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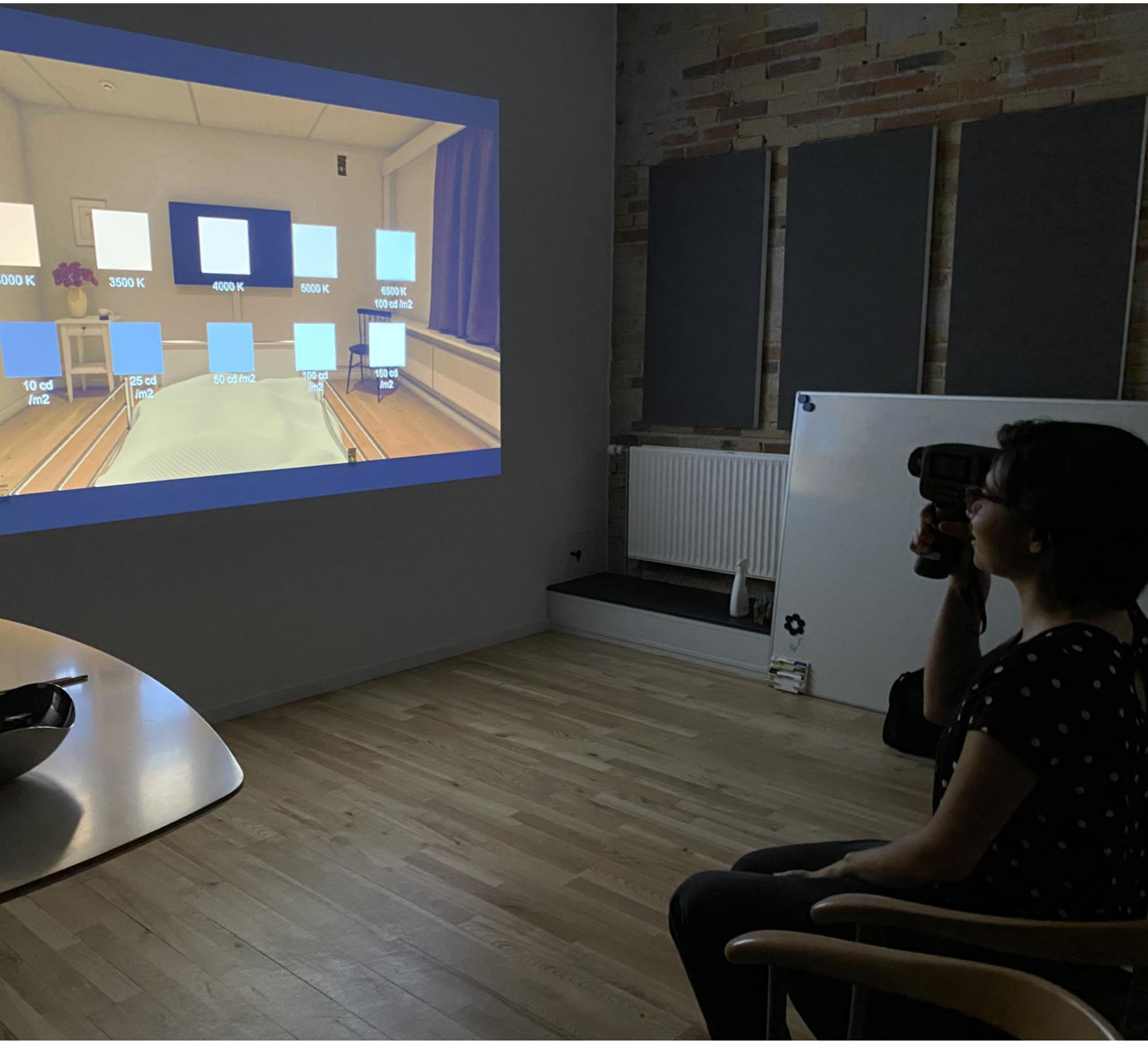
ELFORSK 351-041

Perceived spatial brightness when lighting up vertical or horizontal surfaces



Perceived spatial brightness when lighting up vertical or horizontal surfaces

Sophie Stoffer
Kasper Fromberg Støttrup
Nikodem Derengowski
Inger Erhardtsen
Werner Osterhaus
Marc Fontoynont
Jakob Markvart

BUILD
AALBORG UNIVERSITET

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FORFATTERE	Sophie Stoffer Kasper Fromberg Støttrup Nikodem Derengowski Inger Erhardtsen Werner Osterhaus Marc Fontoynont Jakob Markvart
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TRYK	[Trykkeri]
UDGIVER	Institut for Byggeri, By og Miljø (BUILD), Aalborg Universitet A.C. Meyers Vænge 15, 2450 København SV E-post build@build.aau.dk www.anvisninger.dk

CONTENT

PREFACE

Until now, the focus in lighting design has mainly been on illuminating the areas and surfaces where visual functions must take place. Lighting design has therefore most of all been a practice in optimizing energy performance and compliance with rules. With the development of newer technologies in lighting control, it has become widespread that lighting not only aims to meet visual needs, but also stimulates other non-visual human factors.

The purpose of this report is to evaluate and to generate knowledge about perceived spatial brightness by illuminating vertical or horizontal surfaces. The intention is to get closer to a clarification of whether and how much the light on the horizontal plane can be reduced by compensating with light on vertical surfaces so that perceived spatial brightness is still the same.

In this respect, the report is particularly interesting for lighting designers and other professionals working with lighting systems.

The evaluation is performed by BUILD with input and great help of various kinds from project partners in relation to the project "Dynamisk Døgnrytmelys" (In English: Integrative Lighting). Special thanks to the staff at AFRY who participated in the tests at their location.

The project "Dynamisk Døgnrytmelys" has been carried out with support from ELFORSK project no. 351-041.

Division of Sustainability, Energy and Indoor Environment

Department of the Built Environment

Tine Steen Larsen

Research Director, BUILD, Aalborg University

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INTRODUCTION

2 INTRODUCTION

Lighting has an immense impact on the experience and perception of a space. It does not only influence the atmosphere of a space, but also our ability to orientate safely in the surroundings (Fernberger et al., 1941; Carter and Carter, 1981). A successful lighting design is therefore based on a clear understanding and definition of the use of space in order to create the desired atmosphere, and to support the needs of the users, i.e. visual, physical or biological needs (Veitch et al., 1996; Veitch et al., 1998; Lechner, 2015). However, in practice, lighting design will not only have to create the intended atmosphere that meets the defined user needs but it must also meet the requirements according to standards and energy demands. This will to some degree influence the lighting design, and in some cases even restrain it. The different lighting parameters such as light distribution, light intensities, colour temperature and spectral power distribution create a palette of tools so the lighting designer can make the intended design and the flow of changes over time. Combinations of all the parameters finally creates the design hopefully being both aesthetically pleasing with the desired effect, and also meeting the requirements of building regulations.

Over the years, lighting design has been a practice in optimizing energy performance and fulfilling regulations. Recently there has been a shift of focus on what lighting design is, and it has been progressively utilized as a tool that supports architectural principles and take into consideration physiological and psychological effect on humans. This approach is based on scientific evidence for both visual and non-visual effects, officially termed as integrative lighting (CIE, 2019). What can be claimed to be integrative lighting solutions to some degree is now being applied in different building types such as offices, schools and healthcare facilities. Currently the most common place to implement lighting that supports and maintaining our biological need is in the 24h healthcare premises.

Now, several Danish healthcare premises are using light without short wavelengths during the night, in order to restore/maintain patients and healthcare workers sleep. The human circadian system is especially sensitive to the shorter wavelengths of the visual light spectrum, since this the blue wavelength part of the spectrum was found to suppress the melatonin level (Brainard et al., 2001; Rea et al., 2005). In many cases, these light installations have predominately focused on the colour spectrum and how the lighting supports the biological needs, and less on how the lighting affects our perception of space. However, it is known that our visual system and circadian system do not react to light in the same way (Rea et al., 2002).

When talking about our visual system, one can refer to variety of topics connecting light and vision, such as perception of objects, colours, distance, visibility, contrast, and others – in short, all the signal within the visible spectrum of electromagnetic waves, that the instruments in our eyes and nerve system are able to catch and process. The circadian system does not consider all these areas. Important factors are the total light energy reaching the retina of the eye where the lower end of the visible spectrum (short wavelengths, so called 'blue light') matters the most (Duffy et al, 2009). How our circadian system responds to the light that reaches the retina is still unclear and depending on several factors including the individual internal clock phases at the time of exposure. The direction of the light entering the eyes, may also be an important factor for circadian stimulus. Nevertheless, the direction of the provided illumination and how it is distributed on the retina have a large impact on our visual system and affect how visual information is formed and processed in the brain.

Lighting that predominantly illuminates vertical surfaces often creates higher perceived spatial brightness than illumination of horizontal surfaces, since vertical surfaces (in enclosed spaces) typically cover a larger part of our visual field (Cuttle, 2013; Duff et al., 2017). Duff et al. (2017) have reported on a pilot study where they found a clear relationship between mean room surface exitance and spatial brightness, but not the same relationship was found for horizontal illuminance. Most standards clearly state requirements for the horizontal illuminance and DS/EN 12464-1 (DS/EN 12464-1, 2012) does in fact have requirements for vertical illumination to obtain a balanced luminance distribution. However, illuminating vertical surfaces will most often result in a higher energy use and is consequently a less used lighting strategy in practice. Nevertheless, if illuminating vertical surfaces can create a brighter perception of a space, it may be possible to reduce the horizontal illumination and at the same time create a perceived spatial brightness comparable to a downlight scenario meeting the horizontal illuminance requirements according to the standard DS/EN 12464-1. By comparing lighting scenarios based on illumination of either vertical (via wall-washers) or horizontal (via downlights) room surfaces and the effect on spatial brightness perception, this study investigates if the horizontal illumination can be reduced without negatively affecting the perceived brightness of a space. If it is possible to reduce the horizontal illumination, and at the same time maintain a perceived spatial brightness equivalent to a downlight scenario that meets the requirements of DS/EN 12464-1, it will make the two strategies more comparable from an energy point of view.

The perceived brightness is not only influenced by how the light is distributed. It is also dependent on the spectral power distribution of the light. The spectral sensitivity curve for our visual system does not match the sensitivity curve of our circadian system being most sensitive to the shorter wavelengths peaking around 484 nm (Prayag et al., 2019) (figure 1). Our visual system is most sensitive to the middle wavelengths in relation to brightness perception, with a sensitivity peak around 555 nm (Lockley, S.W., 2010).

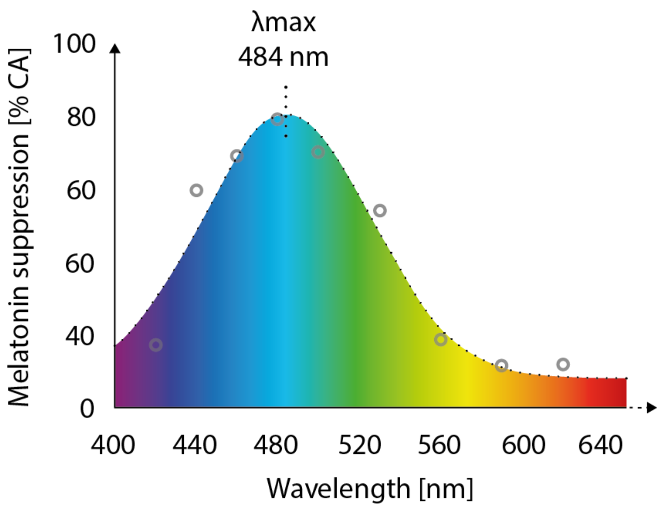


FIGURE 1. Melatonin suppression in relation to the visible spectrum wavelengths. The curve is noticeably peaking at 484nm. Modified figure from: “Light Modulation of Human Clocks, Wake, and Sleep” by Prayag et al., (2019).

This study investigates the perceived brightness of a space. Lighting scenarios with vertical and horizontal illumination concepts were tested. We used *Full Spectrum Lighting* (FSL) and lighting without radiation in the short wavelengths band that we here refer to as *Reduced Spectrum Lighting* (RSL). Lighting that is diminished in the short wavelengths band around 484nm (sensitivity peak curve shown in Figure 1), or so called 'blue light wavelengths', has less effect on human circadian system, while suppressing the melatonin production to less extent. In other words, a light source reduced in the short wavelengths results in less suppression of the melatonin production by the pineal gland. Thus, RSL is more beneficial during night time towards an improved sleep quality, and appears visually more orange or reddish.

This study is a subpart of a larger study investigating the spatial perception, user need, -interaction and -satisfaction with circadian lighting and how it performs energy wise. Nevertheless, this study will only focus on the spatial brightness perception while other parts of the project will address other issues.

3

APPROACH

3 APPROACH

This chapter describes the scientific approach including the aim and hypothesis of the study. The test is based on a method developed in 2017 by Fontoynont et al.

3.1 Aim of the study

According to standards, there are minimum illumination levels on both horizontal and vertical surfaces. However, most work planes requirements base on the horizontal illuminance. The aim of this study is to investigate if illuminating vertical surfaces of a space resulting in reduced horizontal illumination from reflected light on the floor can create the same perceived spatial brightness, as a more traditional downlight lighting scenario that meets the illumination requirements on horizontal surfaces according to DS/EN 12464-1. We examine if the perceived spatial brightness is the same between the two scenarios or lighting designs strategies of vertical illumination (wallwashing) and horizontal illumination (downlighting). This is done under full spectrum lighting and a lighting spectrum being diminished in the short wavelength band, thus resulting in differences in CCT on the screen, to explore possible differences between the two.

Thus, we test two different spectral power distributions and two designs strategies of vertical illumination (wallwashing) and horizontal illumination (downlighting). The test is conducted through simulations of two different types of spaces in a healthcare facility being a hallway and a patient room.

3.2 Hypothesis

Focus on illuminating vertical surfaces may result in a greater perceived spatial brightness than focusing on illuminating horizontal surfaces only. Thus, the horizontal illuminance suggested by the relevant standards can be decreased, while still creating the same perceived spatial brightness.

3.3 Method

To investigate this, a comparison test was conducted. The test participants were to differentiate and select between different simulated lighting scenarios. This was done for lighting scenarios with both full spectrum lighting and lighting with diminished radiation in the short wavelength band.

The method used is based on a method developed and used in a previous study, conducted at the Department of the Built Environment, Aalborg University in Copenhagen (Fontoynont et al., 2017), using high quality photorealistic visualisations on a calibrated projection on a screen.

4

SPATIAL BRIGHTNESS PARAMETERS

4 SPATIAL BRIGHTNESS PARAMETERS

In this chapter, we describe the simulated space and the many different parameters defining the space. Furthermore, we go through the test procedure and calibration of the test setup at AFRY in Aarhus.

4.1 Concept

The concept of the test was to investigate if it is possible to use indirect lighting reflected from the walls for illuminating the floor, to justify and compensate for a lower minimum required horizontal illuminance (according to DS 12464-1). And in doing so, maintaining the same perceived brightness of a space as when the floor is directly illuminated by downlights, see figure 2 below.

FIGURE 2. A downlight reference scene with the light directly hitting the horizontal plane (left) and a wallwasher scene providing diffuse light reflected from the walls on the horizontal plane (right), under full spectrum lighting (FSL).

Participants of the test were asked to assess two different lighting strategies (vertical vs. horizontal illuminated surfaces) through a questionnaire. During the test, the reference lighting scenario ('downlight') was presented pairwise with six vertically wall illuminated scenes, each with a different illuminance level on the floor. The test participants were asked to select the lighting scenario that they perceived as equally bright as the reference downlight scenario.

From all the options, only the reference lighting scene and three of the vertical wall illuminated scenes corresponded to the horizontal illuminance minimum requirements according to DS 12464-1, of 50 lux. Moreover, one of the vertically illuminated scenes had the same average pixel value (RGB average values between 0-255) as the reference scenario, which was translated to average luminance of the projected pixels. Average pixel value is not the same as mean exitance from the final projected image, but it was used as a threshold in the processing of images for the tests and digitally measureable parameter used for comparison.

The lighting scenes were presented to the test participants in form of photorealistic renderings projected on a white wall and being calibrated in luminance and CCT. There were two scenes – patient room and a hallway – with two types of light spectrum. Table 1 below summarize the combinations of the scenes and horizontal light levels for the two simulated spaces:

TABLE 1. Concept of the simulated scenes for the two different room types. Test were performed both under full spectrum lighting (FSL) and reduced spectrum lighting (RSL).

