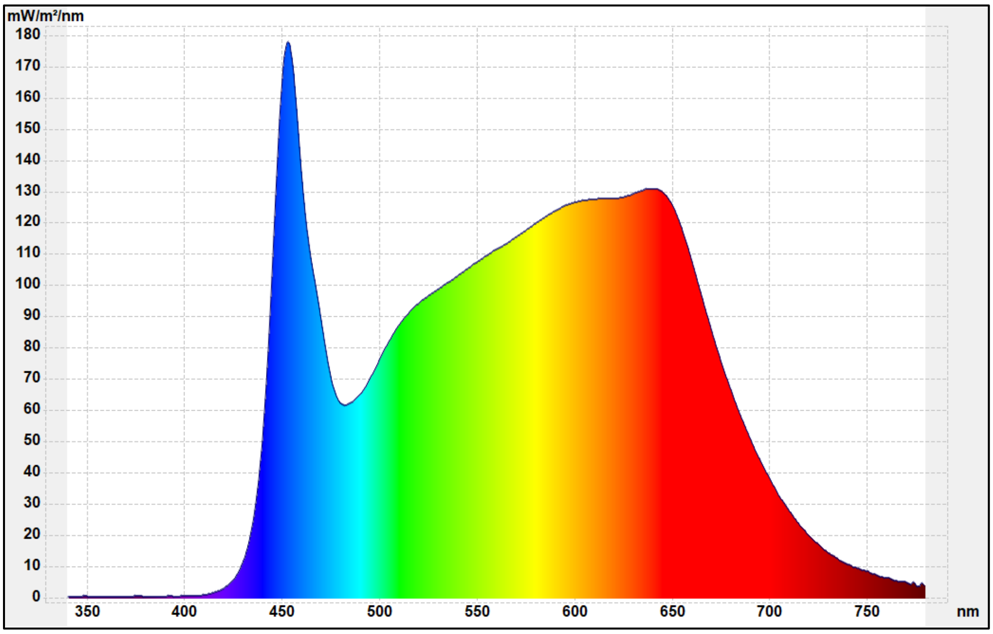

Figure 21. Spectral power distribution of Fagerhult Multilume Flat Delta panel with 4000 K correlated colour temperature.

4.2.5 Experiment 3 – Double Dynamic Lighting

The third experiment tested combination of direct and diffuse light with a ratio of 40/60 between them. In this simulation, the lumen output for both luminaires was changed with 40% lumen output for direct light and 60% for diffuse light. The change of the lumen output was done at first by manipulation of ldt files of both luminaires in the LDT editor where the value of lumen output was changed and the file was saved. Next, the ldt files of luminaires were imported to the IES viewer where they were converted into IES files to be later placed in the ALFA luminaire library.

The location of direct and diffuse light is presented in Figure 22 and Figure 23.

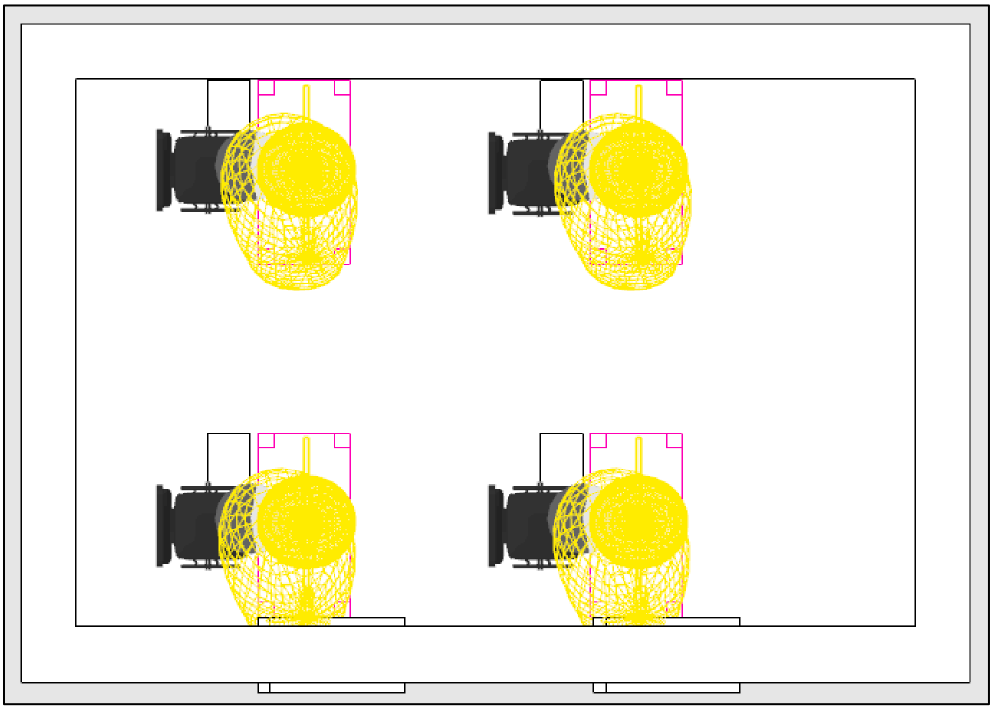

Figure 22. Top view of Double Dynamic Lighting in the office space model.

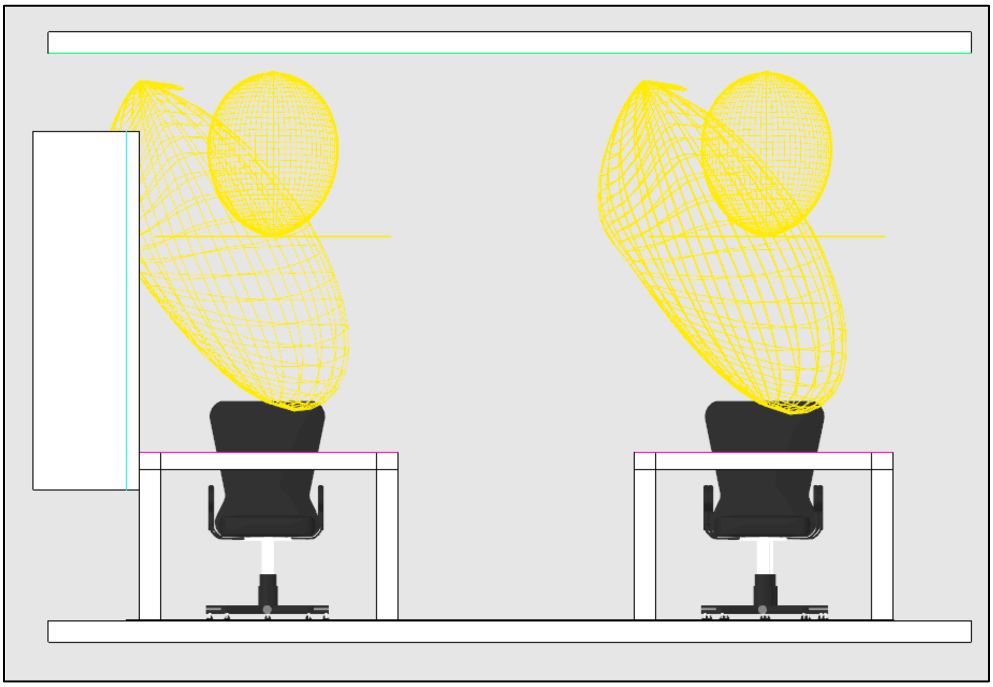

Figure 23. Front view of Double Dynamic Lighting in the office model.

As mentioned above 40/60 ratio has been investigated in the Double Dynamic Light research and has been proved to have a positive impact on the perception of the space by participants especially with a neutral – neutral (4200K) and warm – cold (3300K/5800K) spectral power distribution (Hansen et al., 2020). The spectral power distribution was measured as with GL

Spectis 1.0 spectrometer just like in Experiment 2. Due to the limited access to university and DDL lab the spectral power distribution for neutral – neutral and warm – cold could not be measured and spectral power distribution from other LED lights measured with similar CCT was used which are presented in Figure 24 and Figure 25. For neutral – neutral scenario the same spectral power distribution was used as in Experiment 2 which is illustrated in *Figure* 21. The spectral power distributions for warm – cold scenario are presented in Figure 24 and Figure 25.

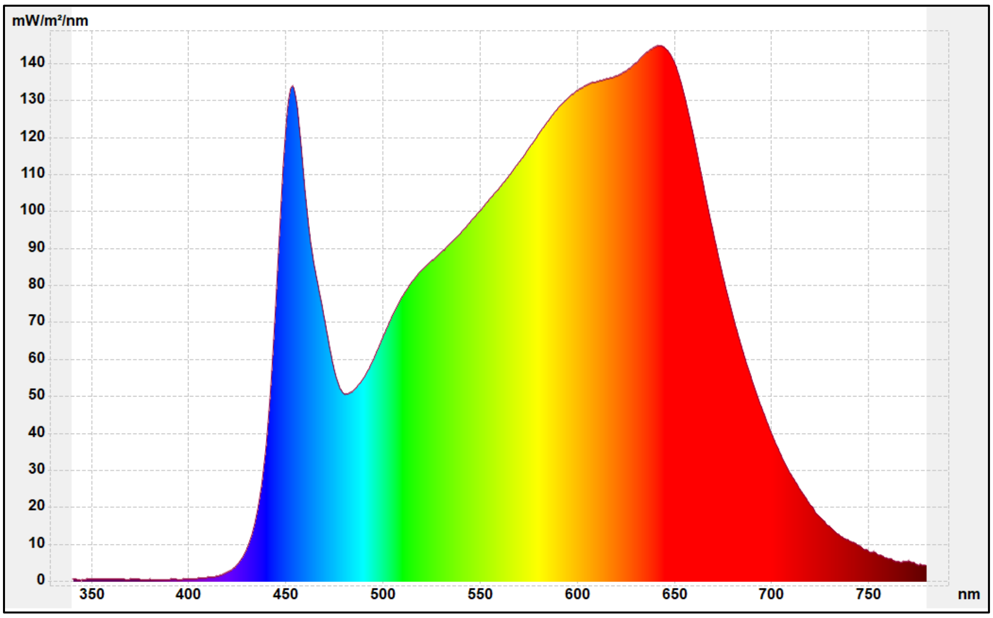

Figure 24. Spectral power distribution of LED light source with 3400 K correlated colour temperature.

