MASTER

The influence of a lighting solution on the circadian rhythm of patient in a hospital patient room

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The influence of a lighting solution on the circadian rhythm of patient in a hospital patient room

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''THE RIGHT AMOUNT OF THE RIGHT LIGHT AT THE RIGHT TIME''
LE CORBUSIER

ACKNOWLEDGEMENTS

Dear reader,

Hereby, my final thesis of my graduation project as master student Building Physics and Service at the University of Technology, Eindhoven. My name is Charlotte Rosenkötter and I would like to thank you for taking some time to read this report.

This report described the research I did in collaboration with the University of Technology, Eindhoven and Deerns, to investigate the lighting design in a one-occupancy patient room in a hospital, which also enhances the circadian rhythm and well-being of a patient. My motivation to perform this master thesis is the great impact of lighting characteristics regarding the circadian rhythm, by keeping in mind the recently discovered intrinsically photosensitive Retinal Ganglion Cells (ipRGC).

This research was not possible without the help of some important people. Therefore, I would like to express my gratitude here. I would like to thank my supervisor Alexander Rosemann for all that you learned me about light, and your critical view during this research process. I would like also to thank my second supervisor Helianthe Kort for her support and critical comments.
Then, I would like to thank Deerns, especially my supervisor Ralph van den Berg, for his support and guidance through this research process and that you shared your experience and gave me the opportunity to gain new insights in the field of lighting. Furthermore, I would thank all my colleagues of Deerns for supporting me during this research.

A special thanks to my boyfriend Do for the supporting words, listening to me and being so patient during this challenging research. I would like to thank my parents Harold and Monique and my sisters and brother Elise, Eveline and Wolter for their support during my study, thank you all so much!

Enjoy reading.

Abstract

The focus of this graduation project is to determine how the lighting solution can be realized that enhances the circadian rhythm and well-being of a patient in a hospital patient room. The study is a continuation of a previously performed literature study, which gives an overview of relevant literature about different aspects regarding the lighting design in healthcare facilities. To answer the research question; the influential factors of the lighting solution were examined using on-site measurements, a simulation model by using DIALux evo and a calculation. It is important to notice that the lighting solution is based on artificial lighting including luminaires and control, daylight is not taken into consideration in this study. Basic configurations of the patient room in the Jeroen Bosch Hospital were used in the simulation model. A case study research is used to make a realistic situation and therefore a more reliable lighting solution.

The lighting solution in a patient room needs to provide sufficient lighting for different activities and persons and simultaneously need to stimulate the circadian. Activities which occur in a patient room are subdivided into three scenarios; general, treatment and relaxing, these scenarios are an outcome of the literature study and used throughout the report. Furthermore, the sleep and wake rhythm i.e. circadian rhythm of patients has a strong relation to patients' health. Compared to healthy people, patients are more sensitive for a disturbed circadian rhythm (BaHammam, 2006). A disrupted circadian system may create long-term health problems. The melatonin production regulates the sleep and wake cycle and is influenced by lighting. Lighting is divided in several characteristics i.e. timing, dose, exposure duration and spectrum. These aspects are important to synchronize the circadian rhythm.

Where, average illuminance and spectrum are defined by the requirements of the NEN-EN 12464-1 regarding an activity. A specific combination of lamp types is found by using a simulation model, the vertical effective irradiance on patient's eye level is derived from simulation model. The maximal exposure duration (before melatonin suppression occur) of each activity is calculated by the threshold of melatonin suppression divided by the vertical effective irradiance. The threshold of melatonin suppression is assumptive regarding the study of Brainard 2015. Furthermore, timing is defined regarding the melatonin production; melatonin is increasing from 19:30 and therefore it is recommended to have no melatonin suppression from this point (19:30).

In conclusion, activities during the general scenario could be performed during the whole day in a one occupancy patient room. A treatment and complex treatment can be performed during the day, but from 19:30 the time of a treatment is critical which means that a treatment has a maximal performing time of 66 min and for complex treatment (68 min) before melatonin suppression occur. For the activities within relaxing can be perform the whole day except for reading, in bed 1h and 51 min and on the desk 68 min maximal performing time from 19:30, before melatonin suppression occur. It is recommended to use the maximal performing time from 19:30 to stimulate the circadian rhythm.

Glossary

UGR	Unified Glare Rating
U_o	illuminance uniformity (ratio between the lowest (E_{min}) and the average illuminance level in an area)
E_{min}	minimum illuminance
E_{max}	maximum illuminance
$\overline{E}$	average illuminance in lx, $\overline{E} = \frac{1}{n}(E_1 + \ldots . E_n)$
R_a	Color Rendering Index
ipRGC	intrinsically photosensitive Retinal Ganglion Cells
E_e	Effective irradiance [$\mu W/cm^2$]
Δt	Exposure duration [hours]
Circadian rhythm	sleep/wake rhythm of a human
$V(\lambda)$	sensitivity function of the eye
$H_{threshold}$	threshold effective radiant exposure for half-maximum melatonin suppression
$E_{e,c}$	vertical effective irradiance
CCT	Correlated Color Temperature
E_{oog}	vertical/horizontal illuminance level of patient's eye
SPD	Spectral Power Distribution

Overview of Lighting Settings

Different lighting settings are described in this report and refer to letters (A-H). The table shows which lamps ar used relative to the lighting setting.

Lighting setting	**Lamps on are grey**			
	General	Indirect	Direct	Desk
A				
B				
C	Night luminaire			
D				
E				
F				
G				
H				

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1 Introduction

1.1 Research objective

The present study is a continuation of a performed literature study, which gives an overview of available and relevant literature about different aspects, i.e. visual perception, performed activities, technical characteristics of lighting system and building characteristics. These aspects have an influence on the lighting design, e.g. artificial- and day lighting in a patient room (Rosenkötter, 2016). Furthermore, the present study will elaborate on a ''lighting solution'' which is defined as *a lighting design in a patient room including luminaires (technical characteristics, position, quantities) and control (characteristics, position, personal control)*, although daylight is excluded from this study. The aim of this graduation project is to make an improvement in the lighting design of a one- occupancy patient room in a hospital, while focussing on a better circadian rhythm and well-being of patients. Improvement in the lighting design is regarding

(1) Evaluation of the current situation of a typical lighting design in a case study research compared to NEN 12464-1. A measurement by NEN1891 is used to evaluate the lighting design of the case study research and validate the simulation model of a typical one-occupancy patient room;
(2) Medical treatment could be performed in a one-occupancy patient room, since the environment of a patient is more considers as important and benefits increases. Therefore other lighting is needed.
(3) The impact of the non-image forming process in the visual system by using the vertical effective irradiance on patient's eye. The impact is conducted by mathematical equations.

This chapter elaborates to the background of this study, the research purpose, delineation, method and the structure of the entire report.

1.2 Research context

In recent years, the discussion about the impact of the built environment on patients' comfort is becoming more important in healthcare facilities. Moreover, the focus on patients' well-being is taken more into consideration as an argument to design these facilities (Harris, McBride, Ross, & Curtis, 2002). Therefore, a new development has arisen and is called: a healing environment. This new development refers to the concept Evidence Based Design (EBD), where many companies are working with during the design process (in 't Veld, 2015) (Meinsma, 2015). The purpose of EBD in health care facilities is to create a(n) (healing) environment where positive features influence the healing process and well-being of patients and create a better and more efficient working environment for staff (Ampt, Harris, & Maxwell, 2008; Salonen et al., 2013; Zorginstellingen, 2008).

In the present study, focus is on the ambient design feature, i.e. artificial lighting. Artificial lighting could have an impact on the circadian rhythm (sleep and wake cycle human), which consist of hormones such as melatonin and cortisol. Generally patients are more sensitive for a disturbed rhythm (BaHammam, 2006) therefore, with the right settings of different lighting characteristic, i.e. timing, irradiance, exposure duration and spectrum could stimulate the circadian rhythm.

A radiant exposure of 90 minutes with 3.1 μW/cm^2 and higher at 460 nm (highest sensitivity of ipRGC) obtains melatonin suppression (Brainard et al., 2001). Furthermore, the most effective time to induce a phase shift by light exposure is during the early night or morning (Warman, Dijk, Warman, Arendt, & Skene, 2003). The amount of phase shift depends on the length of duration and luminous radiation. However, the exact length of effective radiant exposure is not found in literature (Bonmati-Carrion et al., 2014; St Hilaire et al., 2012; Khalsa et al., 2003).

In conclusion, a comfortable (healing) environment can improve the well-being of patients which in turn could result in a decreased duration of stay of a patient in a hospital (Tooren, 2015; Ulrich et al., 2004).

1.3 Research purpose

The purpose of this graduation study is to optimize a lighting solution in an one-occupancy patient room, which can provide sufficient lighting for performed activities by different end-users in a one-occupancy patient room and simultaneously can stimulate the circadian rhythm. Furthermore, melatonin is known as the sleep hormone and is normally produced in the night, therefore melatonin hormones act as a time indicator for the circadian rhythm. The impact of the lighting solution on our visual comfort is known to have an impact on our daily life. This is in contrast to the impact of the non-image forming process is less known. The sensitivity function of the intrinsically photosensitive Retinal Ganglion Cells (ipRGC) is recently discovered and has an action spectrum of lower wavelengths compared to the visual system (Brainard et al., 2001).

This study elaborates on the consequence of the lighting solution and the sensitivity function of the ipRGC regarding the influence on melatonin production. Therefore the vertical effective irradiance will be used in order to analyse the impact of the non-image forming process in the visual system.

1.4 Research question

In order to meet the research purpose the following main research question is formulated:

How can an optimal lighting solution be realized in a hospital patient room that also enhances the circadian rhythm and well-being of a patient?

Sub questions

1. What are the current recommendations, guidelines and typical realizations regarding the lighting solution?
2. How does the lighting solution influence the support of circadian rhythm and well-being?
3. What aspects of luminaires support the circadian rhythm in typical lighting solution?

1.5 Delineation

This section elaborates on research choices and boundaries which were set for the present study. First, this study is performed in the healthcare environment, more specific in one-occupancy patient room in a hospital where a patient is defined as: *'a person who is under medical care or treatment'* (The American Heritage, 2016). Furthermore, the well-being of a patient is different compared to healthy people, a patient needs medical care and more rest and is doing different activities compared to their normal live. However, all medical information is excluded from the scope, such as medical treatment, wound healing, clinical outcomes, pain reduction and medical influences (for example dementia). Nevertheless, patients are more sensitive to their environment compared to healthy people, this needs to be taken into consideration when making a lighting solution in a patient room. Second, in this study daylight is not taken into consideration, in order to exclude the effect of weather changes and sky types during the study.

1.6 Methodological approach

The present study is composed based on a literature study performed in September until December 2015. This literature study used various computerized databases search engines, including (Scopus, PubMed (Medline), Science Direct and Google Scholar). Furthermore, the search strategy and selection criteria have resulted in a selection of 126 academic articles total, consisting of 111 literature articles and 15 review articles.

In line with the literature study, a patient room within a hospital function is performed as a case study research to create a more realistic situation. Besides, this case study more hospitals were visited to get a better overview of the possibilities regarding the lighting solution in a patient room, the description of the other hospitals can be found in Appendix A. These hospitals are chosen since there was a connection via Deerns. Furthermore, before this research was performed, scenarios were defined as an outcome of literature study. These scenarios were a starting point for the present study. This research was divided into several stages as depicted in Figure 1. In the first stage a simulation model of the current lighting situation in a patient room was made, by using the software of DIAL. To make a reliable simulation model, a lighting measurement of the current situation in the patient room of the case study research was performed. This measurement was used to validate the simulation model. The result of this study was a calculation of the effective radiance exposure by different lighting settings for each scenario, by using:

(1) Effective irradiance on patients' eye as an output of a calculation point in the simulation model in DIALux evo;

(2) Specification parameters of a luminaire regarding scenarios;

(3) Evaluation typical lighting design in an one-occupancy patient room of case study research.

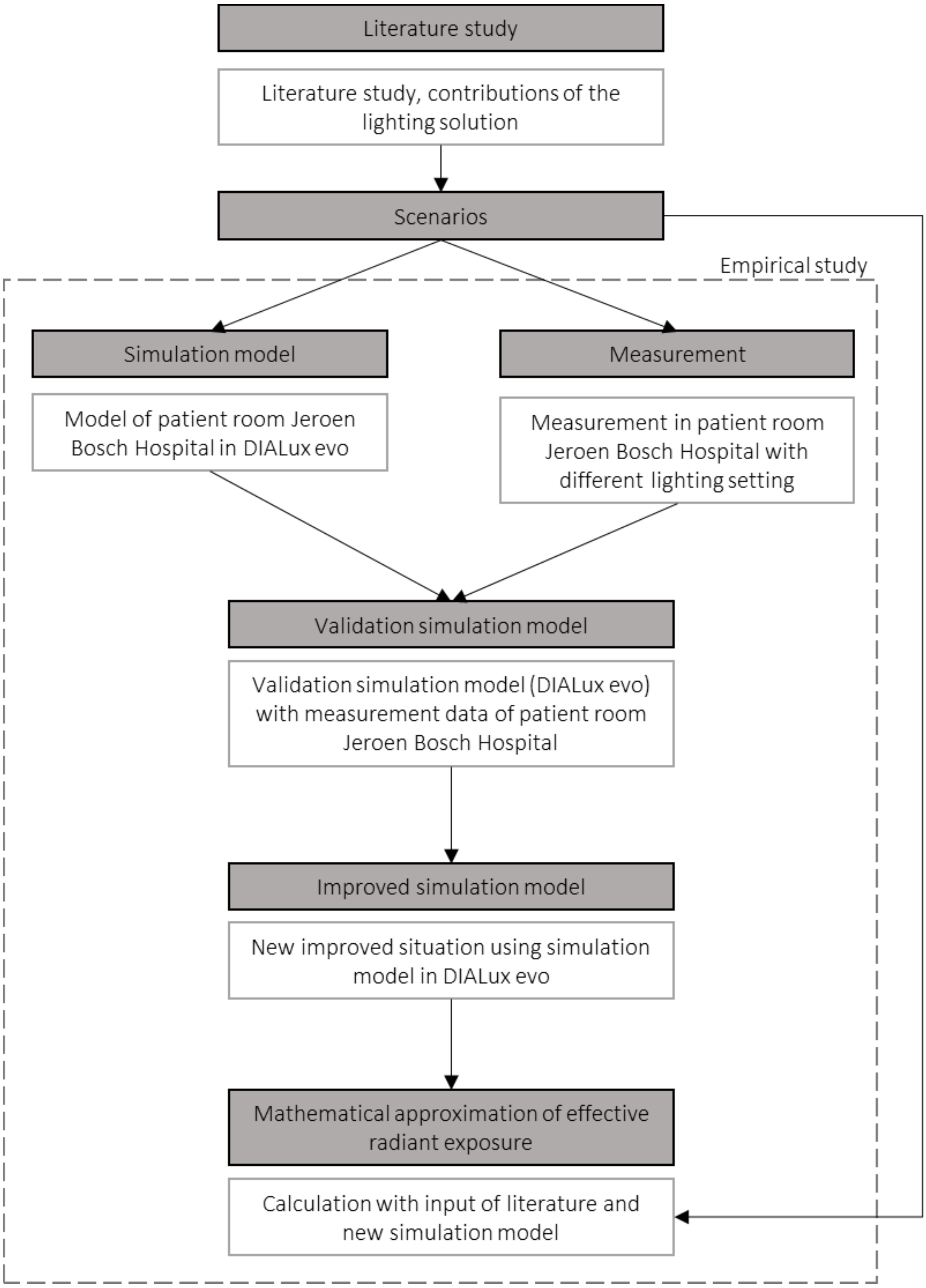


Figure 1. Illustration of the different stage in the methodology of this research

1.7 Report outline

The structure of the present study is as follows: Chapter two describes the theory divided into the scenarios and defined threshold of melatonin suppression. The method in Chapter three elaborates on the current situation of the case study research, where a measurement is performed and a simulation model is conducted, this chapter end by describing the method to calculate the maximal exposure duration. Chapter 4 describes the results derived from the measurement, simulation and calculations which are divided into theoretical and practical part. Outcomes are discussed In Chapter 5. Finally, Chapter 6 describes the conclusions and limitations of this study and gives insight in the recommendations for further research.

2 Theory

The lighting solution in a patient room needs to provide sufficient lighting for different activities and persons and simultaneously need to stimulate the circadian rhythm as is mentioned in the literature study (Rosenkötter, 2016). Furthermore, activities which occur in a patient room are subdivided into three scenarios. Paragraph 2.1 elaborates on these scenarios.

As mentioned, the lighting solution could also supports melatonin concentration, i.e. melatonin production of a patient. The melatonin production is shown in Figure 2 over a time span of one day. Melatonin is known as the sleep hormone and is normally produced in the night. Melatonin production stops in the early morning and starts in the early night. Furthermore, patients are more sensitive to poor sleep quality and therefore a disturbed circadian rhythm (BaHammam, 2006). Therefore, two time points are defined to stimulate the circadian rhythm and shown in Figure 2. These time points are called 'Active' and 'Rest', which are further explained in sub-paragraph 2.2.1 and 2.2.2.

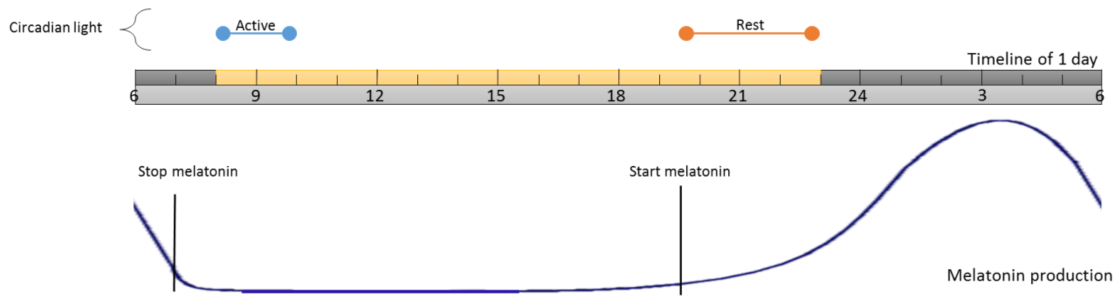


Figure 2. Melatonin production for a human relative to a day (24 hours) (Aarts, 2015). Melatonin production could be supported by lighting at two points defined as Active and Rest.

2.1 Lighting in a one-occupancy patient room

The lighting solution in a patient room has a major impact on patient's health and well-being. However, the well-being of a patient is different compared to healthy people. Since patients are in a different environment, they also perform different activities compared to their regular live. Besides a patient, three other end users are present in a patient room: medical staff, family (visitors) and a cleaner. In addition, more end users are active in a patient room; however in this study these four are defined. The different activities which could occur by different users are divided into three scenarios, 'general', 'treatment', 'relaxing'. For each scenario are corresponding requirements regarding to the lighting solution in the patient room. The different scenarios are used in every part of this study. Most patient rooms have a typical lighting design, which exists of (Yagci, 2016):

- General luminaire in the middle of the room (1)
- Bed head wall panel with direct and indirect luminaire (2, 3)
- Luminaire nearby the desk and sink (4, 5)
- Luminaire for the night lighting (6)

These luminaires are used in the different scenarios.

Three different scenarios; 'general', 'treatment' and 'relaxing' are defined and shown in Figure 3 relative to a timeline of 24 hours. The dots for each scenario represent the begin and end time of each activity. Dashed lines mean that the activity could take place between the dots, not knowing exactly when they will take place. In the next sub-paragraphs, the scenarios will be further described in detail, related to the lighting requirements and activities in the patient room.

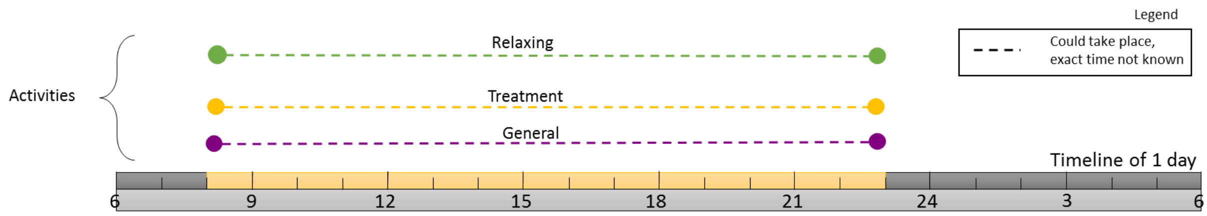


Figure 3. Three different scenarios are defined relative to the time line of one day.

