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Abstract: Light hitting the retina does more than enable vision. It stimulates a range of non-visual responses influenced by the intrinsically photosensitive retinal ganglion cells and is the main driver for entraining the human circadian rhythm. Along with a growing body of scientific evidence proving the many effects and health-promoting potentials from a proper exposure to light, the market of lighting products branded as human-centric or circadian lighting is growing rapidly.

This thesis investigates a lighting system in a specific office space in Gentofte, Denmark, in relation to existing recommendations for lighting meant for entraining the circadian rhythm and stimulating other non-visual responses. It is examined whether these recommendations stating a certain level of melanopic illuminance measured at the retina is compatible with requirements from the European Standard EN 12464-1 (2011), specifically concerning those of horizontal illuminance and UGR. The lighting in Gentofte is not a specific circadian lighting system but provides the basis for investigating the significance of illuminance and spectral power distribution as parameters of considerations within the field of circadian lighting design.

The investigation relies on on-site measurements and calculations in software simulations, and on the basis of these, it is concluded that it is possible to achieve a compatible relationship between recommendations and requirements, but solely meeting the minimum requirements for horizontal illuminance does not assure to reach the minimum recommendations of melanopic illuminance.

Circadian Photoentrainment from Electrical Lighting

- A case study of non-visual responses to light from an electrical lighting system in an office space

Lighting Design, Master Thesis

Aalborg University Copenhagen

28/05/2021

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Abstract

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1. Introduction

Life on earth evolved over millennia in day-and-night cycles where ambient light of the environment determined the time of day. Under the natural conditions of high intensities during the day and darkness at night, the human eye and effects to physiology and behaviour evolved. Plants and animals have a biological clock and rely on these light conditions to control their circadian rhythm. With the invention and implementation of electrical lighting in everyday life these rhythms are susceptible to disruption (Lucas et al., 2014; Zielinska-Dabkowska, 2018).

Research suggests that people in modern society may spend 90% of their time indoors, causing a shortage of bright light during the day and excessive light exposure in the otherwise naturally dark hours of the evening and night, causing the inner biological clock to become misaligned with the solar day, increasing the risk of sleep-wake disorders and diminishes the potential of otherwise improved sleep quality from high-intensity daylight (Schlangen and Price, 2021). The sun on a clear sky can provide up to 100,000 lux, while standard office lighting typically does not reach above 500 lux (Blume et al., 2019; DS/EN 12464-1, 2011). Working indoor in electrically lit environments have found negative effects in especially shift workers, prone to increased risks of cancer, obesity and sleep disorders (Zielinska-Dabkowska, 2018).

On the other hand, light applied appropriately can strengthen and advance the circadian rhythm, enhance alertness, influence hormonal secretion, and even reduce the sensitivity of light in the late hours of evening and night (Schlangen and Price, 2021), hence light can be applied as an effective therapeutic instrument to improve sleep, mood and general well-being (Blume et al., 2019).

These many-facetted effects from light originates from retinal illumination and are referred to as so called non-visual or non-image-forming responses. In the early 2000's an additional fifth retinal photoreceptor was discovered (Berson et al., 2002; Hattar et al., 2002) and proven to be the main driver of the circadian rhythm and many other non-visual responses to light. These are termed intrinsically photosensitive retinal ganglion cells (ipRGC) and has a high sensitivity in the range of short wavelengths in the visible spectrum peaking around 480 nm and therefore, differs from traditional (daytime) photopic illuminance peak sensitivity of 555 nm (Blume, 2019). This discovery meant that traditional quantification of light as photopic illuminance was inadequate to account for non-visual responses, and since then studies have been developing metrics and models to quantify the spectral sensitivity of the circadian system and ipRGC-influenced responses to light (Rea, et al., 2012; Lucas et al., 2014; Sanchez-Cano and Aporta, 2020). Because of the potentially great benefits to human health and well-being from discovering precisely how to predict light's effects on the biological system there has been significant scientific interest (Brown, 2020), but is yet to be implemented throughout the international lighting community. Lucas and others (2014), leading experts in the field, stressed the importance of the need for an awareness and consideration of these non-visual responses for lighting designers, manufacturers and engineers:

> *"Because circadian rhythmicity is a feature of nearly every physiological, metabolic, and behavioural system, this phenomenon brings a wide array of biological processes under indirect retinal control".*
>
> (Lucas et al., 2014).

The lighting industry is beginning to address the lack of daylight in indoor spaces. In recent years, it has promoted biologically effective electrical lighting in office and home environments known as human-centric or circadian lighting. An analysis of the human-centric lighting market forecasts a market size increase from USD 1 billion in 2020 to exceed USD 5.5 billion in 2027 (Global Market Insights, 2021). This type of lighting is designed in reference to daylight, able to mimic its dynamic character during the course of a day in intensity and colour. A few central questions still remain in regard to these novel circadian LED-systems: Do they perform as an alternative to daylight, or should they perhaps only be considered as a supplement; how much light is needed to achieve a certain circadian stimulus; how does these new characteristics of dynamic lighting coincide with traditional approaches in lighting design?

In the scientific field, many aspects of the circadian rhythm are yet to be discovered (Zielinska-Dabkowska, 2018; Blume, 2019). However, with the existing research and recommendations, this project seeks discover a broad range of considerations for applying electrical lighting for circadian stimulation.

The European Standard for Lighting in Work Places (DS/EN 12464-1, 2011) has not incorporated circadian lighting specifications, but other international building standards have already (WELL Building Standard, 2020), or are working towards implementing guidelines and threshold levels of stimulation from light to achieve circadian entrainment in indoors environments (CIE S 026/E:2018; SLL Position Statement, 2019). The requirements proposed from the different institutions and organizations are not identical but comparable in several ways. Most important is the focus on measuring illumination on the vertical plane to account for the amount of lighting meeting the retina of the eye and therefore adds to the vertical dimension of lighting design, to complement the conventional focus of quantifying light on the horizontal plane.

Sanchez-Cano and Aporta (2020) reports that many studies highlight the significant impact of the appropriate intensity and tone of light have on health, mood and many other factors on subjects working under electrical light for longer periods of time, and that an increasing amount projects considering circadian lighting principles are already being realized, but not in a magnitude corresponding to its importance, for several reasons such as:

> "*... the absence of clear regulations; manufacturer and market inertia; unacceptable costs, a lack of appropriate and properly characterized products; and a lack of a sufficient number of trained technicians, product promotion manager, or lighting designers".*
>
> (Sanchez-Cano and Aporta, 2020)

Likewise, the International Committee on Illumination (CIE) expresses concerns about how regulations and practice does not pay attention to the non-visual dimension of light and lighting design but still primarily focuses on aspects of visual function and energy savings. On the other hand, another concern has risen in regard to those products developed for ipRGC-influenced light (IIL) responses-market, because they fail to consider other quality aspects of lighting; the aim should be to find a *balance* between aspects that does not compromise either human health, wellbeing and function or general overall lighting quality (CIE Position Statement, 2019)

This project therefore seeks to investigate this above-mentioned *balance*. This will be done by evaluating a specific office space in Gentofte, where modern dimmable LED fixtures has been installed to replace fluorescent tubes. Additionally, simulations of the lighting in the space without interference of daylight will provide empirical data to assess the sole role of electrical lighting in relation to its melanopic performance.

1.1 Hypotheses

This project has two hypotheses that is sought to be investigated. The first hypothesis gives rise to the second:

1) *Achieving stimulation of the circadian system from electrical lighting is dependent on high illumination levels, significantly exceeding the minimum requirements in the European Standard for Indoor Work Places (DS/EN 12464-1, 2011).*

- Illumination level requirements are stated clearly in standards for the horizontal plane for offices for reading, writing, and typing to be 500 lux (DS/EN 12464-1, 2011, Table 5.26), except for those specified for mean cylindrical (average vertical plane) illuminance of 150 lx (DS/EN 12464-1, 2011, Section 4.2.6). For practical reasons, electrical office fixtures are in general designed for ceiling mounting and designed to distribute light in a ratio favouring the horizontal plane above the vertical plane; to meet the horizontal requirements and not cause glare (DS/EN 12464-1, 2011, Section 4.5). For these reasons, the illumination levels measured on the horizontal plane does not correspond equally to the levels on the vertical plane. The ipRGC-influenced responses to light should be measured vertically at the eye (1,2 m) and it is therefore expected that the minimum requirements for the horizontal plane has to be increased significantly to also achieve a level of vertical illumination sufficient to meet the recommendations (described in section 2.3.2) of ipRGC-influenced responses to light. Hereby the question arises: Should the minimum requirements for light on the horizontal plane be increased?

2) *Increasing the lighting intensity of luminaires designed for ceiling mounting to stimulate the circadian rhythm of office-workers can cause glare problems*

- To stimulate the circadian rhythm, it is necessary that light hits the retina. If light distributed on the vertical plane is too intense it can cause glare, which should be avoided according to the European Standard.

1.2 Problem Statement

This thesis seeks to examine factors of implementing dynamic lighting systems designed to stimulate and sustain an appropriate circadian rhythm of people working daytime jobs in offices spaces. This is conducted through an investigation of a physical office space, and with the knowledge gathered, influential factors of circadian lighting design are considered in relation to the compatibility with the existing European Standard for Indoor Work Places (DS/EN 12464-1:2011):

How does a lighting system in a specific office space in Gentofte perform in accordance to recommendations on ipRGC-influenced photoentrainment of the circadian rhythm and are these recommendations compatible with the European Lighting Standard for Indoor Work Places (DS/EN 12464-1:2011)?

1.3 The office space in Gentofte

The investigations made are using a specific office space that was pre-selected while used in a case study in the research project ELFORSK 351-003. The project aims to study how novel LED-technology can be optimized when replacing old luminaries in open-space offices and classrooms. Today the tendency is that the LED-technology is not utilized to the full extend, meaning a lost potential for improved energy savings and user experience. The intention is to propose advices for installation of LED lighting that can meet proper expectations in most office and classroom renovation cases, considering both electricity savings, mood and visual ergonomics. It is a purpose in itself that these advices are simple and at the same time useful to work with.

The office space in Gentofte is 108 sq. m. and is furnished with 12 work desks (Fig. 1; Fig. 4). There is access to daylight from windows facing north and east (Fig. 2). The office is equipped with 30 dimmable ceiling fixtures without and 11 dimmable wall washers with tuneable white technology. The wall washers are meant to light up wall surfaces adjacent to the windows to light up otherwise darker areas on the walls to minimize contrasts and thereby minimize glare from the daylight intake (Fig. 3).

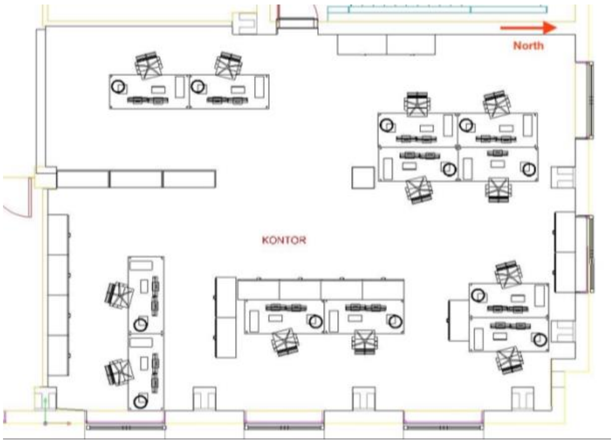


Figure 1, Plan View of Gentofte Office.
Illustration: ELFORSK 351-003 project, Inger Erhardtsen

Figure 2, Outside view of Gentofte Office.
Photo: Jakob Markvart. Edit: Rasmus Daae

The office space in Gentofte is relevant to the topic of this project because; 1) it has installed a modern LED-system with dynamic features, allowing for the system to be dimmed up or down depending on the incoming daylight, with the purpose of lowering energy consumption; 2) it has been designed to meet the minimum requirements of the European Standard (DS/EN 12464-1) for offices, but has not considered circadian factors. However, as a part of the replacement of the old luminaries there have been installed wall washer fixtures directed towards the walls adjacent to the windows with the intention of mitigating contrasts occurring from bright daylight and dark walls to limit glare, which eventually causes the office workers to use shades to block the daylight; something that should be avoided both from an energy consumption and circadian perspective.

Figure 3. Ceiling Luminaire, Zumtobel Mirel and wall washers, Zumtobel Diamo. Photo: Rasmus Daae

The office space will also act as the layout for simulations conducted in the DIALux (www.dialux.com) and ALFA software (www.solemma.com) applications.

Figure 4, Panorama View of Gentofte Inside.

Photo: Rasmus Daae, 2021

2. Theoretical background

This section intends to provide a theoretical understanding of light, covering how it is perceived by the human eye, what effects are caused from light beyond those translated to visual signals; so-called non-visual or non-image-forming responses to light, followed by a description of the complexity of quantifying these responses humans perceive from light and lastly an explanation of the important relationship existing between the natural cycle of day and night and the sleep-wake cycle of human beings, which affects many essential biological processes in the human body and mind, stressing the significance of considering the circadian rhythm in those environments we spend the most time.

> *"In humans, the known effects of light on circadian rhythms and sleep are all, without exception, mediated by the retina"*
>
> (Blume et. al, 2019)

2.1. The Eye

Light entering the eye is focused onto the light-sensitive region at the back of the eye, the retina, consisting of a layer of nerve tissue containing photoreceptors. The retina is responsible for human vision as it contains the photoreceptor cells called rods and cones. The rods all contain the same photopigment (peak sensitivity at ~500 nm.), has a high sensitivity to light, poor spatial resolution and provides vision in dark environments. This is the scotopic vision. The cones on the other hand contains one of three different photopigments, responsive to either short (S), medium (M), or long (L) wavelengths of the visible part of the electromagnetic spectrum, peaking at respectively ~420 nm., ~535 nm., ~565 nm (). This is called the photopic vision and provide the perception of colour and detailed vision (Enezi et al., 2011; Tregenza and Loe, 2014; Lucas et al, 2014; Blume et al, 2019).