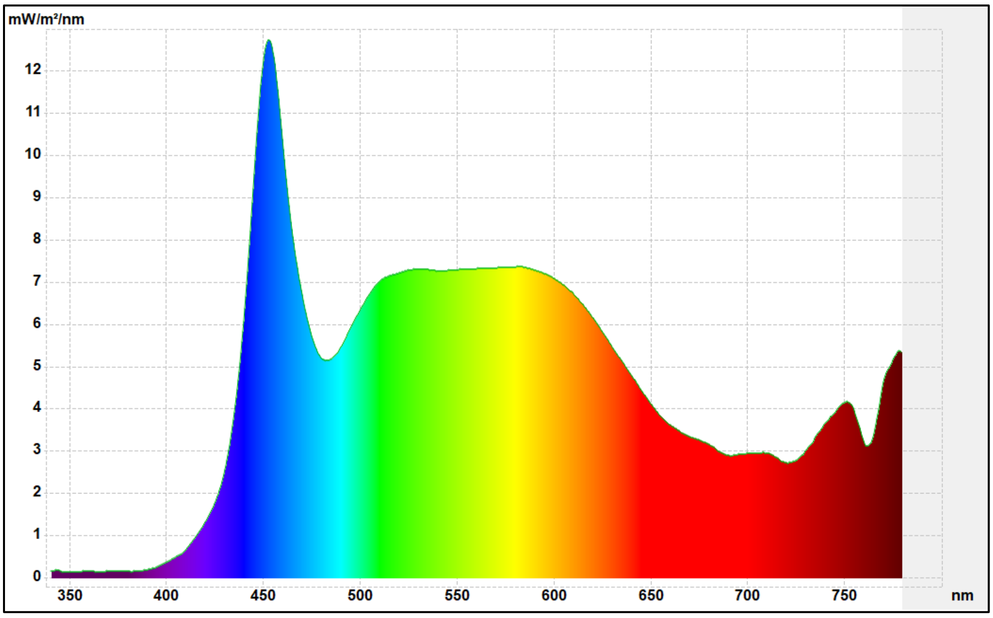

Figure 25. Spectral power distribution of LED light source with 5800 K correlated colour temperature.

4.3 Analysis method

In order to analysis the experiments, factor analysis method was implemented. Since the amount of data from three experiments is significant, factor analysis provides a solution by reducing the large number of results into smaller samples. The following analysis looks into each experiment separately at first and at the end combines the findings from all three studies. For each experiment EML and horizontal illuminance values were analysed by the influence of four factors: season, window orientation, sky condition and time of the day.

5 Results and analysis

In this section, the results of the three experiments will be presented and analysed starting with results presented on graphs and followed by analysis of each factor separately for each experiment.

5.1 Experiment 1 - daylight

Firstly, in the analysis of Experiment 1 of the biological effects of light, the amount of daylight that enters each space was investigated. For each of three seasons (Winter, Summer, and Spring/Autumn), daylight simulations in ALFA were conducted for four window orientations at 9 am and 1 pm, and under three different sky conditions.

The EML results of these experiments with daylight as the only light source are shown in Figures 26-29. Figure 28 is a rescaled version of Figure 27 (Spring/Autumn).

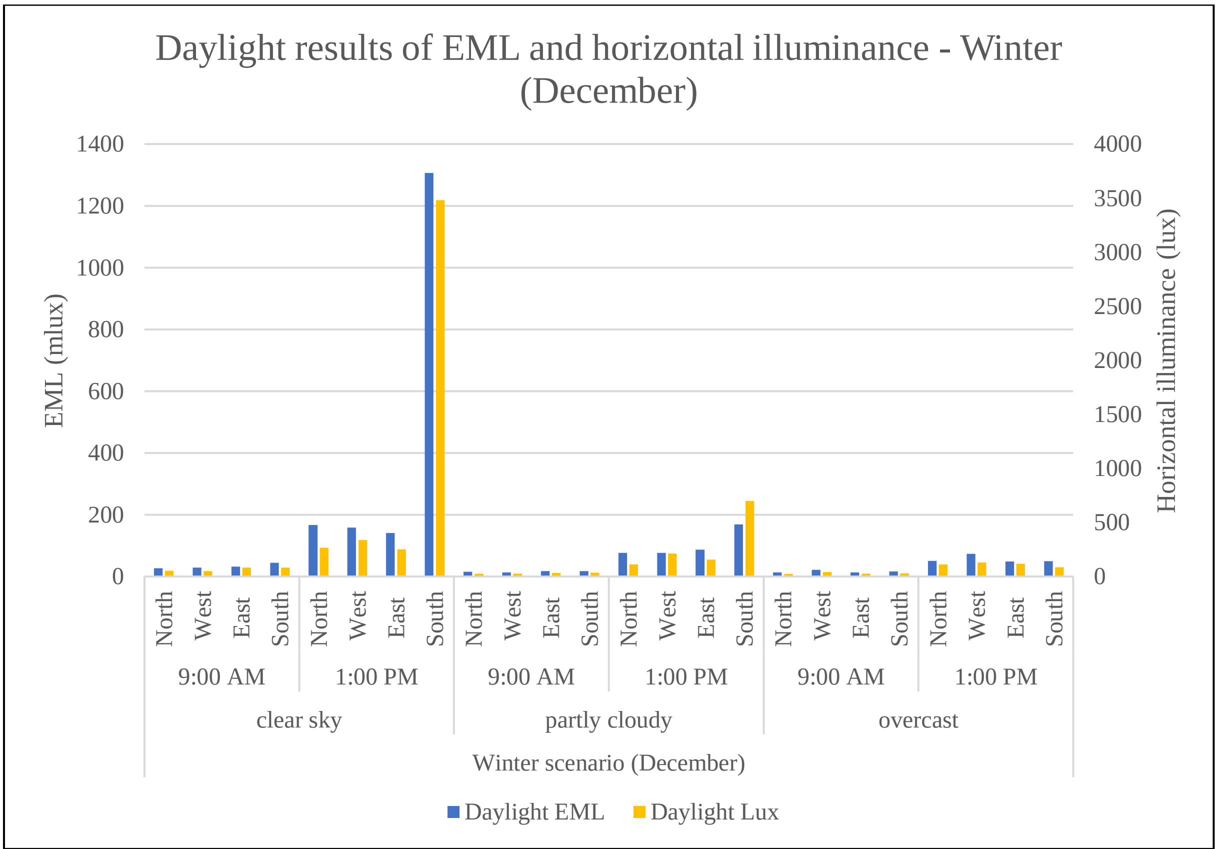

Figure 26. Daylight EML and horizontal illuminance results for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the winter season.

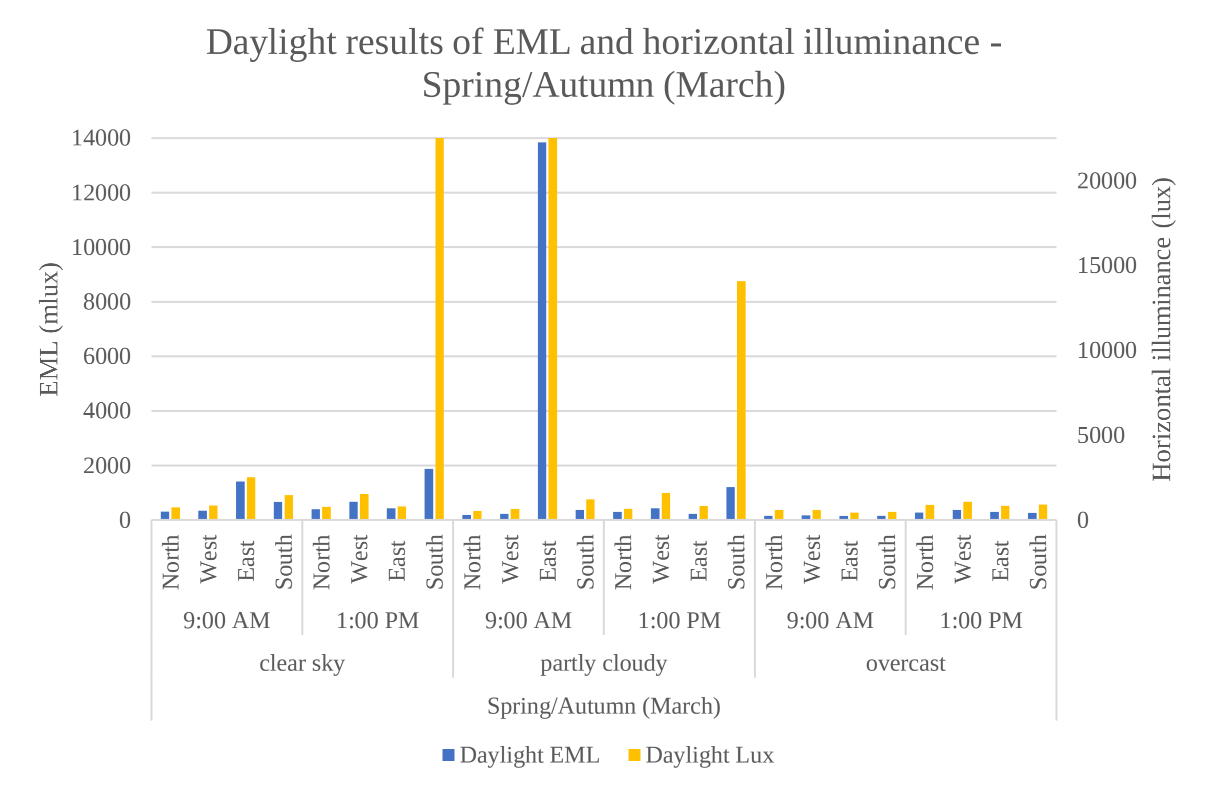

Figure 27. Daylight EML and horizontal illuminance results for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the spring season.