2.1.1 General scenario

This scenario describes a general situation in a patient room where the switch for general luminaire is easily assessable near the door. During this scenario, two activities may occur; (1) someone enters the room and (2) a cleaner uses the general luminaire to clean-up the room. In general, the cleaner cleans up the room in the morning and someone can enter the room the whole day, therefore the time is indicated over the whole day as is shown in Figure 3. These two activities need an average illuminance of 100 lx on ground level (height of 0.2m) conform NEN 12461-1, other requirements are shown in Table 1. The general luminaire should be in the middle of the room with a direct light distribution to have uniformity in the total room illustrated in Figure 4, therefore minimum requirements are obtained. Moreover, the general luminaire can also be used with other luminaries as a composition, for example together with the indirect and direct lighting.

During these activities, (1) the patient is not in the room, (2) the patient is sitting in bed or (3) the patient is lying in bed.

During the night only the night luminaire is on where the average illuminance need to be 5 lx in covering the whole patient room (Table 2). This lighting level is necessary for an overall orientation in the room for the patient and to observe the patient by medical staff.

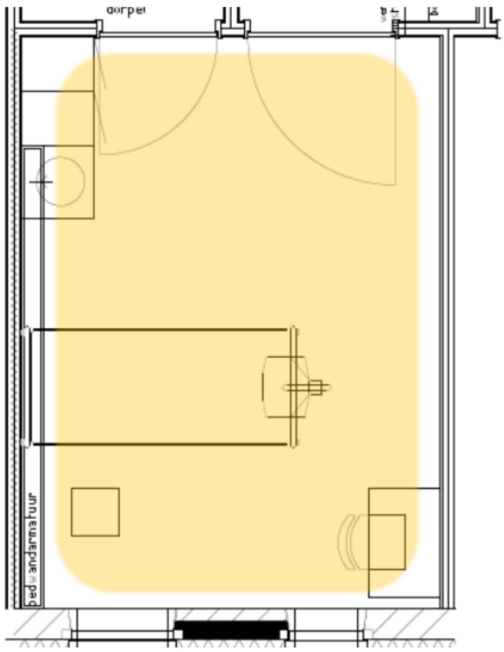


Figure 4. Illustration 'general' scenario in the patient room, yellow shading illustrates the needed uniformity in the patient room

Table 1. Minimal requirements over the total room (NEN 12464-1)	
$\bar{E}_m$ [lx]	100
UGR [-]	19
U_o [-]	0,40
R_a [-]	80
CCT [K]	3000

Table 2. Minimal requirements over the total room, night lighting (NEN 12464-1)	
$\bar{E}_m$ [lx]	5

2.1.2 Treatment scenario

Since the environment of a patient is more considered as important and more benefits occur for a one-occupancy patient room, new healthcare projects prefer a majority of single-occupancy rooms instead of multiple-occupancy rooms. Due to these one-occupancy patient rooms, more medical treatments, patient care, monitoring and other procedures can be performed in the patient room. Therefore the lighting design needs stricter requirements (Sylvania, 2013) (Chaudhury, 2005).

During the medical treatment the patient is lying or sitting in bed, therefore the lighting needs to be on and around the bed for a good view on patient's body, as can be seen in Figure 5. Moreover, to prepare the treatment, a luminaire near the sink is recommended. The lighting requirements specific for the treatment are shown in Table 3, and must merge into the existing lighting design in a patient room. Tanja-Dijkstra & Pieterse, (2011) found that if medical equipment is not visible for the patient, it leads to a more positive emotional state and therefore reduces stress feelings in patients. Therefore, it is recommended to use the current lighting luminaires instead to use a specific luminaire only for treatments. In addition, if luminaires as well as for medical lighting as for other activities the cost are lower, since less luminaire connections are needed.

To meet the requirements, this scenario could make use of general lighting, together with direct and indirect lighting.

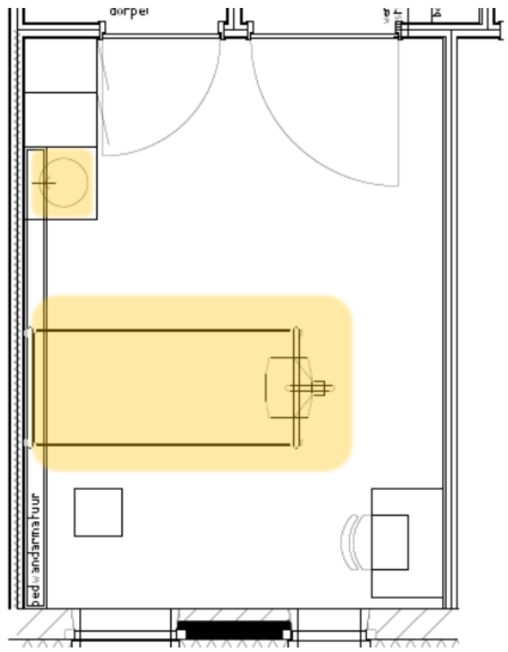


Figure 5. Illustration 'treatment' scenario in the patient room, yellow shading illustrate where light need to be (the lighting situation)

Table 3. Minimal requirements for specific areas (NEN 12464-1)

	Treatment	Complex treatment
$\overline{E}_m$ [lx]	300	500
UGR [-]	19	19
U_o [-]	0.6	0.6
R_a [-]	80	90
CCT [K]	4000	5000

2.1.3 Relaxing scenario

The physical environment plays a significant role in patients' experience in a hospital (Harris et al., 2002). The lighting design in a patient room is one part of the physical environment and needs extra attention. The lighting design must provide patients with a sufficient amount of light regarding activities such as reading, watching television, resting, sleeping, socializing and patient safety (mobility) (Sylvania, 2013). Requirements for these activities are shown in Table 4.

Furthermore, patients need more sleep compared to healthy people, due to their illness; therefore, lighting system could help to stabilize the circadian rhythm (Philips, 2014). The study of Ulrich et al., (2008) describe that when patients get more light exposure during the days, the sleep quality increases. This is beneficial for elderly people, data of (Centraal Bureau voor de Statistiek, 2014) shows that people between 45-80 years are most hospitalized, almost 60% of the total amount of hospitalization days. In addition, many patients have limitations in mobility and vision; therefore, the lighting design must accommodate the aging eye (Sylvania, 2013; Zumtobel, 2015; Philips, 2014). However, the aging eye is not taken into account regarding lighting requirements in the different scenarios.

Social support from family and friends are important for the patients, since patients can better handle stress due to the presence of family (Zorginstellingen, 2008). Which makes family also an end user in this scenario, but no specific requirements for the family are recommended.

Figure 5 illustrates specific areas where lighting distribution needs to be, on the bed and desk, since most activities will occur in these areas. Furthermore, different luminaires can be used to meet the requirements. Most of the time the patient could use direct lighting and desk lighting for their activities. However, uniformity in the total room is recommended, which means that general lighting and indirect lighting need also be used to support the activity.

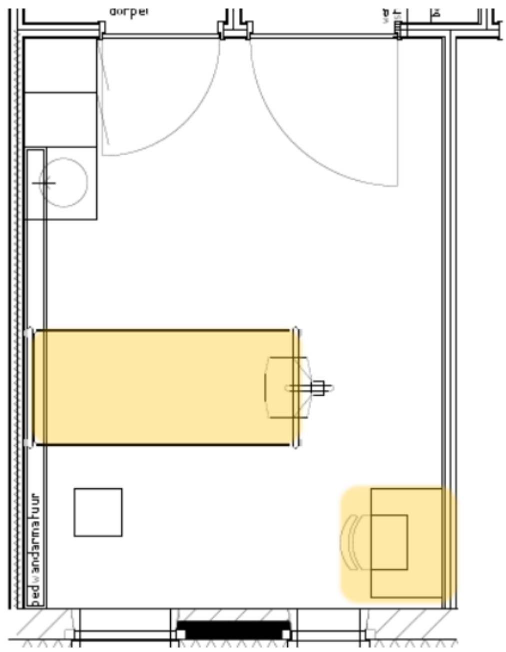


Figure 6. Illustration 'relaxing' scenario in the patient room, yellow shading illustrate where light need to be (the lighting situation)

Table 4. Minimal requirements for specific areas (NEN 12464-1)

$\bar{E}_m$ [lx]	50-300
UGR [-]	19
U_o [-]	0.4
R_a [-]	80
CCT [K]	<3000

2.2 Threshold melatonin suppression

In general, the sleep and wake rhythm i.e. circadian rhythm (primary stimulates by light exposure) of patients has a strong relation to patients' health. Compared to healthy people, patients are more sensitive for a disturbed circadian rhythm (BaHammam, 2006). A disrupted circadian system may create long-term health problems (Bonmati-Carrion et al., 2014; Boyce, Hunter, & Howlett, 2003).

For a long time, the original idea was that rods and cones are the only photoreceptors in the human eye. Nevertheless, in the end of 2001 a new photoreceptor is discovered by Brainard et al., (2001) and called intrinsically photosensitive Retinal Ganglion Cells (ipRGC). These cells are located inside the retina before the rods and cones. The visual pigment for this photoreceptor is melanopsin, this pigment detects intensity of changing levels of light and is very sensitive for bright light. Moreover, the ipRGC play an important role in physiological responses to light i.e. suppression of melatonin production, reset the circadian rhythm and adjusting the pupil diameter. The melatonin production regulates the sleep and wake cycle and therefore the circadian timing system determines the optimal time for sleep (Dijk & Archer, 2009). However, these cells response only to the non-image forming compared to the rods and cones, which relates to the image-forming process (Berson, 2003; Brainard et al., 2001).

Lighting is divided in several characteristics i.e. timing, dose, exposure duration and spectrum. These aspects are important to synchronize the circadian rhythm. Several studies performed an experiment in order to define these characteristics. For example, the study of Warman, Dijk, Warman, Arendt, & Skene, (2003) indicate that the most effective time to give light exposure, is during the early night or morning. Furthermore, the action spectrum for ipRGC is between 446-477 nm (Brainard et al., 2001) as is shown in Figure 7. The irradiance depends on the exposure duration and is described by a few studies (Brainard et al., 2001, 2008, 2015; Burgess, Revell, Molina, & Eastman, 2016; Chellappa et al., 2011; Khalsa, Jewett, Cajochen, & Czeisler, (2003); St Hilaire et al., (2012); Warman et al., 2003). However, Photometric quantities such as illuminance is based on human visual responses and therefore, a relation to the sensitivity of a human eye, this differs from the sensitivity of the ipRGC (Int15). Therefore only studies which are using radiometric quantities can be used, since these quantities are not weighted. In addition, the new photoreceptor is discovered in 2001, which is recently.

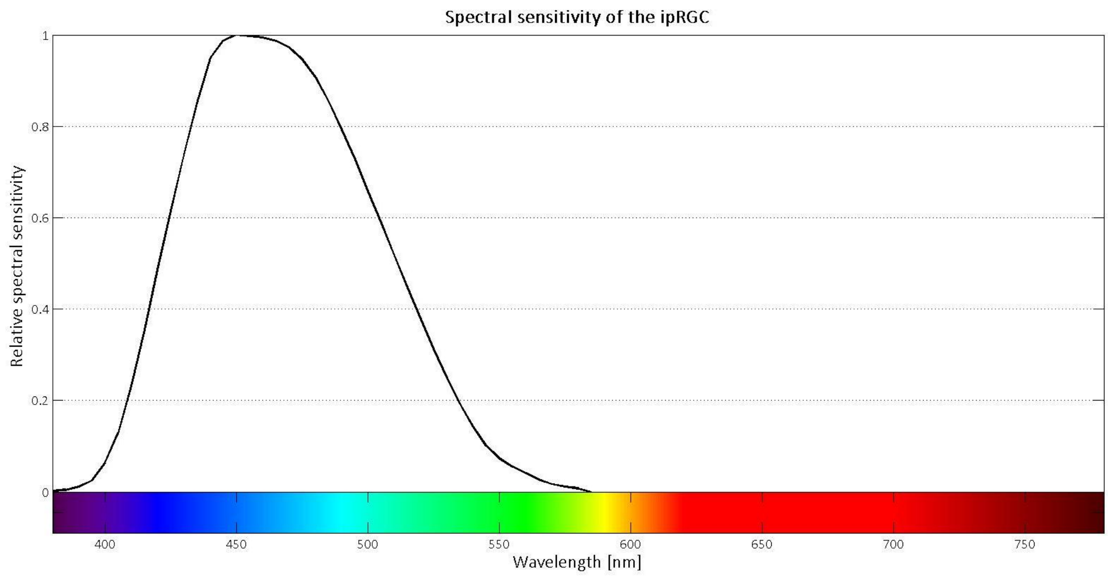


Figure 7. Spectral sensitivity of the ipRGC, peak is between 446-477 nm indicated by Brainard et al., (2001)

Literature studies which are described in the literature focus mainly on the suppression or saturation of melatonin, since melatonin can easily be measured in the human body. The majority of these studies search for a threshold for melatonin suppression. However, currently the threshold for melatonin suppression is not clearly defined. Each study uses its own assumptions for the level where plasma melatonin was assayed by a method called radioimmunoassay. Therefore a general threshold for melatonin suppression is not generalizable; studies are difficult to compare with each other and the value of melatonin suppression means nothing.

In addition, the present study makes use of the experiment which is performed by (Brainard et al., 2015). The method used in this experiment, is already performed (repetition) in other studies by Brainard (Brainard et al., 2001, 2008). Compared to other studies which are described in the literature study, the study of Brainard measured not only melatonin suppression, but defines the value of half-maximum melatonin suppression.
During the lighting exposure, monochromatic lighting stimuli (Brainard et al., 2001, 2008) and polychromatic lighting stimuli (Brainard et al., 2015) are used for 90 minutes between 2:00-3:30 a.m. During the exposure, subjects were sitting behind a light-box with their eyes open. The melatonin concentration was measured for each subject, before and after the experiment. Measured by radioimmunoassay procedure, the minimum detection limit of the assay was 0.5-2.0 pg/ml. The melatonin concentrations were used to define the half-maximum melatonin suppression (X_{50}).

The results of these experiments are shown in Table 5. Where the dose is a result compared to the other parameters which were set during the experiment.

Table 5. Comparing results of experiment for 50% melatonin suppression (Brainard et al., 2001, 2008, 2015)					
Lighting quantities	Brainard 2001	Brainard 2008	Brainard 2015		
	Monochromatic light		Polychromatic light		
Illuminant	460 nm	420 nm	Blue fluorescent	17.000 K	4000 K
Timing [hour]	2:00-3:30	2:00-3:30	2:00-3:30	2:00-3:30	2:00-3:30
Exposure duration [min]	90	90	90	90	90
Irradiance [$\mu W/cm^2$]	12	>89	14	16-21	96

Although, only the results of the study of Brainard et al., (2015) are used, especially the result of 4000K, since this experiment uses polychromatic light and this lighting is comparable with this study. Therefore, the results of this graduation project will be compared with Brainard et al., (2015) this will result in a more reliable outcome.

The effective radiant exposure for melatonin suppression ($H_{threshold}$) is defined in equation 2, regarding the study of Brainard et al., (2015), by using equation 1 and 2. $E_{e,c}$ is the vertical effective irradiance, indicates the impact through the non-image forming process (weighted by the spectral sensitivity of ipRGC) in the visual system (absolute spectral irradiance of a lamp). H_{thres} will be further used in this study, to define the length of exposure duration for a specific lighting setting, with respect to melatonin suppression.

For the calculation the result of the study of Brainard et al., (2015) will be used: irradiance of 96 $\mu W/cm^2$ with exposure duration of 90 min (1.5h). These values will lead to:

$E_{e,\lambda}$ = 96 $\mu W/cm^2$ = 0.0096 $\mu W/m^2$

$$E_{e,c} = \int_{\Delta\lambda} E_{e\lambda} * C(\lambda) d\lambda \quad (1) \quad | \quad E_{e,c} = 0.177 \frac{\mu W}{m^2}$$

$E_{e,c}$: Vertical effective irradiance [$\mu W/m^2$]

$E_{e,\lambda}$: Absolute spectral irradiance at eye level [$\mu W/m^2 nm$]

$C(\lambda)$: Retinal ganglion cells sensitivity function

$$H_{thres} = \int_{\Delta t} E_{e,c}\, dt \quad (2) \quad | \quad H_{thres} = 0.2655 \frac{\mu Wh}{m^2} \text{ at eye level.}$$

H_{thres}: Effective radiant exposure at eye level in [$\mu W/m^2$]

$E_{e,c}$: Vertical effective irradiance in [$\mu W/m^2$] = 0.177 $\mu W/m^2$

Δt: Exposure duration [hours] = 1.5 hour

2.2.1 Active

During the early morning the melatonin production will be decreased and helps us to wake up every morning. This scenario will support the patient in the morning and therefore lighting exposure from wake up time for two hours will be used. To suppress the melatonin production, it is better to have the lighting distribution in the total room, as is illustrated in Figure 8. In addition, lighting supports better in the upper part of the room, then the light reaches the lower half of the retina, where most ipRGC are located (Bieckmann, 2016) (Rosemann, 2015)

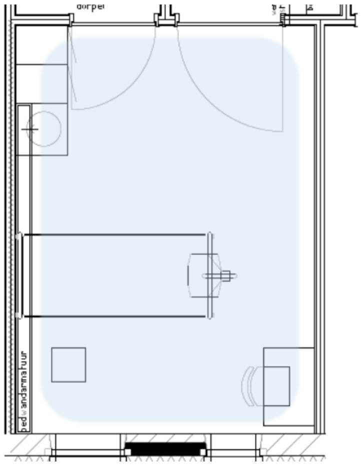


Figure 8. Illustration where the light need to be in the patient room

Table 6. Requirements for qualities of lighting	
H_{thres} $[\frac{\mu Wh}{m^2}]$	≥ 0,2655
Illuminant	Include action spectrum ipRGC
Timing	Morning: 08:00-10:00
Exposure duration [h]	Result of current study

2.2.2 Rest

The melatonin production is increased from 19:30 in the evening as illustrated in Figure 2. Therefore after a few hours, the patient will go to sleep. To stabilize the circadian rhythm it is recommended to have no melatonin suppression from 19:30. Activities by the patient for example, watching television or reading a book occur mostly around the bed or desk (see Figure 9). The activities from 19:30 need to confirm the requirement of scenario ‘rest’, which are shown in Table 7. These requirements ensure that melatonin production will not be suppressed.

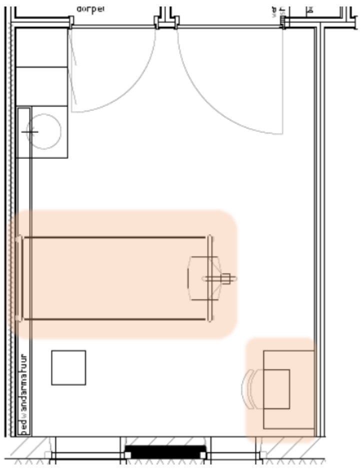


Figure 9. Illustration where the light need to be in the patient room

Table 7. Requirements for qualities of lighting	
H_{thres} $[\frac{\mu Wh}{m^2}]$	$\leq 0{,}2655$
Illuminant	Avoid action spectrum ipRGC
Timing	Evening: from 19:30
Exposure duration [hour]	Result of current study

2.3 Summary

In summary, three scenarios divided into

(1) General;

(2) Treatment, and

(3) Relaxing.

Two time indicators to support the circadian rhythm divided into 'Active' and 'Rest' are defined and shown in Figure 10.

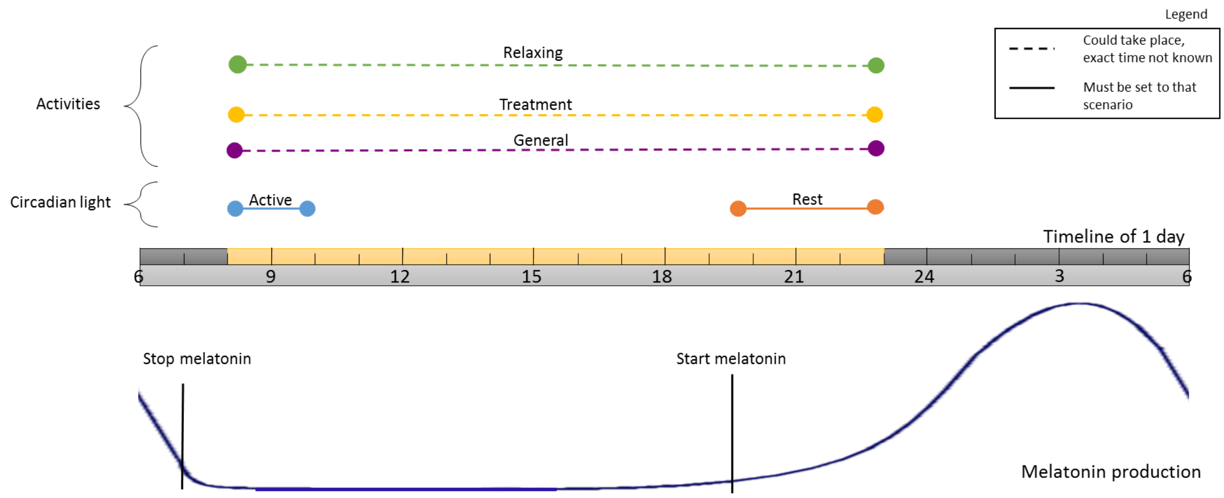


Figure 10. Melatonin production for a human relative to a day (24 hours) (Aarts, 2015). Melatonin production could be supported by lighting at two points defined as Active and Rest and three different scenarios are defined called General, Treatment and Relaxing with respect to different activities which could occur in a patient room.