2.1.2. Non-visual effects of light

Light incident on the retina influences and drives many physiological and behavioural processes unrelated to the visual functions of the eyes. Especially within the past thirty years the empirical

evidence has been building in relation to the many aspects non-visual effects of light influences the biological system of human beings.
It is the primary synchronizer of the human biological clock by impacting the timing of one's sleep/wake cycle and ability to shift the circadian rhythm. Light in the night time hours can suppress the secretion of melatonin and has it has been reported that light can increase heart rate and regulate body temperature, stimulate cortisol production, improve alertness, attention and reaction time, and be applied as a treatment for depression, sleep disorders and circadian disruption caused from jetlag and shift work (Lucas et at., 2014; CIE S 026/E:2018; Blume, 2019; Brown et al., 2020).

2.1.3. ipRGC's

For 150 years, rods and cones were the only known photoreceptors of the mammalian eye. Only less than two decades ago, another photoreceptor was discovered (Hattar et al., 2002; Berson et al, 2002) which differ from the cones and rods; for one, they express the photopigment melanopsin with a peak sensitivity of ~480 nm, and second, they are ganglion cells and therefore communicate directly with the brain via the optic nerve (Berson, 2003). A small fraction (1-5% depending on the method of estimation) of the retinal ganglion cells are directly photosensitive, thus termed intrinsically photosensitive retinal ganglion cells; ipRGC's. Furthermore, compared to rods and cones, the ipRGC's has a slower response to light and are less sensitive (Wong et al., 2005; Lucas et al., 2014). The ipRGC's are thought to mediate most effects of light to the endogenous circadian rhythm, however they are not independent from rods and cones input:

> *"Rather, they also receive information from these receptors, suggesting that ipRGC's indeed act as 'integrators of information' regarding the light environment across a wide range of wavelengths and light levels".*
>
> (Blume et al., 2019)

As the quote suggests, there are no dichotomy in light-induced responses, although it has been thought so, that rods and cones mediate visual functions and ipRGC's the non-visual. Evidence suggests instead; that melanopsin signals may also contribute to conventional visual perception (Enezi et al., 2011, Blume et al., 2019); that all known photopigments contribute to the spectral sensitivity of the circadian system (Rea and Figueiro, 2018); and that there exist different types of ipRGC's with distinct connections to the retina, combining rod, cone and melanopsin signals (Schmidt et al., 2011). Studies have even shown how a blind individual with no functioning rods or cones could detect if a stimulus from monochromatic light of 480 nm was on or off, but could not with stimuli in other ranges of wavelengths (Schlangen and Price, 2021).

In other words, responses from light stimuli is fundamentally context-dependent, determined by the combination of the spectral characteristics of irradiance incident on the retina and timing and duration of exposure (Lucas et al., 2014; Xiao, et al., 2021). Despite the challenges of a precise prediction of the impacts from NIF-responses, some simple guidance does exist. The consensus paper from Lucas *et al.* (2014) remarks that if the aim is to have minimal activation of ipRGC outputs, one should keep irradiance as low as possible and rely on light sources emitting longer wavelengths of light in the visible spectrum; and if the objective is the opposite, the principles are also.

2.2. Circadian photoentrainment

Light does more than enable vision. Daily and seasonal cycles of natural light are used by the body to regulate physiological changes in accordance to our endogenous circadian rhythm in order to be synchronized with the local environment. The registration of light and darkness over time is registered by the eyes, but it is not mediated through visual spatial patterns, rather it exists as a "nonimage" vision. The non-image vision is probably far more ancient than image vision and is widespread in living species (Do and Yau, 2010).

The retinal ganglion cells are connected to a part of the brain called the suprachiasmatic nucleus (SCN), that functions as the primary circadian pacemaker driven by input from light – even when all synaptic input from rods and cones are blocked. A pacemaker is necessary to keep the human sleep-wake cycle synchronized with the solar day because the period of the SCN oscillator is not exactly 24 hours, rather 24.2 hours for humans. Therefore, light is relied on for this synchronization, and this process is called circadian photoentrainment (Berson et al, 2002; Berson, 2003). When living in constant dim light conditions the circadian rhythm is free-running, causing the sleep-wake cycle to slowly shift to a later time every next day (Schlangen and Price, 2021). The amount of exposure to light throughout daytime ("photic history") is important to keep this cycle in alignment with the environmental day and night, since it influences both the suppression of melatonin and the circadian rhythm (Blume et al., 2019)

The effects from light on the secretion or suppression of the sleep hormone melatonin has been studied widely (Brown, 2020) and its detectability in the blood stream is a reliable indicator of the human circadian rhythm. It follows the sleep-wake cycle closely and is only secreted in the usual bedtime-hours, making us feel sleepy and stay asleep. In general, the onset of melatonin secretion is typically two hours before going to bed, and ten hours after the onset is the habitual wake-up time (Schlangen and Price, 2021).

In this modern age with the use of electrical illumination after sunset or traveling to a different time zone, the unnatural changes in light stimuli can disrupt the phase of the circadian rhythm and trigger acute melatonin suppression. The circadian system works on a time scale of exposure down to a matter of few minutes and even intermittent bright light can shift the circadian phase. If we are exposed to light in the night-time the melatonin levels will decrease – in itself being asleep or awake does not affect it (Schlangen and Price, 2021).

In general, light in the morning will advance the circadian clock and evening or night time light will postpone melatonin secretion and sleep initiation (Blume et al., 2019).

2.3. Quantifying non-visual light

The quantification of visual light relies on photometric measurements of the radiant power of the visible spectrum that weights the response to different wavelengths in accordance to the human photopic vision, called the $V(\lambda)$ spectral weighting function with a peak sensitivity at 555 nm. The unit of photopic measurements is illuminance or “lux” and refers to the total power of incident light on a surface (Lucas et al., 2014). The early studies on behavioural and physiological responses from light proved that the $V(\lambda)$ spectral weighing function was inadequate for evaluating the non-visual responses, sparking a scientific interest in discovering a novel measure (Enezi et al., 2011).

As established in the previous section, the effect of the ipRGC’s on both visual and non-visual functions are still being studied. Several different action spectra and metrics have been proposed, but there is no consensus or established method for a precise evaluation of melanopic lighting on both visual and non-visual function (Sanchez-Cano and Aporta, 2020) – recent studies also suggest that melanopsin-based photoreception may have a significant influence on the perception of brightness and other aspects of spatial vision (Schlangen and Price, 2021).

A precise and complete measure has proven to be a complex task because more evidence suggests that ipRGC's are not alone in producing non-visual responses to light, that these responses can originate as a combination of any of the five photoreceptors in the human eye, and furthermore, that the relative contribution to the circadian system from the different types of photoreceptors varies depending on the duration, intensity, spectrum, timing, and light history (Rea and Figueiro, 2018; CIE Position Statement, 2019; SLL Position Statement, 2019; Brown, 2020). Schlangen and Price (2021) recently stated that it is not possible to create a single action spectrum that can include all testable variations, but even though the science is not complete it is still possible to produce recommendations for practical applications of the qualities of short-wavelength light distribution.

2.3.1 Different metrics

A model was proposed by The Lighting Research Center, from Rea et al. (2012), introducing the parameters 'circadian stimulus' (CS) and 'circadian lighting' (CLA) to characterize light as a stimulus to the biological clock, designed on data from studies of the impact of light on nocturnal melatonin suppression. CLA is the irradiance at the cornea weighted to reflect the spectral sensitivity of the human circadian system. This is based on a measurement of melatonin suppression after a one-hour exposure to light; and the CS is the effectiveness of the CLA. The CS is given in a scale from 0.1 – 0.7 CS. The LRC recommends an exposure of 0.3 or greater at the eye for at least one hour in the early part of the day for an effective stimulation of the circadian system (Figueiro et al., 2016; Rea and Figueiro, 2018). The CS scale is not linear, but it is given as a reference that 100 lux from a daylight source achieves 0.2 CS and 300 lux achieves 0.4 (LRC Look-up Table, n.d.)

In 2014, a larger group of leading researchers in the scientific field wrote a consensus paper (Lucas et al., 2014) proposing a metric to quantify the effective irradiance for each of the five photoreceptive inputs. This has led to two other quantities – with slight differences – to measure light's effect on the circadian rhythm: One is the WELL Building Standard unit Equivalent Melanopic Lux (EML), which is calculated via a toolbox published as an addition to the consensus paper; the other unit is melanopic Equivalent Daylight Illuminance (mEDI) proposed by The International Commission on Illumination's (CIE S 026/E: 2018). The general difference in these measures is that the weighing of the spectral input in the EML is scaled according to a standard definition of lux for a light spectrum of perfectly uniform energy (CIE Standard Illuminant E) and the EDI measure is scaled equally to illuminance for a daylight source with a CCT of 6500, referred to as D65 (WELL Building Standard, 2020; Brown, 2020; Sanchez-Cano and Aporta, 2020).

2.3.2. Recommendations

The WELL Building Standard recommends for work areas either that 75% of workstations are exposed to minimum 200 EML (daylight may be included) in the hours between 9.00-13.00 o'clock for every day of the year, or that electrical lights provide all workstations a maintained 150 EML or above. The measurements are to be conducted on the vertical plane facing forward 1,2 meter above the floor to simulate eye level of a person sitting down (WELL Building Standard, 2020).

The WELL Building Standard has included mEDI values corresponding to their EML-recommendations and can be converted by this factor: 1,104 * EDI = EML (Sanchez-Cano and Aporta, 2020). This factor is also established when using the CIE S 026 Toolbox (v. 1.49, 2020) to change between output data calculated from scaling between the CIE D65 and CIE Standard Illuminant E.

The CIE has published a system for metrology of ipRGC-influenced responses (CIE S 026/E:2018) along with a toolbox (S 026, v. 1.49, 2020) for calculating EDI and recently a technical note on "What to document and report in studies of ipRGC-influenced responses to light" (CIE TN 011:2020). These CIE-publications however are without specific recommendations for a certain threshold level of EDI for achieving a desired circadian stimulation, which both the CS and the EML includes. But this is most likely to be added to the CIE-system soon. An expert consensus-based paper is in the peer-review process with specific recommendations for healthy daytime and evening/night-time light environments. The recommendations do not comprehend specific indoor areas such as offices or school environments, but generally recommends a minimum of 250 melanopic EDI throughout the daytime (Brown et al., 2020). Compared to the WELL Building Standard values, these newly proposed values

WELL Building Standard recommendations:

181 mEDI = 200 EML (9.00 – 13.00, incl. daylight)

136 mEDI = 150 EML (only electrical light)

Brown et al., (2020) consensus recommendation:

250 mEDI = 276 EML (Incl. daylight, all day)

Figure 5. Recommendations for melanopic illuminance referred to in this project, from WELL Building Standard (2020) and Brown et al., (2020).

present a higher level of melanopic light to achieve a beneficial stimulation to non-visual responses (recommendations summarized in Fig. 5).

For this project, it is not the objective to evaluate the different models to find the best or most comprehensive, but to gather information from different perspectives to create a fundamental understanding of the scientific field to apply it in practice – although many aspects of non-visual responses still remains under study.

3. Circadian Lighting

This section explains the basic principles of what typically qualifies for a circadian lighting system and what parameters are important to consider reaching the minimum levels of recommendations for ipRGC-influenced responses to light. Furthermore, this section introduces the idea of referring to the melanopic efficacy of a light source, for lighting designers and practitioners not to rely solely on CCT for an approximation of the potency of non-visual responses to light.

Circadian lighting, human centric lighting, dynamic lighting or integrative lighting are all terms referring to the same features of modern lighting technology that can control parameters such as intensity and CCT, with the intention of achieving a beneficial stimulation of the human circadian rhythm and other non-image forming responses to light. However, there exists a discrimination in the terminology, since the CIE has proposed integrative lighting as the official term, and at the same time regard circadian lighting, human centric lighting etc. as marketing terms (CIE Position Statement, 2019). Houser *et al.*, (2021) explains how human centric lighting has been misused as a marketing catchphrase to promote sometimes misleading or exaggerated claims of effects from modern lighting systems.

This causes reason for scepticism about such products, but the scientific evidence on the many potentials should not be overlooked. In essence, the different terms are related to the same idea: *"... the potential to support the biological rhythms where they may otherwise be disrupted"* (SSL Position Statement, 2019) – what matters is the specific lighting design.

The most decisive factors to consider for lighting designers and practitioners can be narrowed down to timing and duration of exposure to light; quantity and spectrum; and the distribution of light within a space (Figueiro, 2016; CIE TN 011:2020).

It is overall recognized for subjects in typical everyday life that a high intensity, shorter wavelength of light usually acts to support alertness, the circadian rhythm and a good night's sleep; and a less intense, warmer light in the evening and at night facilitates sleep initiation and consolidation (SSL Position Statement, 2019; CIE Position Statement, 2019). Extensive reviews of field studies in indoor environments including also workplaces has been conducted by Schlangen *et al.* (2014) and Xiao *et al.* (2021) supporting this general tendency of most significant non-visual responses to light found from high intensity high CCT-lighting. This advice makes it more user-friendly to apply lighting benefitting the circadian rhythm, alertness and general mood, and can be programmed into modern LED lighting systems capable of dynamically dimming (intensity) and tuning (CCT) the light.

Remaining is the matter of the direction of the distribution of light; it has to arrive at the retina before it can be evaluated how the lighting system actually performs in terms of ipRGC-influenced responses to light. Therefore, the distribution of light is of great importance and should be considered in an interrelationship with the intensity and spectral power distribution of the light source(s). The Lighting Research Center has created various look-up tables (LRC Look-up Table, n.d) based on software simulations comparing the relationship between horizontal illumination, CCT and direction of distribution from eight different LED manufacturers. These tables do confirm the above-mentioned general principles, but at the same time highlight valuable contradictions and considerations for furthers studies and practical applications. The following findings are based on the table of a suspended linear luminaire type with a vertical:horizontal distribution ratio of 0.63:1:

1) The horizontal illumination levels reach in most cases 450-500 lux before the recommended target of 0.3 CS is met.

2) The spectral power distribution has in most cases a relatively low output in the frequency range around 480 nm. – the peak melanopsin sensitivity.

3) Luminaires of 3500K and 4000K CCT does not even at 500 horizontal lux reach 0.3 CS, which however several luminaires of 3000K CCT does at 450 horizontal lux – contradicting the principle of "the higher CCT, the higher circadian stimulation".