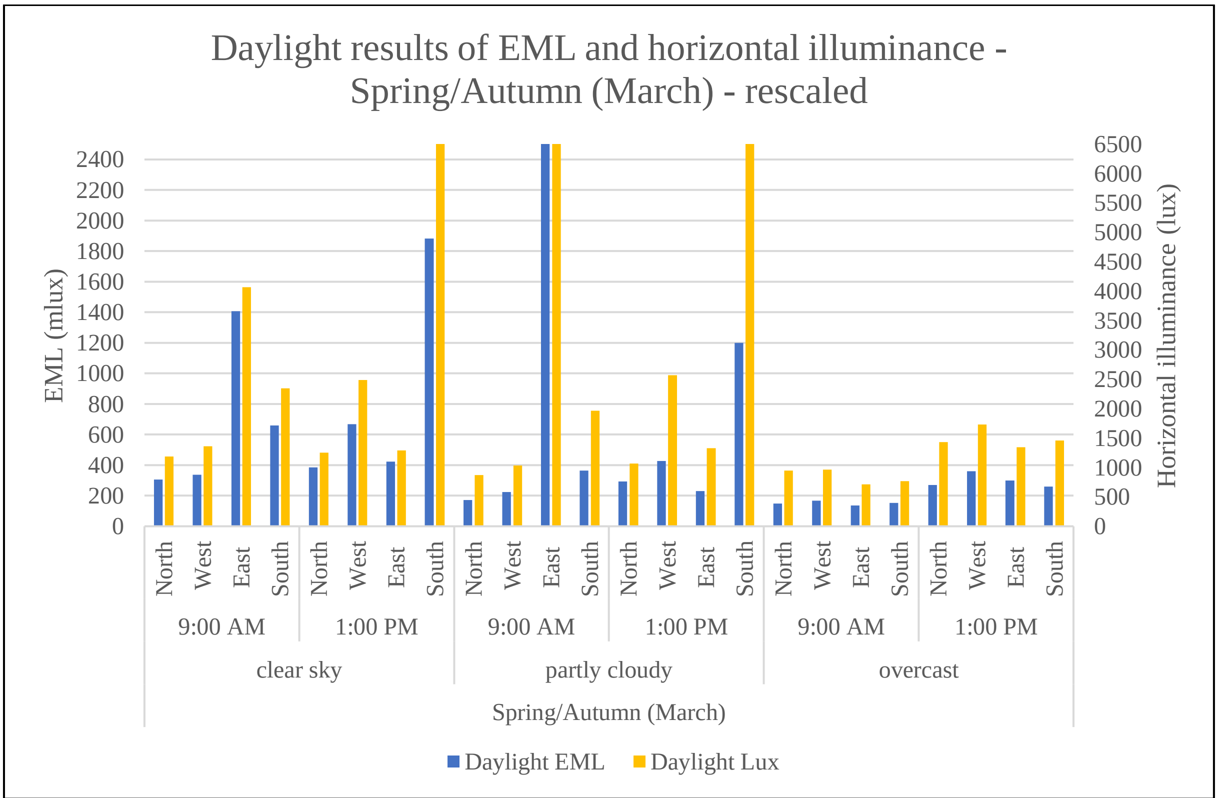

Figure 28. Daylight EML and horizontal illuminance results for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the spring season (re-scaled).

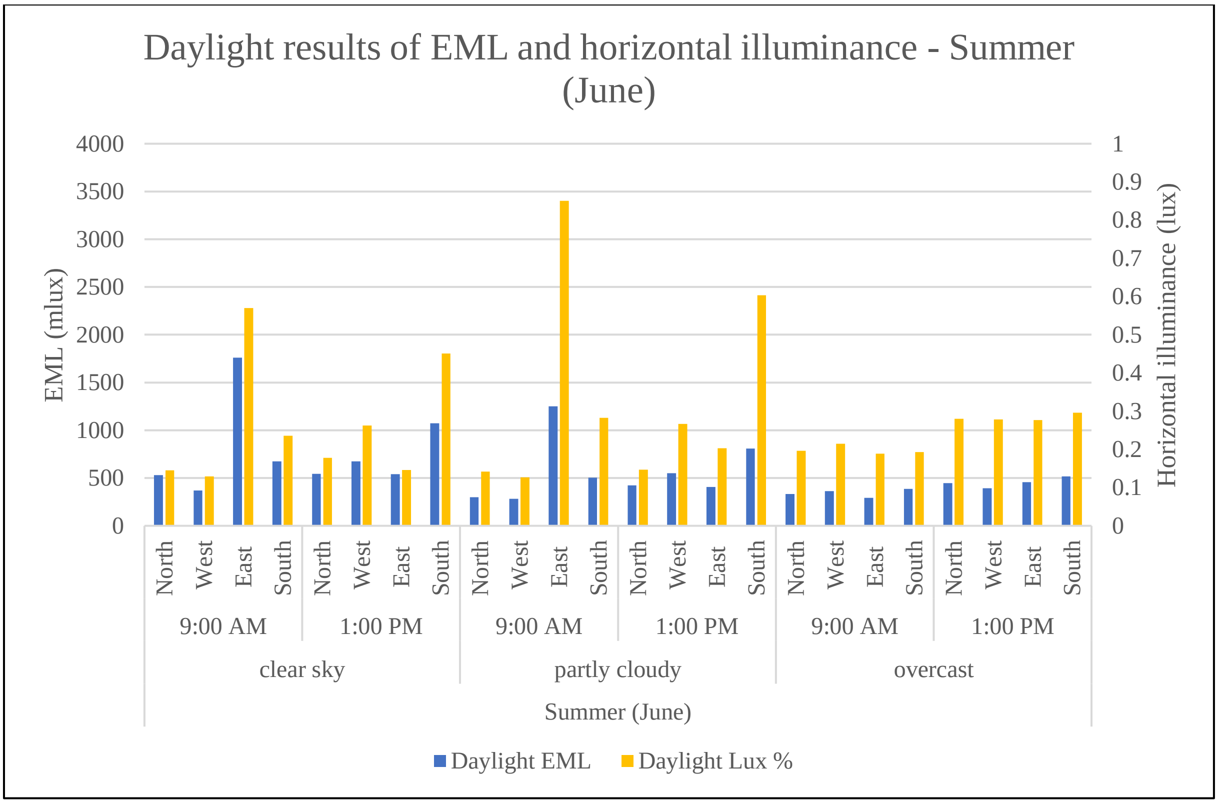

Figure 29. Daylight EML and horizontal illuminance results for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the summer season.

5.1.1 Season

Season has a significant influence on daylight performance within the office space. The highest values of both parameters were reported in the summer, followed by spring and the lowest results for winter. The difference is particularly noticeable when comparing daylight input in the winter and summer. During winter time, daylight EML value meets the WELL standard requirement of 200 EML in one case (for South facing window at 1 pm during clear sky). In terms of horizontal illuminance during winter months, two cases meet the requirement of 500 lux (South facing window at 1 pm during clear and partly cloudy sky).

However, summer season reported contradictory results, showing that during summer months all cases meet both horizontal illuminance and WELL standard requirements with only daylight input. It means that daylight is a sufficient source to provide biological and visual needs in the office in the summer.

Regarding the daylight during spring scenario, the results of EML and horizontal illuminance are in between of the ones from summer and winter. Daylight inflow is sufficient to provide

500 lux and 200 EML in majority of cases, however some will still require electric lighting to meet the standard requirements. The values of both metrics are mainly lower than the values from the summer season.

5.1.2 Window orientation

Window orientation has a notable impact on daylight input. South and East facing window reported the highest values of horizontal illuminance and EML, during clear sky and partly cloudy conditions in the summer and spring. Due to the sun position those spaces receive a great amount of direct sunlight, causing values of horizontal illuminance exceeding 1000 lux in the summer and spring. The values in the winter are only exceeding 1000 lux for South facing window at 1 pm for clear and partly cloudy sky. Nevertheless, South and East facing offices will require daylight control system since the values of both parameters exceed required 500 lux especially in the summer and spring season. Shading system will be necessary in order to avoid heat gain and glare in a space.