Patient room		**Hallway**	
Horizontal illumination (downlight reference)	Vertical illumination (wallwash comparison) - variable lux -	Horizontal illumination (downlight reference)	Vertical illumination (wallwash comparison) - variable lux -
50 lux at floor	*10 lux at floor*	*50 lux at floor*	*20 lux at floor*
	20 lux at floor		*30 lux at floor*
	*27.5 lux at floor **		*40 lux at floor*
	40 lux at floor		*50 lux at floor***
	50 lux at floor		*60 lux at floor*
	60 lux at floor		*70 lux at floor*

* 27.5 lux was chosen instead of 30lx.In this setting the average luminance of the image was the same as in the downlight reference image, based on average pixel value calculated by Photoshop Histogram tool. This was the case under both full spectrum lighting (FSL) and reduced spectrum lighting (RSL).

**50 lux wallwash variation had the same average luminance of the image as the 50 lux downlight reference image. Therefore, in the hallway scenario the vertical illumination of the images vary with equal 10 lux intervals at the floor. This was the case under both full spectrum lighting (FSL) and reduced spectrum lighting (RSL).

4.2 Lighting parameters

The study investigated the perceived brightness between spaces that have directed illumination on vertical or horizontal surfaces (whether the floor, or the walls are directly illuminated). In addition, this study also investigates if there is a difference in the perceived brightness of the two lighting strategies, depending on the spectral power distribution (SPD) of the light source, as it was found in earlier studies, that brightness perception of space can be influenced by the SPD (Bullough *et. al*. 2013). Bullough *et. al*. (2013), confirms that using a yellow spectrum (without short and long wavelenghts), requires to have approximately 2 times more illuminance for the same brightness perception as in light with a SPD that contain the blue component (short wavelengths).

4.2.1 Light distribution

The two lighting strategies based on two different light distribution techniques: vertical illuminated surfaces (through wall washers) that provide light on horizontal plane through reflected light, and directed lighting on the horizontal plane (through downlights). See figure 3 below:

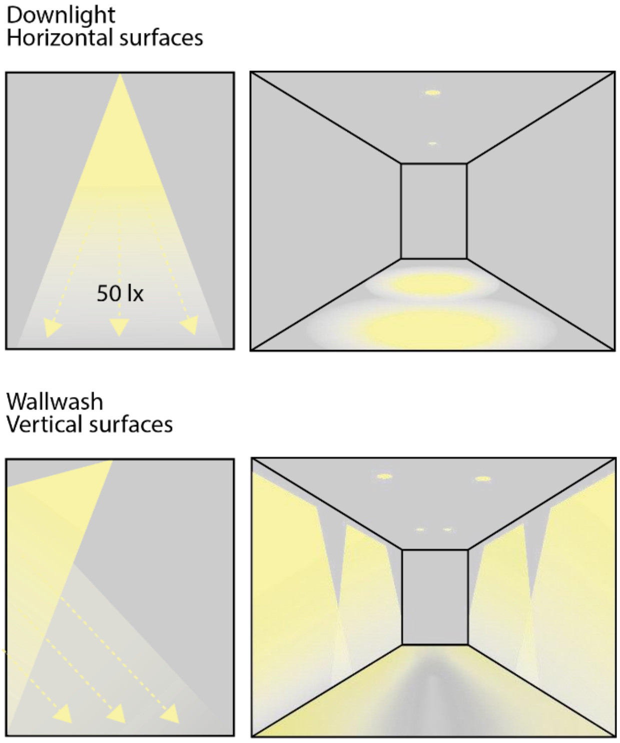


FIGURE 3. Concepts of light distribution examined in this study. The upper illustrations shows the downlight scenario directly illuminating the horizontal plane and the bottom illustrations shows the wallwasher scenario, with wall reflected light illuminating the horizontal plane.

The two light distributions were expected to result in different spatial brightness perceptions, since the vertical surfaces cover more of our field of vision compared to horizontal surfaces (Duff *et. al.* 2017). Additionally, the lighting scenarios based on vertical illuminated surfaces will need a higher lumen output to meet the same illuminance at the floor compared to the scenario based on horizontal illumination, because part of the lumen package is lost through the reflection. However, if vertical illuminated surfaces create a higher perceived spatial brightness, it was anticipated that the illuminance at the floor can be lowered and still have the space perceived as equally bright as when only the horizontal surfaces were directly illuminated. For this study, the reference was a scene where the floor (horizontal surface) was illuminated directly through downlights, with an average of 50 lux. It was compared with a scenario where the average lux level on floor was varying (6 levels, as seen in the table 1), and was provided only through reflected light from the walls. All presented scenes were defined by illuminance on the horizontal floor plane. The lighting scenarios did not consider uniformity according to the DS/EN 12464-1 requirements. In addition, in the selection of scenes, one of the options was based on ‘’average image luminance’’ and it had the same overall image luminance as the reference image, (measured as average pixel value through Photoshop Histogram tool), regardless of the illuminance level on the floor in the scene projected on the screen during the tests.

It is important to mention, that the setup of the scene lighting was chosen with an aim to simplify but still represent the two lighting methods. In reality, the actual lighting design would likely include more complex light scenes – for example including additional task lamps (reading light) by the patient bed.

4.2.2 Spectral power distribution

The main principle of integrative lighting is to exclude the short wavelengths in the lighting provided during nighttime, with a goal of preventing disruption of the users' circadian rhythm. Integrative lighting is defined as lighting that is specifically intended to integrate visual and non-visual effects, producing physiological and psychological effects on humans that are reflected in scientific evidence (CIE International Lighting Vocabulary, currently available as DIS (CIE 2016), "integrative lighting"). According to the physiology of the eye, the perceived spatial brightness is not only affected by light levels and light distribution but also by the spectral power distribution of the light. Since the visual system has sensitivity peak in the middle wavelength (green) span of the visible spectrum, it could be assumed that brightness perception will be dependent on the spectral power distribution as well. Therefore, we test the spatial brightness perception for the two lighting strategies illuminated by two different spectral power distributions; one full spectrum (FSL) and one without short wavelengths (RSL). The FSL and RSL lighting is thus composed by mix of RGB lights, where the B (blue) equal to zero for the RSL lighting. According to DS/EN 12464-1, at night in hospital wards there is a requirement of a Ra = 80, but this will only be achievable for the FSL. Likewise, the CCT of the FSL equals 3000 K in the test, but the lack of B light hinders us from stating a CCT for the RSL. See figure 4 below.

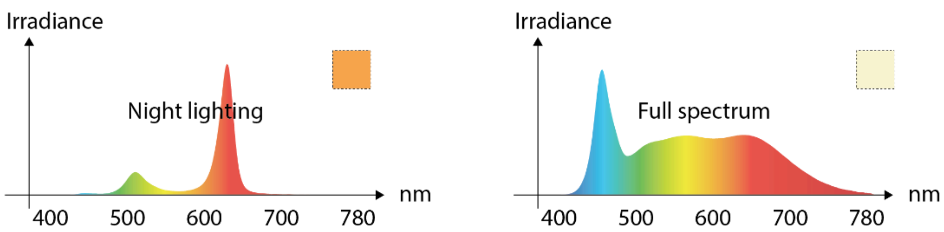


FIGURE 4. Principle of LED Spectral Power Distribution (SPD) for the tested lighting scenarios. On the left-hand side, a lighting scenario without short wavelengths and on the right hand side a full spectrum lighting scenario.

4.2.3 Illuminance

Currently integrative lighting (CIE, 2019) concepts are predominantly applied in healthcare settings. The chosen areas for the case study were therefore a patient room and a hallway – both essential parts of any healthcare facility and with differences in geometry. The spatial brightness perception is influenced by the geometry of the space and highly dependent on the lighting strategies of either mainly illuminating vertical or horizontal surfaces. The illuminance levels are by definition directly linked to brightness, but dependent on the point of measurement or in this case the observer.

According to DS/EN 12464-1, during the day corridors and wards at health care premises require a horizontal lux level of 100 lux (corridors for multipurpose functions require 200 lux). At nighttime, the required illumination is 50 lux at the corridors and 5 lux as observation lighting at night at the wards where patients are present and normally should be sleeping. For the tests, the 50 lux was chosen as a threshold for both rooms differing in their geometry. This was done although the DS/EN 12464-1 states other requirements for the general lighting at the health care wards at night. The same lux threshold was intentionally selected for the purpose of comparing the results of the two rooms differing in the geometry.

To use 100 lux as a threshold was considered but this counteract the idea of simultaneously testing the RSL situation that is designed for night lighting (and thus it would not realistically be used to illuminate the space with >50lx). Testing light levels of 5 lux or below was not relevant, since we wanted to test under photopic light conditions. As seen in table 1, majority of the scenes were representing situations where horizontal illuminance on the floor is below 50 lux.

The spatial brightness perception is influenced by the geometry of the space and the illuminance levels are directly linked to the brightness. Some lighting strategies are therefore more appropriate to use for some spaces or room dimensions than for others. Hence, it was decided to assess the two lighting strategies (vertical vs. horizontal illumination) in two different room layouts/geometry to see how the two lighting strategies are perceived.

The projector used had a limited span of lumen output, both in the dark and bright parts of the projected images. When the projector projects black, the most black colour will be a mix of the colour of the projected surfaces in the given illuminated context and light spill from the projector. The brightest projection is limited to the lumen specifications of the light source used in the projector, in combination with the distance from the projector to the projected surface. Moreover, the span of light levels between the darkest and brightest point on the projected surface, depends on the settings of the projector. Therefore, the calibration part of the test is an essential procedure.

4.3 Simulation tools

The software used for analysis, modelling and creating visualisations were DIALux Evo, Autodesk 3D Studio Max 2020 and V-ray ver.5.00.02.

Initial calculations were made in DIALux Evo to estimate the lumen effect and positioning of the luminaires necessary to achieve the desired lighting effects. In DIALux Evo, the materals' reflectance were 50% for walls, 80% for ceiling and 10% for floor. No furniture or equipment were considered in the initial simulation.

Afterwards, 3D Studio max was used to model the spaces in detail, and later V-ray was used to simulate materials, lighting, and finally render the visualizations. No post processing was applied to the images in order to keep the physical correctness and parameters extracted from the V-ray lighting analysis tool (calculation of illuminance and luminance). Render parameters for the virtual camera were: f stops: f/8; shutter speed: 1/50; ISO: 3072,5; white balance: D65.

V-ray operates in sRGB parameters, therefore all materials and their characteristics are defined within those scales and 0-255 range, and so are the displays/projections. V-ray is capable of reading and simulating lighting from IES files, assuring realism and accuracy of the chosen light sources. However, in terms of parameters such as spectral distribution and colour temperature, they are simulated using RGB values. The colour temperature simulated in the software comes from adjusting of the three base RGB colours, without technical possibility of utilising the full spectrum of a 'real light'. For example, simulated incandescent light or a candle light, which both have very broad spectrum, will not project the same wavelengths to our eyes on a screen or projection surface, as they would in reality due to the limitations of the digital RGB images and used equipment (the projector).

4.4 Simulation models

4.4.1 Patient room

The patient room was modelled based on a patient room from Vikærgården, which is a recovery ward for patients after surgery. Due to restricted access to the site (COVID-19 situation), the room was modelled based on measurements and pictures from a report that used this space as case study: ''Development of a light measurement method: assessing lighting and human light exposure using a RaspberryPi camera and dosimeters in a short-term care facility'' (Dobos, H.F., 2020). Besides simulating existing architecture, the room was fitted with furniture and equipment (digitally) for added realism.

The room was 2.5m high, 15.7m^2 space with a window behind a curtain on one wall, and doors to the small kitchen and bathroom on the opposite wall (see figure 5, figure 6 and figure 7 below). Material for the white wall and ceiling paint specified in V-ray software had the following parameters: Diffuse colour: 230,230,230; Reflect: 100,100,100; Glossiness: 0.3. The material for the floor was a wooden floor texture. As mentioned before, chosen light fixtures for the renderings included downlights in the reference scenario, and wallwashers in the variable scenario – see Appendix section 8.5 for technical specification.

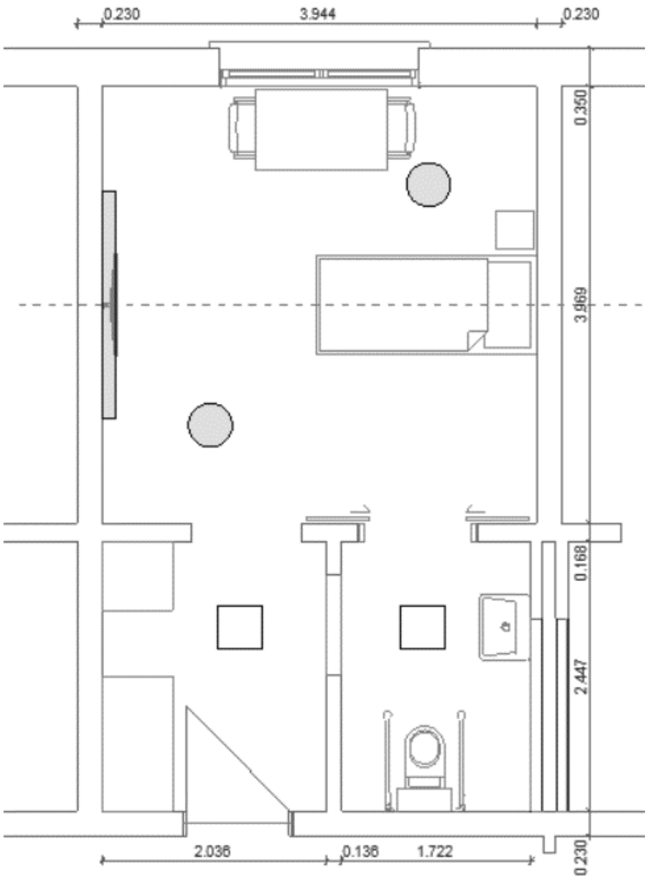


FIGURE 5. Plan drawing of the patient room (Dobos, 2020)

FIGURE 6. Picture of the room with existing electrical lighting (Dobos, 2020)

FIGURE 7. Hemispherical picture of the room at daytime (Gkaintatzi-Masouti, 2020)

Figure 8 shows the reference scene with downlights in FSL. Moreover, figure 9 and figure 10 below show one of the vertical illuminated lighting scenes (wallwasher) of the patient room under full spectrum light and lighting with reduced spectrum, respectively.

FIGURE 8. One of the visualizations of the patient room – reference scene with downlights in FSL 3000K providing 50lx average horizontal illuminance on the floor level.

FIGURE 9. One of the visualizations of the patient room – scene with wallwasher lighting in FSL 3000K providing 27.5lx average illuminance on the floor.

FIGURE 10. One of the visualizations of the patient room – scene with wallwasher lighting in RSL providing 27.5lx average illuminance on the floor.

4.4.2 Hallway

The second simulated room type was a hallway leading to the patient rooms. It was modelled as a standard (not based on an existing area) hallway with 2.5m height, 2.0m width, 16.0m length, doors on each side and furniture for added realism. Again, the chosen light fixtures were downlights for reference scenario, and wallwashers in the second, variable scenario.

figure 11 shows the reference lighting scene of the hallway (downlight) under full spectrum lighting with an illuminance of 50 lux at the floor. figure 12 and figure 13 shows the vertical illuminated lighting scenes (wallwasher) of the hallway under FSL and RSL, respectively.

FIGURE 11. One of the visualizations of the hallway – reference scene with downlights in FSL 3000K providing 50lx average horizontal illuminance on the floor.

FIGURE 12. One of the visualizations of the hallway – Scene with wallwashers in FSL 3000K providing 50lx average horizontal illuminance on the floor.

FIGURE 13. One of the visualizations of the hallway – Scenario with wallwashers in RSL providing 50lx average horizontal illuminance on the floor.

4.5 Selected luminaires

Two types of luminaires from Fagerhult were used in the simulations:

- Pleiad G4 125 Rec DALI 1519LM Black Medium T/W
- Pleiad G4 WW Rec DALI 1095LM Matt RGBW.

The used lumen output was calculated using V-ray Light meter, which is an internal V-ray lighting analysis tool simulating a luxmeter. Measurement grid was placed on surfaces inside the 3D-modeled rooms. They were rectangles placed on level of the floor, with an off-set from the walls – for the room the luxmeter surface area measured 3550mm by 3500mm, and for the hallway 1900mm by 15500mm. The grid was divided into 64 measurement points in the Patient Room, and 240 measurement points in the Hallway. table 2 shows the luminaires used for the renderings. See appendix 9.5 for the technical data sheets of the luminaires.