The Circadian Stimulus (CS) measure is not included as a target in the following analysis of the Gentofte office space, but these findings from the LRC Look-up table nonetheless represent factors for circadian lighting design that increases the complexity in achieving a successful indoor lighting scene. These findings are also related to the two hypotheses of this project, as they confirm that relatively high horizontal illuminance levels are needed to achieve a beneficial circadian stimulation, and moreover, that these simulations from the Lighting Research Center does not include calculations of glare, which stresses the importance of investigating glare, since illuminance plays a significant role in achieving minimum recommendations for ipRGC-influenced responses to light. Furthermore, it raises the matter of evaluating the efficiency of luminaires for circadian purposes in terms of their spectral power distribution.

3.1 SPD > CCT

The spectral power distribution of a white light source determines its correlated colour temperature and describes the tone of white light, e.g. warm or cold. A white light source can imitate the “cold” tone of natural daylight, however the spectral power distribution can be far from similar, and in many cases inferior in terms of melanopic performance. It is the not the tone of perceived white light, but the relative amount of spectral power in the melanopsin-sensitive region of the visual spectrum that determines the efficiency of a light source. This is supported by the facts presented in point “2)” and “3)” in the previous section; and the study from Brown and *et al.*, (2020) comparing the melanopic efficiency between regular LED’s and a custom-engineered LED; and from Souman *et al.,* (2018) determining a significant difference in melatonin suppression from two light sources of similar intensity and CCT, yet different spectral power in the melanopsin sensitive region between 450-500 nm. Therefore, CCT is an inadequate quantity to describe the efficacy of a light source or a lighting design for circadian purposes.

The WELL Building Standard refers to this efficacy as the “Melanopic to Photopic ratio” (M/P Ratio) with these examples (WELL Building Standard, 2020):

- If an incandescent light provides 200 lux in a space, it will also produce 108 equivalent melanopic lux: M/P Ratio of 0,54.
- If daylight provides 200 lux in a space, it will also provide 220 equivalent melanopic lux: M/P Ratio of 1,1.

And similarly, the CIE refers to the “Daylight Efficacy Ratio” (DER) (CIE S 026/E: 2018), as such:

- If a white LED lamp provides a luminous flux of 800 lm in a space, it will also provide a melanopic equivalent daylight (D65) luminous flux of 342,2 lm: DER of 0,428.

The M/P ratio or DER offers an easy tool for lighting designers and practitioners alike to determine an approximate EML or mEDI value from using a regular lux-meter on the spot. This could not be performed precisely with information only of CCT. However, an approximation of this sort necessitates a space with luminaries with similar SPD; if it is mixed with other light sources the ratio could be misleading. These ratios will be a tool included in the analysis-section.

4. Methods

Collecting empirical data for this project has been done by on-site measurements of the spectral power distribution, performed in accordance to the CIE System for Metrology of Optical Radiation for ipRGC-influenced Reponses to Light (CIE S 026/E:2018), as well as simulations of the indoor lighting environment excluding daylight has been conducted in the softwares DIALux Evo, v. 9.1, from DIAL GmbH; and ALFA, v. 0.5.6.2, from Solemma LLC. In combination, these simulations allow for evaluating the new lighting installation in terms of both the European Standard (DS/EN 12464-1, 2011) and recommendations for stimulating the circadian rhythm in indoor work areas in the daytime.

4.1. On-site

In the office space in Gentofte there are twelve desks. The measurements to calculate the mEDI was done individually from each desk at eye height (1,2 m) on the vertical plane perpendicular to the direction of view.

To conduct the individual measurements an illuminance spectrophotometer from Konica Minolta, model CL-500A, was used. This instrument captures spectral data from every single nanometer of 360-780nm of frequency wavelength, and therefore provides precise data when loaded into the CIE Toolbox S 026 (v. 1.49, 2020).

As the WELL Building Standard recommends that 75% of workstations are exposed to minimum 200 EML (daylight may be included) in the hours between 9.00-13.00 o'clock, measurements were performed onsite the 19-th of April 2021, between 11 and 13 o'clock to have data from within the time period defined by WELL. Measurements from the same positions were done twice on a day with a clear blue sky; first with maximum daylight intake; second time with shades partly blocking the sun from the three eastern faced windows, to also capture the difference in effect. Between the first and second round of measurements from each desk position, the daylight entering the office at the inside of the window glass was measured with and without the shades to provide a reference for the daylight conditions in this specific period (See Appendix A).

It is recognized that daylight intensity can change significantly over a short span of time, however these measurements are meant as a snapshot-representation of the influence daylight can have on photopic and melanopic illuminance in a space, by comparing with the simulations not including daylight.

For both scenarios, the luminaires in the office were set to maximum intensity – however, the maximum intensity of the luminaires was programmed by the installer to be less than 100%, so to meet the requirements of approx. 500lx horizontally on the work desks. At the on-site visit a measurement was made as close as possible to the ceiling luminaire to capture the spectral composition to load into ALFA and to determine its M/P ratio.

4.2. Software and Simulations

Simulations in DIALux and ALFA offers some similar tools for calculating light, but also specializes in different aspects. DIALux is 3D-modelling software enabling the user to design, visualize and calculate light for indoor and outdoor areas. It is relied on to evaluate lighting design in accordance to building standards and requirements in the lighting industry, typically calculations of the horizontal illuminance level of a space or specific task planes and of the Unified Glare Rating (UGR). It can also provide results from vertical and cylindrical planes.

ALFA is a plugin developed for usage in the 3D-modelling software Rhino (www.rhino3d.com), meaning that the model is created in Rhino, and the lights and material characteristics is applied through ALFA.

DIALux and ALFA relies on IES files (text files containing photorealistic information about the distribution of a light source), but only ALFA also includes tools for spectral analysis. In ALFA the researcher can determine the spectral power distribution of several light sources (given in M/P Ratios) to calculate the Equivalent Melanopic Lux in the general area of activity or specifically for a certain point and direction of view. ALFA also accounts for the spectral reflection of every material selected for calculation, based on spectrophotometric measurements of real objects (addressed further in chapter 5. Findings, see Fig. 11).

For both DIALux and ALFA the materials chosen are stock materials coming with the software installation packs. The specific reflectance values in the office was not investigated at the on-site visit of the space, and therefore the choice of materials is based on rough estimates of the most corresponding stock materials available in the two software applications. This means that the results from the simulations are not perfectly comparable to the real space, and the differences in stock materials available from the different applications can lead to irregularities, which can be the reason for slightly higher illuminance values generated in ALFA compared to DIALux (other reasons appeared from analysing the results and will be discussed in Chapter 5. Findings, Section 5.2.2.). Another reason for differences in photopic illuminance levels are that the simulated Gentofte office is not the exact same model, because DIALux does not allow to export in a format compatible with Rhino. Moreover, the DIALux-model was created by the ELFORSK-team and the ALFA-model by Rasmus Daae afterwards. Although following the measures of the DIALux model methodically, it could be a reason for minor differences or inconsistencies in the results.

ALFA is able to simulate and calculate daylight scenarios from standardized illuminance sky conditions. Since this is not the objective for the investigation in this project, the Gentofte office-model was placed inside a large box-shape to block all daylight. This allows for a more accurate assessment of the south west corner of the room, which is not closed off by a wall to reflect light back into the space, but has a wide opening to the connected hallway, where directed light will disappear. Eventual light reflected from the hallway into the office is not accounted for. This is the case for both ALFA and DIALux simulations. The light assessed is therefore only from the light provided from luminaires inside the office area.

The calculations made using ALFA measures EML-values by default. Photopic illuminance is also measured on both the vertical (1,2 m) and horizontal plane (0,76 m), as well as the M/P ratio is calculated by default from the given position. The M/P ratio is also determined from the SPD of the luminaires chosen in the lighting scene. For the 30 ceiling luminaires the SPD is fixed to match a CCT of 3000K and the specific SPD was measured at the on-site visit. When loaded into ALFA the M/P ratio was calculated to 0.55. Same procedure was not possible with the 11 wall washers (WW), because of their tuneable white technology. Therefore, to keep the comparison simple to determine the impact from the wall washers, it was decided for one scenario to apply the same SPD as for the 30 ceiling luminaries, and for a second scenario to apply a pre-set SPD included in ALFA replicating a LED-light with a M/P ratio of 1.0, with the intention of comparing the impact from the tuneable white-technology.

Apart from the main investigation, related to the problem statement of evaluating the performance of the current lighting system in the Gentofte office, an additional third simulation was conducted, indented as a hypothetical inquiry of a scenario in which all 41 luminaires in the space emitted the M/P ratio of 1.0. This was meant to present an estimation of the difference the choice of melanopic efficacy in luminaires can do for a space.

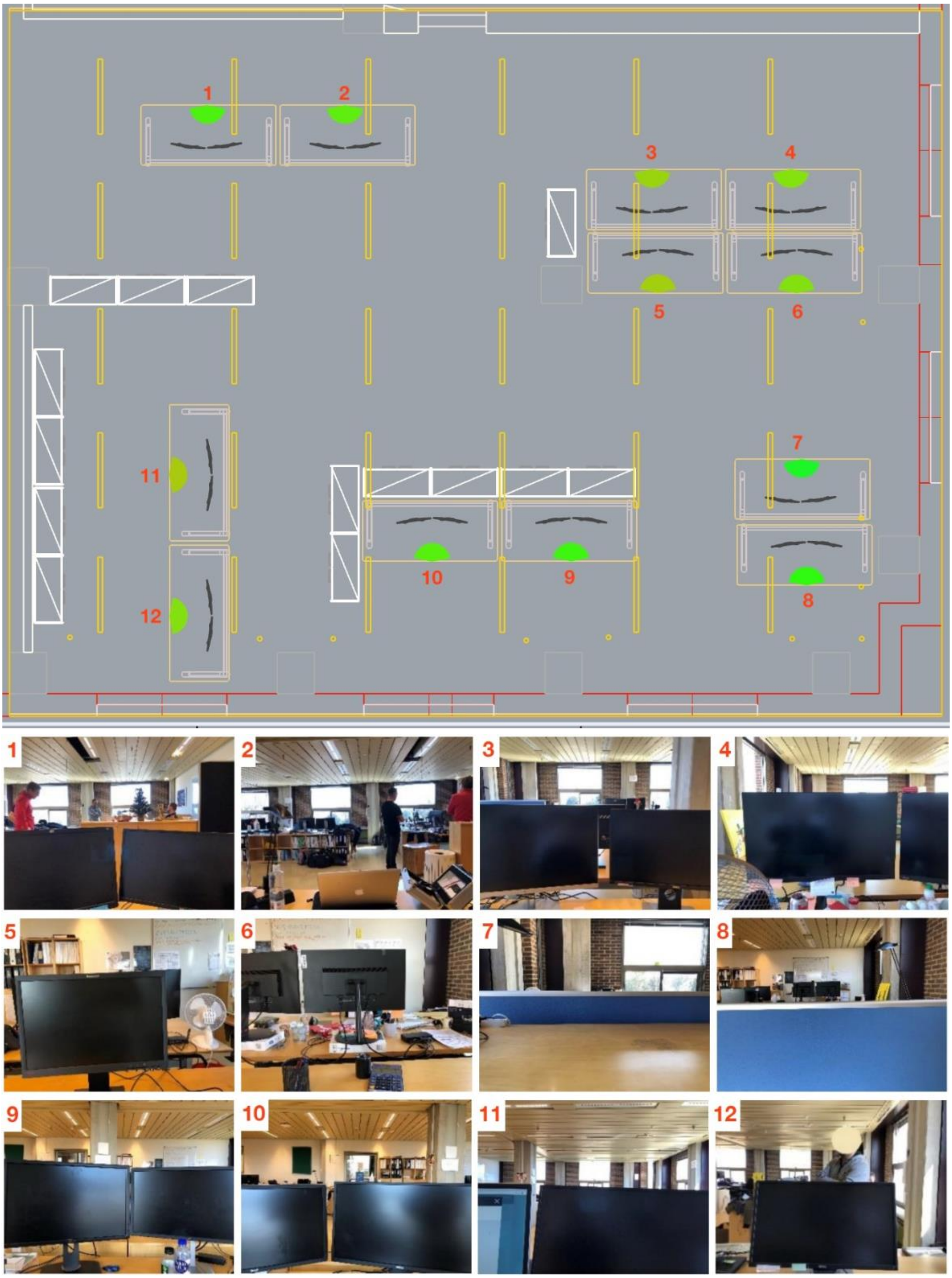


Figure 6, Upper part: Plan Layout from Rhino/ALFA, Gentofte office space. Red numbers 1-12 refers to each desk; green field presents point of measurements and direction of view for both on-site and simulations; Yellow lines and dots represents all luminaire positions.

Lower part: Direction of view from each position corresponding to the numbers assigned and direction (green field) depicted in above plan layout.

Photos: Rasmus Daae

4.2.1 Assumption for calculations

The DIALux software allows the user to dim lighting levels according to a percentage level, but this is not a feature of ALFA, rendering the lighting at 100%. Therefore, an assumption has been made to compensate for this from the data gathered from ALFA:

As the first hypothesis of this project states, it is to be investigated if the minimum requirements from the DS/EN 12464-1 (2011) for horizontal illuminance is compatible with the minimum requirements for ipRGC-influenced responses to light. But since the IES files in ALFA only allows for calculations at 100% intensity, it is not possible to create scenarios to make this kind of comparison. Therefore, simulations in DIALux were done to discover the percentage of dimming needed to achieve a minimum of 500 lux on the horizontal task plane of every desk in the Gentofte office. It was found that a dimming of 50% had every work desk above 500 (for clarification: the 50% dimming is not equal to the "limited maximum" programmed by the installer in the actual office space).

Comparing the values of 100% and 50% intensity clearly reflects that light traveling horizontal and vertically follow the same linear factor when dimmed – in this case 0.5 (Table 1):

Table 1: Calculations from DIALux performed in the Gentofte Office-model comparing levels of horizontal and vertical illuminance before and after dimming, showing a consistent relationship.