East facing window reports higher values of both parameters in the morning than in the afternoon, however only for the spring and summer season. In the winter due to the low sun position at 9 am the values of both parameters are similar for all window orientation since the sun rises later in the winter. West facing spaces report the opposite pattern than East facing spaces with higher values in the afternoon and lower values in the morning.

North facing spaces, due to the lack of direct daylight, report the lowest values out of all four window orientations in most cases. It means that North facing spaces will require electric lighting system in majority of cases, however will not cause glare or heat gain.

Above results show, that window orientation is strongly connected with sky condition and time of the day.

5.1.3 Sky condition

Sky condition plays a key role in terms of daylight access in a space. During clear sky conditions values of horizontal illuminance and EML are significantly higher than for partly clouded and overcast sky. The major impact of sky condition is noticeable between clear and overcast sky. Overcast sky condition caused a significant decrease in EML and horizontal illuminance values. For each of three seasons the pattern for overcast sky of considerably lower values of both metrics repeats. Sky conditions reports the most significant changes during winter season.

5.1.4 Time of the day

Time of the day shows a significant impact on both parameters. In majority of the cases values at 1 pm are higher than at 9 am. The difference is clearly noticeable in the winter when at 9 am daylight input provides only 10% of light required to meet the horizontal illuminance and WELL standard. However, at 1 pm the daylight input increases to around 50-60% of light needed to meet the requirements. The values of daylight at 9 am during winter have similar values for all window orientations and sky conditions, which is a result of the low sun position during this season.

During spring the difference is slightly less noticeable since at 9 am the sun position is higher in March than in December. Nevertheless, the impact of time still causes changes in values of the metrics especially for South, East and West facing spaces. For summer season the time shows the most influence on East and South facing spaces. East facing offices report higher values of EML and horizontal illuminance at 9 am than at 1 pm which is the opposite pattern for South facing offices.

5.2 Experiment 2 - direct and diffuse light

Secondly, in the analysis light distribution of direct and diffuse light was investigated. For each of three seasons, direct and diffuse simulations in ALFA were conducted for four window orientation during two times of a day 9 am and 1 pm under three different sky conditions.

Figure 30 and Figure 31 present the results of EML for both direct and diffuse light in the winter and in the spring. The graphs are followed by results of horizontal illuminance of direct and diffuse light in the winter in Figure 32 and in the spring in Figure 33.

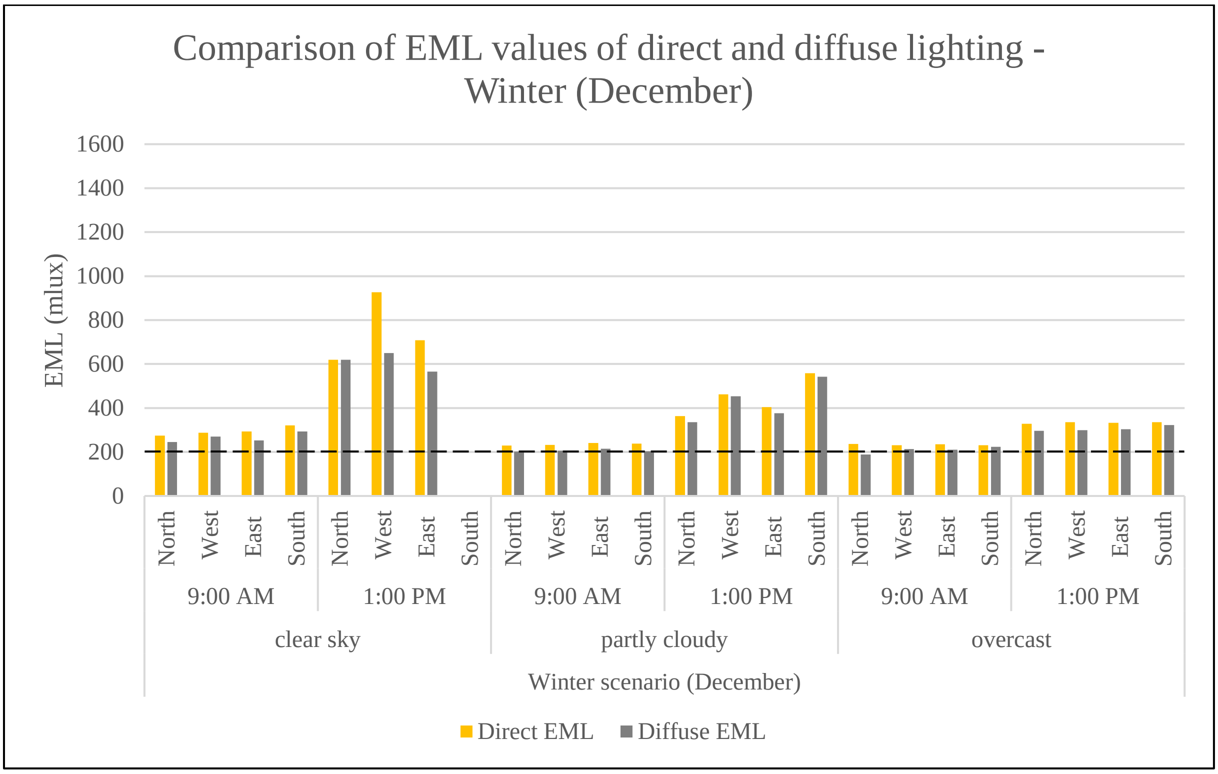

Figure 30. Comparison of EML results of direct and diffuse light for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the winter season.

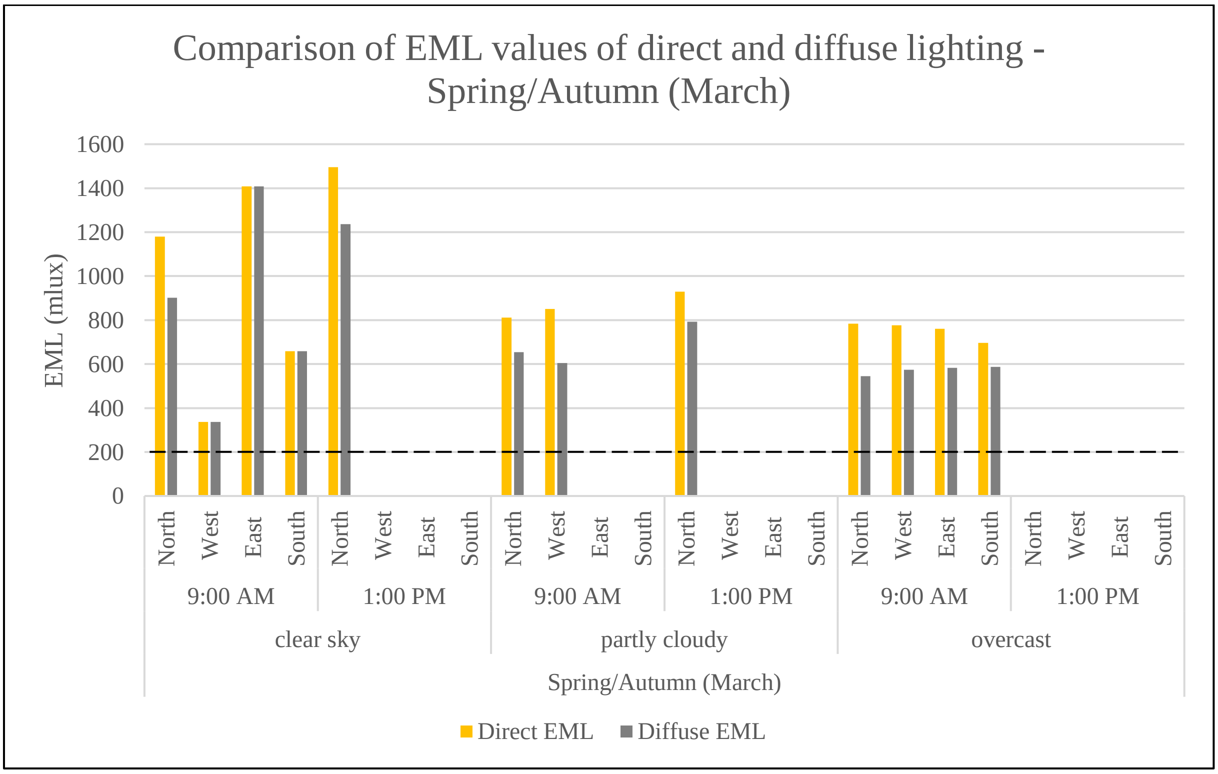

Figure 31. Comparison of EML results of direct and diffuse light for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the spring season.