TABLE 2. Luminaire specifications (From fagerhult.com)

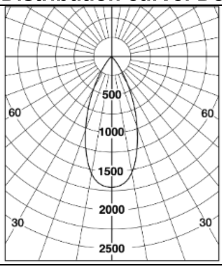
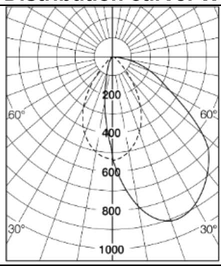
Fagerhult **Pleiad G4 125 Rec DALI 1519LM Black Medium T/W**		**Fagerhult** **Pleiad G4 WW Rec DALI 1095LM Matt RGBW**	
Best.nr.75202-20722		Best.nr.73181	
			
Distribution curve: Downlight		**Distribution curve: Wall-wash**	
			
Specifications:		**Specifications:**	
Watt:	20W	**Watt:**	24W
Efficacy:	80lm/W	**Efficacy:**	46lm/W
CRI:	90	**CRI:**	90
CCT:	T/W (Customized RGBW)	**CCT:**	RGBW
IP class:	64	**IP:**	64
Control:	DALI	**Control:**	DALI
Flux:	1519 lm (Customized below)	**Flux:**	1095lm
Red:	331 lm	**Red:**	186lm
Green:	349 lm	**Green:**	186lm
Blue:	280 lm	**Blue:**	186lm
White:	1684 lm	**White:**	1095lm

Table showing the specifications for the used luminaires in this study.

To meet the required illuminance of 50 lux on the horizontal plane, a calculation study in DIALux Evo has shown that the patient room should be illuminated with four downlights for the horizontal illuminated scenes and six wallwashers for the vertical illuminated scenes.

Moreover, figure 14 show the location of the luminaires in the patient room and the illuminance for the reference lighting (downlight) and one of the wallwasher scenes, respectively. Both of the showed lighting scenes have an illuminance at 50 lux.

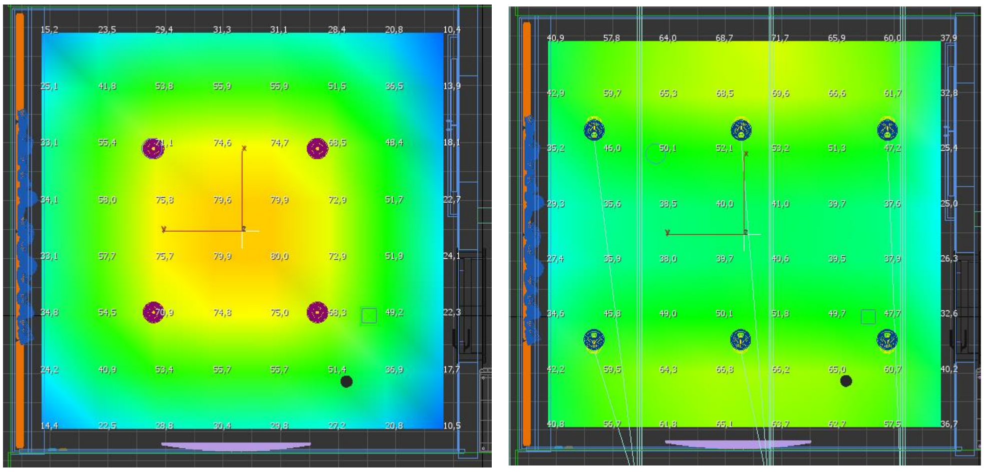


FIGURE 14. Screenshots of V-ray light meter tool, showing illuminance on the floor in the Patient Room with: 1) Reference scenario on the left - four downlights at 190lm each, 2) On the right - six wallwashers at 160lm each. In each scene the light was providing 50lx average illuminance on the floor.

The required illuminance of 50 lux at floor level in the hallway is met with seven downlights for the horizontal illuminated scenes and fourteen wallwashers for the vertical illuminated scenes. figure 15 show the placements of the luminaires in the hallway and the illuminance for the reference lighting (downlight) whereas figure 16 shows this for one of the wallwasher scenes. Both of the showed lighting scenes have an average illuminance at 50 lux. The illuminance distribution for the rest of the vertical illumination scenes can be found in Appendix section 8.4.

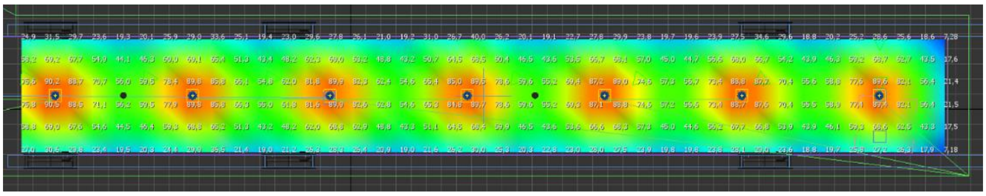


FIGURE 15. Screenshot of V-ray light meter tool, showing illuminance on the floor in the Hallway reference scenario with four downlights at 215lm each, providing 50lx average illuminance on the floor.

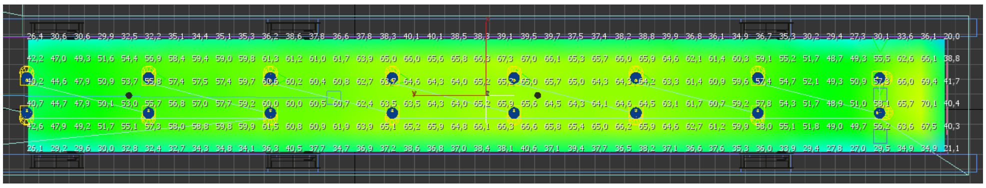


FIGURE 16. Screenshot of V-ray light meter tool, showing illuminance on the floor in the Hallway scenario with 14 wallwashers at 110lm each, providing 50lx average illuminance on the floor.

The table 3 below specifies different luminaries with their simulated lighting output for each of the visualisations:

TABLE 3. Overview of luminaries and their effect used in visualizations

ROOM TYPE	SCENE	AVG. LUX ON FLOOR	FIXTURE NAME	LUMEN OUTPUT IN V-RAY (PER LUMINAIRE)	NO. OF FIXTURES
Patient room	Reference - Downlights	50lx	Pleiad G4 125 Rec DALI 1519LM Black Medium T/W	190lm	4
	1A – Wallwashers	10lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	32lm	6
	1B – Wallwashers	20lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	64lm	6
	1C – Wallwashers	27.5lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	90lm	6
	1D – Wallwashers	40lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	128lm	6
	1E – Wallwashers	50lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	160lm	6
	1F – Wallwashers	60lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	192lm	6
Hallway	Reference - Downlights	50lx	Pleiad G4 125 Rec DALI 1519LM Black Medium T/W	215lm	7
	2A – Wallwashers	20lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	44lm	16
	2B – Wallwashers	30lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	66lm	16
	2C – Wallwashers	40lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	88lm	16
	2D – Wallwashers	50lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	110lm	16
	2E – Wallwashers	60lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	132lm	16
	2F – Wallwashers	70lx	Pleiad G4 WW Rec DALI 1095LM Matt RGBW	154lm	16

Table showing the specifications for the used luminaires in this study.

In terms of estimating the actual lumen output of the luminaires, initial calculation in DIALux showed values approximately 30% higher than the ones later calculated in V-ray, due to differences in reflectance factor of materials. Low reflectance (50%) in DIALux Evo was estimated to take into consideration non-reflective elements that are usually present in such spaces: pictures on walls, posters, infographics etc. In V-ray, the walls had higher reflectance - closer to reality - in order to aim for a realistic simulation of colour.

In the final steps, further cross-checking trials were made in DIALux Evo with a white wall material at 85% reflectance (corresponding to a clear, white painted wall) and lumen values copied from V-ray (the software). Reached average illuminance levels were very close to the ones achieved in V-ray. This gives an indication that despite different interface and workflow (way of defining the parameters), both of the software perform similar calculation methods.

4.6 Spectral Power Distribution

There were two types of simulated spectral power distribution (SPD) of the luminaries – full spectrum, and one without short wavelengths (night spectrum, or reduced spectrum lighting). For the full spectrum SPD, the chosen colour temperature was 3000K. For the scene with RSL, the SPD was first simulated in DIALux Evo (figure 17), with a filter cutting off blue frequencies. Such practice was later translated into V-ray parameters, where the closest effect to the desired lighting temperature/colour was achieved by adjusting the light colour to **255/80/0** RGB values, using "colour mode'' for defining the light sources (as opposed to ''temperature mode'') (figure 18).

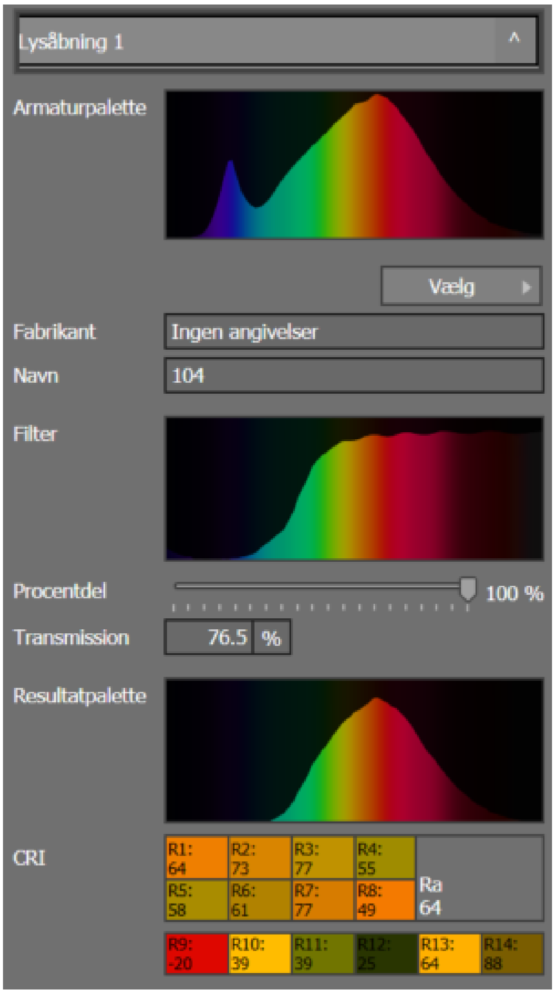


FIGURE 17. Filter in DIALux Evo, showing the initial LED SPD (first diagram), then the applied filter (second diagram), and the result, which is SPD of the simulated night lighting without short wavelengths (third diagram)

FIGURE 18. sRGB settings of simulation of night light in V-ray

5

VISUAL PREFERENCE TEST

5 VISUAL PREFERENCE TEST

In this chapter, we describe the test conditions and the space provided at AFRY in Aarhus, in which the test was performed. Furthermore, we touch upon the calibration of the test setup and the test procedure.

5.1 Test room

Test sessions were performed in a meeting room at AFRY, Søren Frichs Vej 34A, in Aarhus. The room had no access to daylight, and the test coordinators had full control over electric lighting. The dimension of the room was 4.40m x 4.50m (figure 19). The four participants per test were placed side by side, approximately 3.00m from the projected wall.
The projector was installed on a shelf with the lens placed in a height of 1.15m, 3.40m from the projected wall (see picture on figure 20). This exact placing was predetermined in a calibration pre-study, and expected to give the most precise calibration values on the biggest canvas size as possible.

The two test coordinators were positioned just behind the participants on either side of the projector. One was informing the participants about the test procedure and read the questions during the test. The other coordinator was in control of the calibrated presentation, and the time and duration of each presented scene.

The projection size was a 2.60m x 1.60m rectangle on a white wall and is illustrated by the sketch below in figure 19. When two images were presented side by side the size of each image was 1.29m x 0.90m.

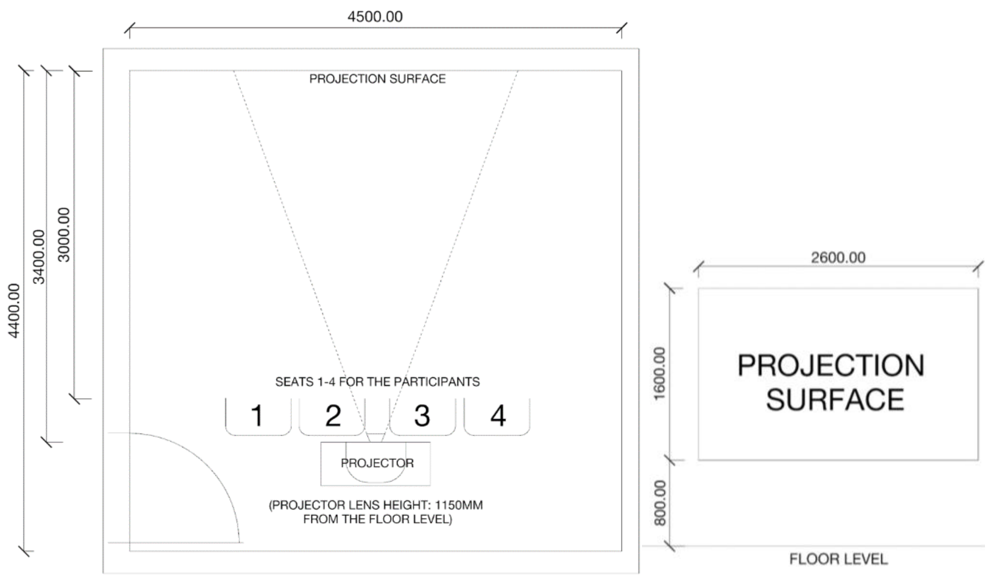


FIGURE 19. Plan drawing of the room (left), and sketch illustrating projection surface on the wall (right).

5.2 Test procedure

Test sessions took place on the 2nd and 3rd of July 2020. Prior to the test, participants were asked to fill in an anonymous information sheet regarding their gender, age, use of visual aids and vision problems.

Participants were introduced to the task they were about to commence. They had to answer two questions for each of the four scenarios (two scenarios with patient room, and two scenarios with the hallway). In the first question, they had to choose images that in their opinion represented a scene equally illuminated as the reference scene (Q.1), and in the second part, the test image that they considered as the most pleasant lighting scene to be in (Q.2). The overview of testing sessions, scenarios, and scenes can be seen in table 5 at the end of this section.

FIGURE 20. Explaining the test procedure

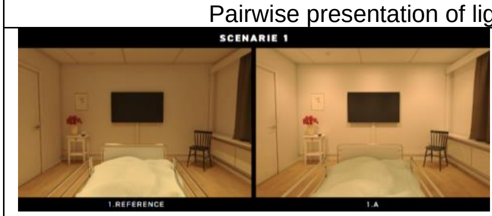
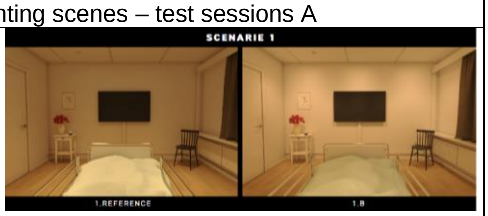
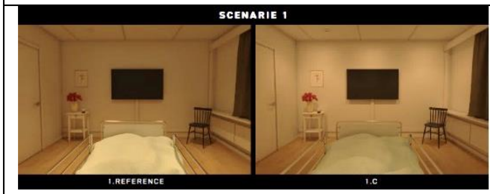
In the first part of the test, the participants were presented with “Scenario 1” which consisted of six slides, each showing two images side by side on the projected surface (See an example of one slide from “Scenario 3” in figure 21).

FIGURE 21. Test session in progress – Scenario 3 (Hallway RSL), slide 3.B, test session (A). (Projected black background appears blue on this image due to the camera quality)

The image (Scene) on the left hand side was the same on all six presentation slides – showing the reference scene representing a room illuminated by downlight luminaries, providing 50lx in average illuminance on the floor.

The images on the right hand side were changing – it was subsequently showing six scenes of the patient room lit up by wallwashers providing different levels of average illuminance on the floor level. Each of the slides were shown for 5 seconds before moving to the next one (see presented slides from scenario 1, in table 4). It should be noted that the participants were not informed about any of the actual light-related parameters/units of the assessed scenes, meaning that the lux levels were not given. This test was purely about the individual “feeling” and “perception”. Test sessions were divided into 10 sessions of 20 minutes, with four participants each. To reduce biases in terms of order effect (Shaughnessy, J. J, et al., 2006), the images were presented from brightest to darkest in sequence A↓, and from darkest to brightest in sequence B↑. Test sessions were divided equally in 5 A↓ sequences and 5 B↑ sequences.