Properties	**E**	**Emin**	**Emax**
Horizontal illuminance 100% Intensity, height 0.75 m.	1375 lx	81 lx	1765 lx
Horizontal illuminance 50% Intensity, height 0.75 m.	688 lx	40.5 lx	882 lx
Cylindrical illuminance 100% Intensity, height 1.2 m	600 lx	284 lx	805 lx
Cylindrical illuminance 50% Intensity, height 1.2 m	300 lx	142 lx	402 lx

On this basis, the assumption is that the values gathered from simulations in ALFA can also be deducted by 50% to represent the amount of illuminance (photopic and melanopic) corresponding to the aforementioned level of horizontal illuminance needed to comply with the DS/EN 12464-1 (2011). By arriving at this level of horizontal illuminance makes it possible to address whether or not the electrical lighting system in itself can provide the minimum values recommended for ipRGC-influenced responses to light.

5. Findings

This chapter presents and discuss the findings from the different approaches used to investigate the lighting in the office space in Gentofte. The findings from each of the three investigation approaches – On-site measurements, ALFA simulations and DIALux UGR calculations – will be presented along with a discussion of findings as three separate sections. Finally, a section will assess what these different investigations in combination has discovered from working with the Gentofte office in relation to the field of ipRGC-influenced responses to light.

The on-site measurements were conducted to obtain an understanding of the influence that daylight can have on a space in relation to melanopic illuminance and thereby ipRGC-influenced responses to light. Although the problem statement is related to electrical lighting, the following scenarios assessing the space with the influence of daylight provides ground for a comparable analysis with simulations excluding daylight, and therefore adds a perspective to the role of electrical lighting.

The simulations provide a nuanced understanding of the influence of individual parameters affecting ipRGC-influenced responses to light. In this case intensity is the main focus parameter, since the 30 luminaries installed in the ceiling in Gentofte is only dimmable – and not tuneable. Also, the spectrum as an influential parameter will be addressed, as well as direction of distribution in terms of glare caused from increased intensity.

5.1 Findings from on-site measurements

The primary target of investigation from the on-site visit to the Gentofte office space was measuring the lighting conditions in accordance to the CIE S026 to be able to calculate the melanopic EDI. These measurements are roughly representative for the daylight contribution to the measurements taken at the 12 positions. The results from mEDI calculations made in the CIE Toolbox S 026 (v. 1.49, 2020) including both scenarios of shades up and down are displayed in figure 7 (all data collected for a comparative perspective including EML-converted values are included in the Appendix A):

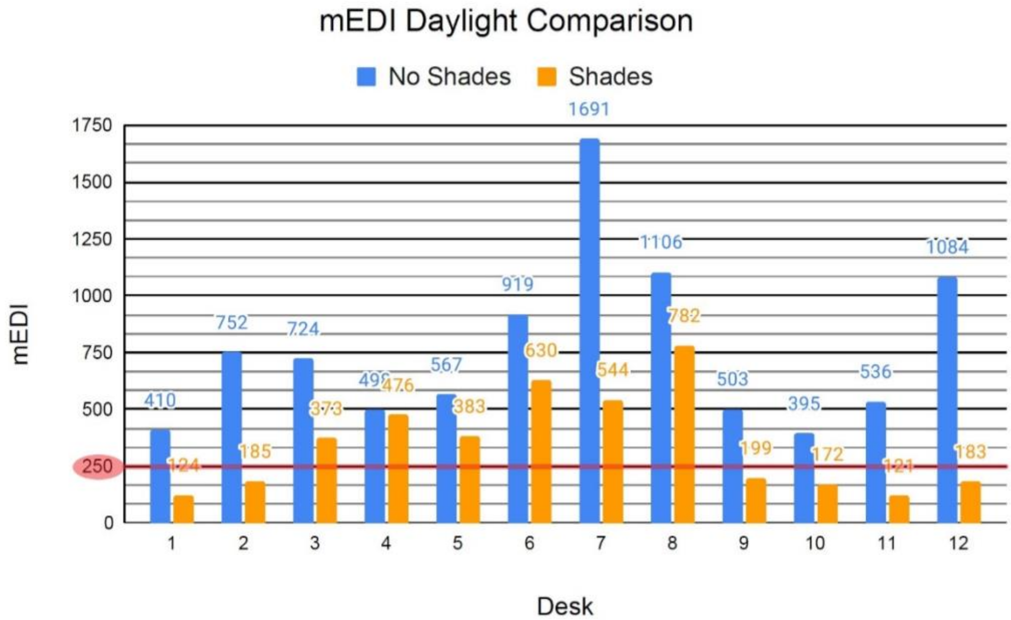


Figure 7, melanopic EDI-values measurements including the influence of daylight, generated from the CIE Toolbox S026 (v. 1.49, 2020). Notice that "shades"-values are based on shading from the three eastern windows and not including shading of the two northern windows. Red marking at 250 mEDI indicates the minimum recommendation (including daylight) from Brown et al. (2020)

5.1.1. Main findings

The main findings from the results of the on-site visit to Gentofte can be summarized as following:

- All desks meet the consensus recommendation of 250 mEDI when the daylight is not shaded,
- Desk 1, 2, 9, 10, 11 and 12 does not meet the consensus recommendation of 250 mEDI when the shades are down (all below 200 mEDI),
- Despite influence of daylight in the scenario with the shades down, desk 1 and 11 does not meet the WELL Building Standard recommendation meant for only electrical lighting of 150 EML, meaning that the electrical lighting does not provide a sufficient amount of melanopic illuminance.

5.1.2. Discussion of findings

Desk 1 and 2, the two desks placed furthest away from the windows in the office space, is affected significantly by the shades limiting the daylight entering the room (Fig. 7). Both desks are directed with a frontal view to the windows that goes from respectively 410 - 124 mEDI and 752 - 185 mEDI, both below the consensus recommendation. However, desk 2 is slightly above the values recommended in the WELL building standard (including daylight). Nonetheless, the significant reduction indicates that the current electrical lighting system should be increased in intensity, if the shades are down – and considering the weather conditions for the day of measurements were conducted on a day with a clear blue sky, the increase could also be needed in the darker days of the year. On the other hand, on darker days the tendency to shade the daylight might be less frequent. However, the decision to use the shades is likely to be made by the workers sitting close to the windows, thus more affected by reflections and glare from monitors and desks caused by daylight. Ironically, shades down impact those positioned the furthest from the windows in terms of ipRGC-influenced responses to light. An issue like this stress the importance of having indoor electrical lighting capable of providing sufficient amounts of melanopic illuminance to accommodate for workstations positioned further from windows in deep office spaces.

The difference in shading also affects desk 9, 10, 11, and 12 with none of them reaching above the consensus recommendation of 250 mEDI (alle four below 200 mEDI) when the shades are down, although they sit much closer to the windows. Desk 9 and 10 have their field of view directed opposite of the windows, meaning that a lot of the vertical illuminance measured must be assumed to come from reflections of pc monitors (see field of view-photo in plan layout Figure 6 or Appendix A) and from the opposing wall. Desk 11 and 12 has the field of view directed toward the northern windows, which could not be shaded, but is still affected considerably, although they have the eastern windows close to their right-hand side; desk 12 most severe with a decrease in mEDI of 83%. This finding could be affected by changes in daylight intensity from the two rounds of measurements, however the measurements captured at the windows glass, which were performed in succession (within two minutes), does support this great decrease caused by shades as the illuminance drop from 10873 lux to 2199 lux. Moreover, the shades absorb more melanopic than photopic frequencies, given by clear the reduction in the M/P ratio, limiting the circadian stimulation even further (see Appendix A).

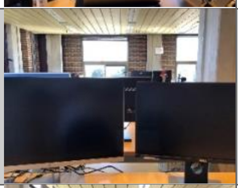
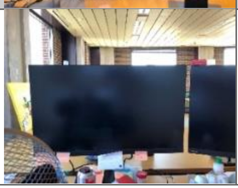
The on-site measurements from scenarios with the influence of daylight and daylight shaded on the eastern windows presents a clear image of the importance of access to daylight and also more specifically the difference it makes to consider the proper viewing directions when designing the placement of work desks. When the shades are down, the consensus recommendation is met by only half of the twelve desks, while no shading of the eastern windows provides sufficient melanopic illuminance for all desks. This indicates that electrical lighting is not able provide enough light in the melanopsin-sensitive region of the visual spectrum, supported by the fact that the M/P ratio of the ceiling luminaires was determined to 0.55.

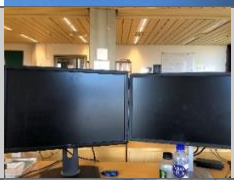
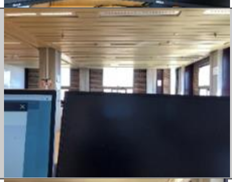
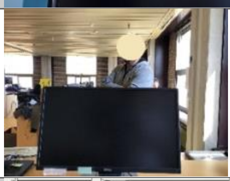
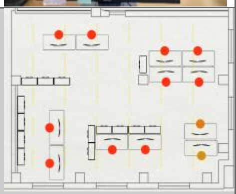
5.2. Findings from ALFA simulations

The simulations conducted in ALFA is performed with the intention of obtaining knowledge about the electrical lighting system without interference of daylight. Two simulations comparable to the actual light system in Gentofte was performed; one with the wall washers emitting the same spectrum of light as the ceiling luminaire, and another where they emit a spectrum equal to 1.0 M/P ratio. All data from these scenarios are included in the following Table 2.

As an addition to the simulations of the current performance, a hypothetical simulation with all lights set to emit the 1.0 M/P ratio, with the intention of exploring the potential for such lighting system had the melanopic efficacy of the luminaires been higher.

Table 2, Findings from ALFA simulations. The values presented are based on 100% intensity from the luminaires and not the limited maximum output as the on-site measurements are based on. These simulations can therefore be considered to represent the maximal potential for melanopic illuminance from solely electrical light in the Gentofte office at present time. The difference in the two values within each square of Table 2 marks the two scenarios simulated: The upper with all 41 lights with the same 0.55 M/P ratio, the lower with the 30 ceiling fixtures on the 0.55 M/P and the 11 WW's set to 1.0 M/P.

Desk	**Field of View**	**EML ALFA** All 0.55 M/P WW 1.0 M/P	**Vertical Illuminance:** All 0.55 M/P WW 1.0 M/P	**M/P Ratio:** All 0.55 M/P WW 1.0 M/P	**mEDI Conversion** All 0.55 M/P WW 1.0 M/P	**Horizontal Illuminance (0,76m)** All 0.55 M/P WW 1.0 M/P
1		249 EML 244 EML	519 Ev 505 Ev	0.48 M/P 0.48 M/P	226 mEDI 221 mEDI	1484 E 1491 E
2		263 EML 257 EML	552 Ev 532 Ev	0.48 M/P 0.48 M/P	238 mEDI 233 mEDI	1534 E 1527 E
3		330 EML 317 EML	671 Ev 640 Ev	0.49 M/P 0.50 M/P	298 mEDI 287 mEDI	1829 E 1796 E
4		297 EML 289 EML	602 Ev 564 Ev	0.49 M/P 0.51 M/P	269 mEDI 262 mEDI	1486 E 1513 E

5		345 EML 347 EML	708 Ev 709 Ev	0.49 M/P 0.49 M/P	313 mEDI 314 mEDI	1797 E 1775 E
6		297 EML 309 EML	609 Ev 598 Ev	0.49 M/P 0.52 M/P	269 mEDI 280 mEDI	1579 E 1571 E
7		201 EML 216 EML	410 Ev 403 Ev	0.49 M/P 0.54 M/P	182 mEDI 196 mEDI	1368 E 1364 E
8		226 EML 250 EML	469 Ev 461 Ev	0.48 M/P 0.54 M/P	205 mEDI 226 mEDI	1356 E 1328 E
9		238 EML 240 EML	510 Ev 506 Ev	0.47 M/P 0.48 M/P	216 mEDI 217 mEDI	1828 E 1848 E
10		257 EML 246 EML	547 Ev 519 Ev	0.47 M/P 0.47 M/P	233 mEDI 223 mEDI	1773 E 1771 E
11		356 EML 373 EML	714 Ev 749 Ev	0.50 M/P 0.50 M/P	322 mEDI 338 mEDI	1902 E 1908 E
12		297 EML 325 EML	591 Ev 621 Ev	0.50 M/P 0.52 M/P	269 mEDI 294 mEDI	1488 E 1491 E
Avg. 1-12		280 EML 284 EML	575 Ev 567 Ev	0.49 M/P 0.50 M/P	256 mEDI 257 mEDI	1619 E 1615 E

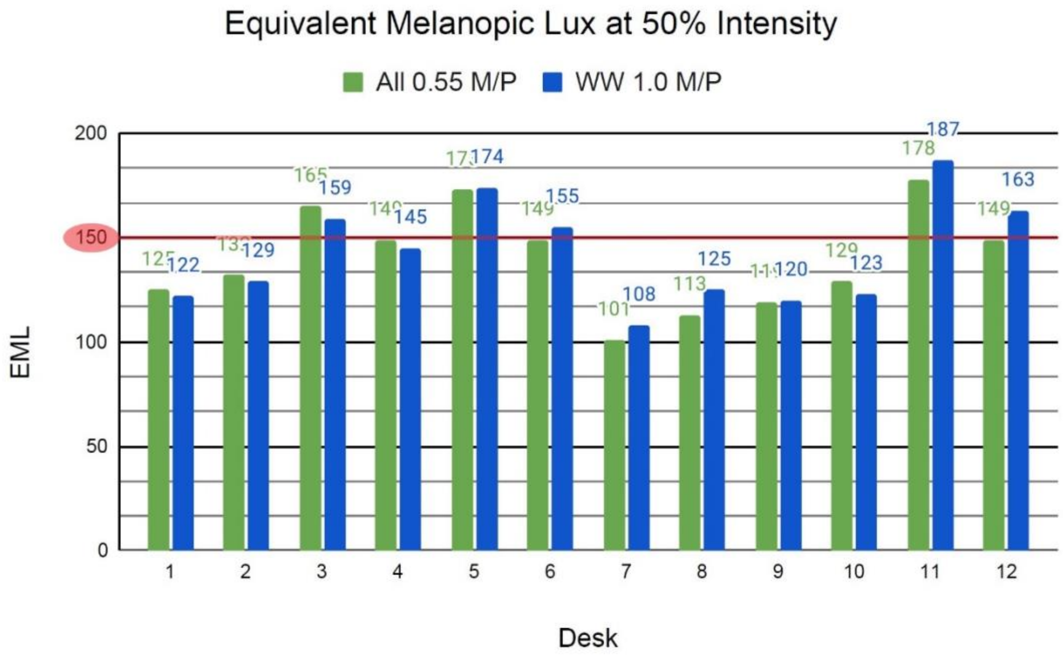


Figure 8, Depicts a 50% deduction of the EML-values presented in Table 2, to show how the desk positons performs when the photopic illuminance is set to match the recommendation of horizontal illuminance given in DS/EN 12464-1 (2011). The value of 150 EML marked with red indicates the minimum recommendation from WELL Building Standard on electrical lighting only. Desk 1, 2, 4, 7, 8, 9, 10 below in both scenarios; desk 6 and 12 below in 0.55 M/P-scenario.