A summary of the requirements for each scenario and time indicator are shown in Table 8, requirements are based on lighting distribution, NEN 12464-1 and literature. The scenarios are further used in the different stages of this study.

Table 8. Summary requirements of scenarios relative to the activities and time indicators to support circadian rhythm

Scenarios	General	Treatment	Relaxing		Scenarios	Alertness	Rest
$\overline{E}_m$ [lx]	100	300, 500	50-300		H_{thres} $[\frac{\mu Wh}{m^2}]$	≥ 0.2655	≤ 0.2655
U_o [-]	0.4	0.6-0.7	0.4		Illuminant	Action spectrum ipRGC	Avoid action spectrum ipRGC
CCT [K]	3000	4000, 5000	<3000		Timing	Morning	Evening

The result needs to be a (adjustable) lighting solution particular for each type of activity and person. Furthermore, the lighting solution needs to be calm for patients and family and therefore can help by creating a home-like environment. This in contrast to medical staff, who need a diversity of illuminance levels, where the lighting has to support (simple) medical treatment. The best result to obtain these needs is to combine requirements, as shown in Table 8, in one luminaire. Therefore LED technology might provide a solution since tunable white can easily obtain within LED. Tunable White creates a continuations alteration of the Correlated Color Temperature (CCT) between 2700K and 6500K. (Srividya & Kurian, 2014; The Netherlands Standardization Institute, 2015).

3 Method

This section elaborates on the different stages in the present study. First, the case study research of a patient room with specific lighting solution is described. Further, the measurement plan and simulation model of the current situation are described in the second paragraph, and the last paragraph elaborates on the equations which are used to calculate effective irradiance at patient's eye.

3.1 Case study: Jeroen Bosch Hospital in 's Hertogenbosch

The Jeroen Bosch Hospital is located in 's Hertogenbosch in the Netherlands. The hospital is recently rebuild 5 years ago. Figure 11 shows the hospital, which consists of four large buildings, rotated 10.5 degrees from north and constructed in parallel, whereby, a boulevard makes a link between these buildings. This hospital is situated on the edge of the city, with on one side of the hospital a view to the city and on the other side a view to the nature. Between the buildings, a courtyard is created to have a greener environment around the hospital as can be seen in Figure 12. However, there is no access to these courtyards.

Figure 11. Overview Jeroen Bosch Hospital (taken from EGM Architects)

Figure 12. Courtyard between the buildings of Jeroen Bosch Hospital (taken from EGM Architects)

The hospital is designed according to the 'healing environment' concept. This concept creates a home-like ambiance with warm colors and interior, the buildings have large windows from the floor till the ceiling which results in lots of daylight and nice views to the nature or courtyard. All these aspects are shown in figure 13 and 14.

Figure 13. One-occupancy room with view to nature

Figure 14. One-occupancy room with a home-like environment

3.1.1 Description patient room

The Jeroen Bosch Hospital was visited for two times before the actual measurement was performed. The exact patient room was assigned on the day of the measurement and chosen randomly (requirement: one-occupancy room). Patient room C2.02.62 was available during the day since it was a quiet day in the hospital, on May the 6th 2016. Furthermore, the dimensions of the room are 4.4 m (length) x 3.5 m (width) and 2.7 m (height), and is used as an isolation room, necessary for patients who have a contagious infection which can be transmissible through the air. Therefore these isolations rooms have their own air system for in- or out-coming air or both ways. The air locked area between the corridor and the patient room was excluded from the measurement. In addition, daylight was excluded in the present study –in measurement and simulation model-, therefore the window in the patient-room-door was taped including windows adjacent to the outside.

During the measurements, there was no patient in the room. However, the setting was the same as when there would be a patient in the room, including furniture. Figure 15 shows the plan of the patient room with the furniture, including the desk, bed, nightstand, 3 chairs, closets and window curtains (open during measurement). In addition, there were no indoor blinds in this patient room. Important to notice, almost all patient rooms in the Jeroen Bosch Hospital have the same lighting design.

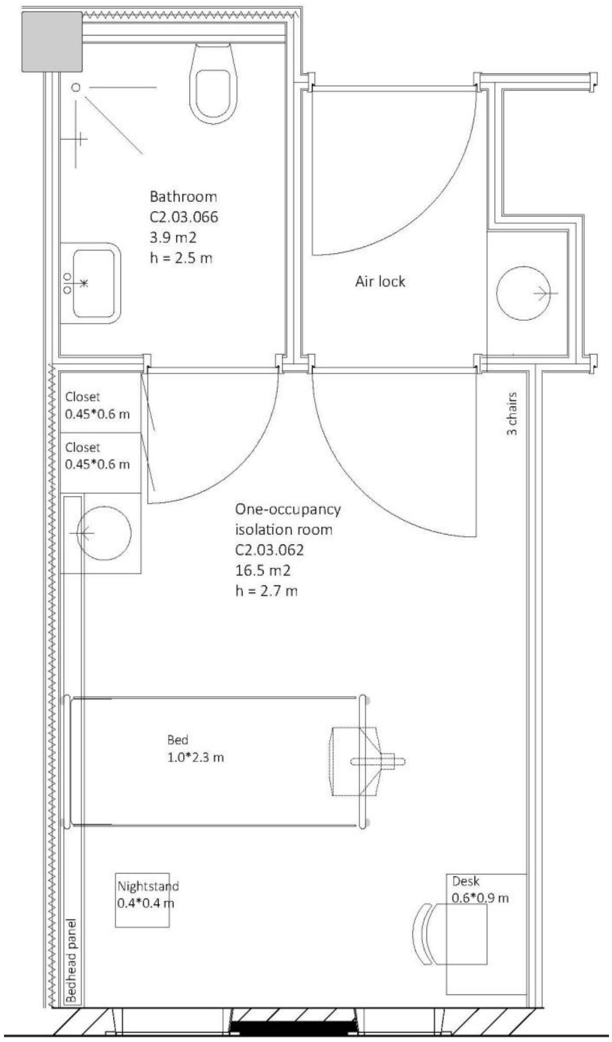


Figure 15. Plan patient room in Jeroen Bosch Hospital with furniture

3.1.2 Description lighting design in patient room

Figure 16 depicts the lighting design in the patient room, each picture represents a different kind of luminaire.

The lighting design in this patient room is divided into:

- General lighting situated in the middle of the patient room, above the bed. The switch is next to the door;
- Behind the bed is a bedhead panel, where direct and indirect lighting is situated. The switch for indirect lighting is on the bedhead panel and the direct lighting is on the hand held where the alarm button is located;
- A Lighting point is situated above the desk, where the patient or family can sit behind. The switch for the desk lighting is next to the desk;
- The four lighting points described above are most of the time used when the patient is awake. During the night, there is a special night lighting point next to the bed on ground level. The switch is located next to the door. More specifications of all these luminaires can be found in Appendix B.

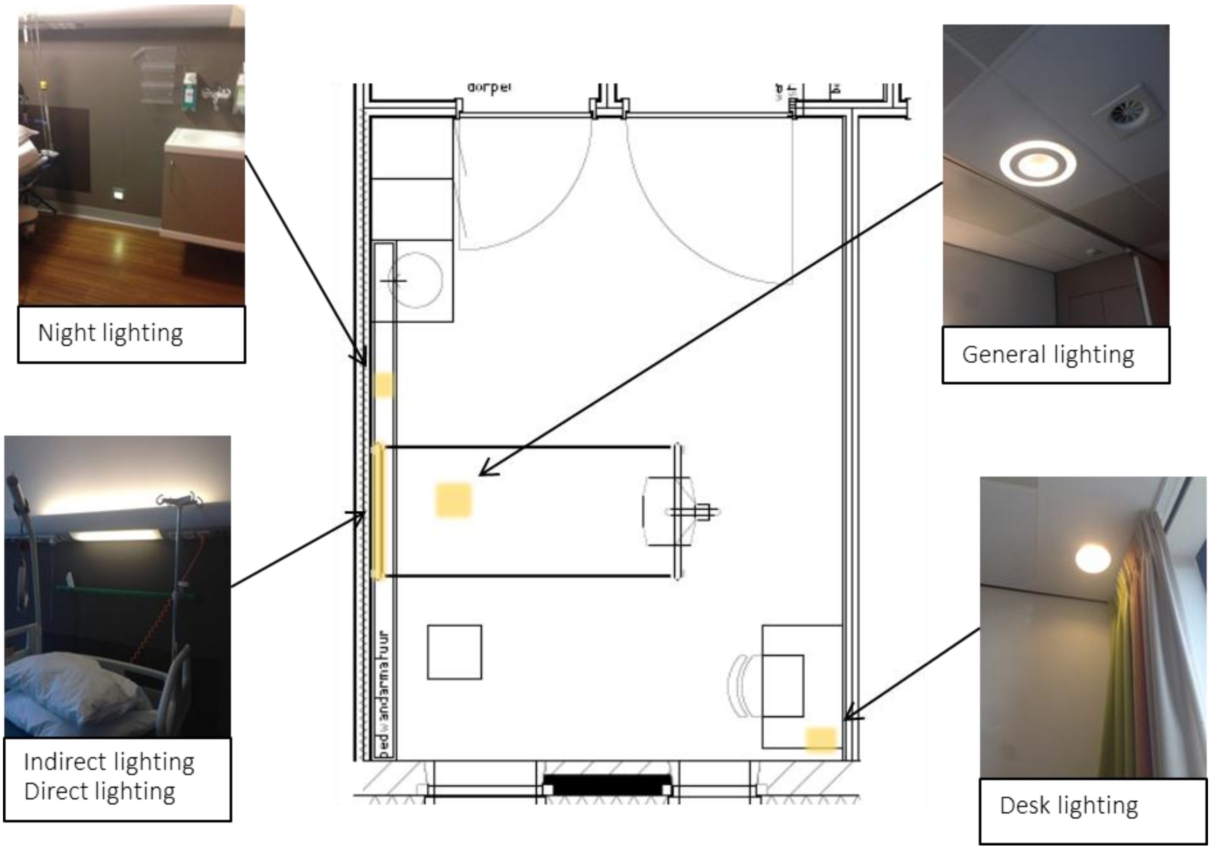


Figure 16. Overview lighting design in the patient room, consists of different luminaires

3.2 Measurement plan

To obtain more knowledge about the current artificial lighting conditions within the patient room of the Jeroen Bosch Hospital in 's-Hertogenbosch, different lighting setting were measured in the patient room to get a complete overview. The measurement took place on Friday 6 of May 2016, 9:00-16:00.

The goal of this measurement was

(1) To evaluate the current lighting design in the patient room relative to recommendations from literature study and NEN 12464-1 and
(2) Measurement data will be used to validate the simulation model to create a more reliable model.

3.2.1 Measurement method according to NEN 1891

The NEN 1891 (improved version 2015) describes a procedure for measuring lighting performances, which described the standard specifies requirements for the measurement set up, report and equipment. Table 9 shows the equipment, which was used during the measurement. (Specifications of the equipment can be found in Appendix B). The equipment was used from the TU/e.

Table 9. Specification measurement equipment

Description	Fabricate	Serial number	Date calibration	Registration number
Illuminance meter	Hagner dectector	Model: EC1-X	Regularly	9588
Luminance meter	Canon	EOS 60D	May 30, 2013	1681032199
Circular fisheye	Canon/Sigma	4.5 mm 1:2:8 DC HSM	-	12505828
Thermometer	Escort data loggers	RH iLog EI-HS-D-32-L	-	1244-0055

All lamps, except the lamp above the desk, were replaced before performing the measurement . This made it easier to determine how many operation hours the lamps were switched on; this value was useful for the simulation model. In addition, daylight was excluded from the measurement. Therefore, the glazing was masked with 2 layers black bags and tape. This resulted in a reflection factor on the inner side of the window less than 10%, which is recommended by the NEN 1891, since this value is in accordance with the usual reflection of glazing.

Starting the experiment, there were some steps to be taken into consideration;

1. All lightings were set on for 30 minutes before the start of the measurement;
2. Measured air-temperature: 22.6 – 23.2 °C;
3. Timing: 10:45 measured illuminance, 14:21 measured luminance;
4. Masked windows;
5. Replaced lamps;
6. Measurement grid in the total room.

3.2.2 Measurement illuminance

The NEN 1891 describes a method to measure illuminance on horizontal and vertical point with an illuminance meter. Furthermore, horizontal illuminance values are useful to calculate for example luminous flux, average illuminance on a surface, lighting efficiency and uniformity. The vertical illuminance is measured to get more knowledge, what amount of illuminance reach the eye of a standing person around the bed.
During the measurement different lighting settings were used, therefore it was more accurate to use different measurement grids. The measurement grid was calculated with equation 3. In addition, an offset of 0.5 m from the wall was excluded of the measurement grid with the total room grid.

$$p = 0.2 * 5^{\log_{10}(d)} \qquad (3)$$

Where:
p = value between the grid points (m) <10 m
d = largest dimension of the calculation area (m)

Length room = 4.437 – 1 (2*0.5) = 3.437 m -> d
Width room = 3.475 – 1 (2*0.5) = 2.475 m

$p = 0.2 * 5^{\log_{10}(3.437)} = 0.48\ m \sim 0.5\ m$, distance between the grid points

The amount of measurement points in the measurement grid of the total room was: 6*9= 54 points, this is shown in Figure 17. In addition, the grid started in the left upper corner; therefore the zone of 0.5 m between the grid and the walls were not always feasible.

During the measurement different lighting settings, which support the scenarios, were used to get a complete overview. To measure different lighting setting in the room, it was necessary to have different measurement grids. Therefore, two other measurement grids were made for the bed and desk, these areas are very important in the patient room.

In addition, the dimensions of a specific grid on an area need to be minimal 1.5*1.5 m. Figure 18 shows the grid on the bed and desk, were the grid on the bed was 6*5 = 30 points and the desk was 2*3 = 6 points.

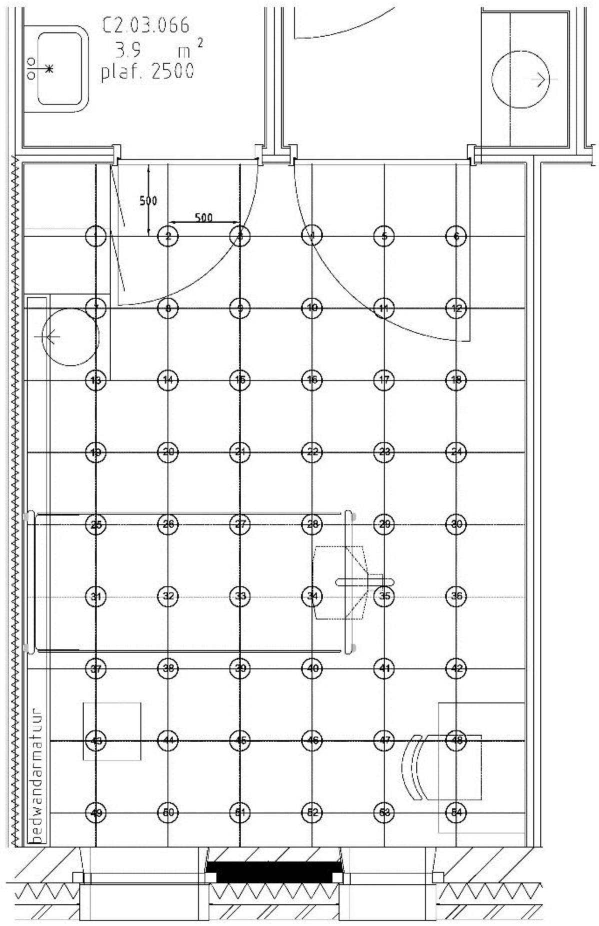


Figure 17. Measurement grid in the total room, 54 points in total with 0.5 m between the points, in Appendix C this figure can be found full-size.

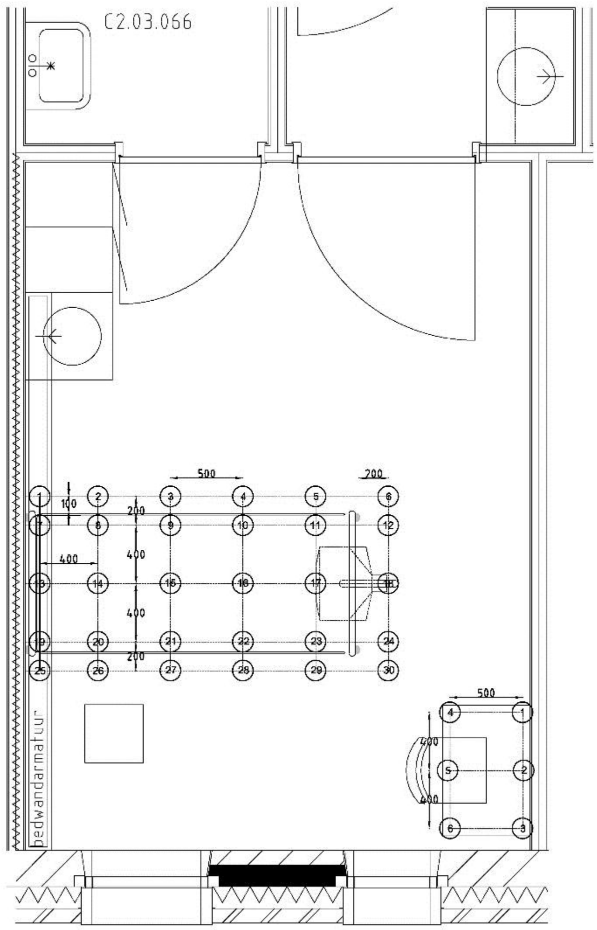


Figure 18. Measurement grid for bed (30 points) and desk (6 points), in Appendix C this figure can be found full-size.

As described before, different lighting settings, which support the scenarios, were used to make a complete overview of the lighting design in the current situation in the patient room. Different lighting settings were determined from the scenarios, which could take place by different end-users i.e. patient, medical staff, family or cleaner in a patient room. Table 10 shows the different lighting settings by using different luminaires i.e. general, indirect, direct and lighting above the desk. In addition, more measurements were performed in the patient room, the overall measurement is shown in Appendix C.

Table 10. Lighting setting to measure illuminance

Setting	Grid	End-user	Lamps on (grey)				Position height [m]
			General	Indirect	Direct	Desk	
A1, A2	Total room	All					0.2; 0.9
B1		Cleaner					0.2
C		Patient, Medical staff	Night luminaire				0.2
D1	Bed	Patient					0.85 (height bed) 30 pt.
E1		Medical staff					0.85 (height bed) 30 pt.
F1		All					0.85 (height bed) 30 pt.
D5	Desk	Patient, family					0.75
E5		Patient, family					0.75
G		Patient, family					0.75
H		Patient, family					0.75

Calculations on measurements illuminance

Different equations (4, 5) were used to describe the qualities of the lighting design in the current situation in the patient room.

E_{min} : minimal illuminance

E_{max} : maximal illuminance

$$\bar{E}_m = \frac{1}{n}\,(E_1 + \ldots . E_n) \qquad (4)$$

Where:

$\bar{E}_m$: average illuminance in lx

n: number of measurement points

E_1 t/m E_n: illuminance in measurements points 1 t/m n in lx

$$U_o = \frac{E_{min}}{\bar{E}} \qquad (5)$$

Where:

U_o: uniformity

E_{min}: minimal illuminance

$\bar{E}_m$: average illuminance in lx

3.3 Simulation

The lighting solution of the current situation was performed in a simulation model by using DIALux evo. Only the basic configurations of the patient room, size, window openings, furniture and reflection factors were used in this simulation. The dimensions of the room were 4.4 m (length) x 3.5 m (width) and 2.7 m (height). This patient room has an airlock as described in paragraph 3.1.1 and was excluded from the simulation model, as well as the bathroom. Again, daylight was excluded in this present study. However, windows were drawn in the simulation model to comply the right reflection values compared to the measurement. Furniture, including desk with chair, bed, nightstand, television, closets and window curtains (open) were found in the library of DIALux evo or via (Archibase planet, 2016) and were used in this simulation. In addition, reflection factors of floor, walls, ceiling and furniture were obtained from EGM Architects, Deerns and the contact person of the Jeroen Bosch Hospital. The reflection factors can be found in Appendix D. Figure 19 and 20 shows pictures of the simulation model of the patient room in DIALux evo, more pictures are shown in Appendix D.