TABLE 4. overview of presented slides with scenes for Scenario 1, sequence A↓.

Pairwise presentation of lighting scenes – test sessions A	
 Slide 1.A	 Slide 1.B
 Slide 1.C	 Slide 1.D
 Slide 1.E	 Slide 1.F

See appendix 9.3 for bigger images.

After presenting the first round of images, the process was repeated one more time, to give the participants enough time to judge between the images. Then, the participants were asked to answer the first question (Q.1) in the questionnaire, about which of the two scenes they perceived as equally bright (see section 5.4 for the questionnaire).

Afterwards, a third round of the first set of images was carried out, after which the participants were asked to answer the second question (Q.2) regarding which of the lighting strategies (horizontal illumination (reference) or vertical illumination) they found most pleasant to be in. The participants, however, had the questionnaire at hand from the very beginning, so they could answer or change their answers during the entire test session.

In the end, participants had an option to express additional observation in the ''comments'' field of the questionnaire. This procedure was then repeated in scenario 2, 3 and 4:

- Scenario 1 – Patient room illuminated by FSL
- Scenario 2 – Patient room illuminated by RSL
- Scenario 3 – Hallway illuminated by FSL
- Scenario 4 – Hallway illuminated by RSL

An illustration of the overall test procedure is shown in table 5 below.

TABLE 5. Example of test session pr. 4 participants, showing both an A and B session

Round	Scenario	Sequence	Reference scene compared to:	SPD	Question
-	Introduction	-	-	-	-
1.1	Scenario 1 (Patient room)	A↓ or B↑	A - B - C - D - E - F	FSL	Q.1
1.2			A - B - C - D - E - F		
1.3			All		Q.2
2.1	Scenario 2 (Patient room)		A - B - C - D - E - F	RSL	Q.1
2.2			A - B - C - D - E - F		
2.3			All		Q.2
3.1	Scenario 3 (Hallway)		A - B - C - D - E - F	FSL	Q.1
3.2			A - B - C - D - E - F		
3.3			All		Q.2
4.1	Scenario 4 (Hallway)		A - B - C - D - E - F	RSL	Q.1
4.2			A - B - C - D - E - F		
4.3			All		Q.2
-	Round off	-	-	-	-

Table showing the test protocol and executed steps in pairs of four test participants. This was repeated 5 times for sequence A and 5 times for sequence B, giving a total of 40 test participants. Q.1 was asked after round X.2 and Q.2 after round X.3.

5.3 Test participants

There were 40 test participants - 11 females and 29 males - in the age spanning from 22 to 60 years (mean=36.58, median=37).
Regarding the participant’s use of aids in relation to their vision, 57.5 % answered that they never use visual aids, 7.5 % answered that they use visual aids from time to time and 35 % answered that they use visual aids all the time.

Despite the fact that 57.5 % answered that the never use visual aids, only 42.5 % answered that they never have had problems regarding their vision. This was mainly commented as fatigue due to screen work or very little effect of distorted vision. One test participant was colour-blind.

5.4 Questions to assess the perceived spatial brightness

Below are the two questions (Q.1 and Q.2) the participants were asked for each of the four scenarios. The participants were asked to answer the question after end of the round, after seeing the whole set of scenes for each scenario. The questionnaire was handed in the beginning of the testing session, therefore the participants could adjust their answers at all times.

(Q.1) When are the scenarios equally bright?
The reference room on the left (1. Reference) is perceived to have the same brightness as scene:

☐ 1.A	☐ 1.B	☐ 1.C	☐ 1.D	☐ 1.E	☐ 1.F

(Q.2) Imagine that you are in bed, which lighting scene do you prefer?
Based on the reference (1.Reference) and the selected scene (1.A-F) under question 1.1:

☐ 1. Reference	☐ 1.(A-F)

For the hallway scenarios, the second question Q.2 altered in the wording:
(Q.2) Imagine that you are walking down the hallway, which lighting scene do you prefer?
Based on the reference (1.Reference) and the selected scene (1.A-F) under question 1.1:

☐ 1. Reference	☐ 1.(A-F)

The second question was not assessing the lux levels – it was focused on the preference for the lighting technique.

5.5 Calibration of visual test

The process and method for validation and the calibration of the presented photorealistic renderings used in the test, are based on the method developed in an earlier Elforsk project PSO project no. 346-046, Energieffektiv belysning gennem fotorealistisk visualisering (M. Fontoynont et al., 2017).

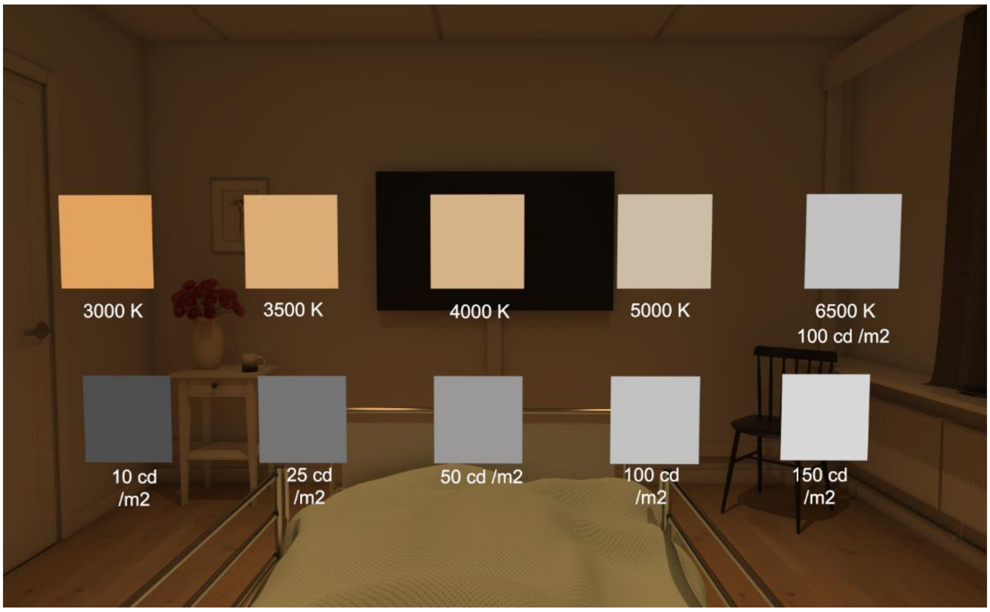


FIGURE 22. Calibration image for Patient Room scenario

At the test setup, a projector was calibrated to display acceptable values in relation to the range presented on the images (both luminance, and colour temperature) (see figure 22). The instrument used for calibration was a Konica Minolta LS-150, and the projector was EPSON G6050W. figure 23 shows a picture from the calibration process and the measured calibration values.

FIGURE 23. Calibration process

The measured values from the calibration test are presented in table 6. These gave a percentage of deviation of which the correctness of the projected screen could be discussed.

TABLE 6. Calibration references and measured values in both hallway and patient room

REFERENCE	Correlated Colour temperature [K]					Luminance [cd/m2]				
	3000	**3500**	**4000**	**5000**	**6500**	**10**	**25**	**50**	**100**	**150**
Patient room										
Measured value	3001	3494	4008	4969	6377	11,9	28,6	53,6	92	111
Deviation [%]	0,03%	0,1%	0,2%	0,6%	1,9%	19%	14%	7%	8%	26%
Hallway										
Measured value	3007	3504	4010	4972	6316	11,9	28,6	54	90	111
Deviation [%]	0,2%	0,1%	0,2%	0,6%	3%	19%	14%	7%	10%	26%

When looking at the projected CCT values of the images, the projected screen was unequivocally accurate with a maximum deviation of 3 %.

The projected luminance levels differed slightly from the target values both under high and low luminance.

The projected references differed 1.9 cd/m^2, 3.6 cd/m^2, 3.6 cd/m^2, 8 cd/m^2 and 39 cd/m^2 respectively, from the target luminance. Inaccuracy in measurements or relative great amount of spilled light may cause the relatively high % deviations from the target values in the low range of luminances whereas the inaccurate projection of high luminances more likely is caused by the limitations and maximum capacity of the projector. These phenomenon Projecting darkness and brightness are known difficulties using this method.

6

RESULTS

6 RESULTS

The results are divided into the four light scenarios presented earlier, containing both the selection of an equally illuminated/bright image compared to a reference, and the selection of the most pleasant lighting method (horizontal lighting versus vertical lighting), and a comparison chapter:

- (1) Patient room, FSL
- (2) Patient room, RSL
- (3) Hallway, FSL
- (4) Hallway, RSL
- Result comparison

6.1 Spatial perception

Results regarding the selection of an equally bright image to a reference are presented in the figures 25, 28, 31 and 34. The y-axis on the graphs represents number of participants in percent and the x-axis represents the different images the participants could choose between.

Lux values marked with (*) point out the vertical illuminated scene with the same average illuminance (50 lux) on the horizontal plane, as the reference horizontal illuminated scene. Lux values marked with (**), point out the vertical illuminated scene (vertical surfaces) with the same pixel value projected onto the screen as the reference horizontal illuminated scene.

It is important to note that the lux values given on the x-axis, were not shown during the test. Instead, participants had to choose between six different letters corresponding to different lux values in the scenes presented on images.

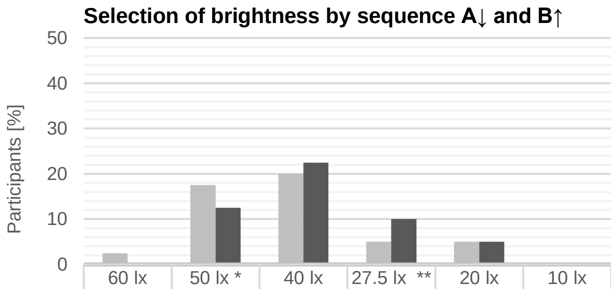
Half of the participants participated in the test sequence comparing the reference picture with pictures having surfaces decreasing vertical illumination (A↓), while the other half participated in the test sequence with increasing illuminance (B↑). Results from the different sequences are reflected in figures 24, 27, 30 and 33.

Results regarding the preferred lighting method are presented in figures 26, 29, 32 and 35. There are two sections of the graph - participants preferring the reference scene with horizontal illuminated surface and participants preferring the selected scene with vertical illuminated surfaces.

Lastly, in order to get a deeper understanding of the presented data, the results from the four different light scenes are collected in section 6.2.

6.1.1 Patient room, Full spectrum lighting

The results from the first light scene are presented in Figure 24, figure 25 and figure 26, and table 7. This light scene was formed and simulated based on a patient room at Vikærgaarden under full spectrum lighting conditions, FSL.



	60 lx	50 lx *	40 lx	27.5 lx **	20 lx	10 lx
A↓ [%]	2,5	17,5	20,0	5,0	5,0	0,0
B↑ [%]	0,0	12,5	22,5	10,0	5,0	0,0

Notes:
* This is the vertical illuminated scene with the same average illuminance (50 lux), at 0,8m height, as the reference horizontal illuminated scene.

** This is the vertical illuminated scene (vertical surfaces) with the same pixel value projected onto the screen as the reference horizontal illuminated scene.

FIGURE 24. Images (lux) evaluated as equally bright as reference, by decreasing and increasing sequence - Patient room, FSL

	60 lx	50 lx *	40 lx	27.5 lx **	20 lx	10 lx
[%]	2,5	30,0	42,5	15,0	10,0	0,0

FIGURE 25. Images (lux) evaluated as equally bright as reference - Patient room, FSL (Combination of sequence A↓ and B↑). Note: * and ** as in figure 24.

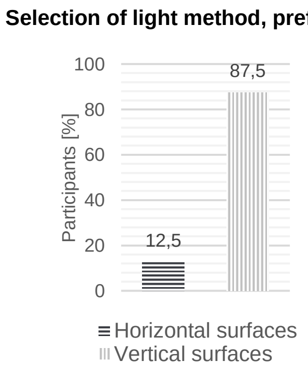


FIGURE 26. Preferred lighting method - Patient room, FSL

TABLE 7. Listed results showing the selected matching reference ≥ 50 lux >

Matching reference scene:	**≥ 50 lux**	**< 50 lux**
Participants	*32.5 %*	*67.5 %*

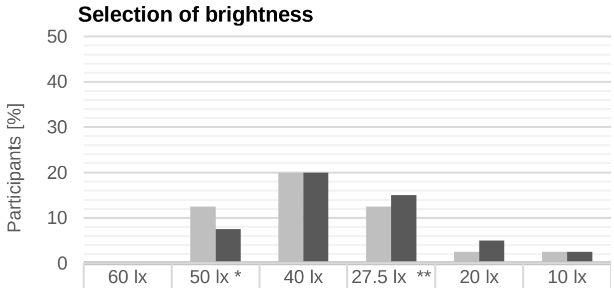
Tabelnote

Short summary of the results listed in Figure 24 figure 25, figure 26, and table 7 above:

- More than 2/3 of the participants found a lower illumination (on the horizontal surface achieved through reflected light from vertical surfaces) needed to match the illumination of the horizontal surface achieved through direct down-lighting (reference).
- In other words - more than 2/3 of the participants perceived the vertical illuminated scenes as equally illuminated as the reference, under lower illumination levels, in full spectrum lighting conditions.
- When looking at the two different test sequences, participants tended to prefer higher illumination levels in the test sequence A, compared to test sequence, B.
    - In test sequence A, 20% of the participants preferred ≥ 50 lx compared to test sequence B, where 12,5% participants preferred ≥ 50 lx.
    - In test sequence A, 30% of the participants preferred < 50 lx compared to test sequence B, where 37,5% participants preferred < 50 lx.
- 88% of the participants find lighting up vertical surfaces more pleasant than lighting up horizontal surfaces. This was backed with the following comments showing preference for wall-washing lighting technique:
    - "The surroundings are better lit and seem more friendly"
    - "Light on the bedspread is experienced as much brighter in the reference scene"

6.1.2 Patient room, Reduced spectrum lighting

The results from the second light scene are presented in Figure 27, Figure 28, and Figure 29 and table 8. This light scene was formed and simulated based on a patient room at Vikærgaarden reduced spectrum lighting conditions, RSL.

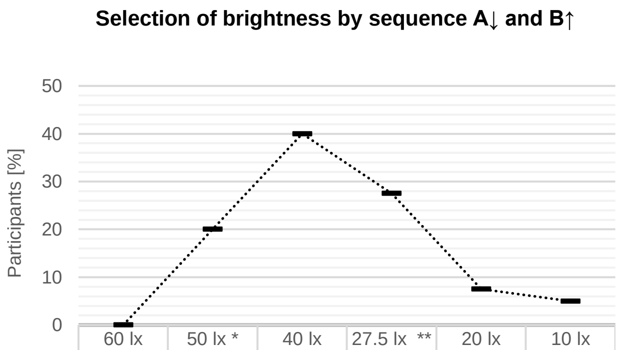


	60 lx	50 lx *	40 lx	27.5 lx **	20 lx	10 lx
A↓ [%]	0,0	12,5	20,0	12,5	2,5	2,5
B↑ [%]	0,0	7,5	20,0	15,0	5,0	2,5

Notes:
* This is the vertical illuminated scene with the same average illuminance (50 lux), at 0,8m height, as the reference horizontal illuminated scene.

** This is the vertical illuminated scene (vertical surfaces) with the same pixel value projected onto the screen as the reference horizontal illuminated scene.

FIGURE 27. Images (lux) evaluated as equally bright as reference, by decreasing and increasing sequence - Patient room, FSL



	60 lx	50 lx *	40 lx	27.5 lx **	20 lx	10 lx
[%]	0,0	20,0	40,0	27,5	7,5	5,0

FIGURE 28. Images (lux) marked as equally bright as reference - Patient room, RSL (Combination of sequence A↓ and B↑). Note: * and ** as in figure 27.

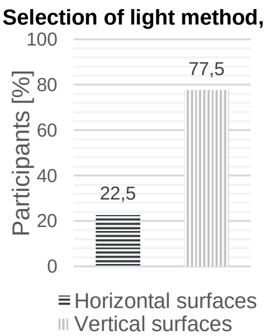


FIGURE 29. Preferred lighting method - Patient room, RSL

TABLE 8. Listed results showing the selected matching reference ≥ 50 lux >.