5.2.1. Main findings

Based on the data included in Table 2 and Figure 8, the main findings from simulations in ALFA are:

- Every desk position reaches above the recommendation from the WELL Building Standard recommendation of 150 EML from only electrical lighting,
- At 50% intensity 7/9 (depending on simulation scenario) does not reach above the WELL Building Standard recommendation,
- The M/P ratio from each desk position is below the M/P ratio of the luminaires,
- Changing the M/P ratio of the 11 wall washers has a low overall impact.
- The difference between horizontal illuminance and EML/mEDI is significant,

5.2.2. Discussion of findings

The EML achieved with the 41 luminaires at 100% intensity – including both scenarios of different M/P ratio of the wall washers – is above 150 EML at all 12 desk positions, which means that the potential for a beneficial stimulation of the circadian rhythm is possible with the current light installation in the Gentofte office according to the recommendations given in the WELL Building Standard (2020). However, not all desks meet the higher minimum threshold given in the consensus recommendation by Brown *et al.,* (2020) of 250 mEDI (276 EML by conversion), although the average mEDI from the 12 desks does reach above 250 mEDI and thereby could indicate, that a rearrangement of the work desks could achieve better individual melanopic stimulation. This is supported by calculations based on a grid of 88 positions, 352 views (see Appendix B), which graphically presents a higher concentration of melanopic lux the closer to the center of the room, as well as a lower concentration from positions along the outer walls and windows. This is meant as a hypothetical example, because daylight in a real scenario would provide sufficient amounts of melanopic lux along the windows, as was found from the on-site measurements.

Desk 1, 2, 7, 8, 9, and 10 is found to be below the mEDI-consensus recommendation, meaning that 1, 2, 9 and 10 again (they were also below recommendations in the on-site measurements with shades down) appear among the desks positioned most unfortunate in terms of melanopic illuminance. Based on the assumptions explained in the methods chapter (section 4.2.1.), illuminance values should be reduced by 50% to correspond to the minimum values of maintained 500 horizontal lux on each desk required by the European Standard DS/EN 12464-1 (2011). The values are given in EML to compare with the WELL-recommendation, since no desk meets the consensus mEDI recommendations. At 50% it is desk 1, 2, 4, 7, 9, and 10 scoring below the WELL-recommendations of 150 EML in both scenarios, however the difference in melanopic illuminance from the wall washers causes desk 6 and 12 to reach above 150 EML when the M/P ratio is set to 1.0, but below when the ratio is at 0.55 M/P. Results are summarized in Figure 8.

From the data presented in Table 2 it is evident that the overall level of M/P ratio compared to the on-site measurements has decreased. This is caused by the SPD from the ceiling luminaires with a M/P ratio of 0.55. The spectrum of the ceiling luminaire is depicted in Figure 9, where it is noticeable that the SPD dips right in the melanopsin-sensitive region around 480 nm., whereas the SPD of the 1.0 M/P used for the wall washers peak in that same region (Fig. 10):

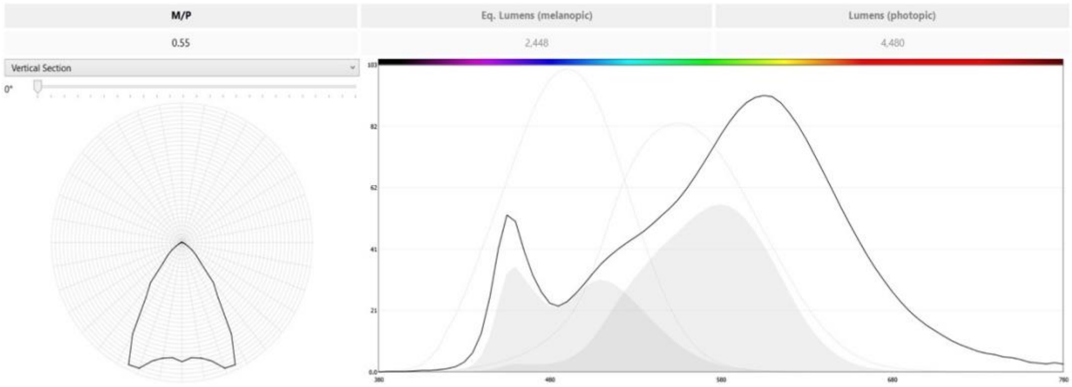


Figure 9. Ceiling luminaire SPD with M/P 0.55 from ALFA. Included also: On the left is the distribution of light; and above the SPD the luminous flux in melanopic and photopic values.

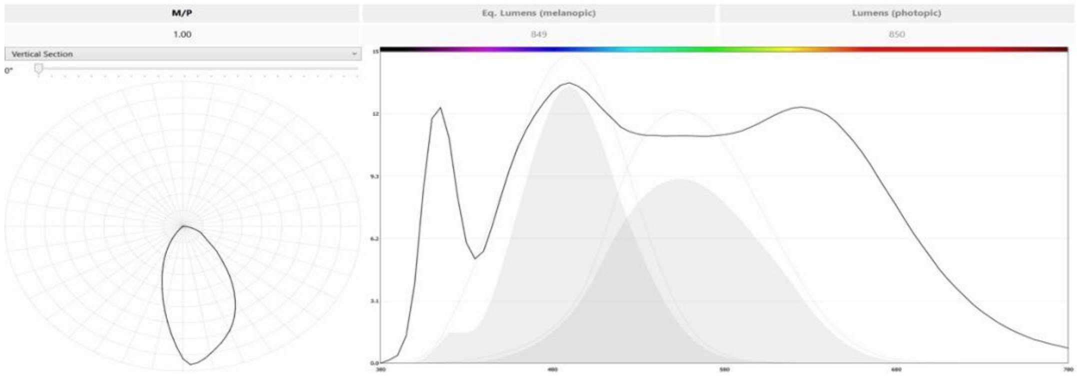


Figure 10. Wall washer luminaire SPD with M/P 1.0 from ALFA. Included also: On the left is the distribution of light; and above the SPD the luminous flux in melanopic and photopic values.

Another finding related to the M/P ratio is found from reviewing the relationship between the two scenarios presented in Table 2 it is understood that a higher M/P ratio from luminaires cannot necessarily in all cases be expected to reach a higher EML (or mEDI). The data shows that desk 1, 2, 3, 4, and 10 reaches a higher amount of both EML and vertical photopic illuminance when the WW's emits an SPD equal to a M/P ratio of 0.55 than a M/P ratio of 1.0. The explanation being that the reflectance of materials in ALFA are based on spectrophotometric measurements of real objects, meaning that the included materials in the space can change the spectral power distribution by reflecting some frequencies and absorbing others to a certain degree that the SPD hitting the eye is not the same as that emitted from the light source. In this specific case, it means that the relative spectral power distribution from the 0.55 M/P light source provides more light in the melanopsin-sensitive region than the otherwise more melanopic-effective 1.0 M/P light source.

This finding emphasizes the importance of considering materials in a space, which can be a powerful tool to improve circadian stimulation. As seen below in figure 11, the specific viewpoint in ALFA (the enlarged green tringle) has a M/P ratio of only 0.45, although the luminaires providing the light in this specific simulation all emits a M/P ratio of 0.55. The “Red Brick” material in figure 11 is an example of the material data characteristics – this specifically used for the brick walls on the eastern and northern side in the Gentofte office, reflecting 13.7% photopic and 9.0% melanopic illuminance, equalling a M/P ratio of 0.65.

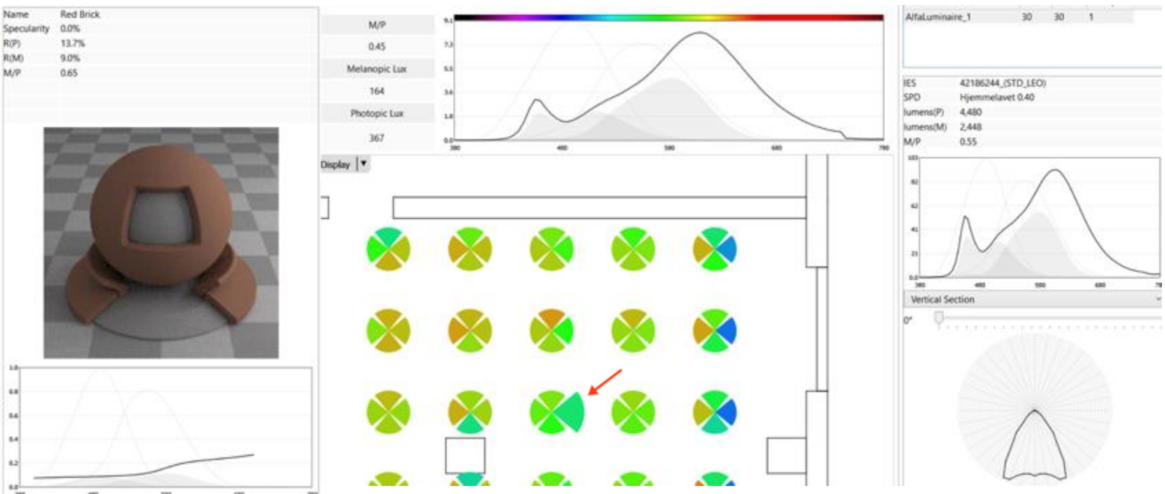


Figure 11, Results from ALFA from scenario of only ceiling luminaires with 0.55 M/P-spectrum. In the bottom left corner is the SPD of reflectance from the “Red Brick” material. The SPD in the top center shows that the specific view position is exposed to a 0.45 M/P ratio, despite luminaires emitting 0.55 M/P illuminance.

The role of the wall washers in minimal. The effect is as expected a higher EML in the 1.0 M/P-simulation than in the 0.55 for the desks (3, 5, 7, 8, 12) positioned close by with a directly or partly direct view to the pillars which the WW’s are directed towards. The overall impact is however low (see Appendix C) at 19 photopic lux and 17 photopic in average, and therefore the WW’s should in this case mainly be seen as tools for mitigating glare, which was the objective from the ELFORSK team. Spots directed towards vertical planes could although prove to be a useful tool in deep spaces with desks positioned far from windows.

The work plane illuminance for desk 10 and 12 is above 1500 lux – the average from the two scenarios varying closely from 1619 (all 0.55) to 1615 (WW’s 1.0). Comparing with the average vertical illuminance (1.2 m.) it is almost reduced by 2/3 for both scenarios. Adding to this the average M/P ratio of 0.49 / 0.50, it demonstrates how horizontal work plane photopic illuminance is reduced significantly before it meets the retina as melanopic illuminance. This reduction gives reason to consider alternative lighting design approaches for offices and other indoor environments for a greater utilization of electric light sources for stimulating ipRGC-influenced light responses. A such consideration was made as a hypothetical investigation of potentials:

It was calculated how the office space would perform if all 41 lights were installed with a 1.0 M/P ratio-spectrum. The results proved that every desk exceed 300 EML, and deducted by 50% to correspond the DS/EN 12464-1 (2011) requirement for horizontal illuminance, it thereby do exceed the WELL-recommendation of 150 EML for only electrical light. The consensus recommendation of 250 mEDI (276 EML by conversion) was after the 50% deduction in intensity met by 33% of the desks. The consensus recommendation is however including daylight (See Appendix D for data from these hypothetical simulations).

5.3. DIALux calculation of UGR

The calculations of Unified Glare Ratio (UGR) performed in DIALux at 100% intensity is summarized in figure 12:

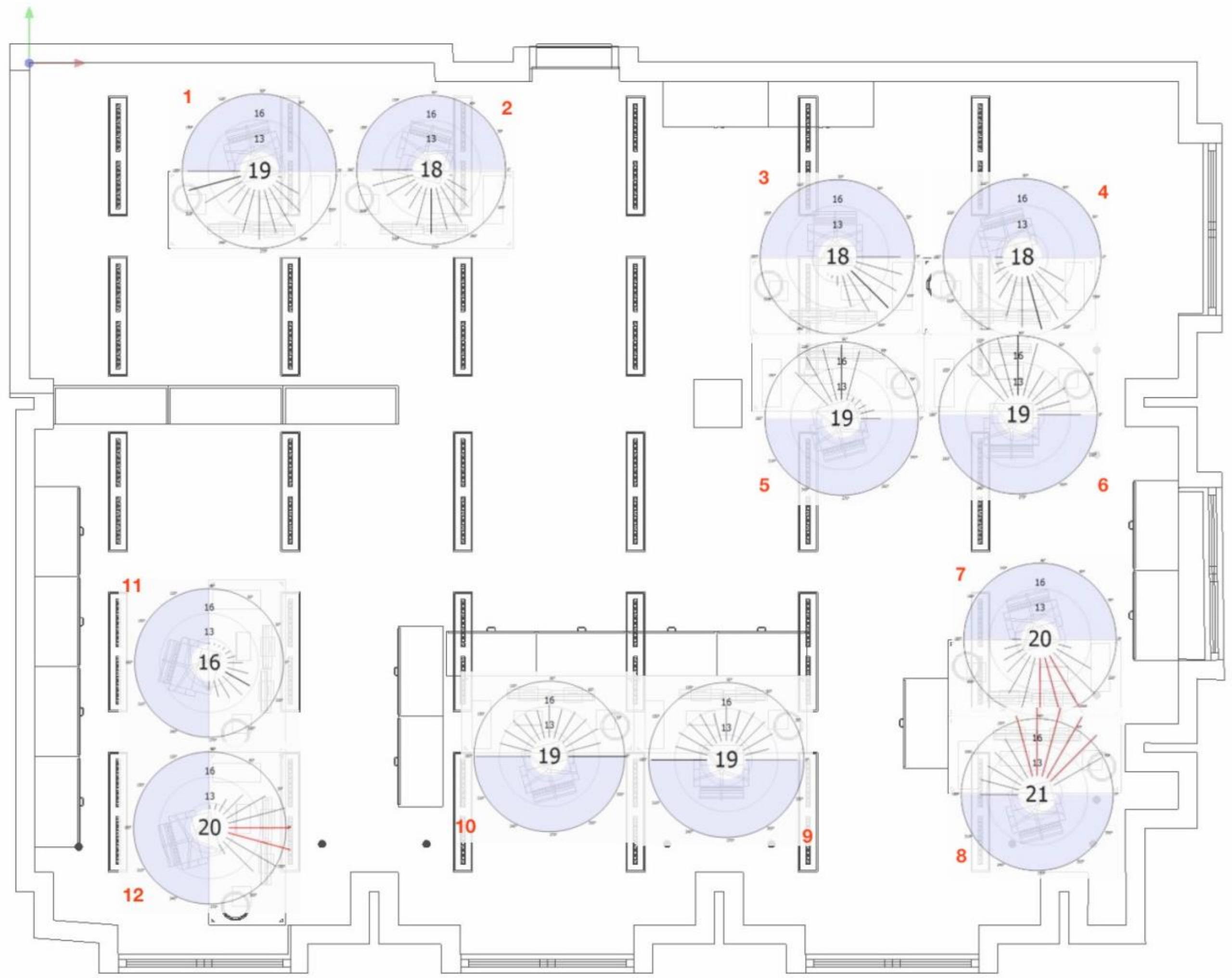


Figure 12, Plan layout from DIALux, superimposed with UGR Calculations generated in DIALux from 12 calculation points (1.2m height) at 100% intensity. Each point has calculated UGR to correspond to the direction of view for each work desk in a 180-degree angle.