Figure 19. Patient room, viewpoint from windows in simulation model (DIALux evo)

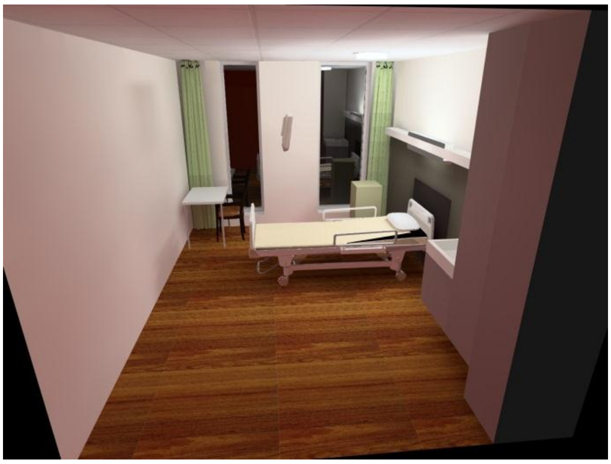


Figure 20. Patient room, viewpoint from entrance in simulation model (DIALux evo)

The luminaires, which were used in the simulation model of the current situation in the patient room of the Jeroen Bosch hospital, are shown in Appendix D. In addition, the Belia ID (Zumtobel) was two times applied in the bed head panel, otherwise the indirect and direct lighting cannot be set on/off separately.

3.4 Validation

Creating a reliable simulation model of the current lighting solution, the simulation model (paragraph 3.2) will be validated with the measured illuminance values (paragraph 3.1) in the patient room in the Jeroen Bosch Hospital. The validated simulation model was used, to make an improvement in the current situation. Paragraph 3.2 describes the method to measure illuminance on a specific grid. The validation compared the illuminance values of three lighting settings within the total room grid (same as defined in paragraph 3.2), as shown in Table 11. In addition, a comparison with the total room grid is more accurate since this grid has a large surface area with a lot of grid points.

Table 11. Lighting setting for validation illuminance values

Setting	End-user	Lamps on (grey)				Position height [m]
		General	Indirect	Direct	Desk	
A1, A2	All					0.2; 0.9
B1	Cleaner					0.2

Where necessary, parameters in the simulation model were modified in order to have a better match with the measurements. Parameters which can be modified are:

- Reflection factors walls, ceiling, floor, furniture;
- Furniture (other model);
- Luminous flux lamp.

Parameters were changed until the illuminance values in the simulation model were related to the measurement data in the patient room.

3.5 Effective radiance exposure

This chapter will elaborates on the calculation of the effective irradiance on a patients' eye within the different scenarios. The scenarios are defined with respect to the activities which occur in the patient room by different (end) users. The different parameters within the scenarios are based on literature, regulations and interviews and by using the simulation model in DIALux evo, the scenarios are described in Chapter 2. In addition, a new lighting situation was created in the simulation model. Also, LED technology is used due to a lot of benefits which are described in paragraph 2.5.

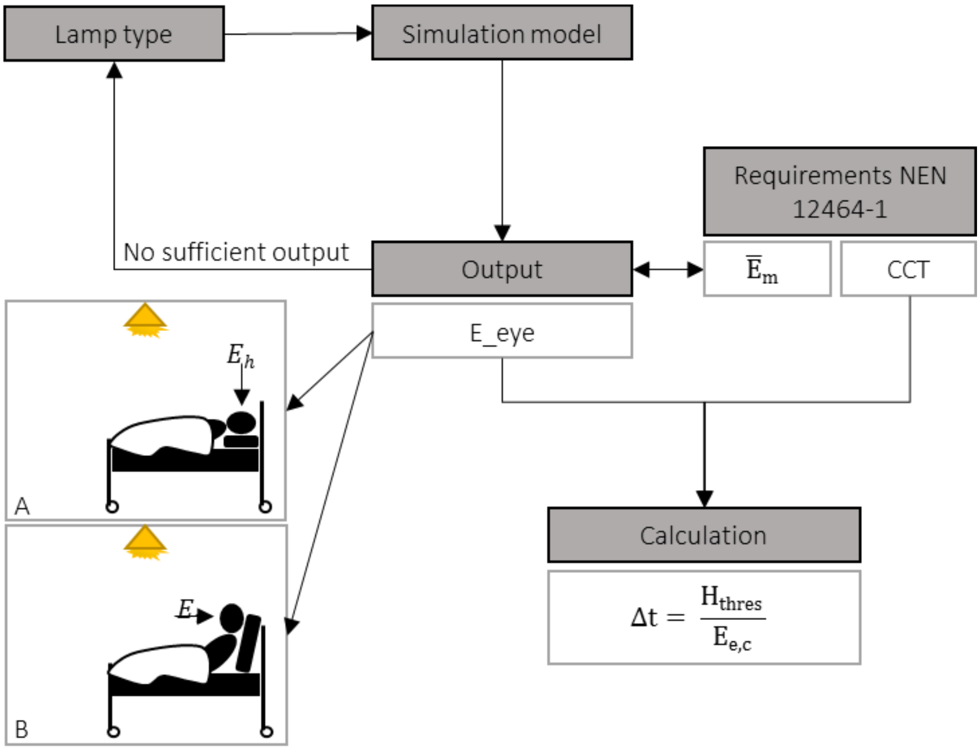


Figure 21. Schematic method which shows different steps to which are needed to calculate the exposure duration (Δt)

The method of the calculation is shown in Figure 21. The simulation model is used to find the combination of lamp types to meet the requirements of the average illuminance value depending on the activity. The outcome of the simulation model is the illuminance value on patient's eye, where the assumption is that the patient is sitting (vertical illuminance, h: 1.12 m) or lying (horizontal illuminance, h: 0.87 m) in bed, as is illustrated in

Figure 21 A and B within the different scenarios. In addition, a patient lying in bed, receives less illuminance on the eye, since the luminaire is further away of the patients' eye and the shadow of the bed head wall reach the patients' eyes, compared to a sitting patient in bed. Together with the output of the simulation model and a SPD with required CCT value, can be calculated the vertical effective irradiance. The vertical effective irradiance can be used to calculate the exposure duration relative to the threshold of melatonin suppression.

In addition, DIALux evo does not need all parameters to calculate the illuminance value on the patient's eye in the simulation model. The spectral power density of the radiant flux of the lamp is related to the luminous flux, CCT and Ra. However, DIALux evo uses only the <u>luminous flux</u> of the lamp for the lighting calculation instead of using luminous flux, CCT and Ra. The CCT and Ra are defined in the documentation of the lamp, but these are not a parameter for the lighting calculation. The Spectral Power Distribution (SPD) graph was needed for the calculation of the vertical effective irradiance. DIALux evo uses 'typical SPD graph' with respect to CCT and Ra, These graphs were used to calculate the vertical effective irradiance, in this study three different SPD's are used LED of 3000K, 4000K and 5000K, shown in Figure 21, where on the x-axis the wavelength 380-780nm and the y-axis the <u>relative</u> spectral irradiance 0-1 [-] are shown. In addition, LED 3000K, 4000K and 5000K are used as a requirements for different activities.

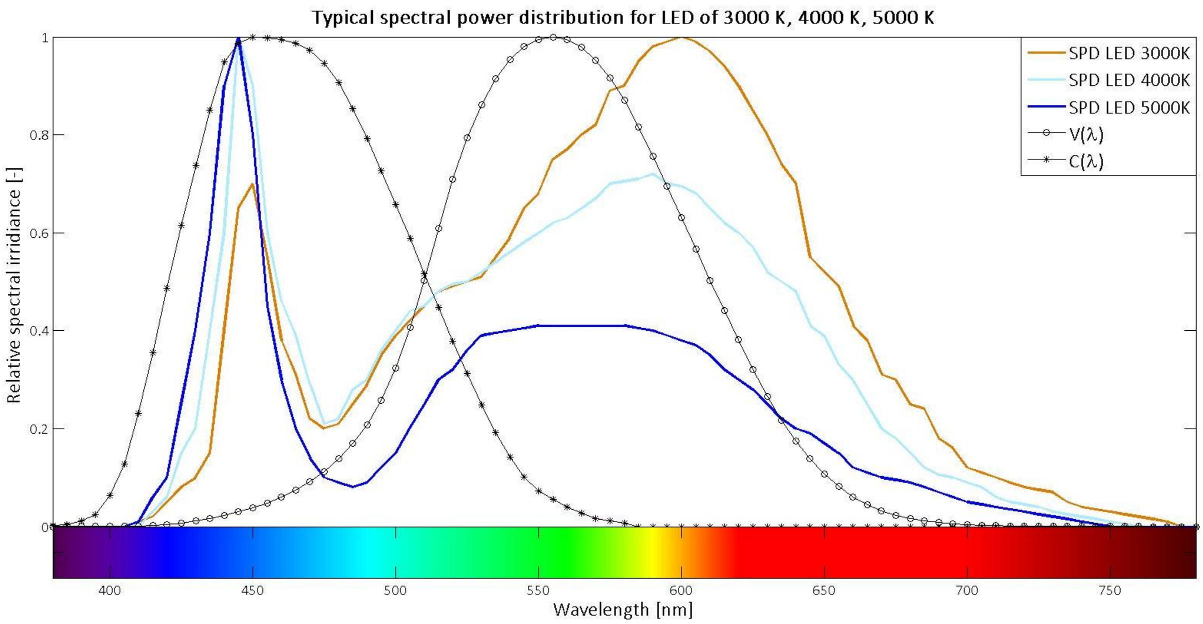


Figure 22. Typical spectral power distribution used in DIALux evo for LED lamp of 3000K, 4000K and 5000K and the spectral sensitivity of the eye - V(λ) and ipRGC - C(λ)

The effective irradiance is indicated by a dose per hour, were melatonin suppression of 50% will occur. This calculation consists of different calculation steps, these steps are described by equations 6-11. The calculations were performed by using MATLAB R2013a, this program was also used to make the graphs. The MATLAB script can be found in appendix G.

The SPD as shown in Figure 22, has on the y-axis the <u>relative</u> spectral irradiance (0-1). However, relative values cannot be used for the calculation of effective irradiance, therefore relative values need to transform to absolute values. The K-value (equation 6) is the ratio between relative and absolute values, where E_{oog} is divided by the relative spectral distribution (equation 7) weighted by the eye sensitivity function V(λ) and maximum of the luminous flux efficacy of radiation (K_m: 683 lm/W).

Part 1: Calculation ratio (K) between <u>relative</u> and <u>absolute</u> spectral irradiance

$$K = \frac{E_{oog}}{E_{rel}} \quad (6)$$

Where:

K: Ratio between relative spectral irradiance and absolute spectral irradiance [-]

E_{oog}: Vertical/horizontal illuminance on patient's eye – output of DIALux evo [lx]

E_{rel}: Relative spectral power distribution weighted by the eye sensitivity function V(λ) and maximum of the luminous flux efficacy of radiation [μW/m^2]

$$E_{oog} = K * \underbrace{K_m * \int_{\Delta\lambda} \overbrace{E_{e\lambda\_rel} * V(\lambda)}^{E_{e,v,rel}} \, d\lambda}_{E_{rel}} \quad (7)$$

Where:

K_m: Maximum of the luminous flux efficacy of radiation, defined as 683 lm/W for photopic vision

$E_{e\lambda\_rel}$: Relative spectral power distribution of the lamp [μW/m^{2}nm]

V(λ): Eye sensitivity function [lm/W]

Δλ: Delta wavelength ~ 380-780nm

The second part of the calculation, calculates the effective irradiance. The vertical effective irradiance will be used in this calculation, which indicates the impact through the non-image forming process (weighted by the spectral sensitivity of ipRGC) in the visual system (absolute spectral irradiance of a lamp), this is shown in Figure 22.

Equation 10 was used to calculate the effective irradiance, which is the vertical effective irradiance multiplied with the exposure duration, e.g. time interval. The effective radiant exposure is not known and can be obtained by threshold effective irradiance divided by the vertical effective irradiance. In addition, the time interval indicates the maximum exposure duration for a specific lighting scenario before melatonin suppression of 50% arise. For this equation, the threshold of 50% melatonin suppression (H_{thres}) is already defined from the study of Brainard et al., (2015), which is 0.6555 μWh/m2 as described paragraph 2.4.

Part 2: Calculation effective radiance by using <u>absolute</u> values

$$E_{e\lambda} = E_{e,\lambda\_rel} * K \quad (8)$$

Where:

$E_{e\lambda}$: Absolute spectral irradiance at eye level [μW/m^{2}nm]

$E_{e\lambda\_rel}$: Relative spectral distribution [μW/m^{2}nm]

K: Ratio between relative spectral irradiance and absolute spectral irradiance

$$E_{e,c} = 1 * \int_{\Delta\lambda} E_{e\lambda} * C(\lambda)\ d\lambda \quad (9)$$

Where:

$E_{e,c}$: Vertical effective irradiance [μW/m^2]

$E_{e\lambda}$: Absolute spectral distribution [μW/m^{2}nm]

$C(\lambda)$: Retinal ganglion cells sensitivity function

$$H_{e,c} = \int_{\Delta t} E_{e,c}\ dt \quad | \quad H_{e,c} = E_{e,c} * \Delta t \leq H_{thres} \quad (10)$$

Where:

$H_{e,c}$: Effective irradiance [μWh/m^2]

$E_{e,c}$: Vertical effective irradiance [μW/m^2]

Δt: Exposure duration [hours]

H_{thres}: Threshold effective radiant exposure: 0.2655 μWh/m^2 – output of literature study can be found in paragraph 2.4

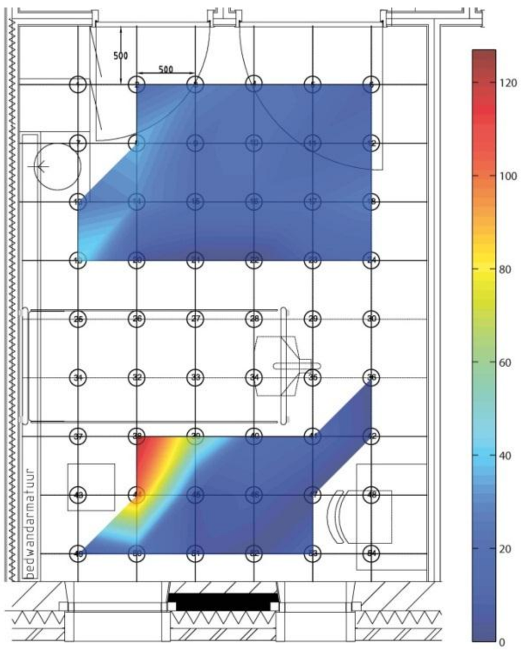
4 Results

In the beginning of the report, three different scenarios are defined as an outcome of the literature study.
Results for each scenario will be elaborate and are divided into: an evaluation of the current situation and a new situation where the calculation of the effective irradiance will be calculated and as result the maximal duration of a lighting setting within a specific scenario. In addition, to make a new situation, the simulation model is validated with the measurements, these results are first presented.

4.1 Validation results

Creating a reliable simulation model of the current lighting solution, the simulation model will be validating with the measured illuminance values in the patient in the Jeroen Bosch Hospital. The validated simulation model will be further used to make an improvement in the model.
Figure 23-25 show the comparison between the illuminance values of the measurement and simulation model. The minimal and maximal differences between these values are shown below the figure. Lighting setting A1, A2 and B are used, since these settings are measured using the total grid (large surface) of the patient room.
In addition, the scale of each figure is different; therefore different lighting setting cannot be compared with each other. The raw data of the illuminance values of the measurement and simulation model can be found in Appendix E.

4.1.1 Lighting setting A1

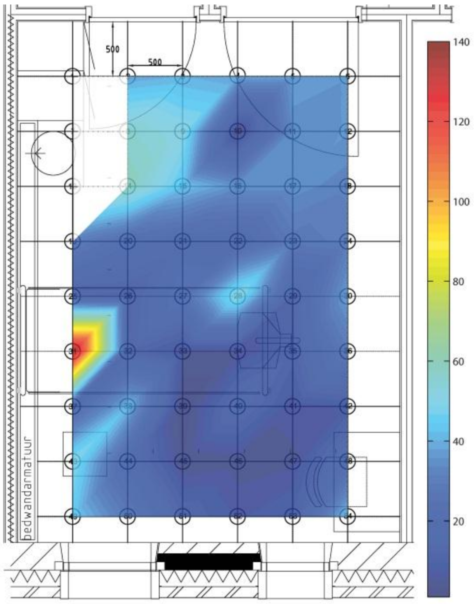


$E_{min,diff}$	0 lx	$E_{max,diff}$	127 lx

Figure 23. Contour plot of illuminance values, comparison measurement and simulation for lighting setting A1 (indirect + direct + general, h=0.2)

During the measurement of lighting setting A1; general, direct and indirect lighting are used. The measurement is performed using the total room grid with a height of 0.2 m. Figure 23 shows the illuminance values between the measurement and the simulation model. Most values are low and therefore in line with the measurement. One peak of 120 lx is shown in the figure, due to not corresponding reflection factors of the bed in the simulation model.

4.1.2 Lighting setting A2

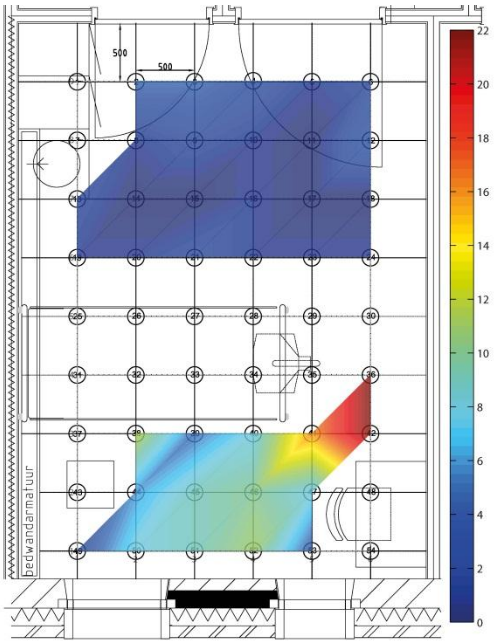


$E_{min,diff}$	2 lx	$E_{max,diff}$	140 lx

Figure 24.Contour plot of illuminance values, comparison measurement and simulation for lighting setting A2

Lighting setting A2 is used during this measurement, which consist of; general, direct and indirect lighting. The measurement is performed using the total room grid with a height of 0.9 m. Figure 24 the illuminance values between the measurement and the simulation model. Most values are low and therefore in line with the measurement. One peak is shown in figure; 140 lx, indicates that measurement values are higher.

The value is higher, due to the lighting distribution of the direct lighting; the angle of distribution is less widely compared to the current situation. In addition, the luminaire which is used in the simulation model is the best comparison with the current luminaire, although the exact luminaire was not found since this is an old type.



$E_{min,diff}$:	0 lx	$E_{max,diff}$:	22 lx

Figure 25. Contour plot of illuminance values, comparison measurement and simulation for lighting setting B1

4.1.3 Lighting setting B1 – general, h: 0.2m

During this measurement only general lighting is used. The measurement is p1erformed using the total room grid with a height of 0.2 m. Figure 25 shows the illuminance values between the measurement and the simulation model. These values are very low, between 0 lx and 22 lx, and in line with the measurements. The peak of 22 lx indicates that simulation is higher than the measurement. The value in the measurement is 17 lx and is not in line with the other values around this point, 30 lx. The only argument which can be given is a failure in the measurement. However, the values are very low and in line with the measurement therefore these values can be taken into account in the new model.

4.2 General scenario

This scenario described a general situation in the patient room. This scenario is if someone enters the room and the cleaner use general lighting to clean-up the patient room. The corresponding requirement for these activities is an average illuminance of 100 lx on ground level (0.2m), other requirements are shown in Table 1 in paragraph 2.1.1.

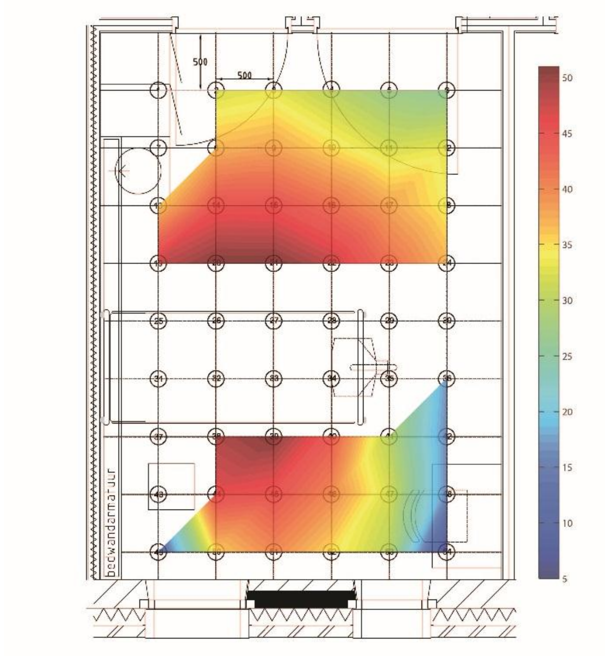
Furthermore, in these situations, (1) the patient is not in the room, (2) the patient is sitting in bed or (3) the patient is lying in bed.