Matching reference scene:	**≥ 50 lux**	**< 50 lux**
Participants	*20,0 %*	*80 %*

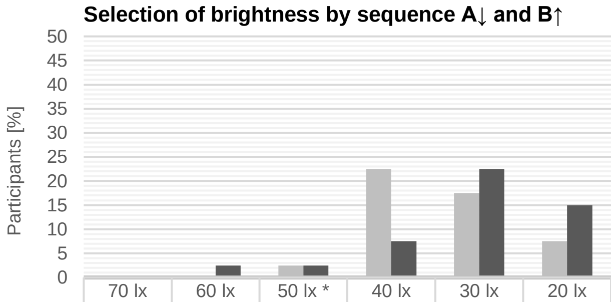
Tabelnote

Short summary of the results listed in Figure 27, Figure 29, Figure 28 and table 8 above:
4/5 of the participants found a lower illumination, on the horizontal surface achieved through reflected light from vertical surfaces, needed to match the illumination of the horizontal surface achieved through direct down-lighting (reference).

- In other words, 4/5 of the participants perceived the vertical illuminated scenes as equally illuminated as the reference, under lower illumination levels, in night lighting conditions.
- When looking at the two different test sequences, participants tended to prefer higher illumination levels in the test sequence A, compared to test sequence B.
    - In test sequence A, 12,5% of the participants preferred ≥ 50 lx compared to test sequence B, where 7,5% participants preferred ≥ 50 lx.
    - In test sequence A, 37,5% of the participants preferred < 50 lx compared to test sequence B, where 42,5% participants preferred < 50 lx.
- 78% of the participants found lighting up vertical surfaces more pleasant than lighting up horizontal surfaces.

6.1.3 Hallway, Full spectrum lighting

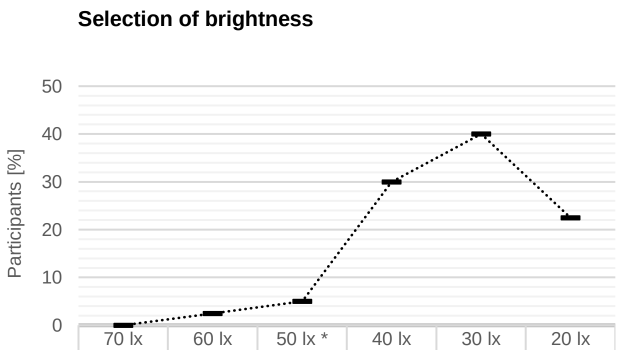
The results from the third light scene are presented in Figure 30, figure 32, figure 31 and table 9. This light scene was formed and simulated as a generic hallway room under full spectrum light conditions, FSL.



	70 lx	60 lx	50 lx *	40 lx	30 lx	20 lx
A↓ [%]	0,0	0,0	2,5	22,5	17,5	7,5
B↑ [%]	0,0	2,5	2,5	7,5	22,5	15,0

Note: * This is the vertical illuminated scene with the same average illuminance (50 lux), at floor level, as the reference horizontal illuminated scene. Moreover, the vertical illuminated scene (vertical surfaces) with the same pixel value projected onto the screen as the reference horizontal illuminated scene.

FIGURE 30. Images (lux) evaluated as equally bright as reference, by decreasing and increasing sequence - Hallway, FSL



	70 lx	60 lx	50 lx *	40 lx	30 lx	20 lx
[%]	0,0	2,5	5,0	30,0	40,0	22,5

FIGURE 31. Images (lux) marked as equally bright as reference - Hallway, FSL (Combination of sequence A↓ and B↑). Note: * same as for figure 30.

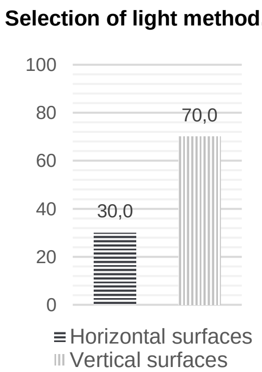


Figure 32. Preferred lighting method - Hallway, FSL

TABLE 9. Listed results showing the selected matching reference ≥ 50 lux >.

Matching reference scene:	**≥ 50 lux**	**< 50 lux**
Participants	*7,5 %*	*92,5 %*

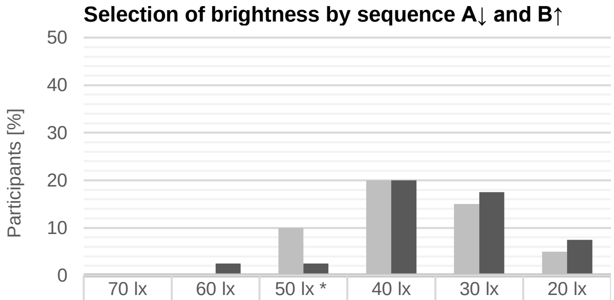
Tabelnote

Short summary of the results listed in Figure 30, figure 32, figure 31 and table 9:

- More than 9/10 of the participants found a lower illumination on the horizontal surface achieved through reflected light from vertical surfaces, needed to match the illumination of the horizontal surface achieved through direct down-lighting (reference).
- In other words, more than 9/10 of the participants perceived the vertical illuminated scenes as equally illuminated as the reference under lower illumination levels in full spectrum lighting conditions.
- When looking at the two different test sequences (A and B) from 20 lux to 40 lux, participants clearly tended to prefer opposite illumination levels.
    - At 20 lux, there was a difference of 7,5 % between the participants preferences in test sequence A and B, where B peaked at 15%.
    - At 40 lux, there was a difference of 15% between the test participants preferences in test sequence A and B, where A peaked at 22,5%.
- 70% of the participants find lighting up vertical surfaces more pleasant than lighting up horizontal surfaces. This was followed up by the following comments:
    - "Lighting up the walls is nice!"
    - "Better lighting on the floor"
    - “More comfortable because it is the one with most light”

6.1.4 Hallway, Reduced spectrum lighting

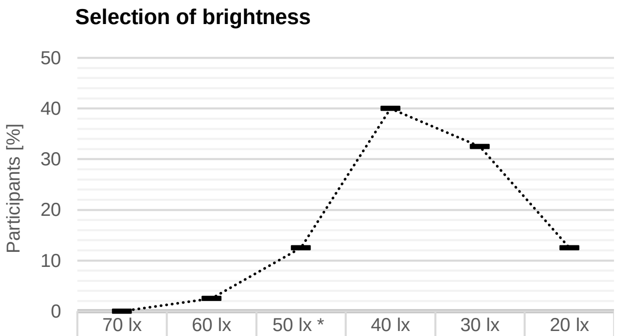
The results from the fourth light scene are presented in Figure 33, Figure 35, Figure 34 and table 10. This light scene was formed and simulated as a generic hallway under reduced spectrum lighting, RSL.



	70 lx	60 lx	50 lx *	40 lx	30 lx	20 lx
A↓ [%]	0,0	0,0	10,0	20,0	15,0	5,0
B↑ [%]	0,0	2,5	2,5	20,0	17,5	7,5

Figure note:
* This is the vertical illuminated scene with the same average illuminance (50 lux), at floor level, as the reference horizontal illuminated scene. Moreover, the vertical illuminated scene (vertical surfaces) with the same pixel value projected onto the screen as the reference horizontal illuminated scene.

FIGURE 33. Images (lux) evaluated as equally bright as reference, by decreasing and increasing sequence - Hallway, RSL



	70 lx	60 lx	50 lx *	40 lx	30 lx	20 lx
[%]	0,0	2,5	12,5	40,0	32,5	12,5

FIGURE 34. Images (lux) marked as equally bright as reference - Hallway, RSL (Combination of sequence A↓ and B↑). Note: * Same as in figure 33.

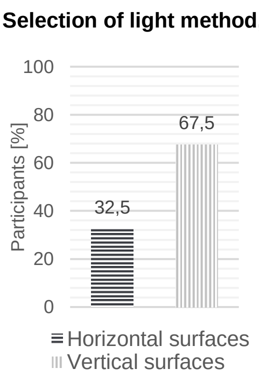


FIGURE 35. Preferred lighting method - Hallway, RSL

TABLE 10. Listed results showing the selected matching reference ≥ 50 lux >, a ranking of the selected scenes compared to the reference and a preferred lighting method, for the hallway in RSL.

Matching reference scene:	**≥ 50 lux**	**< 50 lux**
Participants	*15,0 %*	*85,0 %*

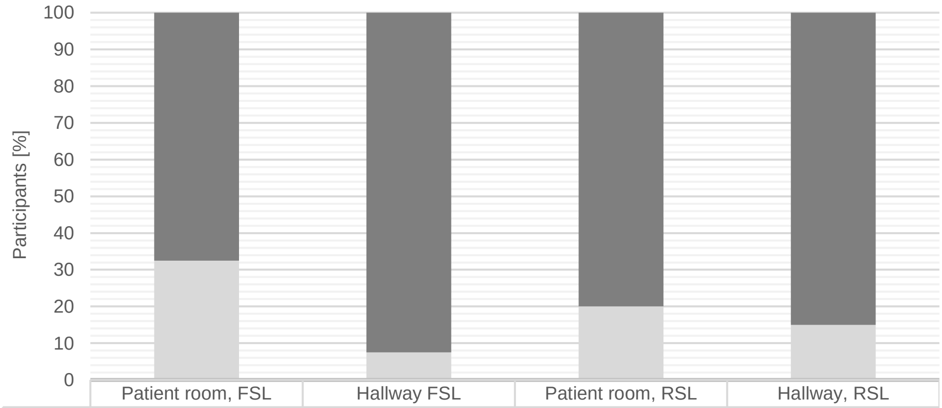
Tabelnote

Short summary of the results listed in Figure 33, Figure 35, Figure 34 and table 10:

- More than 4/5 of the participants found a lower illumination, on the horizontal surface achieved through reflected light from vertical surfaces, needed to match the illumination of the horizontal surface achieved through direct down-lighting (reference)
- In other words, more than 4/5 of the participants perceived the vertical illuminated scenes as equally illuminated as the reference, under lower illumination levels, in night lighting conditions
- When looking at the two different test sequences, participants tended to prefer higher illumination levels in the test sequence, A, compared to test sequence, B.
    - In test sequence A, 10% of the participants preferred ≥ 50 lx compared to test sequence B, where 5% participants preferred ≥ 50 lx.
    - In test sequence A, 40% of the participants preferred < 50 lx compared to test sequence B, where 45% participants preferred < 50 lx.
- 68% of the participants find lighting up vertical surfaces more pleasant than lighting up horizontal surfaces. This was followed up by the following comments from the test participants:
    - "I would rather walk there (vertical illuminated surfaces)"
    - “Contours and shadows helps to define the hallway (horizontal illuminated surfaces)”
    - "Lighting up the walls is nice!"
    - ”The visible light patterns on the walls are disturbing” *(referring to the wall-washer scenario)*

6.2 Result comparison

In order to get a deeper understanding of the presented data, the results from the four different light scenarios has been summarised in Figure 36 and figure 37.



	Patient room, FSL	Hallway FSL	Patient room, RSL	Hallway, RSL
<50 lux	67,5	92,5	80,0	85,0
≥50 lux	32,5	7,5	20,0	15,0

FIGURE 36. Distribution of participants [%] choosing ≥ 50 lux <, under the four different light scenarios.

figure 36, shows a summary of the results of the first analysed question – the perception of equal brightness. The test participants perceived the vertical illumination scenes with less than 50lx on the horizontal plane, as equally bright as the reference scene. This is true for all of the scenarios, with a more significant result in the two hallway scenarios. This might indicate that the geometry, interior design and the use of the illuminated space could have an influence on the perception of brightness.

When comparing the different spectral power distributions in figure 36, there is no indication that the lighting spectrum significantly altered the results – in both variations of SPD, the scenes with less than 50lx were perceived as bright as the reference scene.

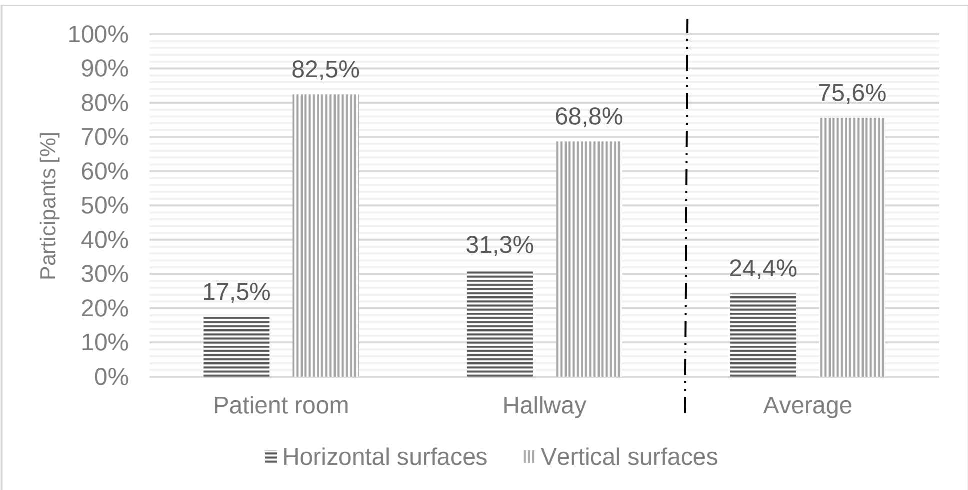


FIGURE 37. Distribution of participants [%] choosing between a vertical and horizontal lighting strategy, under the two different room types.

figure 37 shows a summary of preference of one lighting method over the other in all of the four scenarios - significant amount of the participants find lighting up vertical surfaces more pleasant than lighting up horizontal surfaces, in both of the simulated room types.

Finally, the use of two different sequences A↓ and B↑ emphasized the importance of balancing the sequences of how the images are presented, as the results slightly differs between the two sequences (Figure 24, Figure 27, Figure 30 and Figure 33).

7

DISCUSSION

7 DISCUSSION

This is an initial study, with an aim to get an indication of the perception of the two lighting strategies. In practice, the two scenarios would have been combined in order to get a functional design that meet both regulations, and visual preference. The goal was not to get definite results, but rather an indication if it is possible to reduce the horizontal illumination level when it is coming from vertical surfaces (reflected light), in comparison to when it is provided directly to the horizontal surfaces (direct downlight).

To get a uniform illumination on the floor in the tested cases, it was necessary to put more wallwasher luminaries compared to downlights. Therefore, if we were to compare energy use required to provide the same horizontal illumination level, the wallwashers would be less energy efficient. Moreover, they provide light as a reflected light - and since there is no wall material with 100% reflectance factor, a lumen loss between the luminaire and the final illumination surface (floor) is unavoidable. However, the vertical lighting strategy, using wallwashers, significantly reduces the possibility of glare levelling out luminance contrast - although glare is an aspect which could not practically be tested.

However, it was found in the results that majority of participants (between 67.5% and 92.5% depending on scenario – see figure 36) perceived space illuminated through wallwashers with less horizontal illumination effect on floor, as equally bright as space illuminated with downlights with higher horizontal illumination level. This gives a hypothesis that if the space has illuminated vertical surfaces, it is acceptable to dim the power so there is a lower horizontal illuminance on the floor while still maintaining the visual perception of brightness.

Assessing visual preference associated with the lighting technique, the vast majority of participants chose the wallwasher scenarios as over the downlight, as a preferred space to be in. (between 70-88% depending on the scenario). That gives an indication that even if there are no major energy savings, it could still be a beneficial practice for the users of space.

There is also a topic of room functionality – while asking question of preferred lighting scenario, the patient room was more difficult to assess due to versatile character of activities performed in it such as reading, resting, sleeping, eating, etc. There were in fact some comments from participants about the task that they should imagine they are performing in the simulation.

Continuing to the subject of test content, the assessment of lighting scenarios was not based on a physical light environment, but projection of visualisations in a 2D format. It is important to note that the test participants were not surrounded by the lighting, therefore it could be expected that they would perceive the light environment differently if they were exposed to the lighting in a real, physical space with real luminaries. However, the test method is cheap and quick, when comparing with what would have been necessary in a full-scale test.

The nature of the projection may also influence the perception of light environment, as the projector is not capable of recreating full spectrum of light from a real fixture. Projection was calibrated to be as close to simulated values as possible, however there were minor deviations in the colour temperature (only the higher range) and luminance (again, higher range). Moreover, the projector was also not capable to create complete darkness or black colour (representing 0,0,0 RGB values on the projection surface), and neither was it powerful enough to produce glare. However, simulated scenarios were showing rather dimmed environments with warm lighting, therefore It was not a significant problem that we could not project points of high luminance, or high, cool colour temperature.