5.3.1. Main findings

- Desk 7, 8 and 12 exceed the requirement from the DS/EN 12464-1 (2011) of 19 UGR,
- The general level of UGR is close to 19,
- For desks 3, 4, 7, 8, 11, 12 the highest glare rating occurs in the direction of nearby wall washers.

5.3.2. Discussion of findings

The calculations of UGR measured accordingly to each desk's viewing angle of 180 degree determines that not all desks are within the limits required by the DS/EN 12464-1 (2011) of maximum 19 UGR. However, considering the circumstances for this UGR calculation, the Gentofte office has the potential to increase the "limited maximum" of the ceiling luminaires from the current settings close to the full 100% intensity. The reason being, for one; that the UGR levels exceeding 19 originates from the wall washers (with an exception from desk 8, with one red marker directed towards the inside of the office) (See Appendix E for a grid-based calculation of UGR), and second; that the function of the wall washers is to mitigate glare from dark vertical surfaces increasing the risk of glare when daylight is present; without daylight it is likely that the wall washers can have the opposite effect. A calculation of the same 12 desk positions at 50% proves, that UGR above 19 does not occur (see Appendix E), and indicates, that the wall washers at lower intensities does not cause glare (although desk 8 measures 19 UGR in the direction of a wall washer), and that the level of luminous intensity from ceiling luminaires and wall washers should not follow the same intensity level, but instead be adjusted separately to find a balance – which is how the system is set up in Gentofte already.

The potential to increase light levels to provide horizontal illuminance above the minimum 500 lux required by the DS/EN 12464-1 (2011) is a possibility in terms of considerations of glare. From the calculations it is assumed that a balance between 50% and 100% intensity can be found to provide more melanopic illuminance without causing glare. To determine an appropriate level of balance between ceiling luminaires and wall washers, combined with incoming daylight, further investigations is needed.

5.4. Findings summarized

This project has investigated the role of an electrical lighting system in entraining the circadian rhythm of office workers and whether lighting systems with circadian or human-centric attributes can be considered as alternatives or rather as additions to daylight exposure on a daily basis. To obtain an understanding of this field of lighting design, the project has included an investigation of light sources of different intensities and spectral power distribution in relation to how that light is distributed within a specific office space to evaluate their performance and potential for achieving a beneficial stimulation of the office worker's circadian rhythm, and further, if that stimulation is challenged by the risk of glare caused from the same luminaires.

It was found, that office workers at desk 3, 5 and 11 (both scenarios) were within a balance of melanopic and photopic light that met recommendations from the WELL Building Standard (2020) while not compromising requirements from the European Standard DS/EN 12464-1 (2011). The results of this investigation find that electrical lighting systems with dimmable and/or tuneable features can and should be considered in modern lighting design, but at the same time it should be remarked, that it is not the features of a lighting system that makes it circadian, human-centric or integrative; rather, it is how the lighting design is carried out in practice. This is exemplified by the case in Gentofte (further studies of the influence of daylight including different seasons would be optimal for a more nuanced understanding of the actual difference in effect):

The results from the on-site measurements from each desk proved that daylight allowed in from all five windows reached scores above the mEDI recommendation from Brown *et al.*, (2020) but limiting the daylight with shades on three of the windows caused half of the desks to score below. With this in mind, it could be argued, that the lighting design in Gentofte is circadian, despite the choice of non-tuneable, low-melanopic-efficient electrical light sources installed in the ceiling. Ironically, this is related to the wall washers – that otherwise proved to have a low overall direct impact – because they heighten the potential for stimulation of the circadian rhythm through their intended function of mitigating glare at the windows, which eventually lowers the probability that the office workers pull down the shades.

6. Discussion

The investigations and findings in this project illuminates the complexity in finding the *balance* mentioned in the introduction about implementing ipRGC-influenced responses in lighting design without compromising other aspects constituting a good indoor lighting environment. While evidence from the case study indicates that there exists a compatibility between melanopic recommendations and the European Standard DS/EN 12464-1 (2011), this is founded within the scope of the investigation, and therefore without concerns of other important factors of lighting design that constitutes this *balance* formulated by the CIE (CIE Position Statement, 2019). The following section is meant to introduce and discuss further studies of a broader scope related to implementing circadian lighting design.

This project has proved how lighting for stimulation of the circadian rhythm is not merely a matter of more or less illuminance to gain more or less effect; it will always be a matter of context, that could prove in many cases to be rather complex: In combination with illuminance levels, spectrum and direction of distribution has been investigated and proved that a synthesized consideration of all three parameters is imperative for the efficiency of a lighting design meant for circadian stimulation purposes, as well as it was clear how the positioning of desks and thereby the worker's field of view could account for significant differences.

Beyond these aspects follow several more to heighten the complexity, all of which should be conjoined for a balanced lighting design in relation to all indoor office spaces; perhaps most prominent the question of how the space is experienced by the people working there if the lighting is prioritizing ipRGC-influenced responses to light above the general atmosphere? As explained in Chapter 3 it is generally so, that a higher CCT has a higher melanopic efficacy, but higher CCT (or lower) can invoke a certain atmosphere and influence social behaviour (Casciani and Musante, 2017), and should therefore also be a part of the equation.

Furthermore, this project has found reason for stressing the importance of considering the spectral reflectance of the surfaces in a space, that can be used to optimize the distribution of melanopic illuminance, through which it would be a way to lessen the power consumption by dimming down the intensity. Although this rises another question regarding whether the fixtures should be dimmed, as long as they do not cause glare? Considering the low power consumption of modern LED's and the strong evidence for the many positive effects related to a beneficial stimulation of the circadian rhythm and other related non-visual responses to light such as increased alertness, mood and general health and well-being (see Chapter 1 & 2), it seems the time is ripe to ask, if the money saved on dimming lights (and/or amount of fixtures) to just meet the minimum requirements from e.g. DS/EN 12464-1 (2011) is of greater value than the positive influence more light can have on office workers?

7. Conclusion

This project has investigated aspects of lighting design meant for stimulating non-visual or ipRGC-influenced responses to light. Through a case study of a specific space in Gentofte, a measurement on-site as well as simulations of the space was conducted. The case study provided results that can be used to address general questions regarding the topic of using electrical lighting as alternatives or additions to daylight to entrain the circadian rhythm in indoor environments, in this thesis specifically office workers.

The conclusion of this project will first address the two hypotheses, and thereby creating the basis for answering the problem statement.

7.1. The first hypothesis

Achieving stimulation of the circadian system from electrical lighting is dependent on high illumination levels, significantly exceeding the minimum requirements in the European Standard for Indoor Work Places (DS/EN 12464-1, 2011).

Based on the theoretical background and findings from investigations conducted in this project, it proved that addressing this hypothesis does not allow for a dichotomous answer. First and foremost because illuminance levels from electrical light sources alone cannot be considered apart from other decisive factors of circadian stimulation, which includes spectrum, direction of distribution, timing and duration and photic history – the question of timing and duration and photic history has not been a part of this investigation, because the entrainment of the circadian rhythm has been evaluated in accordance to recommendations from the WELL Building Standard (2020) and Brown *et al.*, (2020), for which considerations of these aspects is already included.

Illuminance as a factor is deeply interrelated with the matter of spectrum and direction of distribution, and therefore dependency on high illuminance levels for circadian stimulation as expected by the first hypothesis, is only the case if illuminance is the only tweakable parameter available. However, if an adjustment of the spectral power distribution and/or the direction of distribution is possible with the result of greater efficiency obtained from the light sources, then high illuminance is not necessarily needed; at least, not at levels significantly exceeding the recommendations from the DS/EN 12464-1 (2011) for horizontal illuminance. Lastly, the increase of illuminance is dependent on which recommendation for melanopic illuminance one chooses to follow.

This is concluded based on the performance of the lighting system in the specific case in Gentofte by simulations of 50% intensity, where it was found, that 7/9 desks were below the WELL-recommendation for electrical lighting only, but in a hypothetical simulation with a greater M/P ratio, all desks were above.

7.2. The second hypothesis

Increasing the lighting intensity of luminaires to stimulate the circadian rhythm can cause glare.

The calculation of the UGR showed that an increase to 100% on all 41 luminaires in the Gentofte office would cause glare for 3 of the 12 desk positions above the maximum of 19 UGR according to the DS/EN 12464-1 (2011). At 50% intensity, there was no UGR above but a single desk at 19. In both scenarios, the primary glare caused originates from directions along the eastern and northern walls where the wall washers are installed. This suggests that a balance between 50% and 100% intensity and a balance between ceiling luminaires and wall washers could be sought for optimal conditions for circadian stimulation without the cause of glare.

7.3. The problem statement

How does a lighting system in a specific office space in Gentofte perform in accordance to recommendations on ipRGC-influenced photoentrainment of the circadian rhythm and are these recommendations compatible with the European Lighting Standard for Indoor Work Places (DS/EN 12464-1:2011)?

The recommendations for photoentrainment of the circadian rhythm from ipRGC-influenced responses to light included in the project was from the WELL Building Standard (2020) and Brown *et al.*, (2020). These recommendations have defined different values for which sufficient levels of melanopic illuminance achieves a beneficial stimulation of the circadian rhythm.

The performance of the lighting system in Gentofte is in relation to the WELL-recommendations achieving a sufficient amount of melanopic illuminance for 3/5 of the 12 desks (depending on the scenario evaluated) for electrical lighting only. In relation to the Brown *et al.*, (2020) recommendation, no desks meet the minimum requirements, but this level is however significantly higher than the WELL-recommendations, both including and excluding daylight.

The compatibility between the recommendations and the European Standard for Indoor Work Places is found to be possible to arrive at, but not with the lighting system in the Gentofte office. For this case, a consideration of the melanopic efficacy of the chosen luminaires could have resulted in a lighting environment allowing intensities to be kept at a level that does not cause glare, but still performs well for circadian purposes.

The case in Gentofte illustrates, that installing an electrical lighting system with the intention of meeting the requirements from the European Standard for horizontal illuminance on work desks, but not at the same time considers factors of ipRGC-influenced responses to light, it can result in some workers receiving below the minimum recommendations of melanopic illuminance – especially if the contribution from daylight is limited.