4.2.1 Evaluation current situation

Illuminance values between 11 lx and 51 lx are measured on ground level in the current lighting situation of the patient room in the Jeroen Bosch Hospital, as is shown in Figure 26. The average illuminance is 37 lx, which is very low compared to the requirement of minimal 100 lx in the patient room. Further, the uniformity in this patient room is 0.30 which is too low compared to the standard of 0.4.

The general scenario is commonly used in hospitals. However, in this hospital this lighting setting is insufficient regarding the requirements.

The general lighting could also support other lighting settings, for example indirect or direct lighting. These examples are shown in Appendix B, lighting setting A1 and A2.



E_{min}:	11 lx	E_{max}:	51 lx
$\overline{E}_m$:	37 lx	U_o:	0,30

Figure 26. Illuminance values of the total room with lighting setting B1

4.2.2 Calculation

Since the current lighting setting in the patient room in the Jeroen Bosch Hospital is insufficient in order to obtain the requirements as described in sub-paragraph 2.1.1, a new luminaire is searched for the general lighting setting.

Improved simulation model

The new luminaire is placed on the ceiling and located in the middle of the room in order to reach the minimum uniformity of 0.4 in the total room. Specifications of this luminaire are shown in Table 14. The general lighting has a wide range of luminous flux and CCT, therefore the general lighting can also be used in other lighting settings.

Table 12. Luminaire parameters of general lighting to obtain requirements	
Luminous flux [lm]	3500
CCT [K]	3000
Ra [-]	80
Position	Ceiling, middle room

Results effective radiant exposure

During the general lighting setting, a patient is sitting or lying in bed. Table 13 shows the calculation for both positions. The equations for the results are explained in paragraph 3.5. The maximal exposure duration of this lighting setting are relative long, due to a low CCT of 3000K.

Table 13. Summary calculation patient sitting or lying in bed, using LED of 3000K		
Position patient	Sitting in bed (vertical)	lying in bed (horizontal)
E_{oog} [lx]	166	130
Ratio K: (E_{oog} / $E_{relative}$) [-]	0.0161	0.0126
$E_{e,c}$ [µW/m^2]	0.1026	0.0803
Δt [h]: $\frac{H_{thres^*}}{E_{e,c}}$	$\frac{0.2655\ \frac{\mu Wh}{m^2}}{0.1026\ \frac{\mu W}{m^2}} = 2.6\text{ h}$	$\frac{0.2655\ \frac{\mu Wh}{m^2}}{0.803\ \frac{\mu W}{m^2}} = 3.3$
* Threshold 50% melatonin suppression		

Figure 27 the effective irradiance which is an outcome of SPD a LED of 3000K multiple with sensitivity function of ipRGC, when the patient is sitting in bed. The graph of a general lighting setting when the patient is lying in bed is shown in Appendix F.

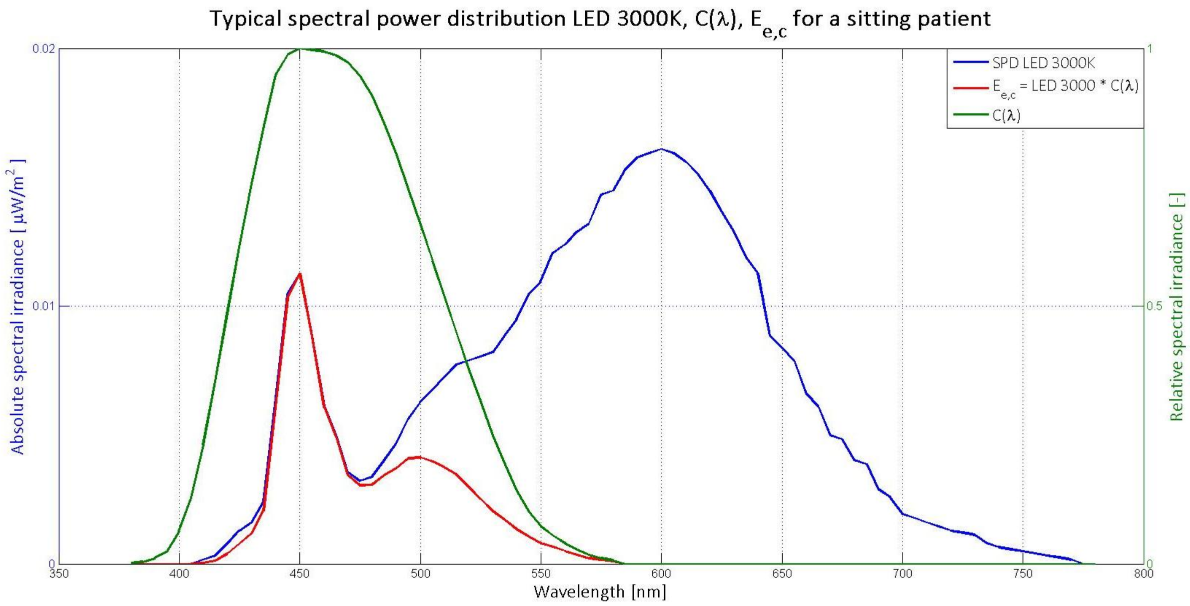


Figure 27. The Red line indicates the vertical effective irradiance in µW/m2nm on patient eye, when the patient in sitting in bed. Which is an outcome of relative spectral power distribution of LED 3000K multiple with the sensitivity function of ipRGC.

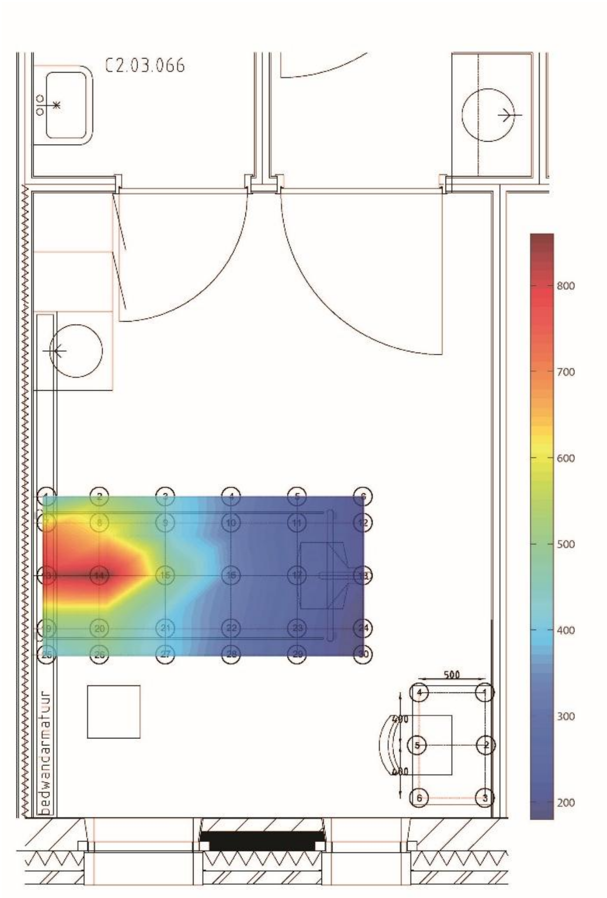
4.3 Treatment scenario

Since the environment of a patient is more considered as important, more one-occupancy rooms occur in hospitals. Therefore, an adjustment in the lighting solution is needed; due to more medical treatment what can be perform in a one-occupancy patient room. During the medical treatment the patient is lying in bed. Furthermore, the lighting needs to be on and around the bed, with a uniformity of 0.6-0.7, to have a good lighting distribution on patients' body. Requirements for a treatment are 300 and 500 lx depends on complexity and the Correlated Color Temperature (CCT) need for simple treatments 4000K and for complex treatment 5000K. Other requirements are shown in Table 3.

4.3.1 Evaluation current situation

The majority of the patient rooms in the Jeroen Bosch Hospital are one-occupancy patient rooms. Therefore, more treatments could be performed in the patient room. However, the lighting solution in this patient room is not sufficient to perform a complex treatment in the patient room, since the requirements of 500 lx conform NEN 12464-1 are not obtained. In addition, lighting setting D1, E1 and F1 are performed regarding a calculation field on bed, setting D1 has the highest average illuminance therefore this setting is shown in Figure 30. However, with an average of almost 400 lx, a simple treatment could be performed.

Lighting setting E1 is shown in Appendix B, and F1 is shown in Figure 32 in the next paragraph.



E_{min}:	180 lx	E_{max}:	860 lx
$\bar{E}_m$:	394 lx	U_o:	0,46

Figure 28. Illuminance values of the total room with lighting setting D1 (direct and indirect lighting, h: 0.85 m)

4.3.2 Calculation

In contrast to the current lighting situation in the one-occupancy patient room in the Jeroen Bosch Hospital, the specifications of the lighting design are changed in this new situation. In the current situation only a simple treatment can be performed, instead of also complex treatments.

<u>Improved simulation model</u>

To obtain the requirements as described in sub-paragraph 2.1.2, general, indirect and direct lighting needs to be used. Specifications of luminaires are shown in Table 15, specifications regarding the activity are shown in Table 16. The indirect and direct lighting are situated in one luminaire and located in the bed-wall panel. The luminous flx is a fixed value and the CCT is variable for the indirect and direct lighting.

Table 14. Specifications luminaire general, indirect and direct

	General	Indirect	direct
Luminous flux [lm]	3500	6395	904
CCT	4000, 5000		
Ra	80		
Position	Ceiling, middle room	Bed head panel	

The indirect luminaire can be rotated, independently of direct luminaire, to obtain the correct illuminance values and uniformity on patients' body. This idea is gained during the visit to TweeSteden Hospital in Tilburg, Figure 30 shows this solution.

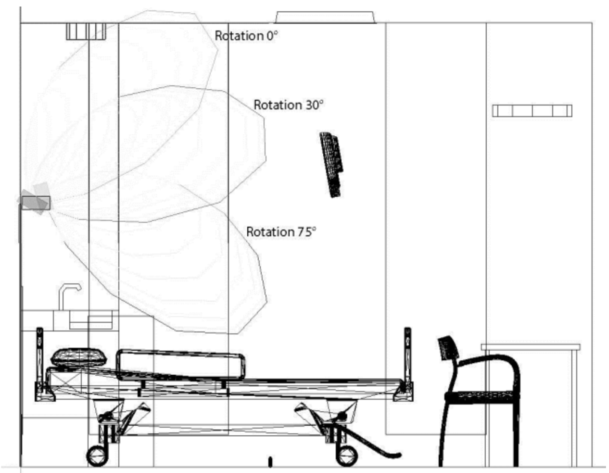


Figure 29. Side view patient room in simulation model, shows different rotation angles of the indirect lighting to perform a medical treatment

Figure 30. Indirect lighting is rotated to perform a medical treatment in a patient room in TweeSteden Hospital in Tilburg.

Table 15. Specification lighting setting depends on activity in treatment scenario

	Simple treatment - 300 lx	Complex treatment - 500 lx
General [lm]	2500	3500
Indirect [lm]	6395 | 30°**	6395 | 75°**

Direct [lm]	940	940
*The raw data the lighting setting can be found in Appendix E. ** Angle of rotation indirect luminaire		

In addition, to prepare a treatment or complex treatment the sink will be used. However general, indirect or direct lighting does not create enough illuminance on the sink therefore a luminaire is add above the sink. The specifications of this luminaire can be found in Appendix F.

Results effective radiant exposure

During the treatment lighting setting, a patient is lying in bed. Table 16 shows the results of different exposure durations depends to different lighting settings. Furthermore, treatment needs 4000K and complex treatment need 5000K, both are shown below. Results indicate shorter maximal exposure duration of a lighting setting which use a higher CCT. Further, complex treatment shows shorter exposure duration in contrast with a treatment, due to a higher luminous flux and colder CCT, which is needed in the lighting setting of an complex treatment (500 lx and 5000K) compared to treatment (300 lux, 4000K).

Figure 30 shows the effective irradiance on patients' eye during an complex treatment. This value is an outcome by a multiplication of SPD a LED of 5000K with sensitivity function of ipRGC, when the patient is lying in bed. Graph of other lighting settings can be found in Appendix F.

Table 16. Results of different treatment were patient is lying in bed		
Activity	Simple treatment	Complex treatment
CCT [K]	4000	5000
E_{oog} [lx]	259	448
Ratio K: (E_{oog} / $E_{relative}$) [-]	0.0306	0.0871
$E_{e,c}$ [μW/m^2]	0.2375	0.5429
Δt [hr]: $\frac{H_{thres}}{E_{e,c}}$	$\frac{0.2655\,\frac{\mu Wh}{m^2}}{0.2375\,\frac{\mu W}{m^2}}$ = 1.12 h = 67.2 min	$\frac{0.2655\,\frac{\mu Wh}{m^2}}{0.5429\,\frac{\mu W}{m^2}}$ =0.49 h = 29.4 min

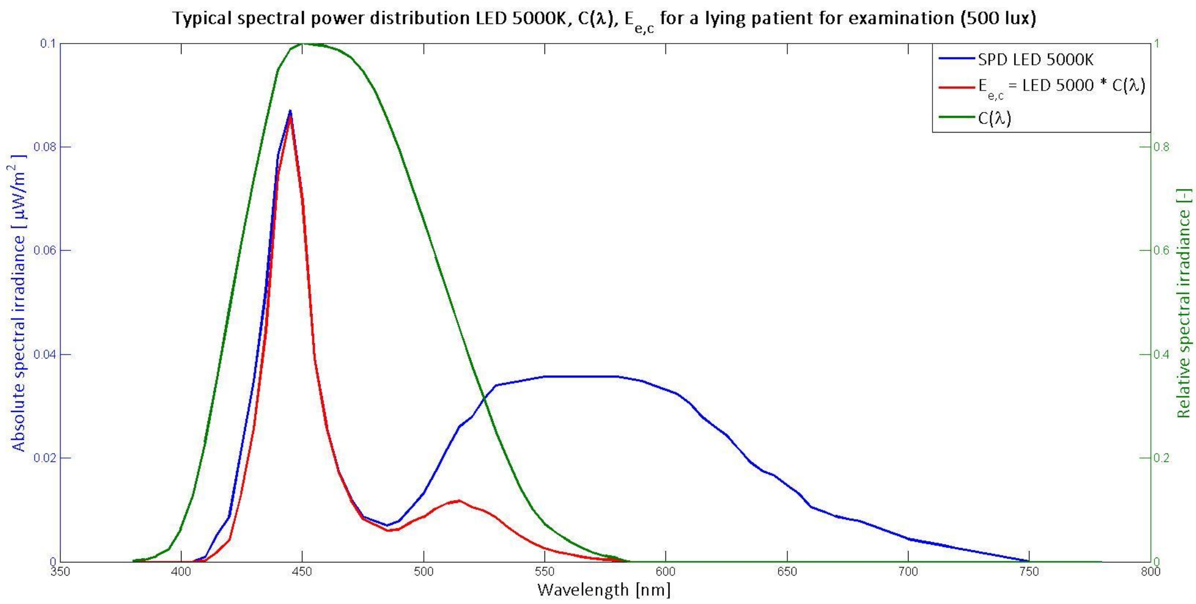


Figure 31. The Red line indicates the vertical effective irradiance in $\mu W/m^2nm$ on patient eye, when the patient in lying in bed and an complex treatment is performed. Which is an outcome of relative spectral power distribution of LED 5000K multiple with the sensitivity function of ipRGC.

4.4 Relaxing scenario

The environment in a patient room is very important to patients' well-being (Harris et al., 2002). Home-like furniture could help, as well as the lighting design in a patient room. Therefore, the lighting design must provide patients a sufficient amount of light regarding activities such as reading, watching television, resting, sleeping, socializing and patients' safety. Requirements are between 50 and 300 lx for these activities conform NEN 12464-1. These activities could take place in bed or on the desk. Furthermore, social support from family and friends is really important; therefore family is also an end user in this scenario.

4.4.1 Evaluation current situation

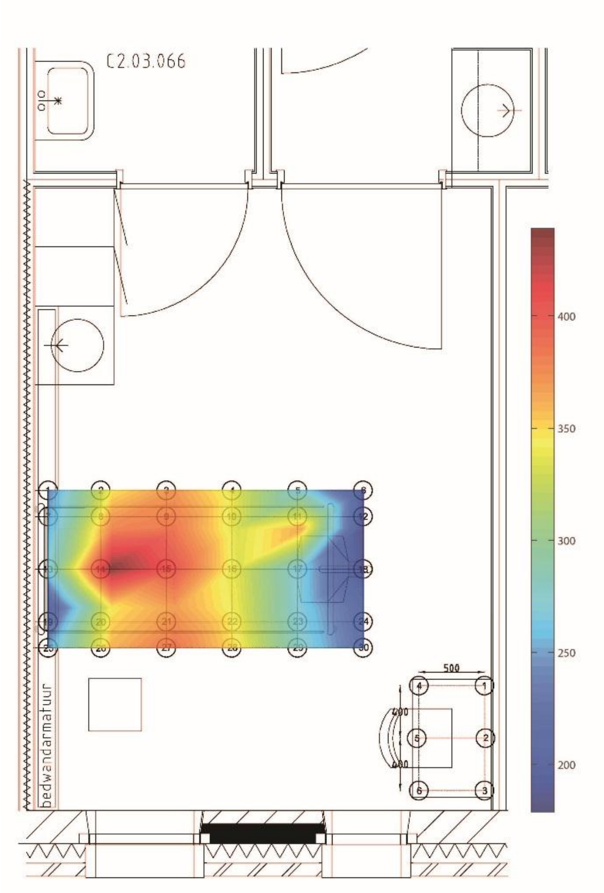


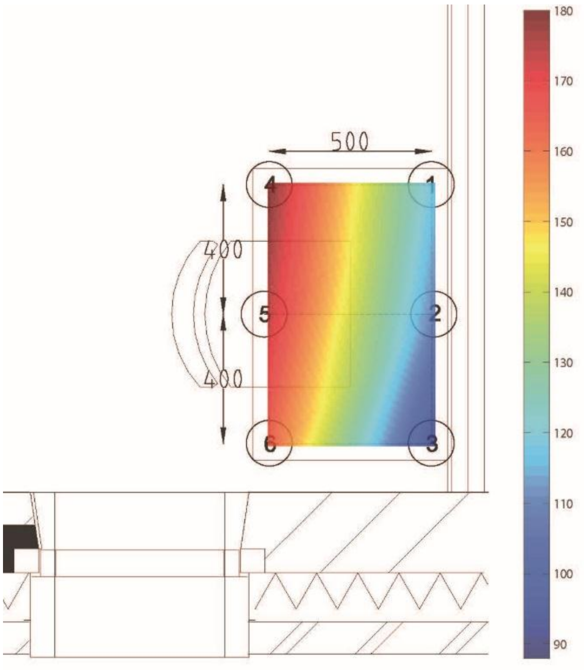
Figure 32. Illuminance values of calculation field bed with lighting setting F1 (general and indirect lighting, h: 0,85 m)

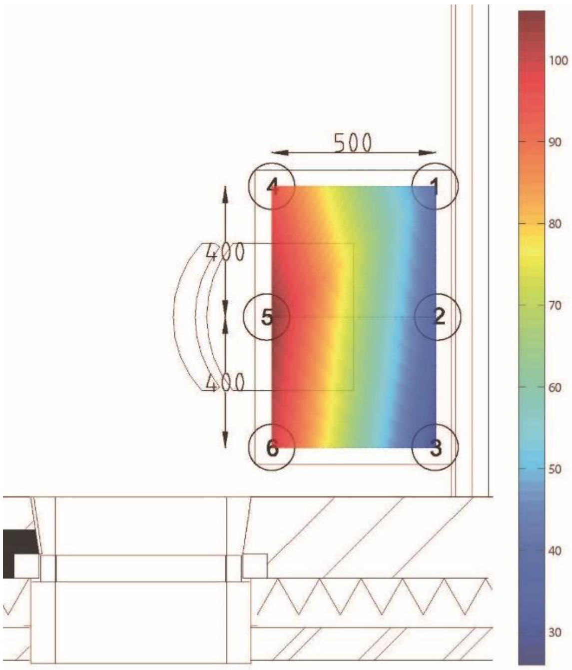
E_{min}:	179 lx	E_{max}:	439 lx
$\bar{E}_m$:	300 lx	U_o:	0.6

Lighting setting, general and indirect lighting is the most common lighting setting in a patient room and is shown in Figure 32 relative to bed area. Illuminance values between 179 lx and 439 lx are measured on a height of 0.85 m (height of bed). The average illuminance is 300 lx, which is a sufficient value regarding the requirements.