The way that the test was build up – with six predefined scenes - indicated whether it is possible to reduce the horizontal illumination when the lighting is provided at vertical surfaces as opposed to directly to the horizontal surfaces. However, it did not indicate a definite number or percentage of the reduction. To get a more detailed result on the dimming range, another test would be necessary – perhaps with individual sessions where a test person has an option to manually adjust the light level to match the reference scene.

Another discussion point about test content is choice of the scenes in terms of level of illumination. It was chosen to work with rather dark environment of 50lx, which could also have an influence on perception of space and lighting. Should we work within levels of illumination according to standard (100lx on the hallway (DS/EN 12464-1:2011, 2012), the results could have been different. As found in previous research, the sensitivity to change of perceived light levels decreases as the lux levels go up. Therefore, some relations found in this test should be directly applied to higher ranges of illuminance (Rea, M.S., 2000).

Another discussion point is darkness adaptation. The participants were only adapted to a dimmed lighting environment for approximately 5 minutes before the test, while they were filling out the initial demographic and personal questions in the questionnaire.

Test results showed a difference in perceived brightness in sequence A↓ and B↑. The preference for a brighter scene was noted in sessions where the participants were shown images from brightest to darkest and reverse tendency when presented from darkest to brightest. This is in accordance with studies that have found that people chose a higher light level when they regulate the light from a higher light level, than when they it from a lower light level from when it is turned off (Newsham et al., 2005; Juslén, 2005).

The scenes were always shown in the same order. The test persons were always showed the same scene (patient room full spectrum) as the first scenario. Since there may be an effect of the learning curve of the test, is could be possible, that this scenario may have more misjudgements than the other scenarios, but this was not further investigated.

About the demographics of the test participants, none of them were lighting specialists, but they were all engineers – and technical character of that job that might have had an influence on the results.

8

CONCLUSION

8 CONCLUSION

This test was about evaluating perception of spatial brightness of two lighting principles – direct illumination on the floor through downlights and indirect through reflected light, using wallwashers. The test was based on calibrated simulations, presented to the test participants in a form of 2D projections. The method used limited the options for further testing (narrow the marginal scenarios), it was a quick and cheap test-method for involvement of a decent number of participants (40). It was possible to calibrate the simulations in a satisfying manner for the use in this pilot study.

Following are the main findings from the test:

- When using vertical illumination for lighting the horizontal plane (floor), we could lower the horizontal level of illumination to achieve same level of perceived brightness, as in scenario where the same space is illuminated only by direct light through downlights.
- Further testing is needed to get more detailed values of ranges, or percentages of lux values that the wallwasher scenario can be dimmed down to, to get the same brightness perception as downlight scenario.
- For general lighting (not task-specific or functional), it might be beneficial for users to use wallwashers as they were perceived as more preferred over downlights. For tasks which require specific light levels according to *DS/EN 12 464-1:2011*, a downlight might be necessary to achieve the required horizontal illuminances efficiently.
- It was found that geometry of space influences perception of the lighting method. Both in the FSL and RSL(full spectrum lighting and reduced spectrum lighting) scenarios of patient room, there was higher preference of wallwashers over downlights. In the hallway scenarios there was a similar tendency, but not as strong as in the patient room.
- When comparing results between full- and reduced spectrum lighting scenarios for both simulated spaces, there was no significant difference. Therefore, in this test setting, the lighting spectrum did not affect the perceived brightness, and neither the preference of the lighting method.

Further testing is necessary in order to create a link between the energy consumption, levels of illumination (vertical and horizontally) and perceived spatial brightness of different scenarios. However, based on the results it is clear that we perceive a space brighter if not only the horizontal surfaces are lit. If room is lit using a wallwash technique primarily lighting up vertical surfaces are lit

8.1 Further research

This project has revealed number of directions for further development, and testing in the following areas:

- Concerning energy savings: Investigate if lower lux level horizontally but with the same perceived room brightness requires a higher energy consumption compared to the reference setting (50 lux)
- Improved the test by using more adjustable and specific illumination values linked with known energy consumption and using a slider with a broad range of possible settings
- Bigger range of lux values to test the results at illumination values also used during daytime (0-500 lux)
- Make tests that are more task specific, (office, hospital, etc.)
- Testing hybrid solutions that is mixed lighting strategies with vertical and horizontal lighting in combinations
- Test in real life with real fixtures.

    - Laboratory
    - On site
  - Using the same test procedure, but in Virtual Reality with the possibility to move around as an observer, and proceed with a comparison of Virtual Reality test with real world test.

Further questions to be further investigated:

Does the light distribution affect the perceived presence of colours when the lighting is not full spectrum? When lighting without short wavelengths is used, rooms and objects illuminated with some wallwasher scenarios could be perceived as less influenced by the colour of the lighting than under downlighting (Stoffer et al., 2017).

8.2 Acknowledgement

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9

APPENDIX

9 APPENDIX

9.1 Simulations of Patient room

FIGURE 38. Patient room, Downlight (reference) 50 lux, FSL

FIGURE 39. Patient room, Wallwasher 10 lux, FSL

FIGURE 40. Patient room, Wallwasher 20 lux, FSL

FIGURE 41. Patient room, Wallwasher 27.5 lux, FSL

* Equivalent overall average luminance of the image as in the downlight scenario

FIGURE 42. Patient room, Wallwasher 40 lux, FSL

FIGURE 43. Patient room, Wallwasher 50 lux, FSL

FIGURE 44. Patient room, Wallwasher 60 lux, FSL

FIGURE 45. Patient room, Downlight (reference) 50 lux, RSL

FIGURE 46 Patient room, Wallwasher 10 lux, RSL

FIGURE 47. Patient room, Wallwasher 20 lux, RSL

FIGURE 48 Patient room, Wallwasher 27,5 lux, RSL

* Equivalent overall average luminance of the image as in the downlight (reference) scenario