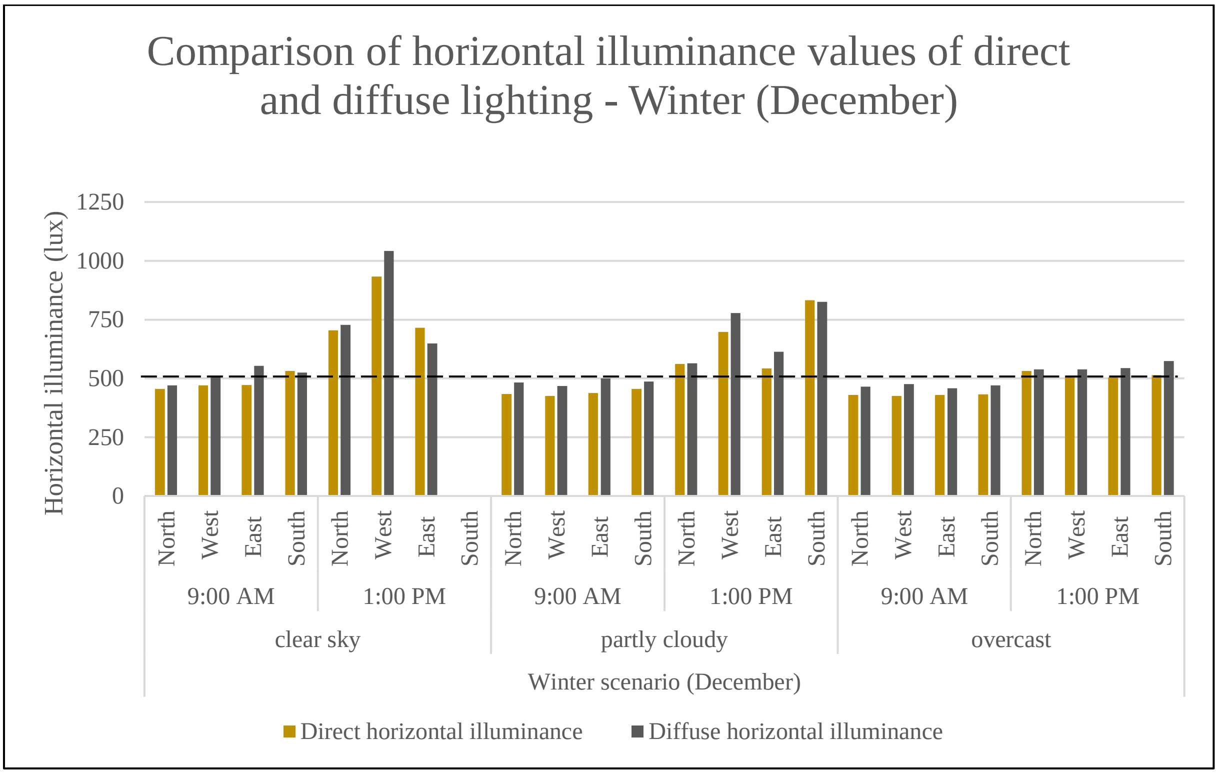

Figure 32. Comparison of horizontal illuminance results of direct and diffuse light for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the winter season.

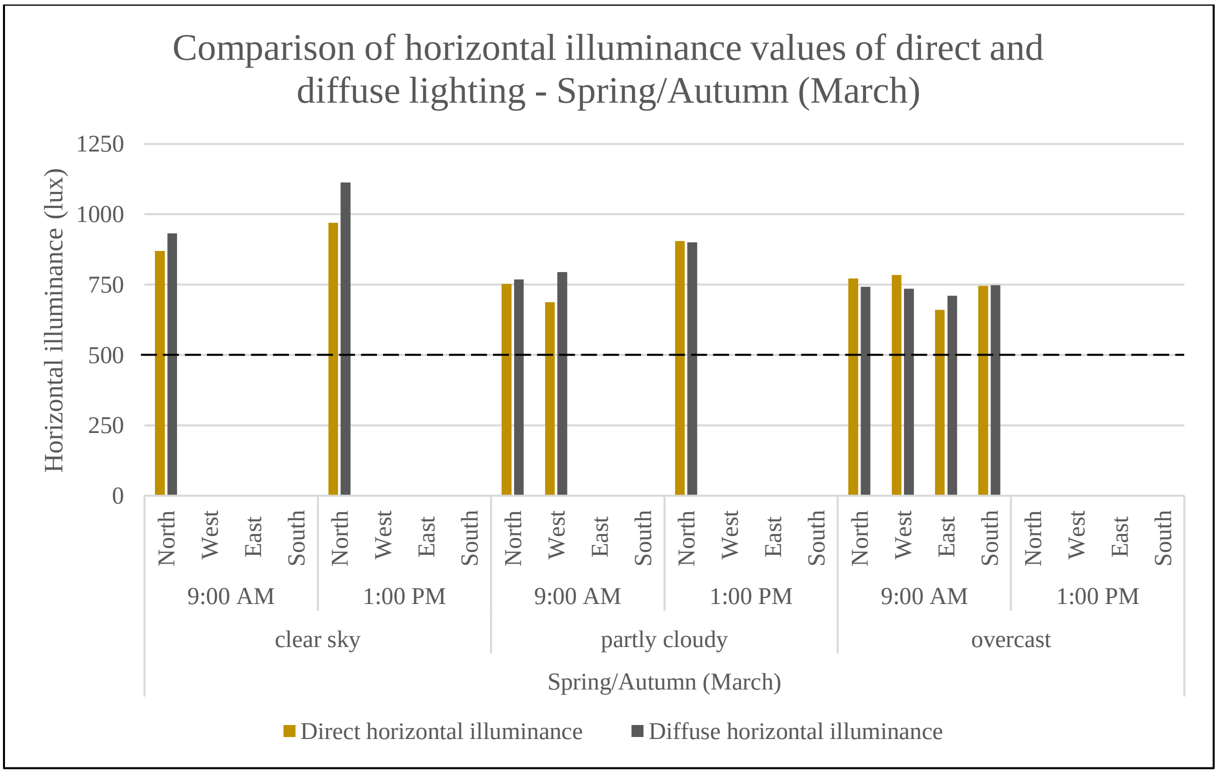

Figure 33. Comparison of horizontal illuminance results of direct and diffuse light for offices facing North, West, East and South at 9 am and 1 pm under clear, partly cloudy and overcast sky in the spring season.

5.2.1 Season

In the winter months direct lighting performed slightly better than diffuse light. Direct lighting provided sufficient amount of light to meet WELL standard requirements in all cases in the winter and spring, which was not the case for diffuse lighting. Diffuse lighting performed slightly worse than direct lighting causing insufficient amount of light to meet 200 EML requirement in two cases (North facing window at 9 am for partly cloudy and overcast sky). In December horizontal illuminance did not meet 500 lux for majority of cases at 9 am for both direct and diffuse lighting.

Spring season reported higher values of EML and horizontal illuminance than winter. For spring season both direct and diffuse electric lighting caused that EML and horizontal illuminance met the requirements of 200 EML and 500 lux. Direct lighting performed better rather than diffuse light in terms of EML values. The difference for horizontal illuminance between direct and diffuse lighting is insignificant.

Generally, direct lighting reported slightly higher results of EML than diffuse light. However, the opposite pattern occurs with horizontal illuminance, in winter horizontal illuminance values were slightly higher under diffuse lighting.

5.2.2 Window orientation

During winter months, window orientation turned out to be irrelevant at 9 am since all four orientations reported similar values of EML. The slight change was noticed at 1 pm with West facing window having higher values of EML however, only under clear and partly cloudy sky condition. In terms of horizontal illuminance in the winter at 1 pm for clear and partly cloudy sky, the West and South facing spaces differ in values from North and East. With higher values for West and South than North and East for both direct and diffuse lighting scenario.

During spring season window orientation did not cause major changes in values of both metrics. Under the overcast sky all four orientation report similar values of EML, with slightly higher values for direct lighting than diffuse. There is no significant difference in horizontal illuminance for different window orientation in March.

5.2.3 Sky condition

In December sky condition caused significant changes in EML and horizontal illuminance values. For clear and partly cloudy sky there is a noticeable variation in EML values than for overcast sky. The lack of direct component of daylight caused that all window orientations report similar values of EML with slightly higher results for direct lighting than diffuse. For overcast sky, the difference between 9 am and 1 pm practically disappears. Similar pattern is noticeable for horizontal illuminance results in the winter. Overcast sky condition caused a significant decrease in lux values for South and West window orientation.

During spring the sky condition contributes to decrease of values under overcast sky in comparison to clear sky however, the values of both metrics are still high enough to meet the standard requirements which is not a case during winter.

5.2.4 Time of the day

Time of the day plays a supreme role in the winter months. The values of EML and horizontal illuminance are lower in the morning than in the afternoon. Diffuse lighting reported lower values of EML in at 9 am, causing that diffuse lighting did not meet standard requirements under partly cloudy and overcast sky. At 9 am during winter under all sky conditions horizontal illuminance for direct and diffuse light is in majority of cases under 500 lux. Since the contribution of daylight at that time of the year is insignificant there is a need to provide sufficient electric lighting for visual needs.

In the spring, time of the day provides a slight change in values of EML and horizontal illuminance however, the standard requirements are fulfilled at both times of the day for both parameters. In the spring season all cases meet horizontal illuminance requirements at 9 am since the position of the sun in March vary significantly in comparison to December.

5.3 Experiment 3 - Double Dynamic Lighting

Thirdly, in the analysis, two lighting scenarios from DDL experiment were tested. The investigated scenarios had 40/60 ratio between direct and diffuse light where first scenario (N/N) had neutral spectral power distribution for direct and diffuse light and the second one (W/C) had warm spectrum for direct and cold spectrum for diffuse light. For each of three seasons, simulations in ALFA were conducted for four window orientation during two times of a day 9 am and 1 pm under three different sky conditions.

Figure 34 present the results of EML for both N/N and W/C scenario in the winter and Figure 35 in the spring. The graphs are followed by results of horizontal illuminance of both lighting scenarios in the winter in Figure 36 and in the spring in Figure 37.