In lighting setting with only using indirect light (E1) are measured illuminance values between 140 lx and 345 lx, at a height of 0.85 m. The average illuminance is 232 lx, therefore this lighting setting could be used in this scenario. However, to read a book, 300 lx is needed, than this lighting setting need to be supported by other luminaires. For example general lighting which is shown in Figure 29. Lighting setting E1 is shown in Appendix B

Furthermore, measurement G and H are both lighting settings which can be used to do an activity on the desk. However, both lighting settings are insufficient to obtain the requirements of 300 lx, as is shown in Figure 33 and 34, which is confirm NEN 12464-1 to read a book. In addition, 300 lx is only a minimum, elderly people need a higher lighting level.





E_{min}:	88 lx	E_{max}:	180 lx	E_{min}:	26 lx	E_{max}:	106 lx
$\bar{E}_m$:	138 lx	U_o:	0.64	$\bar{E}_m$:	67 lx	U_o:	0.39

Figure 33. Illuminance values of calculation field desk with lighting setting G (indirect, desk lighting)

Figure 34. Illuminance values of calculation field desk with lighting setting H (general, desk lighting)

4.4.2 Calculation

In the current lighting situation in the patient room in the Jeroen Bosch Hospital, several lighting settings obtain the requirements for the activities by patient. However, the lighting above the desk is insufficient and is changed in the new situation.

Improved simulation model

Several lighting setting can be used to support the activities of the patient and family. General, direct, indirect and desk lighting is used in these settings. The specifications of the luminaires regarding the activities of a patient are shown in Table 17.

Table 17. Specification lighting setting depends on activity in treatment scenario

	General	Indirect	Direct	Desk
Luminous flux [lm]	2500	6395 (0°)	940	1260
CCT [K]	3000	3000	3000	3000
Position	middle of the room	Bed-wall panel	Bed-wall panel	Above desk

*The raw data the lighting setting can be found in Appendix E.

Results effective radiant exposure

During the relaxing scenario the patient is sitting in bed, however if the patient is sleeping it is assume the lighting is off. Table 18 shows the calculation for different lighting settings, were the patient is sitting in bed. Table 19 shows the calculation when the patient is sitting behind the desk. The length of exposure duration is relative long due to low CCT of 3000K. Results indicate that if the patient is near by the luminaire which is switched on, the exposure duration is shorter; this is in line with the assumption.

Table 18. Summary calculation patient sitting in bed

Calculation field	**Bed**					
Lighting setting	E5 indirect	D5 Indirect direct	G Indirect Desk	H General Desk	F1 General Indirect	A1 General Indirect direct
E_{oog} [lx]	108	113	130	141	226	232
Ratio K: (E_{oog} / $E_{relative}$) [-]	0.0105	0.0110	0.0126	0.0137	0.0219	0.0225
$E_{e,c}$ [μW/m^2]	0.0667	0.0698	0.0803	0.0871	0.1397	0.1434
Δt [hour]: $\frac{H_{thres}}{E_{e,c}} = \frac{0.2655}{E_{e,c}}$	3.9778	3.8018	3.3047	3.0468	1.9009	1.8517

Table 19. Summary calculation patient is sitting behind the desk

Calculation field	**Desk**			
Lighting setting	G	H	F1	A1
E_{oog} [lx]	377	357	151	153
Ratio K: (E_{oog} / $E_{relative}$) [-]	0.0365	0.0346	0.0146	0.0148
$E_{e,c}$ [μW/m^2]	0.2330	0.2206	0.0933	0.0946
Δt [hour]: $\frac{H_{thres}}{E_{e,c}} = \frac{0.2655}{E_{e,c}}$	1.1395	1.2034	2.8451	2.8079

5 Discussion

This study explored the effects of the lighting design in an one-occupancy patient room, on the circadian rhythm and well-being of patients. It is important to mention that the patient is defined as: *'a person who is under medical care or treatment'* (The American Heritage, 2016), however medical information is excluded in this study.
The influential factors of the lighting solution were examined using on-site measurements, a simulation model by using DIALux evo and a mathematical approximation. It is important to notice that the lighting solution is based on artificial lighting including luminaires and control, daylight is not taken into consideration in this study. Basic configurations of the patient room (such as size, window openings, reflection factors and furniture) in the Jeroen Bosch Hospital were used in the simulation model. A case study research is used to make a realistic situation and therefore a more reliable lighting solution.

Lighting could stimulate the circadian rhythm with the right characteristics of lighting i.e. irradiance, spectrum, timing and exposure duration. A few studies investigate the optimal composition between the characteristics of light relative to the circadian rhythm. The majority of these studies searched for a threshold for melatonin suppression. However, currently the threshold for melatonin suppression is not clearly defined. Each study uses its own assumptions for the concentration where melatonin is assayed. Therefore a general threshold for melatonin suppression is not found yet; studies are difficult to compare, validation of these studies is very low.

The purpose of this study is to optimize the lighting solution in a one-occupancy patient room, which can provide sufficient light for different activities and simultaneously stimulate the circadian rhythm. The outcome of this study is relative to the effect of the lighting solution and the sensitivity function of the ipRGC regarding the influence on melatonin production.

The outcome of the experiment performed in the study of Brainard et al., (2015) used an assumption of the threshold of half-maximum melatonin suppression in order to define the vertical effective irradiance. This value was used to analyse the impact of the non-image forming process in the visual system. The experiment has been repeated three times by Brainard et al., (2001, 2008, 2015), therefore the results seems reliable. Moreover, Brainard measured the value of half-maximum melatonin suppression. During the experiments, participants were sitting behind a light-box with their eyes open and had a lighting exposure of 90 minutes between 2:00 and 3:30 a.m. The melatonin concentration was measured before and after the experiment. This experiment used polychromatic light stimuli with a dose of 96 $\mu W/cm^2$, which results in an effective irradiance at eye level of 2.655 $\mu Wh/m^2$, where melatonin suppression occurs ($H_{threshold}$). In addition, the perfect timing to stimulate the circadian rhythm is in the early morning between 08:00-10:00 and in the early night from 19:30 (Warman et al., 2003). Moreover, in the morning the lighting setting could be used to suppress melatonin concentration in contrast with the evening, then it is better to have no melatonin suppression.

As mentioned before, the lighting solution in a patient room has a major impact on patient's health and well-being. However, the well-being of a patient is different compared to healthy people. Since patients are in a different environment, they also perform different activities compared to their regular live. Furthermore, a patient is not the only end user, also medical staff, family (visitor) and a cleaner performs activities in the patient room. In order to obtain all requirements regarding several activities by these end-users, different scenarios including 'general', 'treatment' and 'relaxing' are defined.

Moreover, this equation $H_{e,c} = E_{e,c} * \Delta t \leq H_{thres}$ calculates the maximal length of exposure duration (Δt) relative to effective radiant exposure for melatonin suppression (H_{thres}) with a specific irradiance ($E_{e,c}$) on the patient's eye.

5.1 Theoretical

The exposure duration is calculated for different activities which occur in a patient room. Therefore the combination of lamps provides the required average illuminance value for an activity and is related to a specific correlated color temperature and irradiance on patient's eye. The exposure duration and irradiance are described for each scenario.

General

In the general scenario two activities occur, someone enters the room and a cleaner cleans up the patient room. The general lighting setting in the patient room in the Jeroen Bosch Hospital provides an average illuminance of 37 lx on ground level, which is very low compared to the standard of 100 lx (NEN 12464-1). In the new situation the general lighting is changed in location (to the middle of the room) and parameters, in order to obtain the 100 lux average illuminance. With this lighting setting, it is better for the patient to sit in bed during the morning, in order to receive more effective irradiance on patient's eye which helps to suppress melatonin, compared to lying in bed. During the early night, from 19:30, the general lighting could be switched on for maximal 2.6 hours before half-maximum of melatonin suppression occur, as can be seen in Table 20.

Table 20. General scenario, results		
	Patient is sitting in bed	Patient is lying in bed
Vertical effective irradiance [$\mu W/m^2$]	0.1026	0.0803
Exposure duration [hours]	2.5880	3.3047

Treatment

Since the environment of a patient is considered as more important, more one-occupancy rooms are built, in today's hospitals. Due to this new trend, more medical treatments, patient care and monitoring can be performed in the patient room. Therefore, the lighting solution needs stricter requirements however, separate medical lighting is not recommended due to stress levels of the patients regarding visible medical equipment (Tanja-Dijkstra & Pieterse, 2011).

Currently, it is only possible to perform a simple treatment (300 lx) in the patient room of the Jeroen Bosch Hospital, meaning that complex treatment (500 lx) cannot be performed in this patient room.

Table 21, shows different lighting settings regarding to treatments and complex treatments in the patient room, during these activities the patient is lying in the bed. Results indicate that it is better to perform treatments during the morning instead of in the evening, especially the complex treatments, in order to stimulate the circadian rhythm. Since the exposure duration for complex treatment is shorter and therefore helps to suppress melatonin, which patients need in the morning to support the wake up rhythm. Furthermore, the shorter the exposure duration for a lighting setting the better it is to perform the activity in the morning. And the opposite, in the evening it is better to perform a simple treatment (average of 300 lx) due to long exposure duration before half-maximum of melatonin suppression occur, however the simple treatment duration can be max 1.1 hour after 19:30.

Table 21. Results of treatment scenario

Correlated Color Temperature	4000K	5000K
Average illuminance for specific activity [lx]	300	500
Vertical effective irradiance [μW/m^2]	0.2375	0.5429
Exposure duration [hours]	1.118	0.4891

Relaxing

The lighting solution in a patient room supports the activities which are performed by the patient, and could help by creating a home-like environment. Patients are doing different activities compared to what they are doing at home. They are reading, watching television, resting, sleeping more, and socializing. The lighting system needs to provide an average illuminance between 50-300 lx on bed and desk. The lighting solution in the current one-occupancy room in the Jeroen Bosch hospital is on the bed sufficient; however, near the desk the lighting levels are insufficient since average illuminance is maximal 138 lx which is not enough to read a book. However, the NEN-EN 12464-1 describes different recommendations regarding activities. Unfortunately, different age groups are not taken into account, the NEN uses the average age for a human. However in hospitals, 39% of the patient are 65 years or older (Centraal Bureau voor de Statistiek, 2014).

Due to different activities which could occur at two locations, the bed and desk in the patient room, several lighting settings are defined. These lighting settings and the effective irradiance with related exposure duration are shown in Table 22. During the morning it is better to have the general lighting switch on, in order to receive more effective irradiance on the patients eye what helps to suppress melatonin (F1 and A1 instead of E5 and D5). In contrast to the evening (from 19:30), lighting setting E5, D5, G and H are better to use, since the exposure duration is longer, when a patient is sitting in bed. However, setting F1 and A1 are needed to read a book in bed, since only with these settings an average illuminance of minimal 300 lx is obtained. When a patient is doing activities on the desk, the exposure duration is shorter when desk lighting is switched on. Therefore it is recommended not to use this lighting (setting H) for more than 1.2 hours from 19:30, due to the suppression of melatonin.

Table 22. Results relaxing scenario

	Patient is sitting in bed					
Lighting setting	E5 Indirect	D5 Indirect Direct	F1 General Indirect	A1 General Indirect direct	G Indirect Desk	H General Desk
Average illuminance for specific activity [lx]	180	200	340	360	220	190
Vertical effective irradiance [µW/m^2]	0.0667	0.0698	0.1397	0.1434	0.0803	0.0871
Exposure duration [hours]	3.9778	3.8018	1.9009	1.8517	3.3047	3.0468
	Patient is sitting behind desk					
Vertical effective irradiance [µW/m^2]	*	*	0.0933	0.0945	0.2330	0.2206
Exposure duration [hours]	*	*	2.8451	2.8079	1.1395	1.2034

* For lighting setting E5 and D5 is assumed that the patient is not sitting behind the desk

5.2 Practical

The lighting design in a patient room has a major impact on patients' well-being, which is influenced by the performing activities by the patient in the patient room and the circadian rhythm of the patient. The influence of the lighting design on the circadian rhythm is described in paragraph 5.1; in this paragraph the impact of the activities on the lighting design will be described. The lighting design should support the activities by the different end users, i.e. medical staff, family (visitors), cleaner, in a patient room. However, in this study the focus is only on patient's well-being. The activities which could occur in a patient room are divided into three scenarios general, treatment and relaxing.

General

Two activities may occur, someone enters the room and a cleaner uses the general luminaire to clean-up the room. These two activities need an average illuminance of 100 lx on ground level. The general luminaire should be in the middle of the room with a direct light distribution to obtain the requirement for uniformity of 0.4 in the total room.

Treatment

Tanja-Dijkstra & Pieterse, (2011) found that if medical equipment is not visible for the patient, it leads to a more positive emotional state and therefore reduces stress feelings in patients. Therefore, it is recommended to use the current lighting luminaires instead to use a specific luminaire only for treatments. To obtain the requirements to perform treatment and complex treatments in a one-occupancy patient room, general, indirect and direct lighting need to be used. To meet the uniformity on patient's body, the indirect lighting needs to be rotated for 30° or 75°.

Relaxing

Most activities may occur on the bed and desk area; therefore different combination of luminaires could be used to meet the requirements of the specific activity, which also depends on the location of the activity, i.e. bed or desk. Most of the time patients use the direct and the desk luminaire for their activities.

The lighting design needs to be sufficient, particular for each type of activity. Calm lighting, 50-300 lx and <3000 K, for patients and family which can create a home-like environment. Compared to the medical staff, who need 300, 500 lx and 4000-5000K. Furthermore, general, indirect and direct luminaires are used for two scenarios; this means that the specifications need to be variable to meet the requirements for each specific activity. Table 23 shows the specifications of the different luminaires in the lighting design of the patient room and Figure X. illustrate the location of these luminaires. The variable specifications are shown in the general lighting which needs a variable luminous flux, general, indirect and direct luminaires need a variable Correlated Color Temperature (CCT) and the indirect lighting must be able to rotate the luminaire independently from the direct lighting to meet the uniformity on the bed. These specifications can be achieved by using new LED technology, by using various aspects of color (tunable white) and dimming constantly should help.

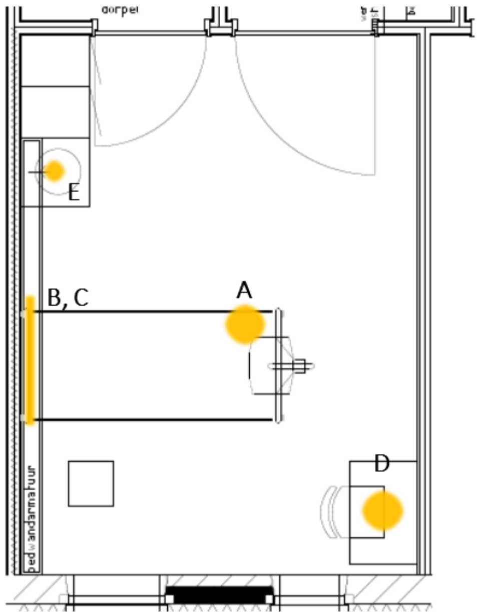


Figure 35. Luminaires are illustrated in the plan of the one-occupancy patient room in the Jeroen Bosch Hospital; the letters are corresponding with the luminaires which are described in Table 23.

In conclusion, with these specifications the lighting design in an one-occupancy patient room can provide sufficient lighting for different activities, to stimulate the circadian rhythm a lighting management system is needed. This lighting management system could be divided into different lighting settings required for various activities. Furthermore, by controlling these lighting settings, patients can also have more control about their environment by easily changing the lighting setting by using the lighting management system. In addition, the vertical effective irradiance is weighted with the sensitivity function of the ipRGC, this value is used to calculate the exposure duration. Therefore the vertical effective irradiance can be used as an argument to design a lighting setting is a patient room. The graph of this calculation is found in Appendix F.

Table 23. Specifications luminaires in lighting design regarding different activities in patient room in the case study research (Jeroen Bosch Hospital)

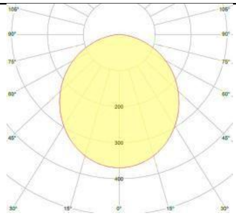
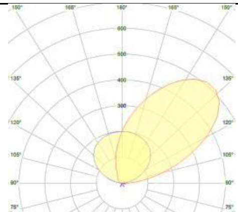
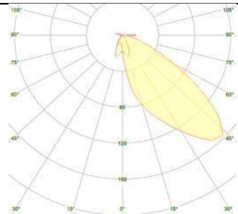
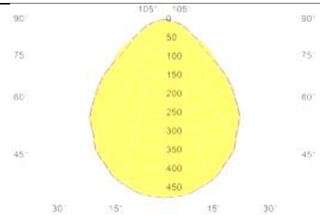
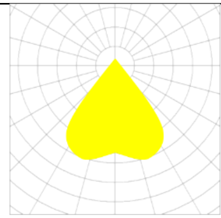
	General (A)	Indirect (B)	Direct (C)	Desk (D)	Sink (E)
Luminous flux [lm]	2500, 3500	6400	900	1250	1000
Correlated Color Temperature [K]	3000, 4000, 5000			3000	4000
Color Rendering Index [-]	90	90	90	80	90
Position (illustrated in Figure 35)	Ceiling, middle room	Bed head panel Rotating only for treatment 30° or 75° degrees	Bed head panel	Above the desk	Above the sink
Intensity distribution	 Direct, downwards	 Indirect, upwards	 Direct, downwards	 Direct, downwards	 Direct, downwards
Dimmable	Yes	yes/no	yes/no	No	No
Tunable white	Yes	Yes	Yes	No	No
Used scenario	General, treatment	Treatment, relaxing	Treatment, relaxing	Relaxing	Treatment

Table 24. Specifications luminaires in lighting design regarding different activities in patient room in the Jeroen Bosch Hospital

Scenarios	Requirements NEN-EN 12464-1			Lighting setting	Timing (illustrated in Figure 36)	Notes
	U_o [-]	E_m [lx]	CCT [K]			
General	0.4	100	3000	General	whole day, 24 hours	
Treatment Treatment Complex treatment	 0.6 0.6	 300 500	 4000 5000	General, indirect, direct Indirect - 30° Indirect - 75°	During the day 8:00-19:30, critical from 19:30 From 19:30 – 66 min maximal performing time From 19:30 – 30 maximal performing time	
Relaxing	0.4	50-300	3000		Whole day, 24 hours Except reading Reading in bed from 19:30 – 1h and 51 min Reading on desk from 19:30 – 68 min	 General, indirect and direct lighting needed to require 300 lux

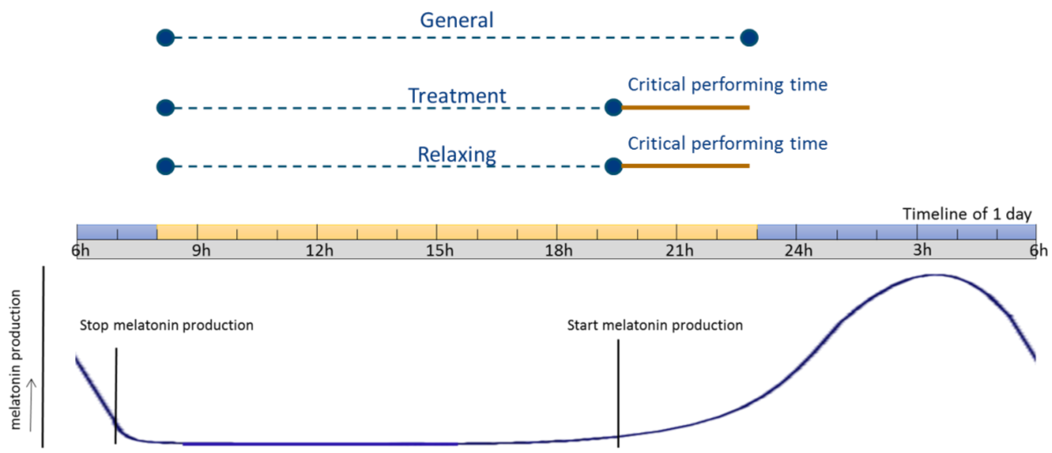


Figure 36. Summary of the results of the different activities. From 19:30 it is recommended to have no melatonin suppression, which is illustrated with ‘critical performing time’.

6 Conclusion and recommendations

This chapter will elaborate on the answering the research question which is the conclusion of this report and the recommendations for further research.

6.1 Conclusion

The aim of this graduation project is: *'to define an optimal lighting solution in a hospital patient room that also enhances the circadian rhythm and well-being of a patient.'* Therefore, the lighting design needs to require to the NEN 12464-1 otherwise activities could not be performed in the one-occupancy patient room by different end users. Besides the influence of the lighting design on the circadian rhythm could have an impact on the healing process of a patient.

The optimal lighting solution needs to be an adjustable lighting solution particular for each type of activity and person. Furthermore, the lighting solution needs to be calm for patients and family and therefore can help by creating a home-like environment. This in contrast to medical staff, who needs a diversity of illuminance levels, where the lighting has to support (complex) medical treatment. The best result to obtain these needs is to combine requirements in one luminaire. Therefore the general luminaire need to be dimmable since 2500 lm, 3500lm can be used for sufficient lighting for treatment and general scenario. And, indirect, direct and general lighting need to have a tunable Correlated Colour Temperature of 3000K, 4000K and 5000K to meet the requirements for the treatment and relaxing scenarios. With this lighting solution, lighting for the treatment scenario is merged into the current lighting design, which reduces the stress level of a patient. In addition, the sink and desk lighting are used for one specific activity therefore these luminaires do not have variable specifications.