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Melanopic Light Intensities for Work Areas, Website accessed 8/4/2021,
HTTP: https://standard.wellcertified.com/light/circadian-lighting-design

Table L1: Melanopic Ratio, and Table L2: Melanopic and Visual Response. Website accessed 8/4/2021,

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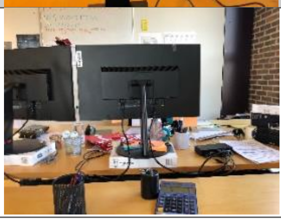
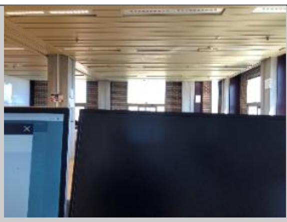
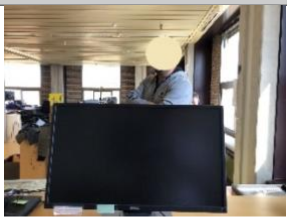
9. Appendix

A, On-site measurements table

Table of all collected values from on-site measurements:

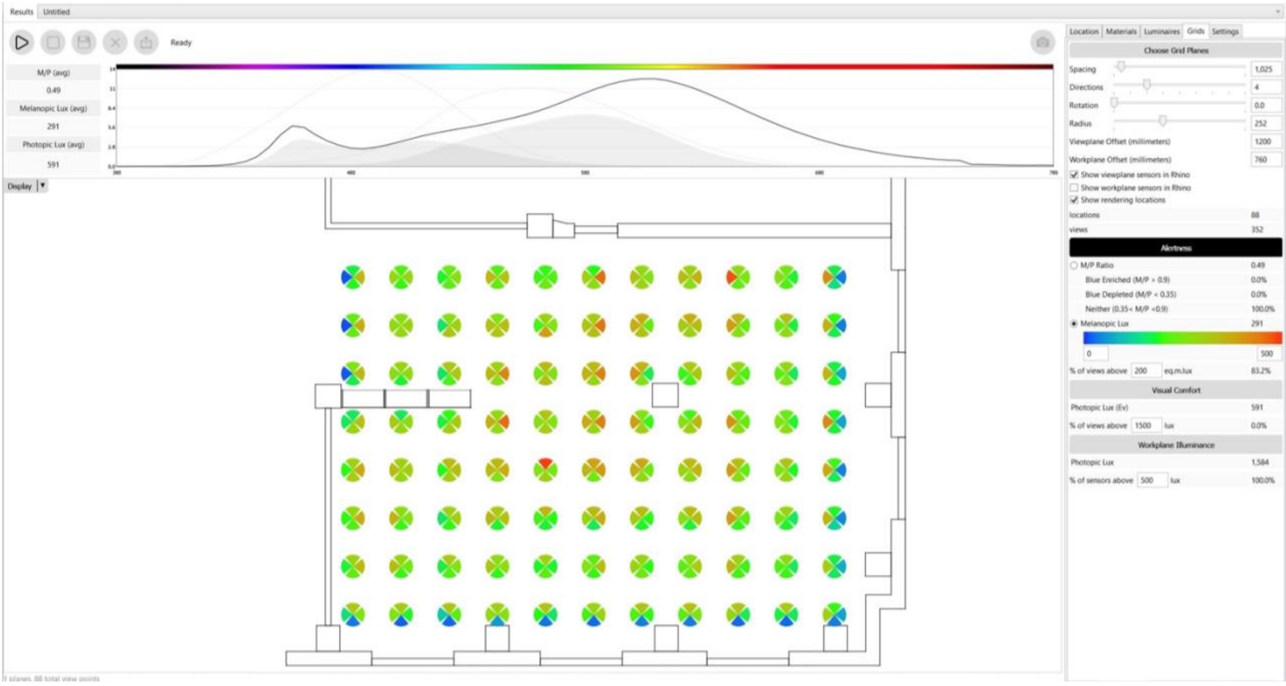
Desk	Field of View	Vertical Illuminance: No Shades Shades	mEDI: No Shades Shades	EML Conversion: No Shades Shades	M/P Ratio: No Shades Shades
1		547 Ev 201 Ev	410 mEDI 124 mEDI	453 EML 137 EML	0.83 M/P 0.68 M/P
2		968 Ev 295 Ev	752 mEDI 185 mEDI	830 EML 204 EML	0.86 M/P 0.69 M/P
3		938 Ev 463 Ev	724 mEDI 373 mEDI	799 EML 412 EML	0.85 M/P 0.89 M/P
4		662 Ev 497 Ev	498 mEDI 476 mEDI	550 EML 526 EML	0.83 M/P 1.06 M/P
5		819 Ev 509 Ev	567 mEDI 383 mEDI	725 EML 423 EML	0.89 M/P 0.83 M/P
6		1143 Ev 680 Ev	919 mEDI 630 mEDI	1015 EML 696 EML	0.88 M/P 1.02 M/P

7		1906 Ev 572 Ev	1691 mEDI 544 mEDI	1867 EML 601 EML	0.98 M/P 1.05 M/P
8		1289 Ev 807 Ev	1106 mEDI 782 mEDI	1221 EML 863 EML	0.95 M/P 1.07 M/P
9		746 Ev 275 Ev	503 mEDI 199 mEDI	555 EML 220 EML	0.74 M/P 0.80 M/P
10		621 Ev 249 Ev	395 mEDI 172 mEDI	436 EML 190 EML	0.70 M/P 0.76 M/P
11		775 Ev 208 Ev	536 mEDI 121 mEDI	592 EML 134 EML	0.76 M/P 0.64 M/P
12		1365 Ev 258 Ev	1084 mEDI 183 mEDI	1197 EML 202 EML	0.88 M/P 0.78 M/P
Win		10873 Ev 2199 Ev	12060 mEDI 1899 mEDI	13314 EML 2096 EML	1.22 M/P 0.95 M/P
Lum		2126 Ev	1052 mEDI	1162 EML	0.55 M/P

B, Alfa Simulations

Grid calculation of melanopic performance. 88 sample locations, 352 directions

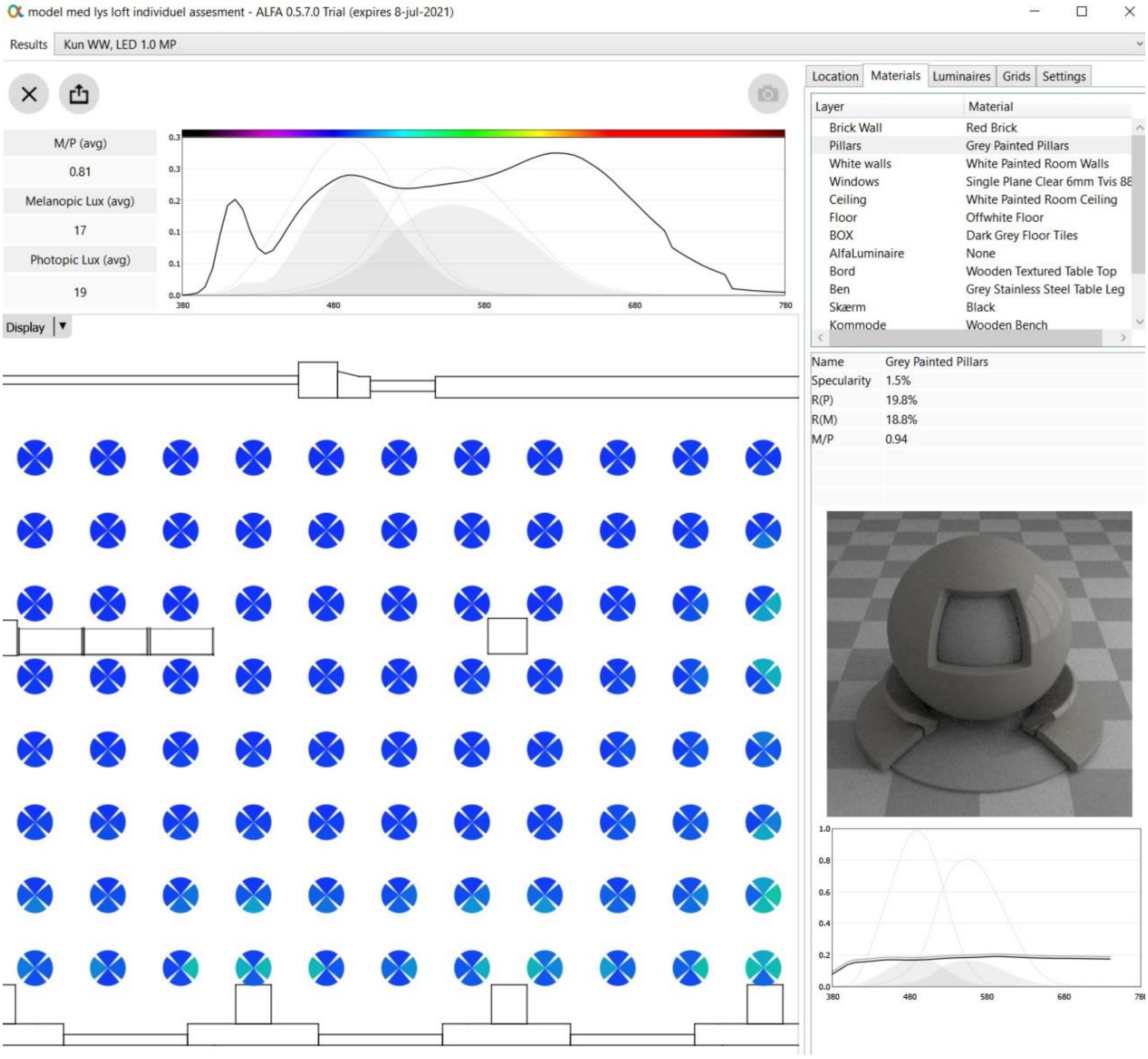
Graphical overview of more melanopic illuminance in the center of the room, less along especially the western and eastern wall:



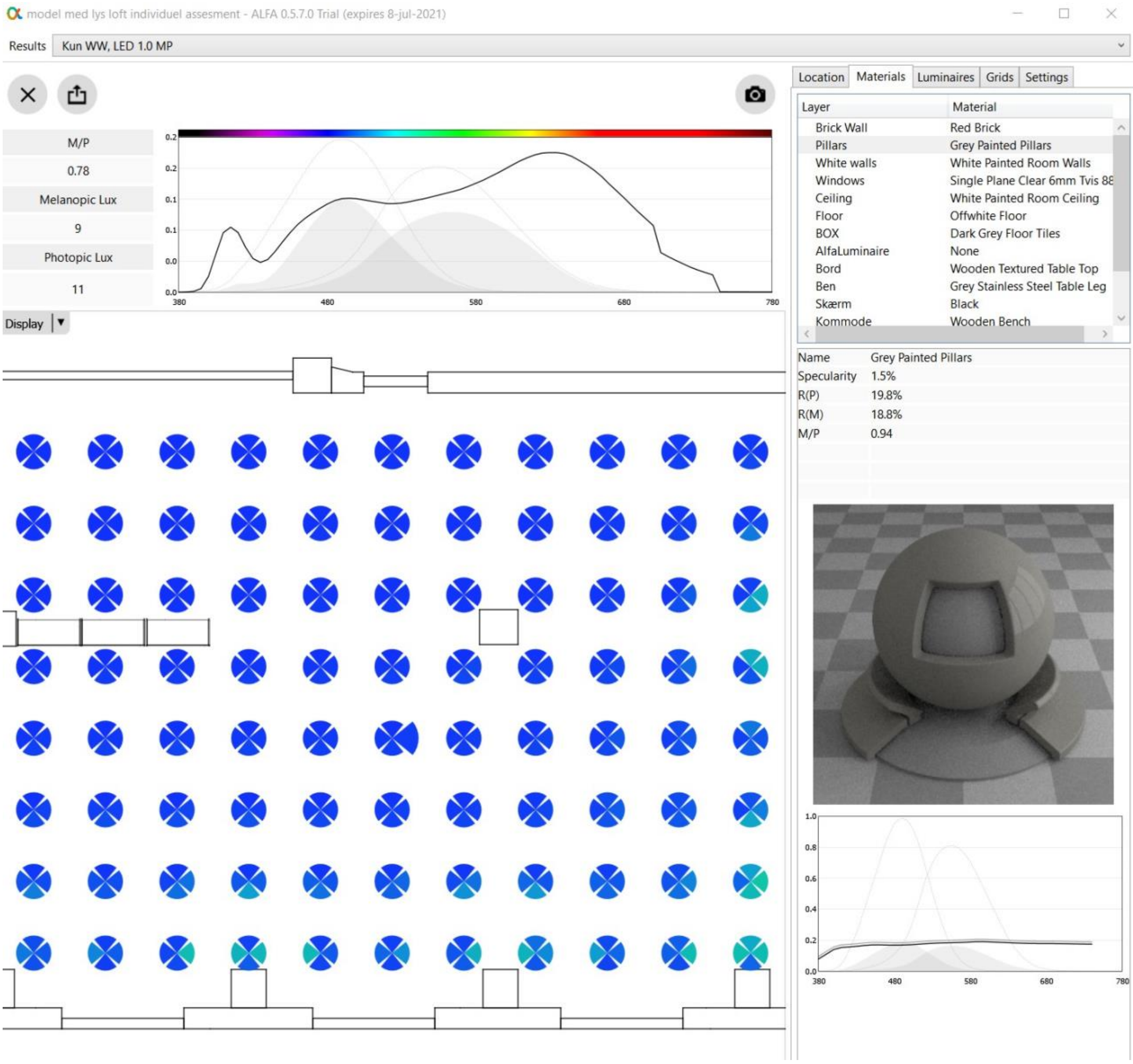
C, Alfa simulation

Calculation of light distribution solely from the 11 wall washers, set to 1.0 M/P.

Average contribution of the WW: 17 melanopic lux, 19 photopic lux:



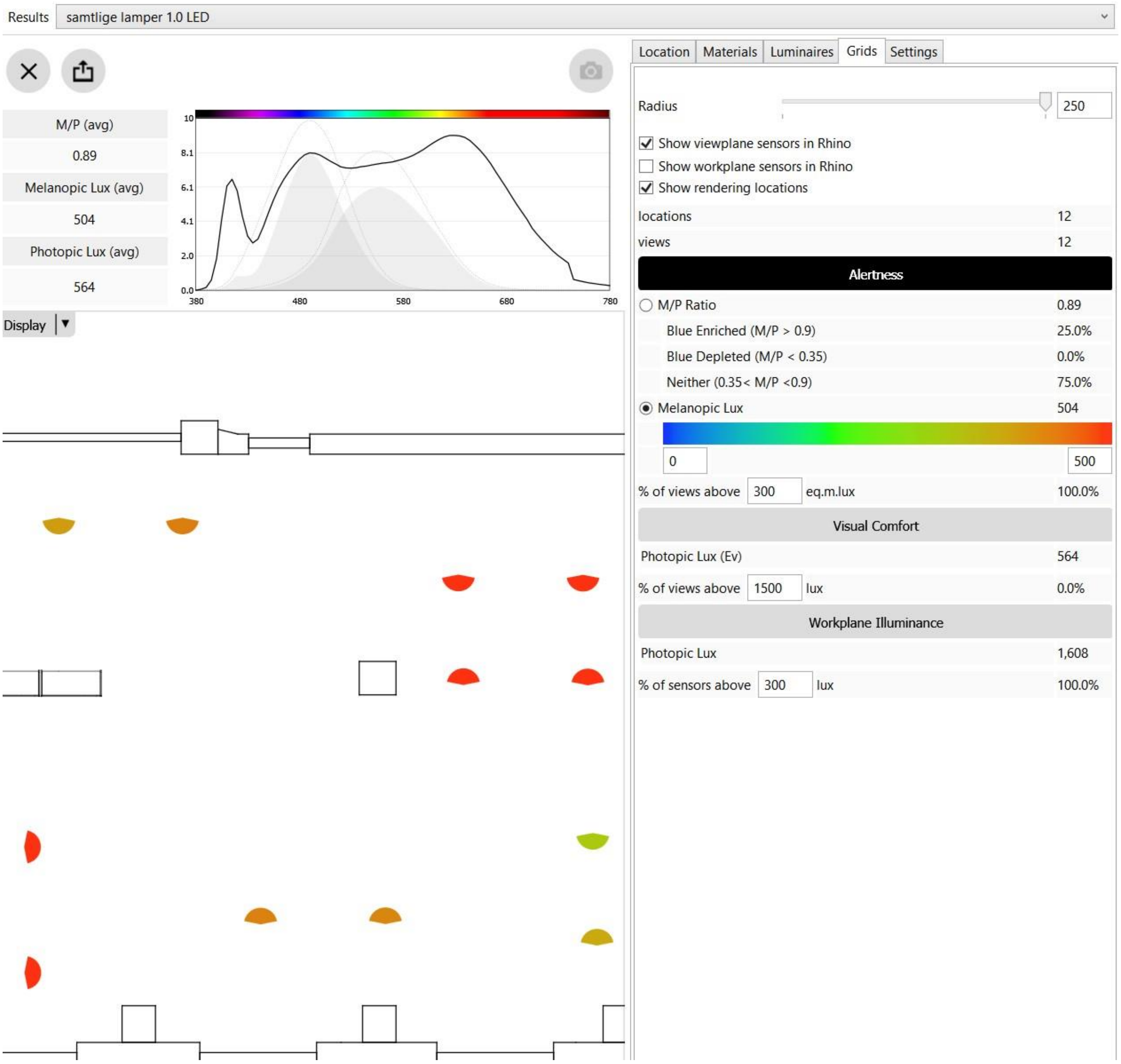
Middle direction view highlighted, results: 9 melanopic lux, 11 photopic lux:



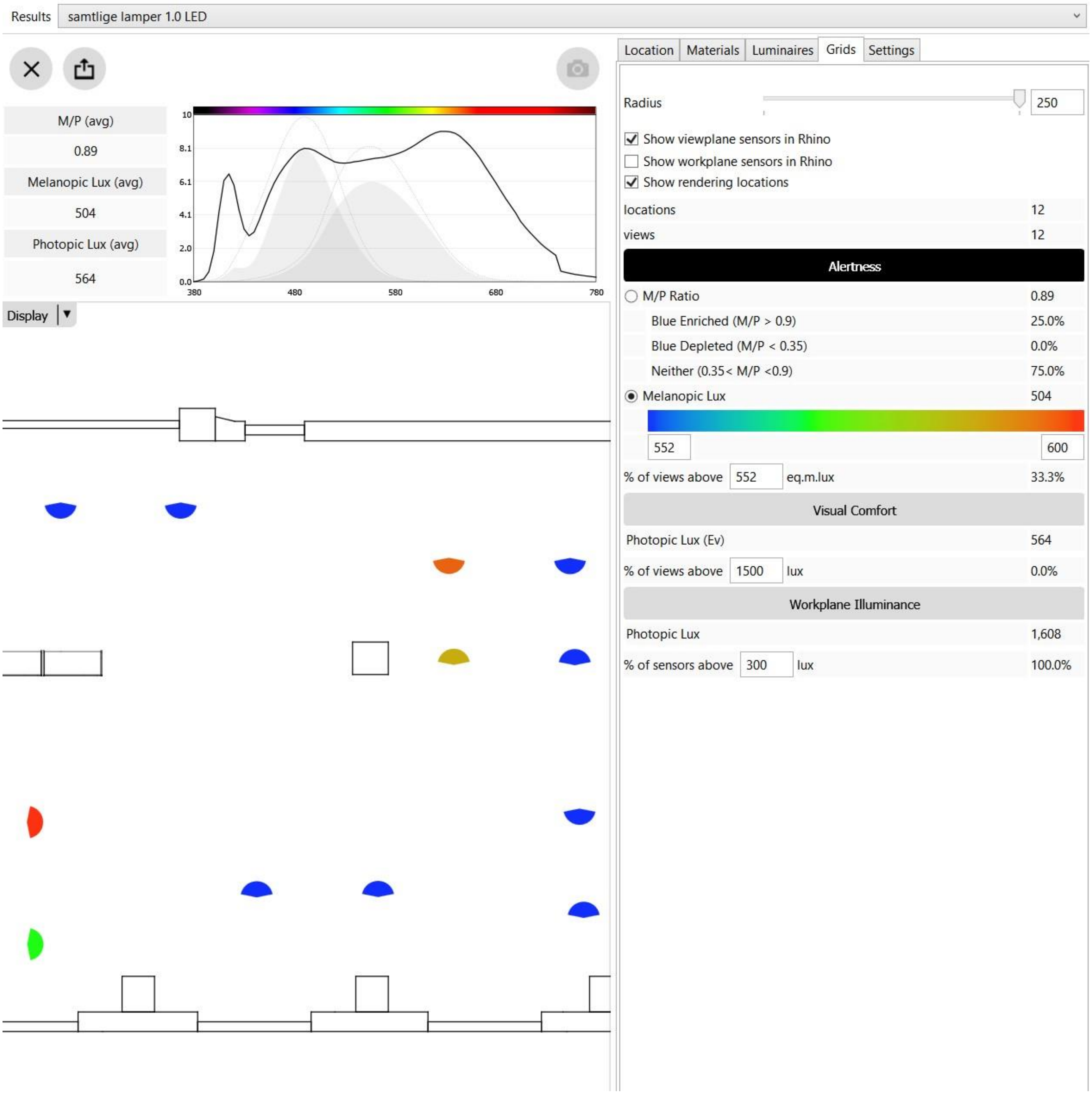
D, ALFA simulations of 1.0 M/P

Simulations of potential for melanopic illuminance had the ceiling luminaires been chosen with a spectral power distribution providing illuminance in a ratio of 1.0 M/P.

Simulation in ALFA showing 100 of views exceeding 300 EML (deducted by 50% = 150 EML):



View positions colored in blue represents desks below the consensus recommendation of 552 EML (deducted by 50% = 276 EML). The four positions in additional colors represents levels above 552 EML:



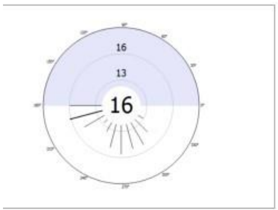
E, UGR calculations in DIALux

UGR calculation of 100% intensity from a grid plane conducted in Dialux, highlighting the UGR caused from the wall washers:

Glare calculations of 50% intensity, proving none of the individual viewing positions from the 12 desks exceed 19 UGR. The numbering of calculation points matches the assigned desk number:

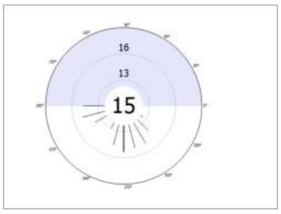
Calculation point 1 (UGR)

Strongest glare at	195°
max	16.1
Target	≤19.0
Viewing sector	180° - 0°
Step width	15°
Height	1.200 m
Index	S5



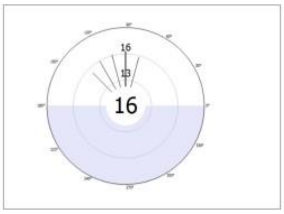
Calculation point 2 (UGR)

Strongest glare at	270°
max	15.3
Target	≤19.0
Viewing sector	180° - 0°
Step width	15°
Height	1.200 m
Index	S7



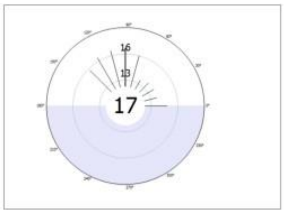
Calculation point 5 (UGR)

Strongest glare at	90°
max	16.2
Target	≤19.0
Viewing sector	0° - 180°
Step width	15°
Height	1.200 m
Index	S10



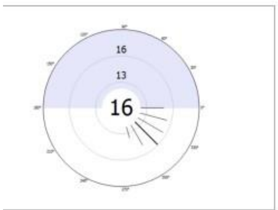
Calculation point 6 (UGR)

Strongest glare at	90°
max	16.7
Target	≤19.0
Viewing sector	0° - 180°
Step width	15°
Height	1.200 m
Index	S11



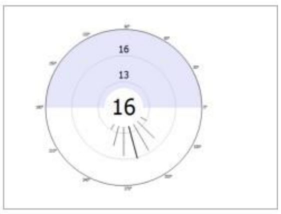
Calculation point 3 (UGR)

Strongest glare at	315°
max	15.9
Target	≤19.0
Viewing sector	180° - 0°
Step width	15°
Height	1.200 m
Index	S8



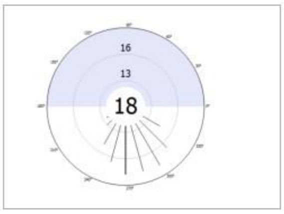
Calculation point 4 (UGR)

Strongest glare at	285°
max	16.1
Target	≤19.0
Viewing sector	180° - 0°
Step width	15°
Height	1.200 m
Index	S9



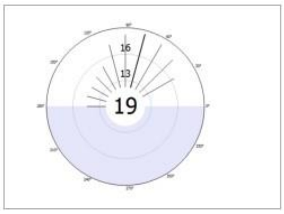
Calculation point 7 (UGR)

Strongest glare at	270°
max	17.8
Target	≤19.0
Viewing sector	180° - 0°
Step width	15°
Height	1.200 m
Index	S12



Calculation point 8 (UGR)

Strongest glare at	75°
max	18.6
Target	≤19.0
Viewing sector	0° - 180°
Step width	15°
Height	1.200 m
Index	S13

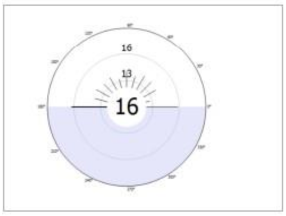


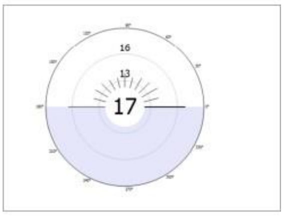
Calculation point 9 (UGR)

Strongest glare at	180°
max	16.3
Target	≤19.0
Viewing sector	0° - 180°
Step width	15°
Height	1.200 m
Index	S14

Calculation point 10 (UGR)

Strongest glare at	0°
max	16.8
Target	≤19.0
Viewing sector	0° - 180°
Step width	15°
Height	1.200 m
Index	S15



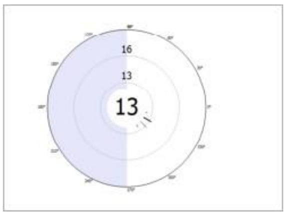


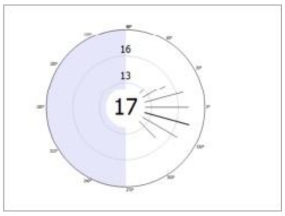
Calculation point 11 (UGR)

Strongest glare at	330°
max	13.2
Target	≤19.0
Viewing sector	270° - 90°
Step width	15°
Height	1.200 m
Index	S16

Calculation point 12 (UGR)

Strongest glare at	345°
max	17.4
Target	≤19.0
Viewing sector	270° - 90°
Step width	15°
Height	1.200 m
Index	S17





F, Summary in Danish

Dette projekt undersøger den rolle, som elektrisk belysning spiller i forhold til at stimulere menneskets døgnrytme og andre relaterede såkaldte ”ikke-visuelle” responser fra lys. Det primære princip for anvendelse af lys for sundhedsfremmende effekter består i, at den elektriske belysning, der omgiver os i vores dagligdag, skal følge solens cyklus for både lys og mørke og til en vis grad spektralfordeling af det pågældende lokale dagslys. Igennem den menneskelige evolution, har solen dikteret, hvornår der var lys og hvornår der var mørke, men i takt med introduktionen af elektrisk belysning i det moderne samfund er afhængigheden af dagslys svundet, og flere, især i urbane miljøer, bruger mere tid indendørs og udsættes for markant lavere niveauer af lys i løbet af dagen, end der findes udenfor i dagslys. I samme forbindelse er flere oppe efter mørkets frembrud og udsættes for lys, når kroppen og hjernen evolutionært er vant til, at der er mørkt. Disse mekanismer kan resultere i en forskydning den biologiske døgnrytme og kan have sundhedsskadelige følger på kroppen såvel som psyken (Lucas et al., 2014; Blume et al., 2019; Schlangen and Price, 2021)

Disse ”ikke-visuelle” responser fra lys er i høj grad influeret af særlige photoreceptorer i øjnene der kaldes intrinsisk-fotofølsomme nethindeganglionceller (ipRGC) som er særligt følsomme i området omkring 480 nm (CIE Position Statement, 2019; Brown et al., 2020) og kan bl.a. derfor ikke kvantificeres på samme traditionelle vis som visuelle responser fra lys hidtil er blevet ved maksimal sensitivitet på 555 nm (Lucas et al., 2014).

Med dette teoretiske afsæt er det blevet undersøgt, hvordan elektrisk belysning kan anvendes til disse sundhedsfremmende formål samtidig med at de overholder krav fra den europæiske standard DS/EN 12464-1 (2011), specifikt i forhold til horisontale belysningsflader og blænding. Dette fordi at ikke-visuelle effekter måles i forhold til den mængde, der rammer nethinden og derfor potentielt kan skabe blænding i forsøget om at opnå disse sundhedsfremmende effekter fra lys.

Et kontor i Gentofte har dannet rammen for at undersøge dette forhold og baseret på arealet og indretningen, er kontoret blevet simuleret i 3d software for at undersøge ovenstående forhold, samt målinger foretaget fysisk med henblik på at få indsigt i dagslysets indflydelse.

Undersøgelserne er blevet evalueret i forhold til vejledninger for melanopisk illuminans (ipRGC-sensitive del af det visuelle spektrum) formuleret af henholdsvis WELL Building Standard (2020) og Brown *et al.,* (2020). Resultaterne viste, at den pågældende elektriske belysning i Gentofte ikke kan løfte opgaven alene, hvis den skal inkludere alle tolv skrivebordspladser, dog var tre skrivebordspladser over minimumsværdien formuleret af WELL Building Standard (2020) i begge scenarier. Samtidig viste de fysiske målinger, at dagslys kan være en uovertruffen kilde til høje

niveauer af melanopisk illuminans og derfor skal der i høj grad tages højde for at udnytte dagslysets kvaliteter i etablering og indretning af kontormiljøer.