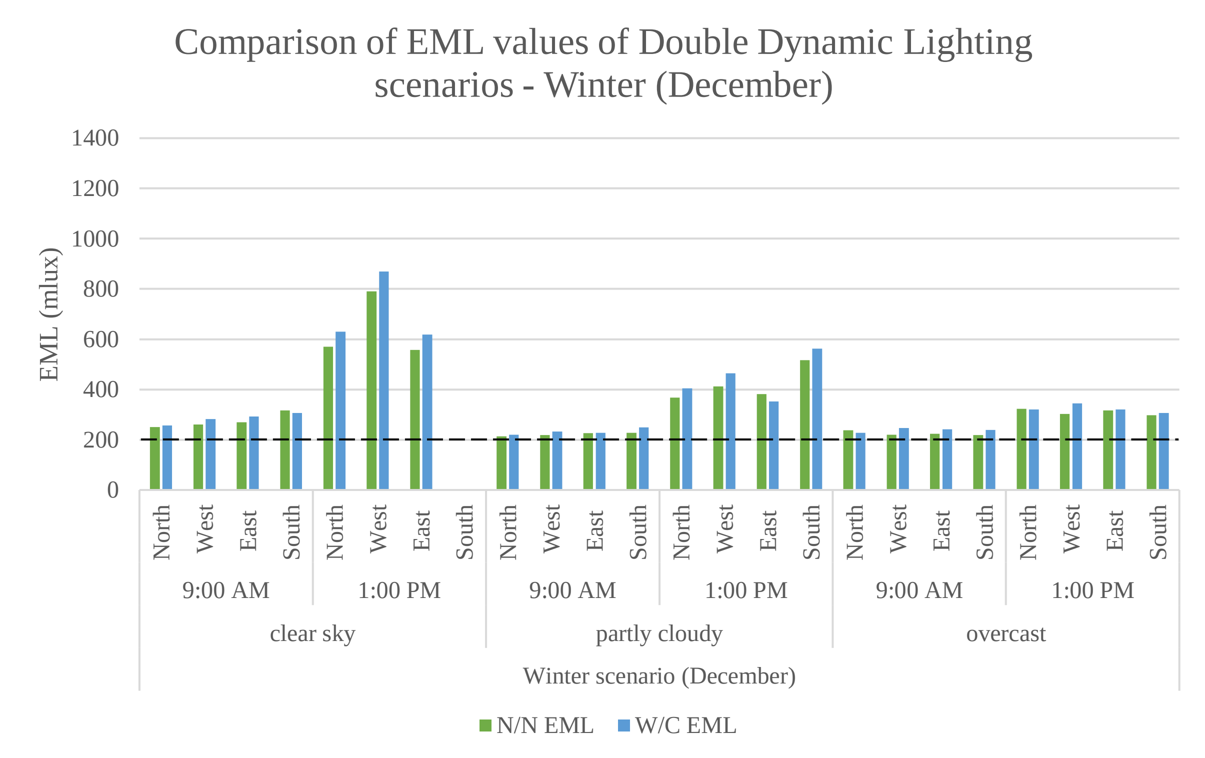

Figure 34. Comparison of EML results of N/N and W/C Double Dynamic Lighting scenario for offices facing North, West, East, South at 9am and 1 pm under clear, partly cloudy and overcast sky in the winter season.

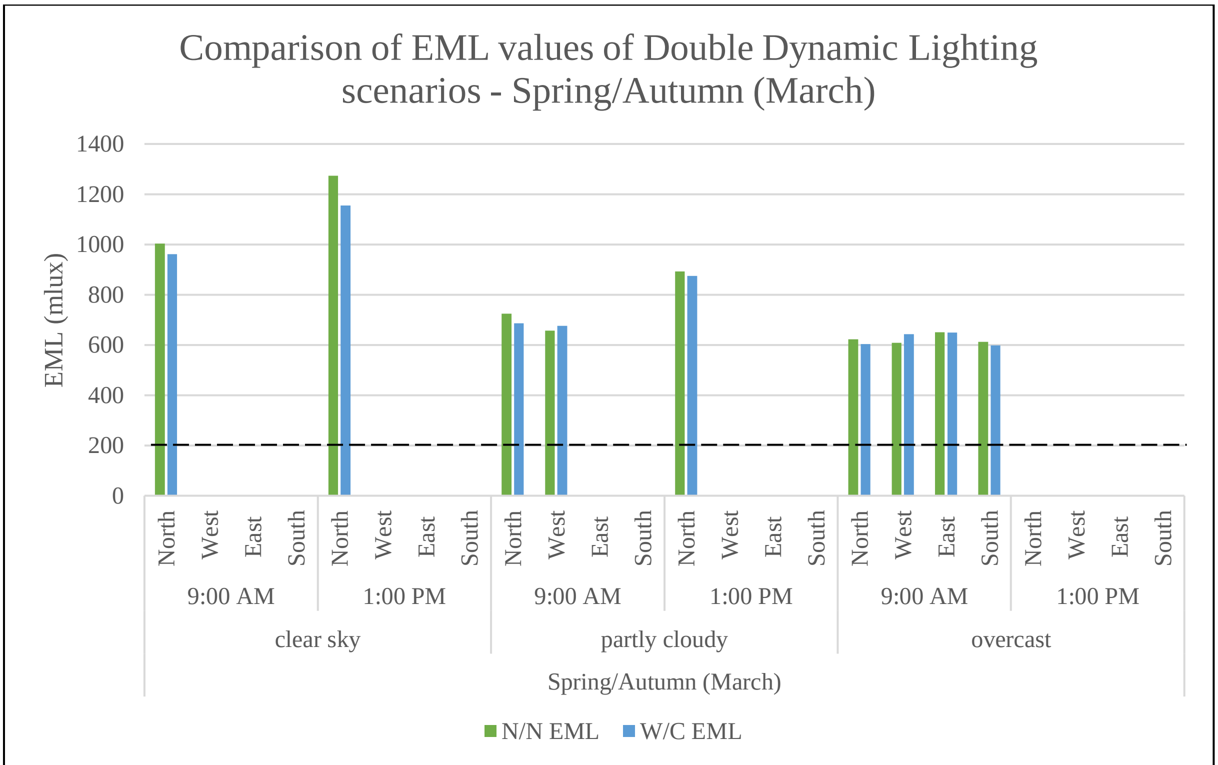

Figure 35. Comparison of EML results of N/N and W/C Double Dynamic Lighting scenario for offices facing North, West, East, South at 9am and 1 pm under clear, partly cloudy and overcast sky in the spring season.

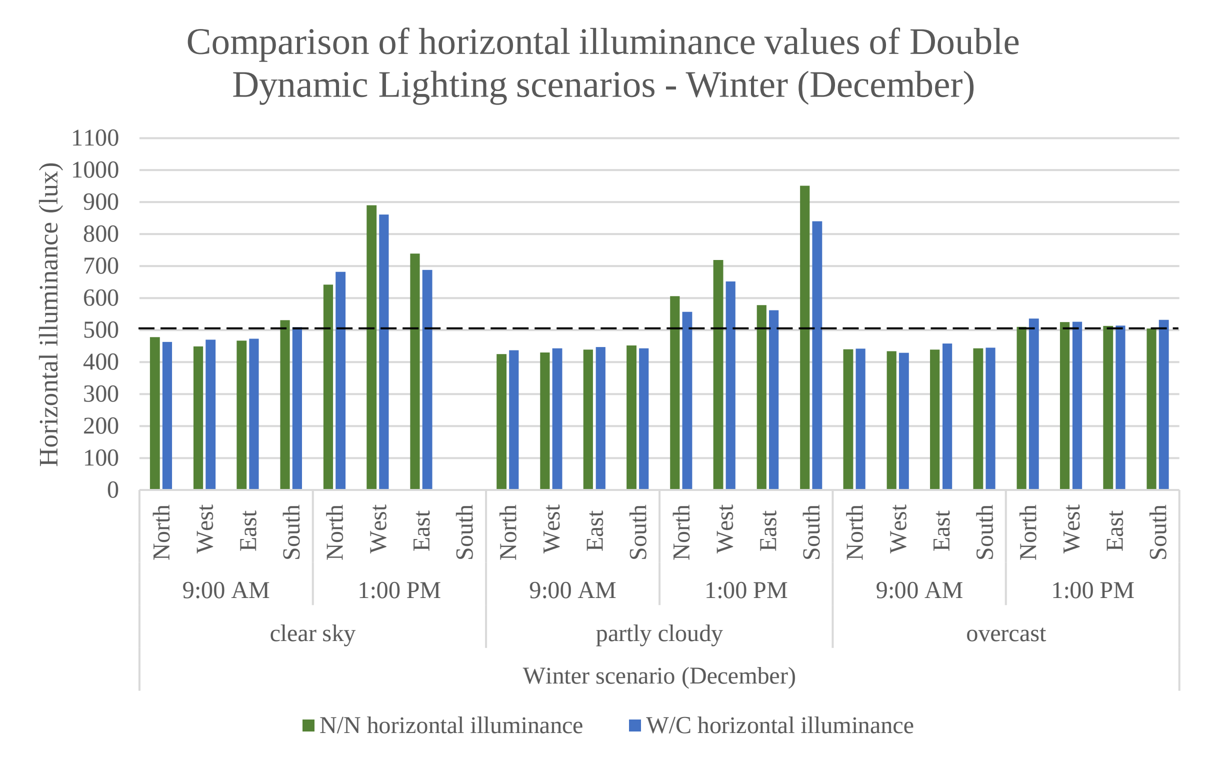

Figure 36. Comparison of horizontal illuminance results of N/N and W/C Double Dynamic Lighting scenario for offices facing North, West, East, South at 9am and 1 pm under clear, partly cloudy and overcast sky in the winter season.