In general, the sleep and wake rhythm i.e. circadian rhythm of patients has a strong relation to patients' health. Compared to healthy people, patients are more sensitive for a disturbed circadian rhythm which may create in long-term health problems. Furthermore, the melatonin production regulates the sleep and wake cycle and can be stimulated by lighting. However, melatonin suppression depends on the characteristics of the lighting, e.g. spectrum, irradiance, exposure duration and timing. Where, average illuminance and spectrum are defined by the requirements of the NEN-EN 12464-1 regarding an activity. A specific combination of lamp types is found by using a simulation model, the vertical effective irradiance on patient's eye level is derived from simulation model. The maximal exposure duration (before melatonin suppression occur) of each activity is calculated by the threshold of melatonin suppression divided by the vertical effective irradiance. The threshold of melatonin suppression is assumptive regarding the study of Brainard 2015. Furthermore, timing is defined regarding the melatonin production; melatonin is increasing from 19:30 and therefore it is recommended to have no melatonin suppression from this point (19:30).

In conclusion, the optimal lighting solution needs to be variable in irradiance and spectrum to meet the NEN requirements regarding different activity scenarios. During specific activities, timing and exposure duration require special attention regarding the circadian rhythm.

6.2 Recommendations

With the results and corresponding discussion, some recommendations for further research can be given.

The ipRGC are recently discovered in 2001, therefore a limit amount of literature is performed. It would be very interesting to perform more experiments regarding the influence of lighting on the ipRGC. Furthermore, there are several literature gaps found;

- Threshold of melatonin suppression is not found yet;
- What specific characteristics of lighting, i.e. spectrum, irradiance, exposure duration and time suppress melatonin production is not found yet;
- The study of Brainard in 2015 only used polychromatic lighting stimuli compared to other studies which only used monochromatic lighting. Polychromatic lighting is more related to the practical lighting design.
- Most studies are using for the experiment young participants. However, this is not in line with the average age of hospitalized patient, who are much older

From the literature study it is shown that daylight has a large influence on the healing process of patients. New healthcare facilities prefer a majority of daylight, since literature confirmed the benefits of daylight. Therefore, it might be interesting to study the influence of daylight on the circadian rhythm.

The current study focused only on patients. However, medical staff performed a lot of activities in a patient room. Therefore it is very interesting to investigate the influence of the lighting solution on the performing quality of medical staff. In addition, if the working quality of medical staff can be improved, this could result in a shorter healing process of a patient in a hospital.

Recently LED lighting technology is develop and used in new health care facilities. However, the blue peak in LED lighting is critical, which is also shown in the result of current study. There need to be more studies perform to investigate the influence of this blue peak one the hormones in a human body.

7 Limitations

During this study, daylight is not taken into consideration in order to exclude the effect of weather changes and sky types. However, daylight exposure has a major impact on human health, especially on the light and dark cycle (Aries, Aarts, & Hoof, 2013). Daylight is an optimal lighting source to support the circadian rhythm, since daylight provide dynamically lighting over the day with the all the characteristics, i.e. timing, dose, exposure duration and spectrum as is mentioned in the literature study of (Rosenkötter, 2016).

DIALux evo does not need all parameters to calculate the illuminance value on the patient's eye in the simulation model. The spectral power density of the radiant flux of the lamp is related to the luminous flux, CCT and Ra. However, DIALux evo uses only the luminous flux of the lamp for the lighting calculation instead of using luminous flux, CCT and Ra. The CCT and Ra are defined in the documentation of the lamp, but these are not taken into account during the lighting calculation. The Spectral Power Distribution (SPD) graph was needed for the calculation of the vertical effective irradiance. DIALux evo uses 'typical SPD graphs' with respect to CCT and Ra, These graphs were used to calculate the vertical effective irradiance, in this study three different SPD's are used LED of 3000K, 4000K and 5000K. Furthermore, the LDT editor can be modified the luminous intensities however the spectral power distribution cannot be changed in this software.

The Correlated Color Temperature (CCT) of the lamps which are used in the relaxing scenario is 3000K. However, to create a home-like environment in a patient room, the CCT could be lowered to 2700 K. The raw data of a typical Spectral Power Distribution of a LED 2700K was not available during this study. In addition, it was hard to find some SPD graphs of existing luminaires; documents were not available by the lighting producer.

Brainard et al., (2015) performed an experiment and defined the half-maximum melatonin suppression value. This study has some limitations. The study cannot be compared with other studies, since the new development is discovered recently. Furthermore, participants which are used during the experiment, have a low average age of 24.4 years compared to the average hospitalized patients.

During this study, a case study research is used; therefore building configurations are already defined by the case, such as reflection values, dimensions and furniture. So, the results of this study could be used in other project, with in mind this case study research.

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Appendix

The appendixes are divided in different stages and elaborate on background and additional information for specific topics. The structure of the appendix is the same as the report.

Appendix A: Site visits and interviews

During this study several hospitals are visited, to obtain a complete view of today's hospital. During the visits, there is paid attention to the following aspects:

- The amount of daylight into the patient room;
- The outside view;
- What colors are used on walls, ceiling and floor;
- What lightings points are in the patient room and where situated;
- How to control these lighting points, where is the switch situated.

These aspects will be elaborate for each hospital visit. In addition, in Tilburg were visit different departments, these will be described separately.

UMCU – Universitair Medisch centrum Utrecht

Visit date: 10-04-2016

Contact person: Danielle vossenbeld (Promovenda Medische Technologie & Klinische Fysica (MTKF) | Docent Hogeschool Utrecht)

Aspects

- Amount daylight: Large window with (indoor) blinds and colored curtains (not translucent)
- Outside view: Patient room situated on the indoor garden, the garden can be visit by staff and patients
- Colors: Dark colored floor, arguments of blood and other liquids less visible, the wall opposite of the patient is light green
- Simple medical treatment such as an infusion sting will be in the patient room, there is sufficient lighting for this activity.

Table 25. Lighting design patient room		
Luminaire	Switch (1-occupancy)	Switch (2/4 – occupancy)
Indirect in bed head panel	At the door	At the door (notice: 1 bed head panel above two beds. Therefore indirect is on or off for both beds)
Direct in bed head panel	Single hand button/ hand held	Single hand button for each patient
Night/orientation	Single hand button	Single hand button for each patient
No general lighting in the middle of		

the room		
No read lighting at the desk for family or patients		

A One-occupancy room

B Patient rooms around indoor garden

Figure 37. Photographs taken during visit Universitair Medisch centrum Utrecht. A: Bed head wall with lighting direct and indirect. One-occupancy room. B: Window view, indoor garden.

TweeSteden hospital Tilburg

Visit date: 25-05-2016

Contact person: Theo Mols (projectleider Bouw&Vastgoed)

CCU high care

- Visit a one occupancy patient room CCU high care
- Windows, are lower than normal rooms, so the patient can has a better outside view, not translucent curtain and translucent colored curtain
- Lighting design can be used for both activities by patient as treatments by medical staff. The luminaires can be dimmed easily.

Table 26. **two- occupancy patient room –** Cardio CCU high care	
Luminaire	**Switch**
4 tl luminaires for medical treatments	At the door, can be dimmed
Night/orientation	At the door
Read lighting above desk, on the ceiling	At the desk
Spot in ceiling, middle of bed	Hand held

Patient room with several medical equipment — Lighting situation, dimmed luminaires

Figure 38. Photograph patient room taken during visit Cardio department in Tweesteden hospital Tilburg

<u>Geriatrics – elderly care</u>

- Visit a two-occupancy room on ground level
- Windows has not translucent blind and not translucent colored curtain
- less medical equipment, because other kind of patient
- special indirect lighting in bed head panel, luminaire can be rotated therefore it can be used by activities for patients or medical staff where a higher illuminance value is needed

Table 27. **two- occupancy patient room –** Geriatrics	
Luminaire	**Switch**
Indirect in bed head panel	At the door
Direct in bed head panel	hand held
Night/orientation	At the door
Read lighting above on the wall	At the desk
No general lighting in the middle of the room	

Rotating indirect lighting

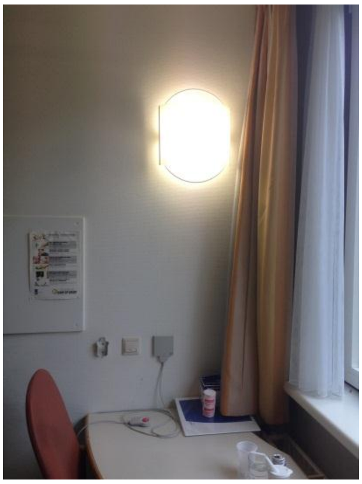


Figure 2. Photograph patient room taken during visit Geriatrics department in Tweesteden hospital Tilburg

<u>Oncologie</u>

- Visit a one-occupancy patient, approximately 10 years old.
- windows not translucent curtain and not translucent colored curtain
- light colors used in the room
- Special chair were patient can sit comfortable

Table 28. **two- occupancy patient room –** oncology

Luminaire	**Switch**
Indirect in bed head panel	At the door
Direct in bed head panel	hand held
Night/orientation	At the door
Read lighting above desk, on the wall	At the desk
No general lighting in the middle of the room	

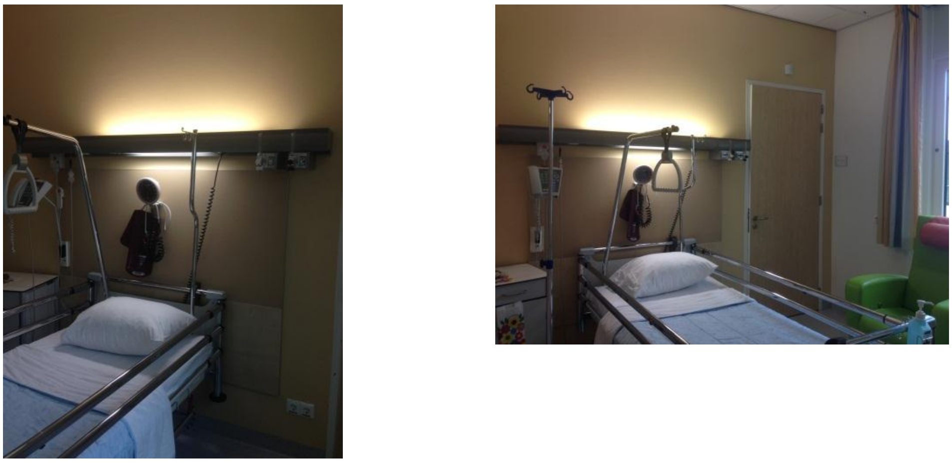


Figure 39. Photograph patient room taken during visit Oncology department in Tweesteden hospital Tilburg

<u>Psychiatrie</u>

- Patient room on ground level, many safety aspects because of this special department
- Large windows, from floor till ceiling with colored not translucent blinds and translucent colored curtains. Patient have a calm green outside view
- No medical equipment in the room, because of special department
- Over days people are not in their patient room, but in the living room
- Calm colors have been used in this department

Table 29. **One- occupancy patient room – psychiatry**

Luminaire	**Switch**
Indirect in bed head panel	At the door
Direct in bed head panel	At the door
Night/orientation	At the door
Read lighting above desk in the ceiling	At the desk
No general lighting in the middle of the room	

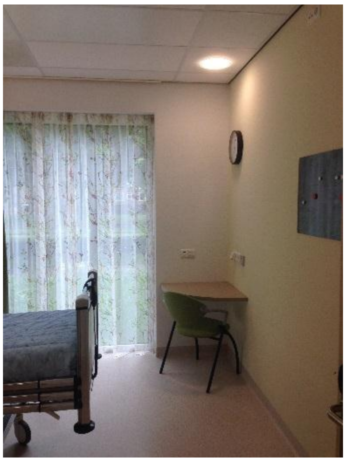
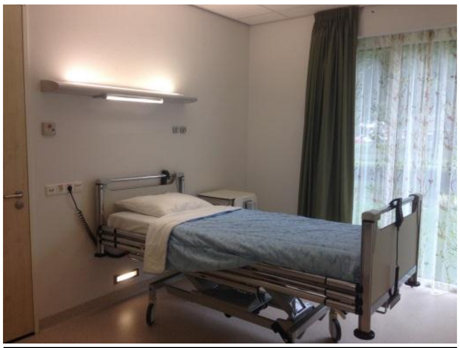



Figure 40. Photograph patient room taken during visit Psychiatrie department in Tweesteden hospital Tilburg

Elisabeth hospital Tilburg

Visit date: 25-05-2016

Contact person: Theo Mols (projectleider Bouw&Vastgoed)

- Indirect lighting can be dimmed by medical staff as well as by patient itself.
- Home-like luminaires, not practical since the luminaires has two switches.
- If the patients press the alarm button the button will light up, so the patient knows that he/she pressed the button.
- Outside view to roof of other buildings, better to have a view to a green garden.

One- occupancy patient room – psychiatry	
Luminaire	**Switch**
Indirect in bed head panel	At the door
Direct in bed head panel	At the door
Night/orientation	At the door
Read lighting above desk in the ceiling	At the desk
No general lighting in the middle of the room	

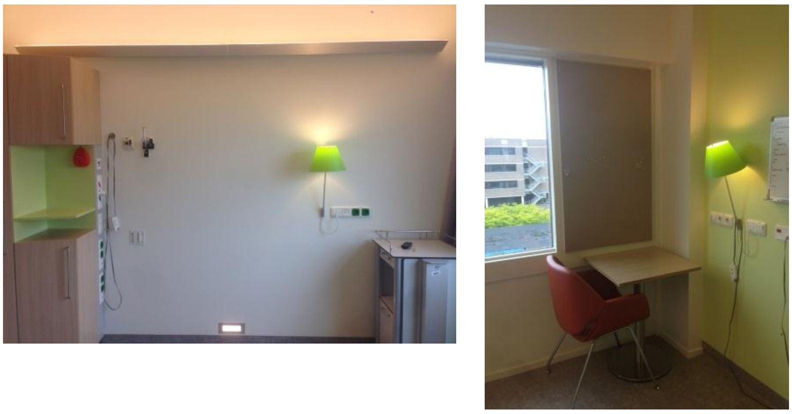


Figure 41. Photograph patient room taken during visit department in Elisabeth hospital Tilburg

Interviews

- Saadet (Healthcare Deerns)
- Cor Prop (Healthcare Deerns)
- Ralp van den Berg (Lighting Deerns)
- Mathijs Sommeijer (lighting Deerns)
- Jack Suijkerbuijk (JBZ)

Appendix B: Current lighting design in patient room

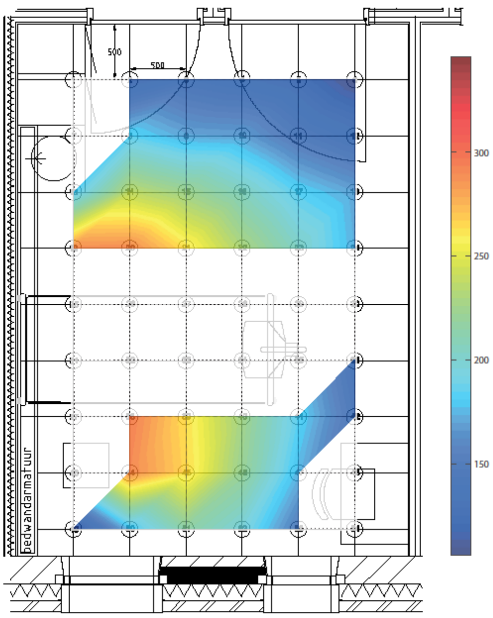
Table 30. General description patient room in Jeroen Bosch hopital

Building	Jeroen Bosch Hospital
Room number	C2.03.62
Address	Henri Dunantstraat 1
City	's-Hertogenbosch
Country	Netherlands
Orientation	East
Internal length [m]	4.437 m
Internal width [m]	3.475 m
Internal height [m]	2.7 m
Color & reflection factor walls	Wand vinyl VesCom, color: soft white (167.027), ocher (167.002), green (167.117), orange (01-A)
Reflection type (diffuse, reflected) walls	Diffuse
Color & reflection factor floor	PVC Armstrong, Timberline PUR color: medium wenge (331-022)
Reflection type (diffuse, reflected) floor	Diffuse
Color & reflection factor ceiling	OWA Stembild (mineral fiber panels), color: RAL 9010
Reflection type (diffuse, reflected) ceiling	Diffuse
Are the rooms in use?	Not during the measurement
Function room	Patient room (isolation room)
Tasks in the room (visual display task, paper work)	Patient, nurse, family

Table 31. **Specification luminaires in the patient room**					
Description	**Specification lamp**	**Specification armature**	**Location**	**Mounting/light height**	**Replacement**
Direct lighting	OSRAM HO 24W/830 Lumilux warm white	Zumtobel pureline	Bedhead wand panel	1.6 m	Not replaced since hospital is yielded
Indirect lighting	OSRAM HO 54W/830 Lumilux warm white	Zumtobel pureline	Bedhead wand panel	1.6 m	
General lighting	OSRAM FC 40W/830 Lumilux warm white	Trilux PolaronIQ WD1-2D	Middle of room in ceiling	2.7 m	
Desk lighting	Philips Master PL-C 18W/830/4p	-	Above desk	2.7 m	

Table 32. Technical specification lamp and armature					
Description	Nominal luminous flux [lm]	Nominal wattage [W]	Rated lamp efficacy [lm/W]	Color temperature [K]	Color rendering index Ra
Direct lighting	1750	24	78	2700	>80
Indirect lighting (2x)	4450	54	82	3000	>80
General lighting	3400	40	85	3000	>80
Desk lighting	1200	16.5	67	3000	>80

Table 33. Specification measurement equipment					
Description	Owner	Fabricate	Serial number	Date calibration	Registration number
Illuminance meter (lux meter)	TU/e	Hagner dectecto	Model: EC1-X	Regularly	9588
Luminance meter	TU/e	Canon	EOS 60D	May 30, 2013	1681032199
Circular fisheye	TU/e	Canon/Sigma	4.5 mm 1:2:8 DC HSM	-	12505828
Thermometer	TU/e	Escort data loggers	RH iLog EI-HS-D-32-L	-	1244-0055
Tripod	TU/e				
Tapeline	Own				
Camera	Own				
Notebook + pen, drawing tools	Own				
Tape measure	Own				



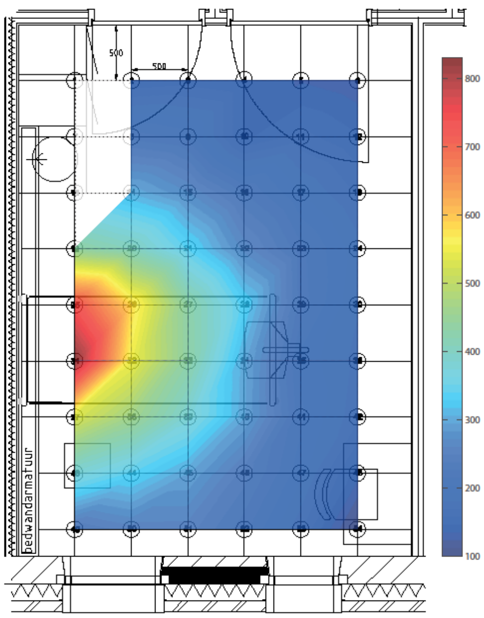


Figure 42. Illuminance values of the total room with lighting setting A1

E_{min}	106 lx	E_{max}	346 lx
$\bar{E}$	196 lx	g	0,54

Figure 43. Illuminance values of the total room with lighting setting A2

E_{min}	100 lx	E_{max}	830 lx
$\bar{E}$	283 lx	g	0,35

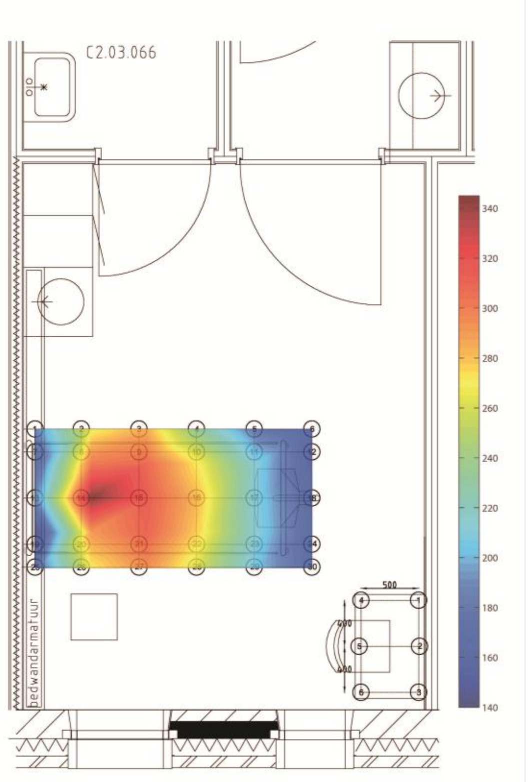


Figure 44. Illuminance values of calculation field bed with lighting setting E1(indirect lighting, h: 0.85 m)