FIGURE 49. Patient room, Wallwasher 40 lux, RSL

FIGURE 50 Patient room, Wallwasher 50 lux, RSL


FIGURE 51. Patient room, Wallwasher 60 lux, RSL

9.2 Simulations of hallway

FIGURE 52. Hallway, Downlight (reference) 50 lux, FSL

FIGURE 53 Hallway, Wallwasher 20 lux, FSL

FIGURE 54. Hallway, Wallwasher 30 lux, FSL

FIGURE 55 Hallway, Wallwasher 40 lux, FSL

FIGURE 56. Hallway, Wallwasher 50 lux, FSL

** Equivalent overall average luminance of the image as in the downlight (reference) scenario

FIGURE 57. Hallway, Wallwasher 60 lux, FSL

FIGURE 58. Hallway, Wallwasher 70 lux, FSL

FIGURE 59. Hallway, Downlight (reference) 50 lux, RSL

FIGURE 60 Hallway, Wallwasher 20 lux, RSL

FIGURE 61. Hallway, Wallwasher 30 lux, RSL

FIGURE 62 Hallway, Wallwasher 40 lux, RSL

FIGURE 63. Hallway, Wallwasher 50 lux, RSL

** Equivalent overall average luminance of the image as in the downlight (reference) scenario

FIGURE 64. Hallway, Wallwasher 60 lux, RSL


FIGURE 65. Hallway, Wallwasher 70 lux, RSL

9.3 Test slides – Session A, Scenario 1 – Round 1

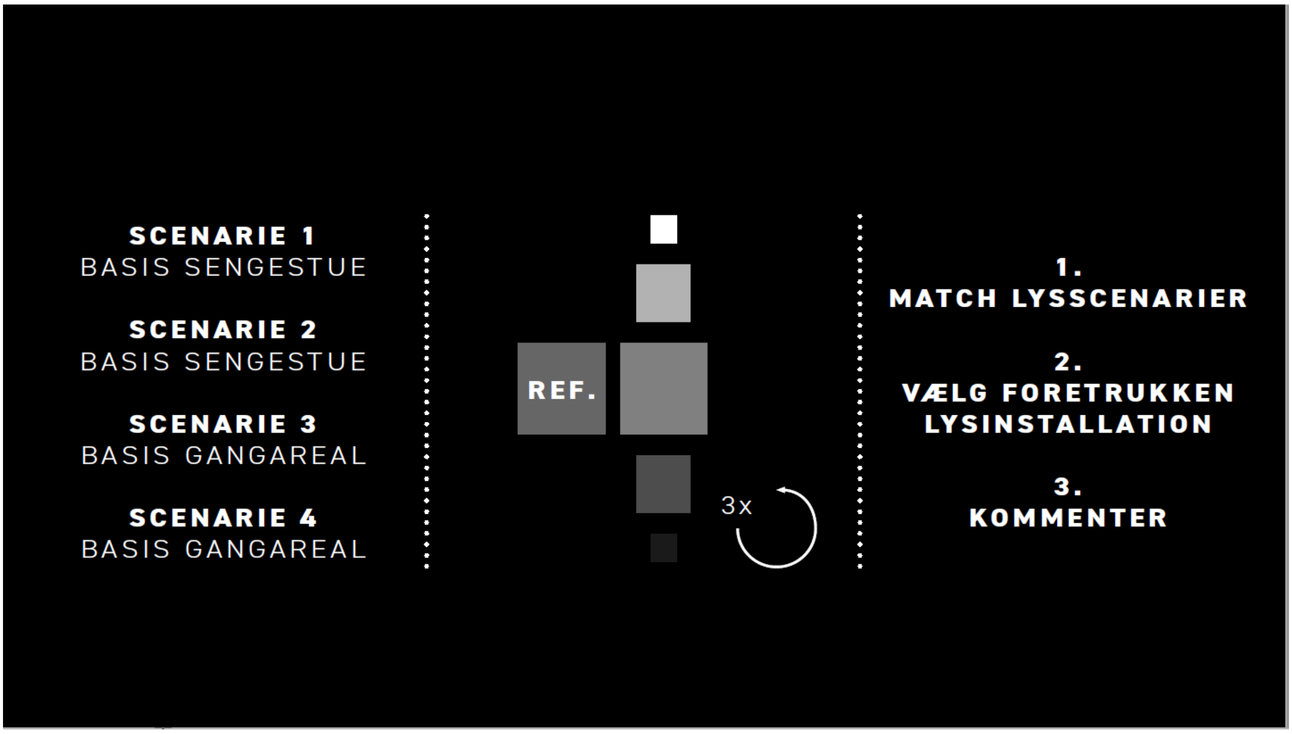

FIGURE 66. Session A introduction slide

FIGURE 67 Scenario A – Session A – First slide

FIGURE 68. Scenario A – Session A – Second slide

FIGURE 69 Scenario A – Session A – Third slide

FIGURE 70. Scenario A – Session A – Fourth slide

FIGURE 71. Scenario A – Session A – Fifth slide

FIGURE 72. Scenario A – Session A – Sixth slide

9.4 V-ray light meter

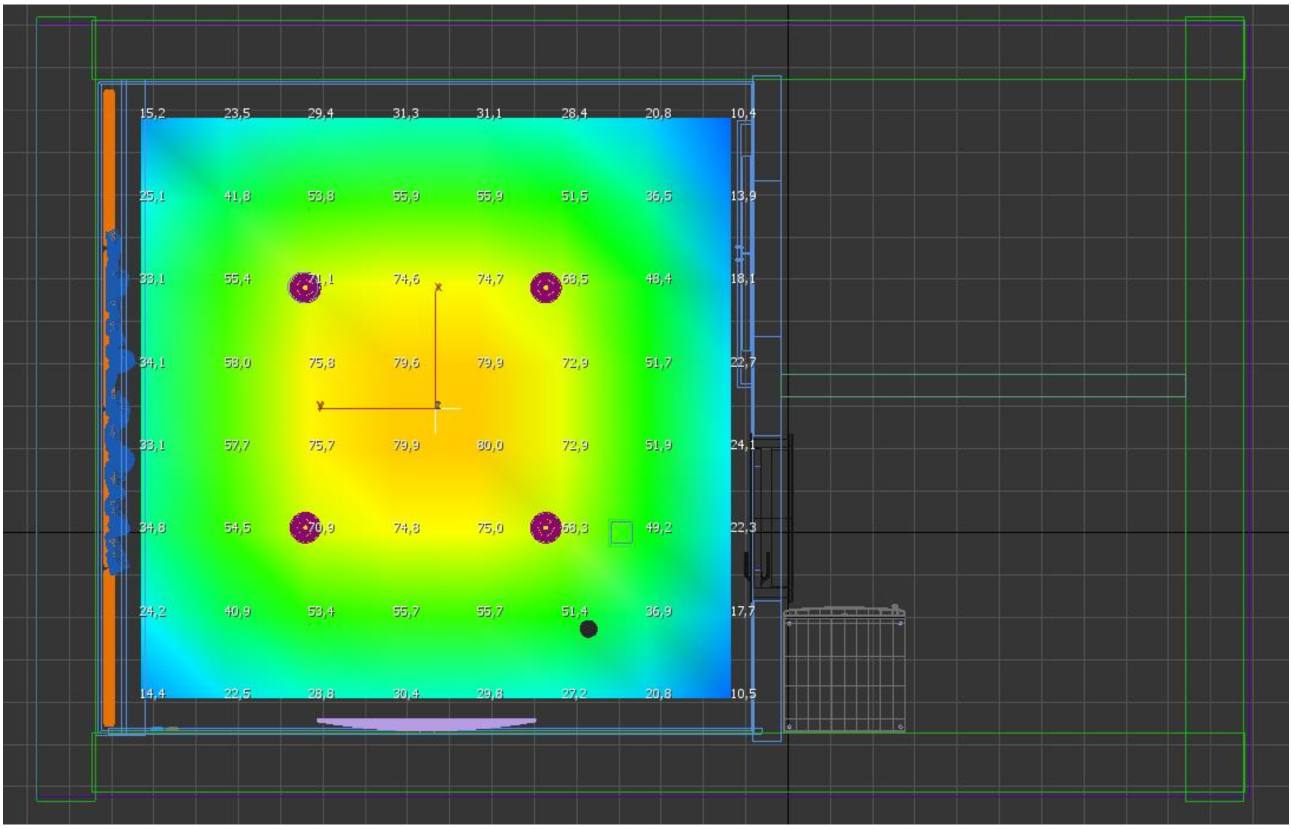

FIGURE 73. Patient room illuminance simulation - Downlight (reference) 50 lux

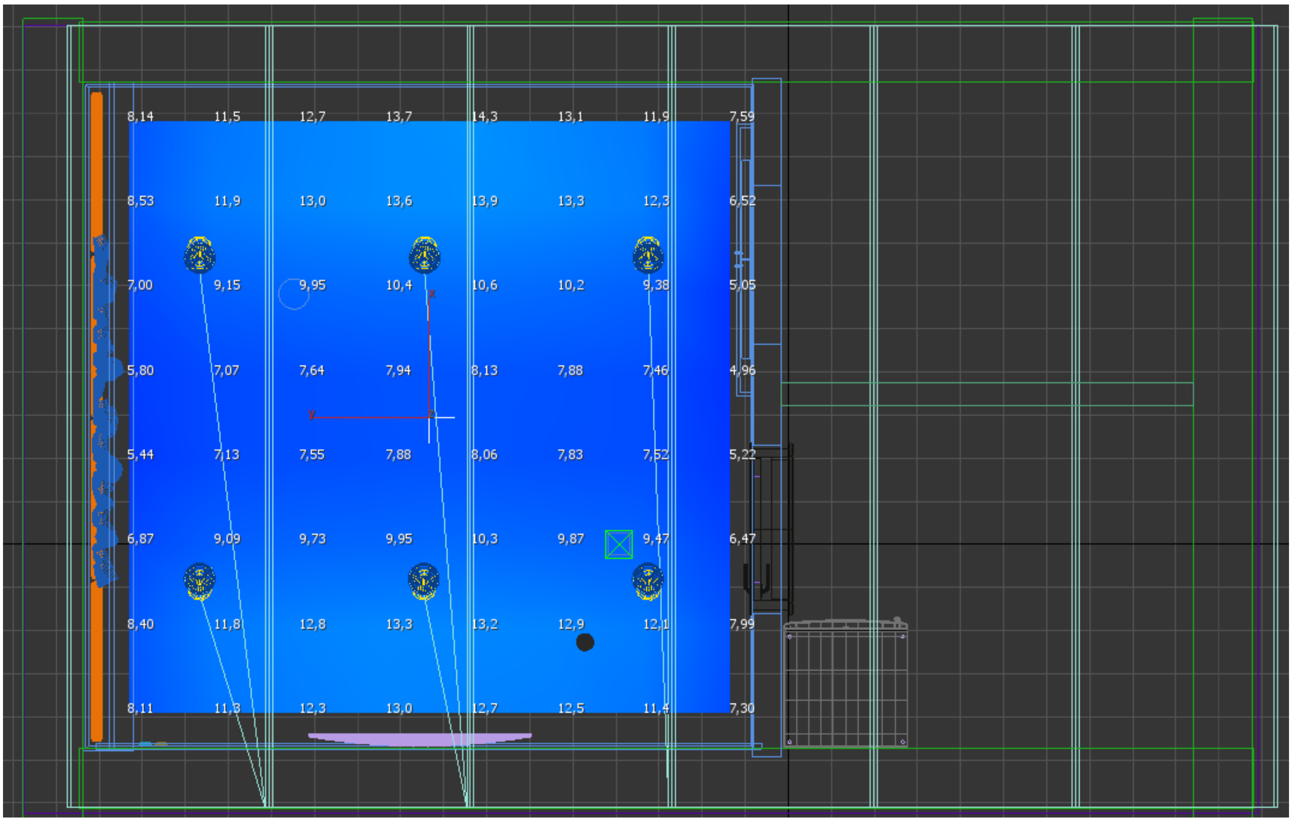

FIGURE 74 Patient room illuminance simulation - Wallwasher 10 lux

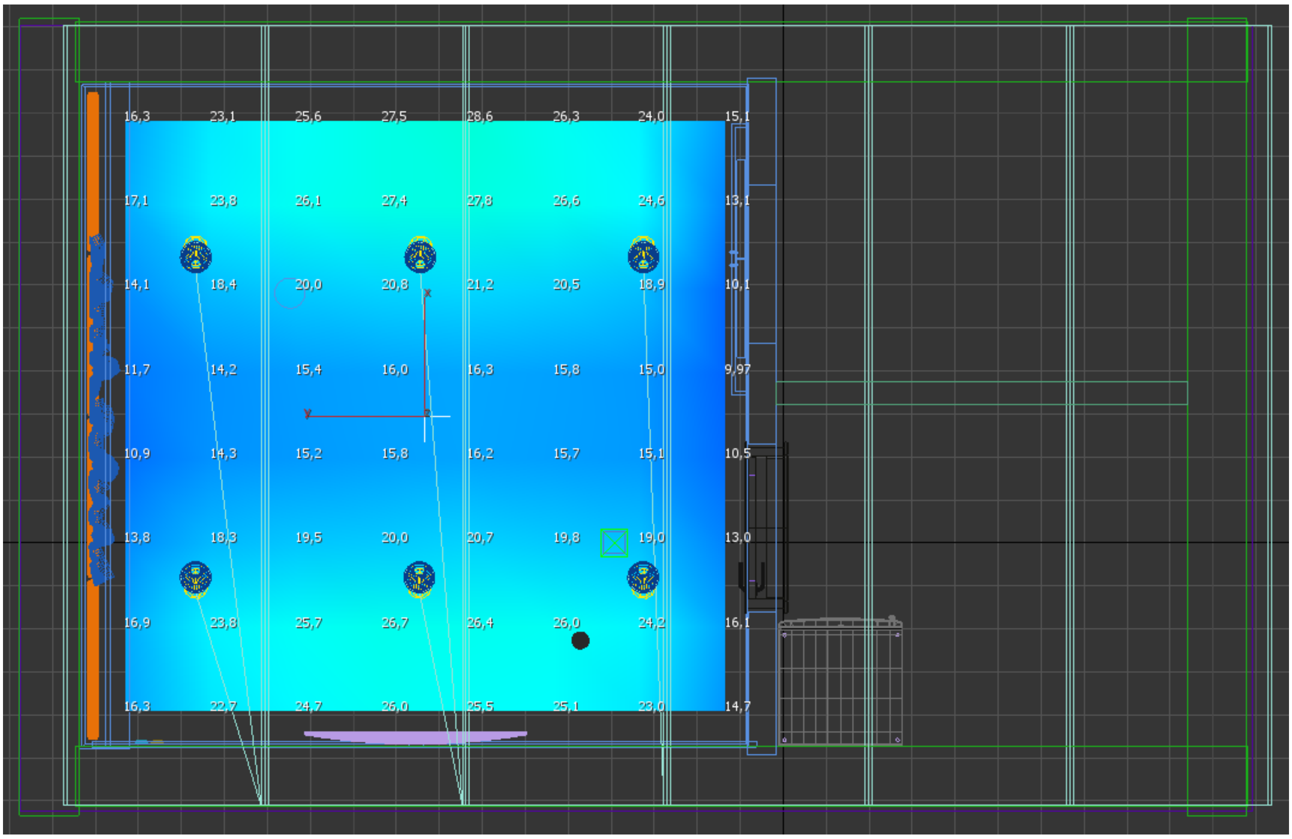

FIGURE 75 Patient room illuminance simulation - Wallwasher 20 lux

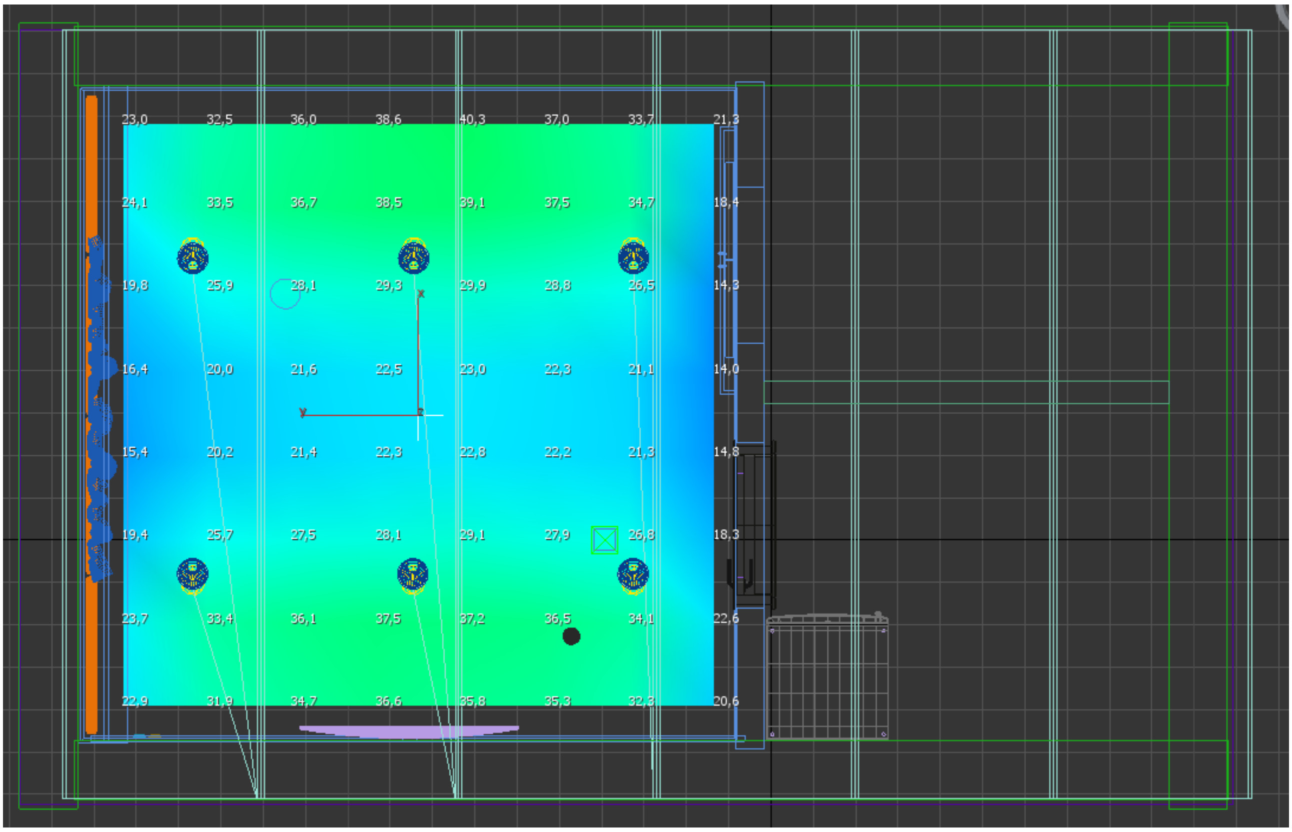

FIGURE 76 Patient room illuminance simulation - Wallwasher 30 lux

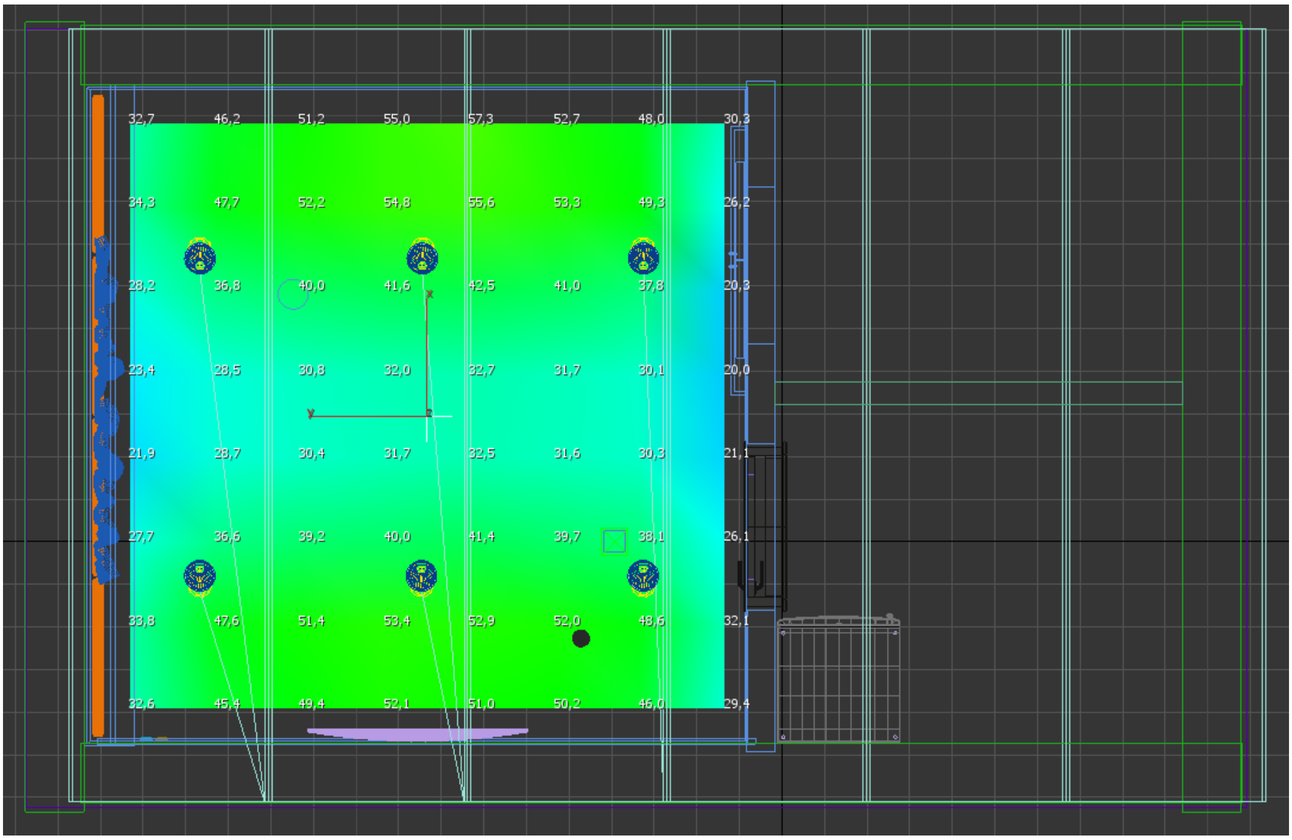

FIGURE 77. Patient room illuminance simulation - Wallwasher 40 lux

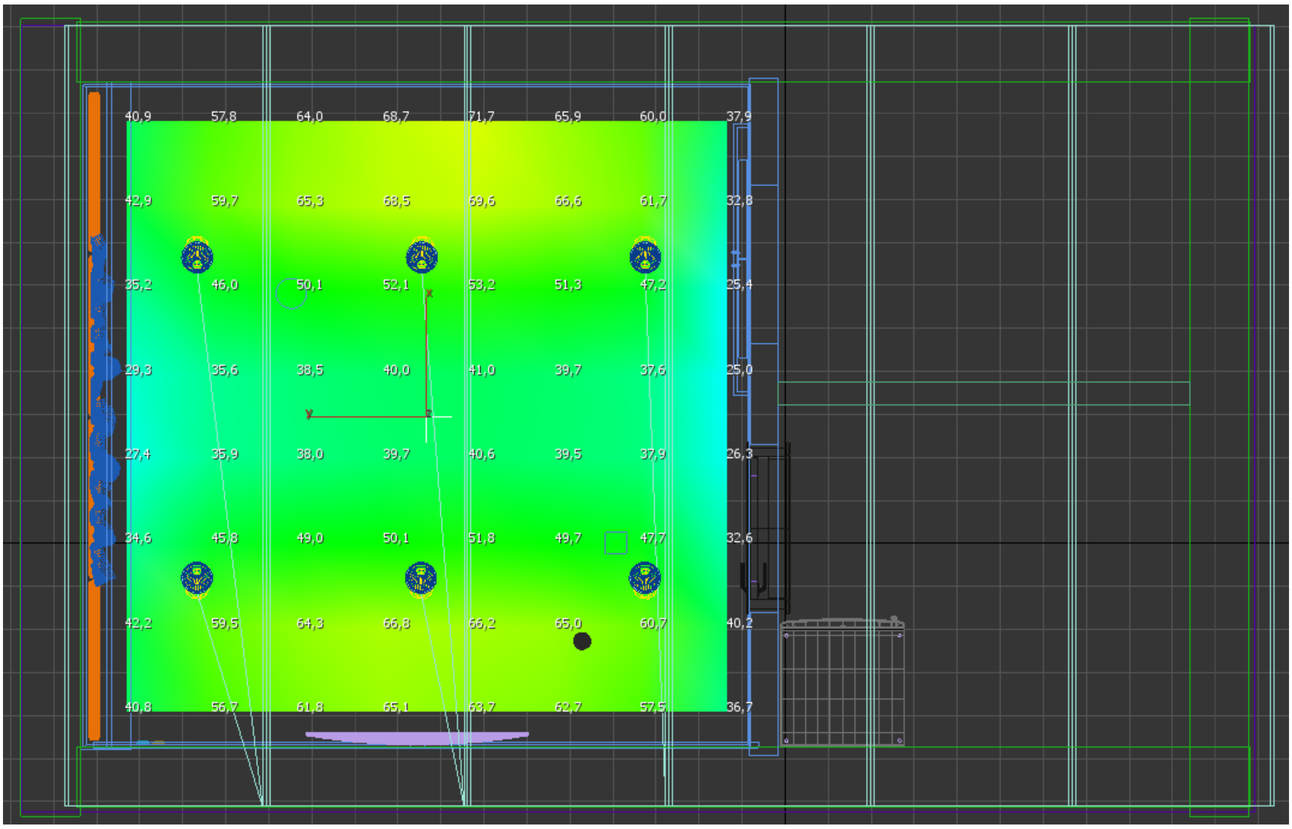

FIGURE 78. Patient room illuminance simulation - Wallwasher 50 lux

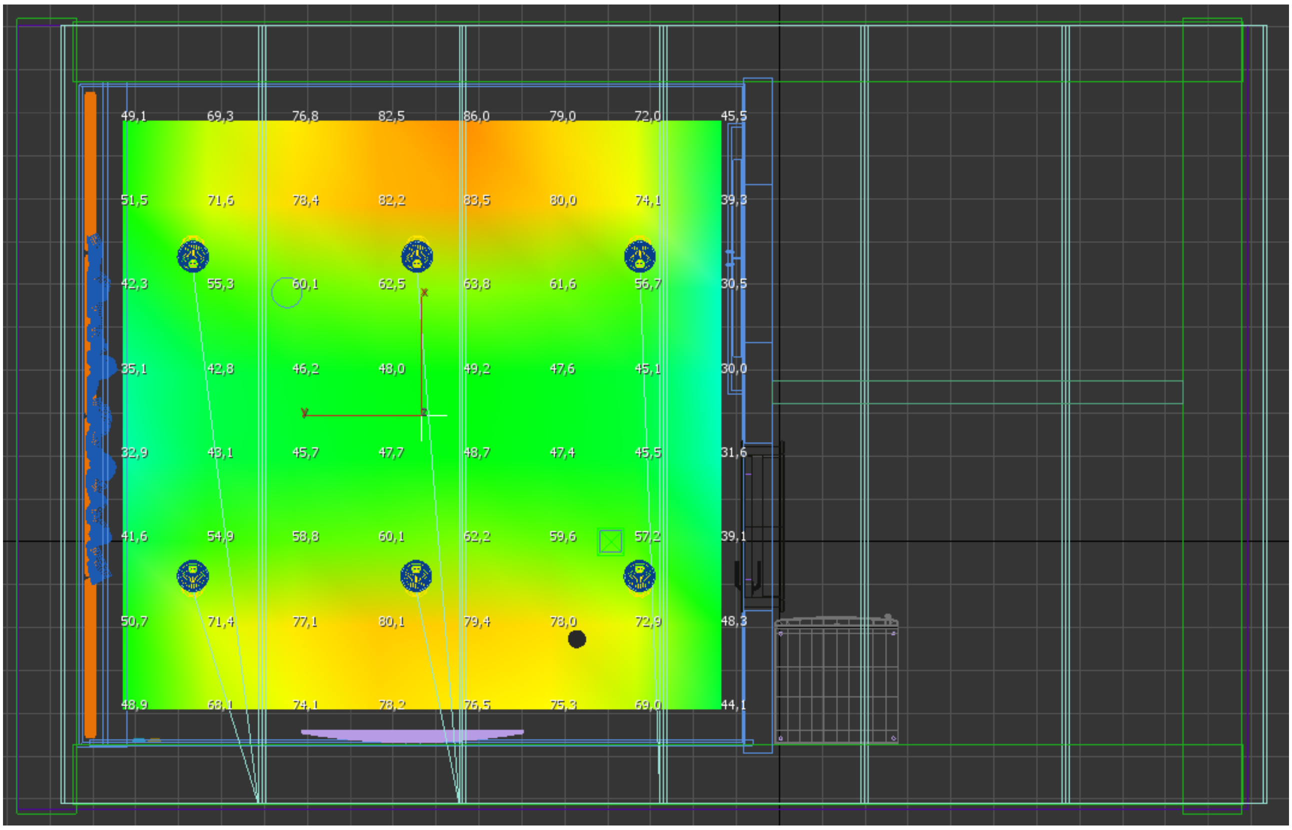

FIGURE 79 Patient room illuminance simulation - Wallwasher 60 lux

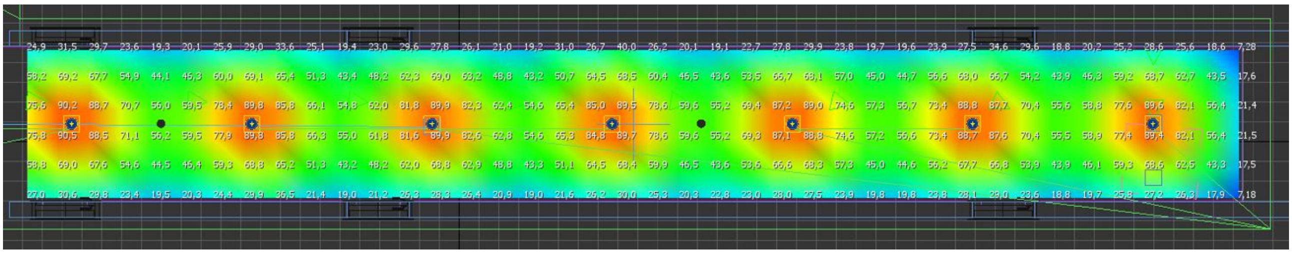

FIGURE 80. Hallway illuminance simulation - Downlight (reference) 50 lux

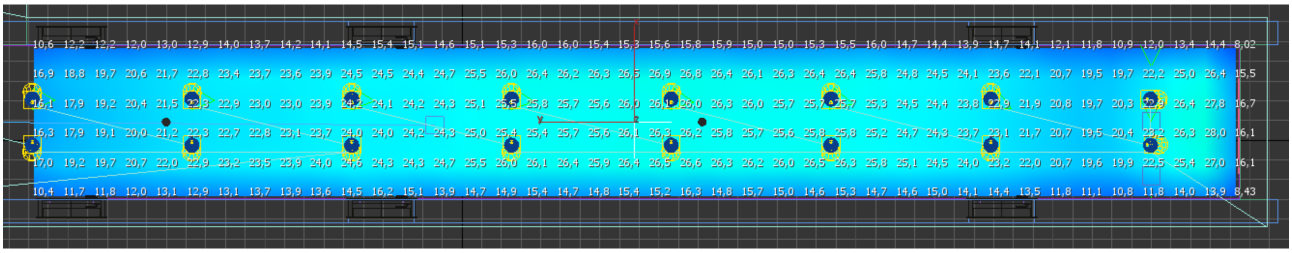

FIGURE 81 Hallway illuminance simulation - Wallwasher 20 lux

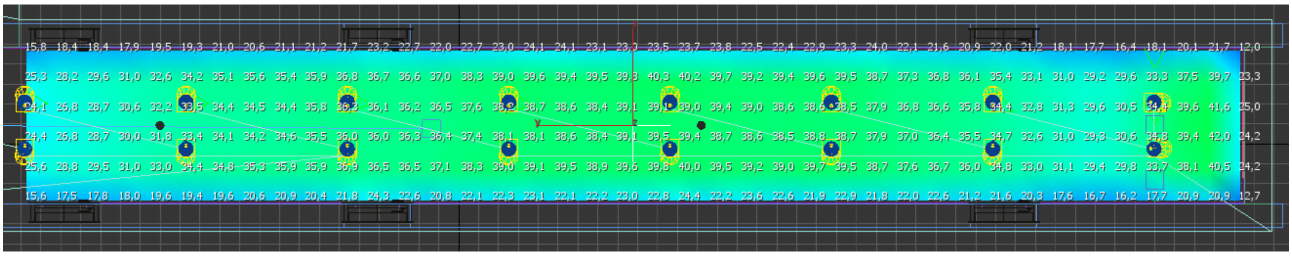

FIGURE 82 Hallway illuminance simulation - Wallwasher 30 lux

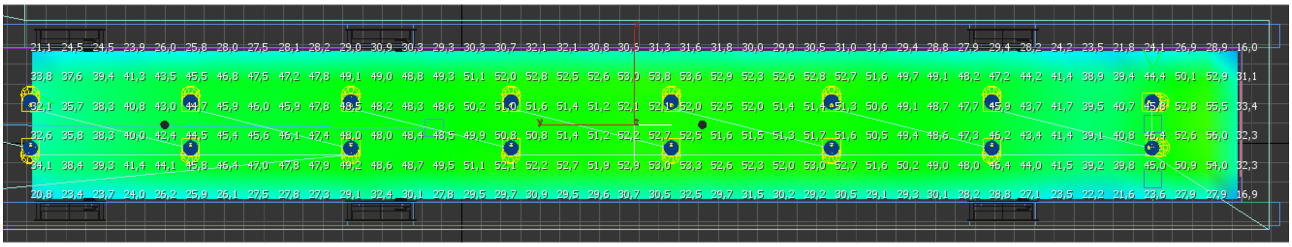

FIGURE 83 Hallway illuminance simulation - Wallwasher 40 lux

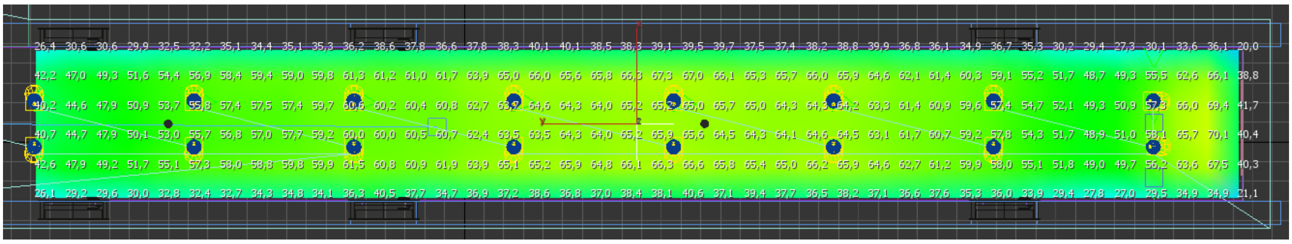

FIGURE 84. Hallway illuminance simulation - Wallwasher 50 lux

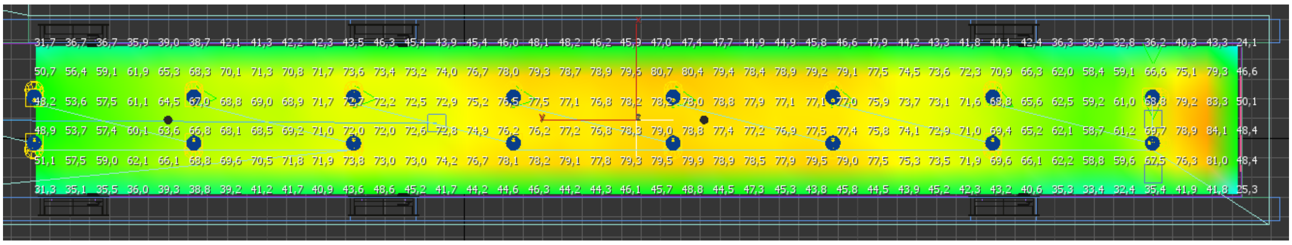

FIGURE 85. Hallway illuminance simulation - Wallwasher 60 lux

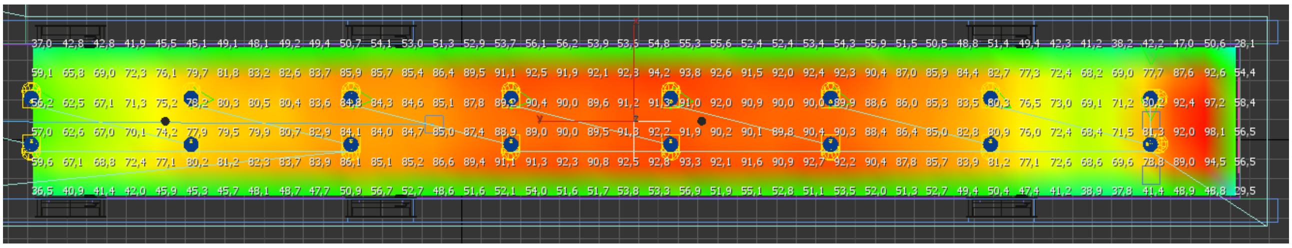

FIGURE 86 Hallway illuminance simulation - Wallwasher 70 lux

9.5 Luminaire specification sheets

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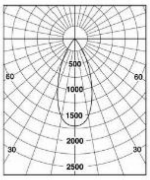

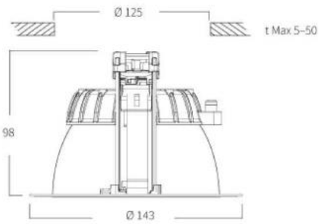

Pleiad G4 125 Rec DALI 1519LM Black Medium T/W

White and DALI with phase-pulse control

UDFØRELSE	
Farve White	**Højde, mm** 98
Reflektor Black	**Diameter, mm** 143
Vægt, kg 0.3	

TEKNISKE DATA	
Tilslutning Fixed connection	**IP Klasse** 64
	IP rating (above suspended ceiling) 20
	Min. omgivelsestemp, °C -25
	Max. omgivelsestemp, °C 25

EL TEKNISKE DATA	
Netspænding, V 220-240	**W** 20
Mains frequenzy, hz 0, 50, 60	**Effekt faktor ved 100 % lysstrøm** 0.96

LYSDATA	
Lumen, lm 1519	**SDCM** 3