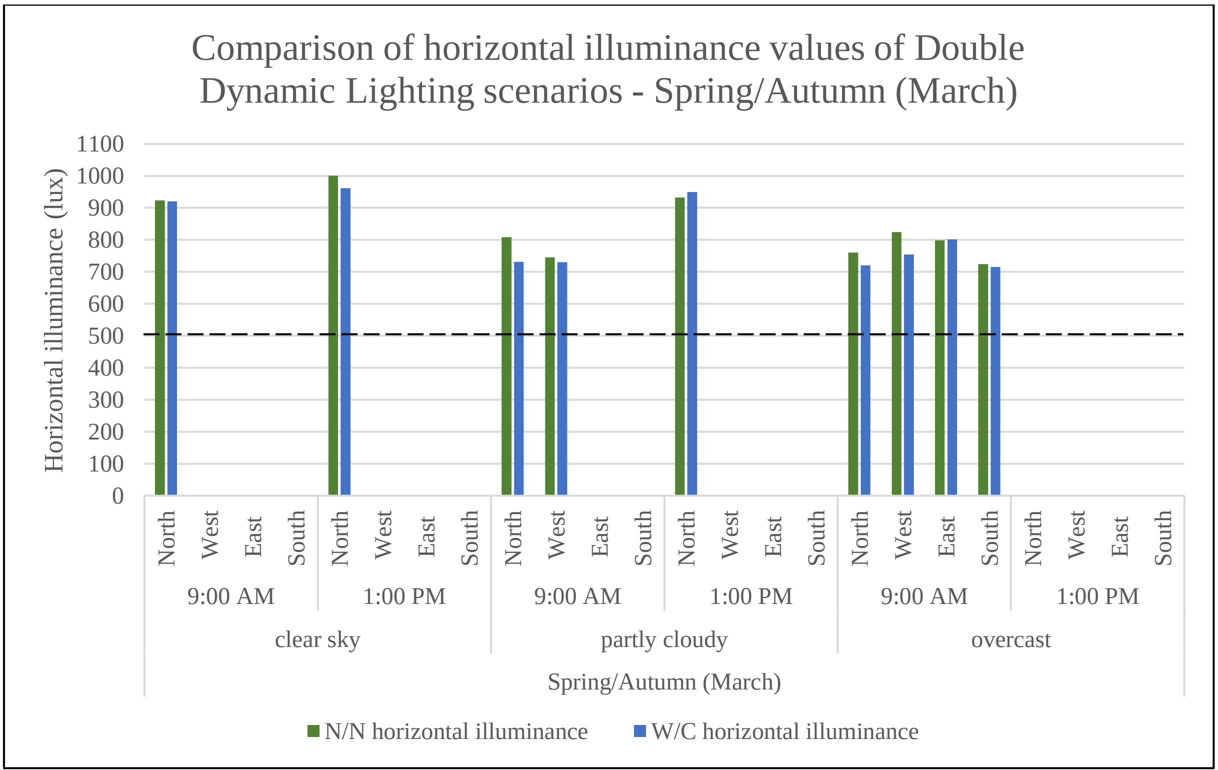

Figure 37. Comparison of horizontal illuminance results of N/N and W/C Double Dynamic Lighting scenario for offices facing North, West, East, South at 9am and 1 pm under clear, partly cloudy and overcast sky in the spring season.

5.3.1 Season

Generally, results of N/N and W/C scenario of Double Dynamic Lighting reported similar values of both parameters in majority of cases. Season has a significant impact on both EML and horizontal illuminance values. The W/C scenario reported slightly higher values of EML than N/N scenario in the winter. In December EML values are around 2-3 times lower than in March (except West facing window). The reason to that is the difference in sun position between March and December. The difference between seasons is particularly noticeable during overcast sky at 9 am, when values of EML are slightly over 200 EML in December and in March the value reaches 600 EML. Horizontal illuminance did not meet requirements in all cases. At 9 am both lighting scenarios did not reach 500 lux for all window orientations (except South facing window under clear sky).

During spring season the values of EML for both lighting scenarios are similar since the impact of daylight is much greater than in December. The difference between scenarios is not as clear for horizontal illuminance. At 9 am the values for both parameters are similar with slightly higher values for W/C scenario, however at 1 pm N/N reported higher values but only under clear and partly cloudy sky in the winter. In the spring season horizontal illuminance requirements are met in all investigated cases.

5.3.2 Window orientation

The results from previous experiments regarding window orientation repeat in this test as well. In the winter the EML values are only dependent on window orientation at 1 pm for clear and partly cloudy sky when the sun position provides a significant input of daylight. Nevertheless, the values at 9 am under three sky conditions are similar for all four window orientations with a value of EML slightly above the 200 threshold.

The main finding regarding window orientation in December is that at 1 pm under clear and partly cloudy sky, West and South facing spaces report higher values of EML in comparison to North and East. Results of horizontal illuminance follow the same pattern of dependency on window orientation as EML.

5.3.3 Sky condition

Sky conditions are causing major changes in EML and horizontal illuminance values. In December at 1 pm main differences can be noticed. Under clear sky condition both lighting scenarios N/N and W/C reported values from 550 – 850 EML (depending on window orientation). However, for partly cloudy sky the value of EML decrease to 400 – 550 with even greater reduction for overcast sky reporting around 300 EML. In terms of horizontal illuminance the decrease in values from clear to overcast sky in the winter reoccurs. Nevertheless, the pattern is only noticeable at 1 pm since 9 am reports similar values for all window orientations under different sky conditions due to the winter low sun position.

In March the similar pattern of high values under clear sky and lower values under the overcast sky is repeated, however the values are significantly higher in the spring than in the winter. In the spring both lighting scenarios met horizontal illuminance requirements for all cases.

5.3.4 Time of the day

Time of the day has a major influence on EML and horizontal illuminance values under clear and partly cloudy conditions. In the winter the value of EML at 1 pm can be two to three times higher than at 9 am. Overcast sky reports the slight change between values at two different times of the day as well. Time of the day influenced values of horizontal illuminance in the same way as EML values with higher lux levels at 1 pm in comparison to 9 am. The change of values of horizontal illuminance in winter between times is especially vital since at 9 am the horizontal illuminance does not meet the required value of 500 lux however the slight increase of the value at 1 pm contributes to meeting the standard for both tested lighting scenarios.

5.4 Findings summary

Daylight is a sufficient source to provide biological and visual needs in the office in the summer. This finding turned out to be major discovery since in the summer electric lighting is unnecessary.

The horizontal illuminance and EML values differ significantly throughout a season with the highest values in the summer, as seen in Figure 29, and lowest values in the winter, as seen in Figure 26, making the season the most significant parameter in terms of designing lighting with consideration of biological needs.

Values of both parameters are strongly dependant on time of the day especially for East and West facing spaces. Due to the differences in sun position throughout the day offices with different window orientation provide better access to daylight at different times of the day.

Time of the day plays a vital role in biological effects of light. During winter months at 9 am both metrics values are significantly lower than at 1 pm meaning that when designing with consideration of biological effects of light it is important to involve the changes of daylight access during the day into the design concept.

Clear sky condition provides the highest values of both parameters indicating that daylight has a major influence on meeting biological and visual needs within an office space.

Parameters for North facing window fluctuate the least out of all four window orientations. Since the North facing spaces have limited access to daylight the parameters depend mainly on electric lighting. The main impact on North facing spaces has season.

Figure 32 and Figure 33 show that diffuse lighting reported slightly higher values of horizontal illuminance in comparison to direct lighting. On the other hand, Figure 30 and Figure 31 demonstrate that direct lighting performed better than diffuse lighting in terms of EML values in the winter and spring seasons. This can indicate that distribution of light can affect biological and visual needs with direct lighting providing better lighting conditions for biological needs and diffuse lighting for horizontal illuminance.

The lack of dependency of horizontal illuminance and EML on window orientation occurred for each season for the overcast sky. Both parameters have similar values with slightly higher values at 1 pm than 9 am indicating that during overcast sky and limited access to daylight office spaces rely mainly on electric lighting.

Both DDL scenarios, which were tested reported sufficient values of EML. In the winter, W/C scenario results were slightly higher than N/N, however the difference is insignificant. This finding confirms that DDL concept besides being favoured by participants in the previous studies (Hansen et al., 2020) also meets biological needs.

The ideal scenario would be W/C since it provided required amount of light to meet WELL Standard requirements, however in the winter at 9 am the horizontal illuminance results were slightly below 500 lux. This may be caused by not precise location of the luminaire in the office model. The results of horizontal illuminance should be investigated further.

6 Discussion

This section consists of a discussion of the experiment results and comparison with other relevant studies. The limitations of the ALFA software and issues occurred during the simulations are also discussed.

6.1 Results

With a knowledge regarding the office workers' preferences in terms of lighting and the influence light can have on people's alertness, it is necessary to apply this understanding in practice. This investigation shows the potential of DDL in providing integrated lighting solution by meeting visual, biological and psychological needs in majority of tested cases.

The approach of office lighting design should shift the focus from meeting only visual needs at the work station to creation of environment, which is preferred by workers and provides an appropriate exposure to light throughout the day in sync with people's circadian rhythm. The solution, in which electric lighting is communicating with outdoor daylight conditions and fulfils visual and biological needs and at the same time is perceived as positive by office workers, is still in progress. Lighting designers, when designing office lighting, should take into consideration the importance of providing a space that meets biological needs since the number of beneficial effects it has on people's alertness, well-being and productivity proves to be significant.

As it was stated by Kuijsters et al. (2015) the effects of light should not be treated separately since they are all connected. This study confirms that the DDL scenarios, which were preferred by office workers in terms of psychological needs, also met biological needs. This finding supports other research, which reported that if biological needs are met, better cognitive performance of office workers is reported (Chellappa et al., 2011).

Designing the holistic office lighting is a complex task and requires to look at each space individually. As the study shows the biological effects of light are strongly dependant on season, sky condition, window orientation and time of the day. That is why comprehensive design of office lighting should not be generalised and should be designed independently.

Even though quantifying biological effects helps designers to grasp a better understanding of the issue, the numbers cannot describe the quality of the design. That is why results from lighting scenarios from DDL are most vital since DDL proved to be successful at providing quality of light in office environment and this study shows the potential of providing quantity as well.

This study provides an insight into effects of light in offices in Copenhagen in a fixed office model. The investigation looked into the impact of seasons, window orientations, sky conditions and time of the day, however there is a number of other parameters that can influence human's physiology in an office such as window size, room size, geographical location, daylight control system, materials etc. This reveals the complexity of designing with consideration of biological needs in offices and further research within this field needs to be done to be able to provide a cohesive lighting solution involving all three effects.

This study supports the Zheng (2021) statement that East facing windows can be considerate as beneficial in terms of influence on circadian system. Also this study confirms the findings from Zheng (2021) regarding sky conditions with variation of EML values under clear sky condition for different window orientation and similar values for overcast sky for all four orientations. However, window orientation should be investigated together with time of the day since as this study proved those variables are strongly connected with each other.

6.2 Software limitations

The evaluation of biological effects of light was done with a use of a new and prospective programme ALFA, which allows lighting designers to simulate lighting within a space and have an insight into the biological effects of light through an equivalent melanopic lux (EML) value. ALFA is a promising tool to get a general idea of the influence of light in a space on human's physiology. With ALFA it is possible to measure impact of light in different points within a space and various view directions much faster than with on-site measurement. However, ALFA provides limited library of sky conditions, which can make it hard for lighting designers to simulate desired sky conditions. Such narrow choice of types of sky can decrease the simulation value. During simulation an issue occurred with light placement. The precision of the room model turned out to play a key role in simulating biological effects of light. Small change in position of the light source within a model caused significant changes in EML values. Additionally, accuracy of light source placement is also related to location of measuring planes. It is vital to correctly place luminaires in relation to calculated planes. Besides the complications mentioned above ALFA does not provide any daylight control through blinds etc. therefore the daylight control is not implemented in this study.

Moreover, simulation of the same case conducted twice or more times reported slightly different values of EML each time, suggesting that ALFA may not be a reliable tool if precise results are needed. However, for general understanding of biological effects within a space ALFA provides basic overview of biological effects of light within a short period of time.

ALFA is a new tool and is still not well investigated. There is a need of more research within the subject light effects on human's physiology with a use of ALFA. There is a little number of studies, which implemented ALFA as a method to evaluate biological effects of light (Altenberg Vaz & Inanici, 2020; Safranek et al., 2020). However, the number of options and opportunities it provides makes this a promising tool in terms of evaluation of biological effects.

7 Conclusions

Since office workers spend the majority of the day inside the office, and their exposure to daylight during the day is limited, it is important to provide a comfortable and suitable work environment (Kamarulzaman et al., 2011). Currently, the main focus, when designing office lighting, is drawn towards the visual effects and meeting the required light levels on the task area (Smolders et al., 2012, 2013). However, meeting only visual needs is not enough. It is vital to design lighting in a space with a holistic approach, with consideration of psychological and biological needs. Light is not only able to help us see better, but is also able to change the perception of the space as well as have an impact on our alertness, circadian rhythm and well-being.

This study investigated the influence of each type of light from the DDL concept (daylight, direct, diffuse and combination of direct and diffuse) on the biological effects of light in offices. This investigation provides an overview of impact of four variables (window orientation, sky condition, season and time of the day), which may be used as a guideline in basic understanding of how biological effects of light in offices are affected by those various conditions.

Three experiments of different types of light, which are used in the DDL concept were conducted. In order to understand the contribution and impact on biological effects, each type of light was investigated separately. First, daylight was assessed, followed by a test of electric lighting with direct and diffuse light, and lastly, two lighting scenarios from previous DDL studies, which were reportedly favoured by participants (Hansen et al., 2020), were examined.

Conducted experiments showed that each geographic location should be investigated with consideration of daylight access and changes in light throughout a year and day. Additionally, it is beneficial to begin design of lighting with consideration of biological effects of light with investigation of daylight access since as the study shows in many various cases the daylight provided enough light to meet the requirements and is perceived positively by office workers.

Conducting experiments of daylight and electric light separately resulted in a finding that daylight provides sufficient amount of light to provide biological and visual needs in the summer. Daylight simulations also showed the tendency of North facing windows to report the lowest values of EML and horizontal illuminance in comparison to other window orientations. EML and horizontal illuminance values for South, East and West facing windows are strongly dependent on the time of the day, season and sky condition. Additionally, these window orientations will require a daylight control system, since daylight access is significant throughout the day and can cause glare and heat gain. Based on the daylight simulation, it was easy to select cases which required electric lighting to meet EML and horizontal illuminance standard.

The second experiment showed that direct lighting performed slightly better at meeting WELL Standard requirements than diffuse lighting which was the opposite case in terms of horizontal illuminance where diffuse light provided higher results. This may indicate that directionality and distribution of light may have a significant influence on measurements on vertical and horizontal plane.

The third experiment proved the potential of DDL scenarios in meeting biological needs. Both tested scenarios performed sufficient EML and horizontal illuminance values in majority of cases.

However, as this study shows, designing lighting with a comprehensive approach is challenging and complex. Nevertheless, the study points out the prospect of DDL approach in fulfilling different needs within office environment.

8 Future work

This study evaluated biological effects of light with a use of software ALFA. However, since simulated spectrum from ALFA can be exported there is a possibility to investigate results with CIE Toolbox Kit, which can be used as a substitute of on-site measurements. With CIE Toolbox there is a possibility to look into action spectra graphs as well as parameters such as Equivalent Daylight Illuminance, Daylight Efficacy Ratio etc. The further analysis of the data can provide new findings and new perspective since in ALFA only EML is used to evaluate biological effects of light.

Results from simulations can also, to some extent, be further investigate with on-site measurements in DDL lab, however window orientation would be limited in investigation.

DDL concept should be further explored since this study proved the potential of providing biological and visual in majority of cases with lighting scenarios which were preferred by office workers.

Directionality and distribution of light also needs a further research in terms of biological effects of light. However, ALFA might not be the ideal method since a small change in the position of the light source in the model contributed to significant changes in EML values.

Due to the fact that direct lighting performed slightly better than diffuse light it provides an insight into importance of directionality of light.

As a result of limitations in access to university building not exact spectral power distributions were used when testing DDL concept which could have an influence on simulation results.

Besides investigated variables in this study there is still a number of various metrics which can have a significant influence on biological effects of light. This study did not took into consideration daylight control system, different geographical locations, various room, window size etc.

Summary

This study investigates the influence of each type of light from the DDL concept (daylight, direct, diffuse and combination of direct and diffuse) on the biological effects of light in offices. Additionally, the season, window orientation, sky condition and time of the day were looked into as potential variables, which can have an impact on biological effects of light. This investigation includes three experiments of different types of light, which are used in the DDL concept. In order to understand the contribution and impact on biological effects, each type of light was investigated separately. First, daylight is assessed, followed by a test of electric lighting with direct and diffuse light, and lastly, two lighting scenarios from previous DDL studies, which were reportedly favoured by participants are examined. The evaluation of biological effects of light was done with a use of a new and prospective programme ALFA, which allows lighting designers to simulate lighting within a space and have an insight into the biological effects of light through an equivalent melanopic lux (EML) value. Conducting experiments of daylight and electric light separately resulted in a finding that daylight provides sufficient amount of light to provide biological and visual needs in the summer. Daylight simulations also showed the tendency of North facing windows to report the lowest values of EML and horizontal illuminance in comparison to other window orientations. EML and horizontal illuminance values for South, East and West facing windows are strongly dependent on the time of the day, season and sky condition. Additionally, these window orientations will require a daylight control system, since daylight access is significant throughout the day and can cause glare and heat gain. Based on the daylight simulation, it was easy to select cases which required electric lighting to meet EML and horizontal illuminance standard. The second experiment showed that direct lighting performed slightly better at meeting WELL Standard requirements than diffuse lighting which was the opposite case in terms of horizontal illuminance where diffuse light provided higher results. This may indicate that directionality and distribution of light may have a significant influence on measurements on vertical and horizontal plane. The third experiment proved the potential of DDL scenarios in meeting biological needs. Both tested scenarios performed sufficient EML and horizontal illuminance values in majority of cases.

However, as this study shows, designing lighting with a comprehensive approach is challenging and complex. Nevertheless, the study points out the prospect of DDL approach in fulfilling different needs within office environment.

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