lm/W 80	**CRI** 90
CLO, Constant light output Yes	**CCT, K** TW
	Lumen pakke, lm Tunable White (Max lumen)

Effektiv downlight med rigtig gode lystekniske egenskaber. Flere lysstrømme, reflektormuligheder og spredningsvinkler.

Installation Indbygning i loft. Uventileret eller ventileret bygningsdel. Stabile monteringsfjedre medfølger. Ved montering i bløde lofter skal der anvendes monteringsplade. Driveren er separat, hvilket gør monteringen hurtig og fleksibel.

Tilslutning Tilslutning til separat driver. Klemrække 3 x 1,5 mm² (x2), sløjfning muligt. 5 x 1,5 mm² (x2) ved lysstyring. Kan også leveres med chassismonteret stik i driveren, hvor der er mulighed for T-splitter eller jordet tilslutningsledning og stikprop. Armaturhus og driver sammenkobles med quick connector.

Udførelse Armaturhus i støbt aluminium. Synlig reflektorring i hvid aluminium (RAL 9003).

Reflektor Reflektor i mat metalliseret aluminium, hvidlakeret (RAL 9003) eller sortlakeret (RAL 9005). Reflektorring i hvid (RAL 9003). Linse i klar akryl.

Øvrigt Udstyret med støvbeskyttelse i lysåbningen. IP 64 under loftet, IP 20 over loftet. Armaturhus i klasse III. Den medfølgende driver skal sluttes til jord. CLO (Constant Light Output) betyder at armaturet giver samme lysmængde i hele den specificerede brændetid.
Med hensyn til belastning af loftet skal den valgte loftsleverandørs anbefalinger følges.

FIGURE 87. Specification sheet: Plaid G4, downlight

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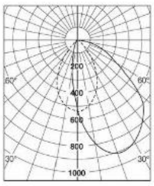
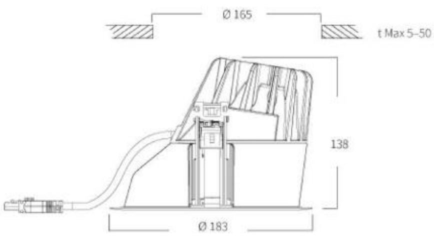
Best.nr.73181

Pleiad G4 WW Rec DALI 1095LM Matt RGBW





UDFØRELSE

Farve White	**Højde, mm** 98
Reflektor Matt	**Diameter, mm** 183
Vægt, kg 0.5	

TEKNISKE DATA

Tilslutning Fixed connection	**IP Klasse** 64
	IP rating (above suspended ceiling) 20
	Min. omgivelsestemp, °C -25
	Max. omgivelsestemp, °C 25

EL TEKNISKE DATA

Netspænding, V 220-240	**W** 24
Main frequenzy, hz 0, 50, 60	

LYSDATA

Lumen, lm 1095	**SDCM** 3
lm/W 46	**CRI** 90
CLO, Constant light output Yes	**CCT, K** RGBW
	Lumen pakke, lm RGBW (Max lumen)

En effektiv og asymmetrisk downlight til lyssætning på vægge. Lyset når helt op til vinklen mellem væg og loft. Flere lysstrømme og reflektormuligheder. Fås også med Tunable White og RGB/W

Installation Indbygning i loft. Uventileret eller ventileret bygningsdel. Stabile monteringsfjedre medfølger. Ved montering i bløde lofter skal der anvendes monteringsplade. Driveren er separat, hvilket gør monteringen hurtig og fleksibel.

Tilslutning Tilslutning til separat driver. Klemrække 3 x 1,5 mm² (x2), sløjfning muligt. 5 x 1,5 mm² (x2) ved lysstyring. Kan også leveres med chassismonteret stik i driveren, hvor der er mulighed for T-splitter eller jordet tilslutningsledning og stikprop. Armaturhus og driver sammenkobles med quick connector.

Udførelse Armaturhus i støbt aluminium og hvid PBT-plast. Synlig reflektorring i hvid PBT-plast (RAL 9003).

Reflektor Metalliseret PBT i blank eller mat aluminium. Reflektoren er beskyttelseslakeret med ridsefast klar lak.

Øvrigt Udstyret med støvbeskyttelse i lysåbningen. IP 44 under loftet, IP 20 over loftet. Armaturhus i klasse III. Den medfølgende driver skal sluttes til jord. CLO (Constant Light Output) betyder at armaturet giver samme lysmængde i hele den specificerede brændetid.
Armatur med Tunable White (2700-6500 K), som er udstyret med driveren DALI Device Type 8.
Med hensyn til belastning af loftet skal den valgte loftsleverandørs anbefalinger følges.

FIGURE 88. Specification sheet: Plaid G4, Wallwasher

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