E_{min}	140 lx	E_{max}	345 lx
$\bar{E}$	232 lx	U_o	0.6

Appendix C: Measurement plan

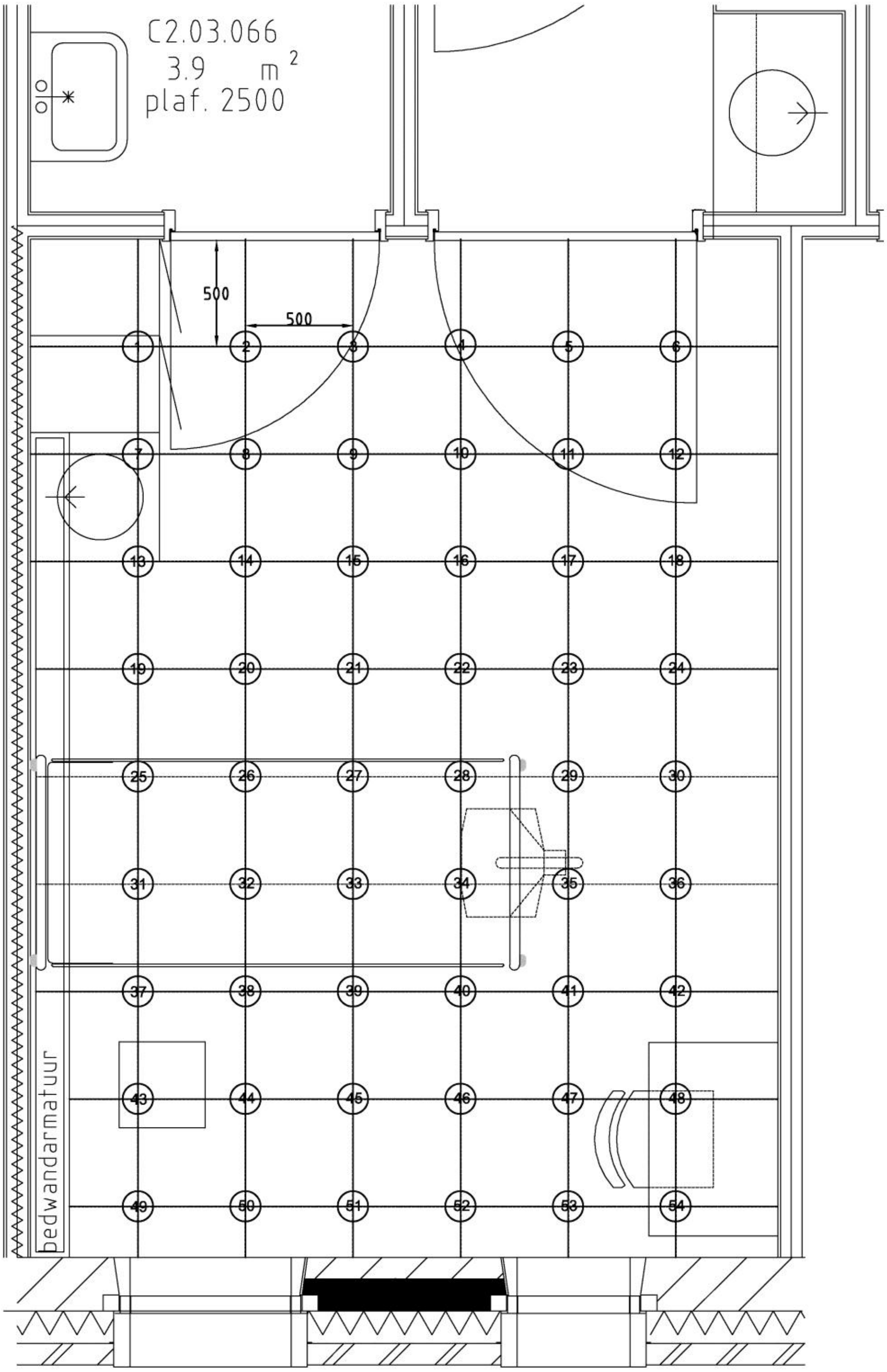


Figure 45. Measurement grid total room

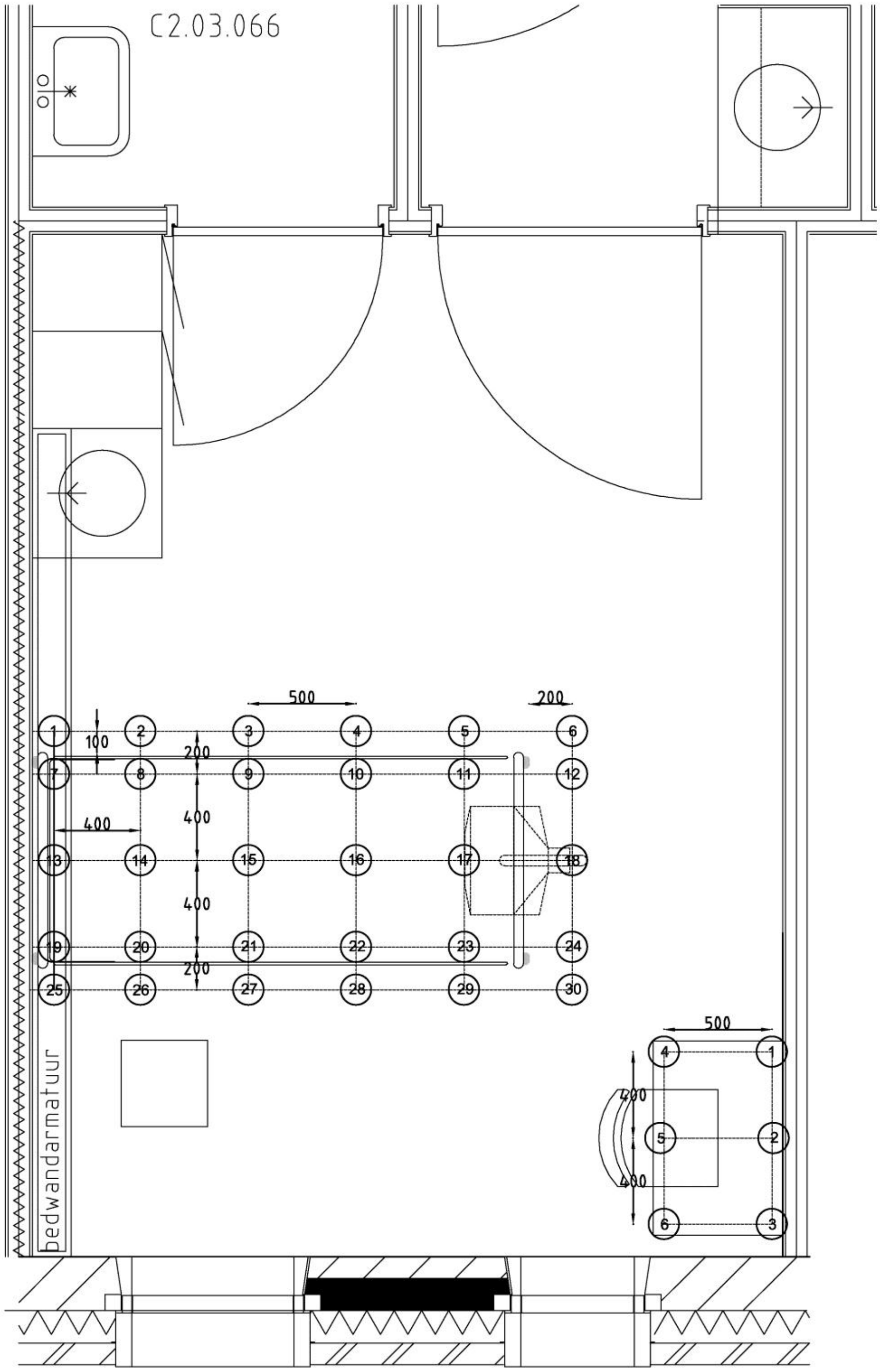


Figure 46. Measurement grid bed and desk

Table 34. **Overall setting to measure illuminance with different lighting settings**							
Setting	Grid	End-user	Lamps on (grey)				Position height [m]
			General	Indirect	Direct	Desk	
1 - A1	Total room (54 pt)	All					0.2
2- A2		All					0.9 (height nightstand)
3 - B1		Cleaner					0.2
4- C		All	Night				0.2
5 - D1	Bed (30 pt)	Patient					0.85 (height bed)
6- E1		Medical staff					0.85 (height bed)
7- F1		all					0.85 (height bed)
8- F2	Bed (7 pt)	All					1.6 (vertical)
9- E2		patient					1.6 (vertical)
10 -D2		Patient					1.6 (vertical)
11- D3	middle pillow (bed in sit stand)	Patient					0.7 (vertical) from bed
11.1- E3							0.7 (vertical) from bed
11.2- F3							0.7 (vertical) from bed
11.3 B2							0.7 from bed
12 B3	upside pillow (bed in sit stand)	Patient					Upside pillow
12.1 -F4							Upside pillow
12.2- E4							Upside pillow
12.3- D4							Upside pillow
13 – D5	Desk (6 points)	Family					0.75
14 – E5							0.75
15 – G							0.75
16- H							0.75

Appendix D: Simulation model

Table 35. Reflection factors of floor, walls, ceiling and furniture		
Surface	**Color**	**Reflection factor [%]**
Wall, Wand vinyl VesCom, color	soft white (167.027) | RGB: 213-211-204	80
	orange (01-A) | RGB: 185-65-4	13
	wall behind bed | RGB: 108-106-94	10
	Board behind the bed | RGB: 53-46-46	3
Floor	PVC Armstrong, Timberline PUR color: medium wenge (331-022)	20
Ceiling	OWA Stembild (mineral fiber panels), color: RAL 9010 | (ceiling panels)	70
Furniture		
Closet	RGB: 162-152-151	29
	RGB: 241-236-225 | white	76
Night closet	RGB: 174-173-139	37
Head wall panel	RGB: 237-235-231	75
Bed	RGB: 237-226-195	69
Chair	RGB: 237-207-123	58
Desk	RGB: 230-236-236	70
Sink	RGB: 248-247-244	80
Curtain	RGB: 193-213-162	55

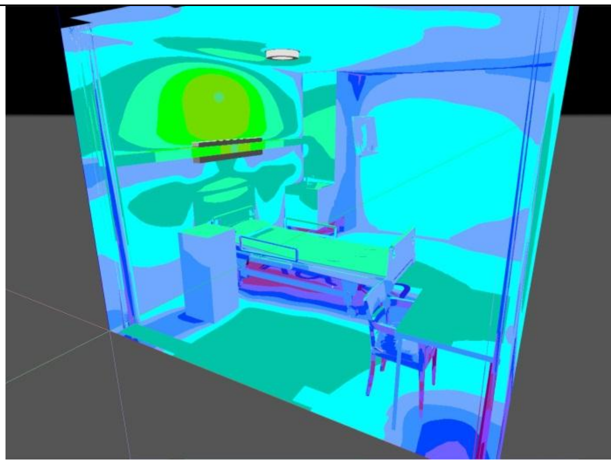
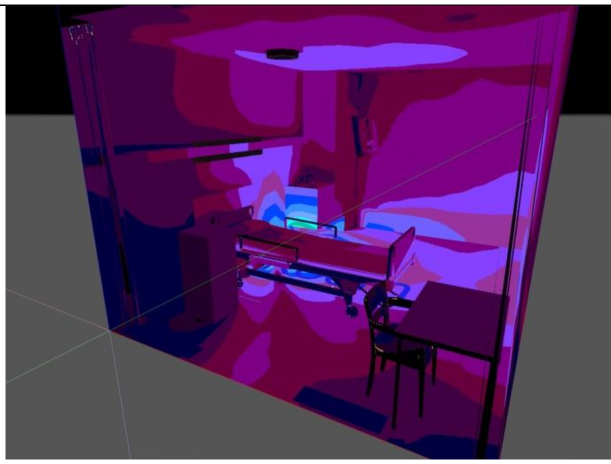
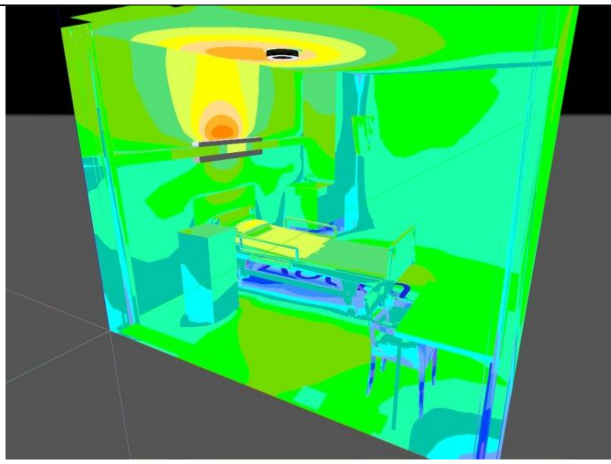
Table 36. Technical specification lamp and armature from documentation					
Description	Nominal luminous flux [lm]	Nominal wattage [W]	Rated lamp efficacy [lm/W]	Color temperature [K]	Color rendering index Ra
Direct lighting	1750	24	78	2700	>80
Indirect lighting (2x)	4450	54	82	3000	>80
General lighting	3400	40	85	3000	>80
Desk lighting	1200	16.5	67	3000	>80

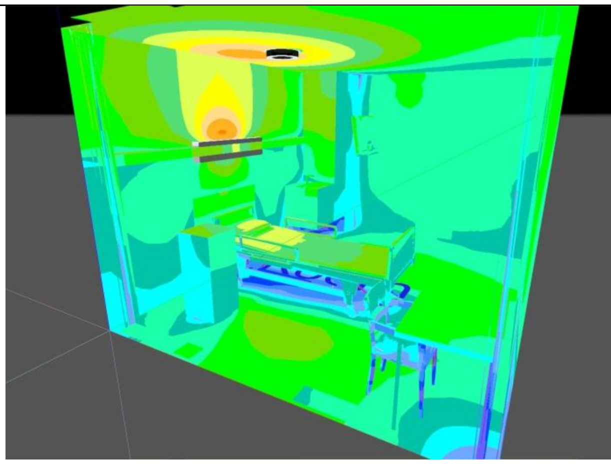
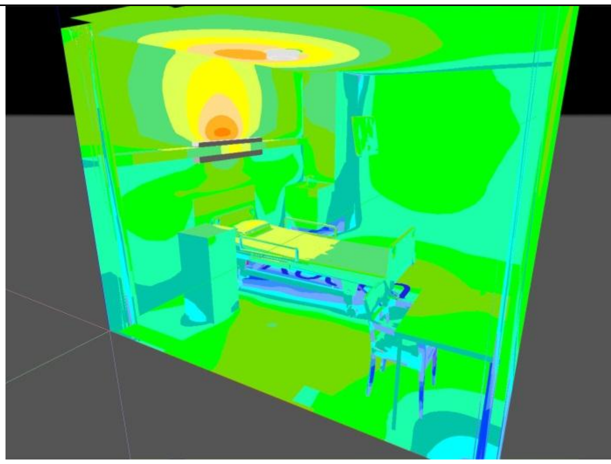
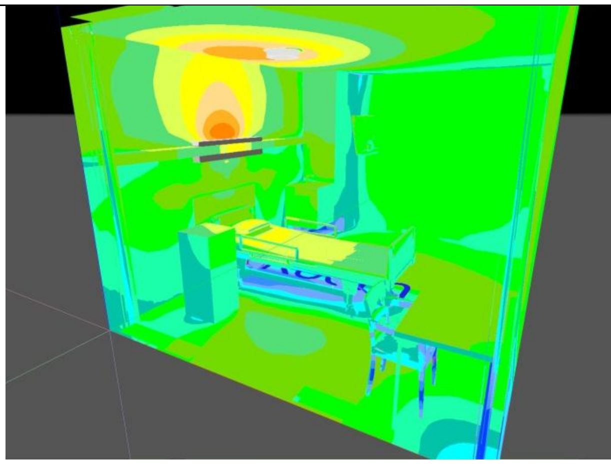
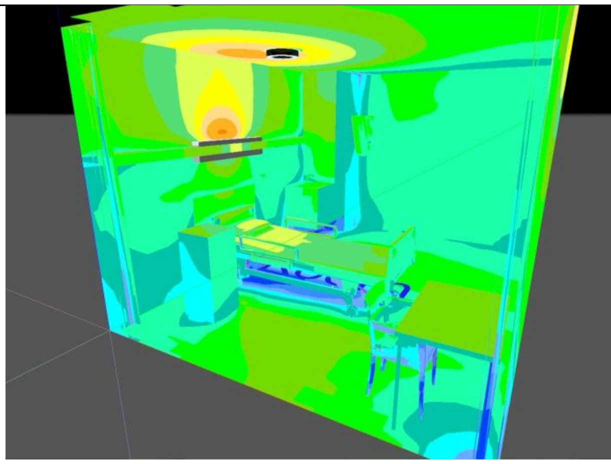
Table 37. Technical specification lamp and armature in simulation model					
Luminaire	Lamp type	Luminous flux [lm]	Power [W]	Color	Color

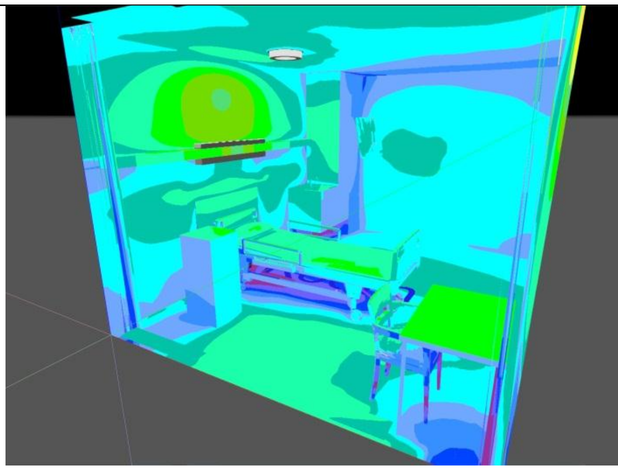
				Temperature [K]	rendering
Belia ID – zumtobel	Indirect 2x 39W	4450	54	3033	83
		4450	54	3033	83
	Direct 1x T16/24W	1	0	300	83
Belia ID – zumtobel	Indirect 2x 39W	1	0	300	83
		1	0	300	83
	Direct 1x T16/24W	1752	24	3033	83
EVG – D(1) Polaron WD2 Trilux	2x TR40W LIS ULD interface	3400	40	3000	100
		1	0	300	100
TEE 200 INFÄLLD 2X18W HF X-REFLEKTOR	2x FSM	1200	18	3000	83
		1200	18	3000	83

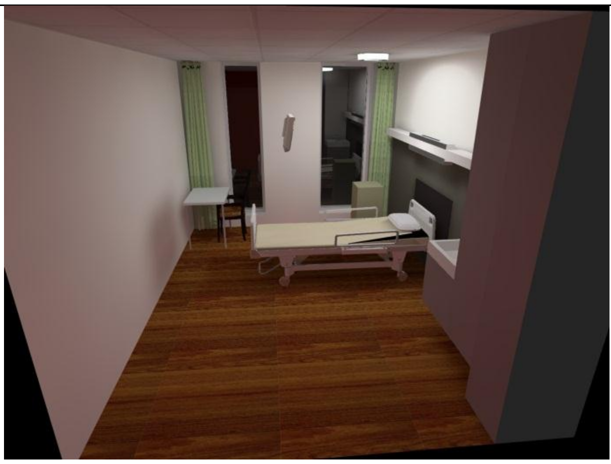
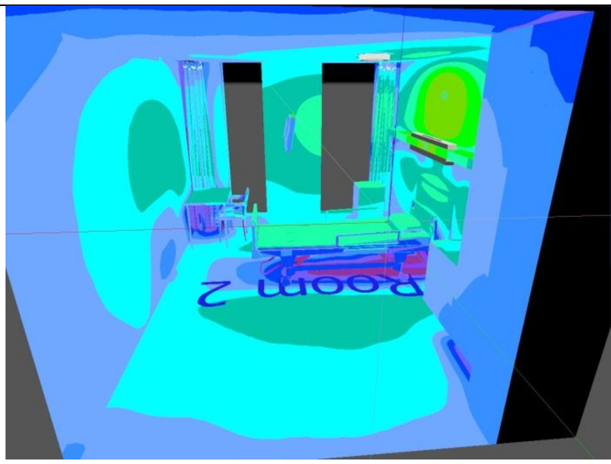
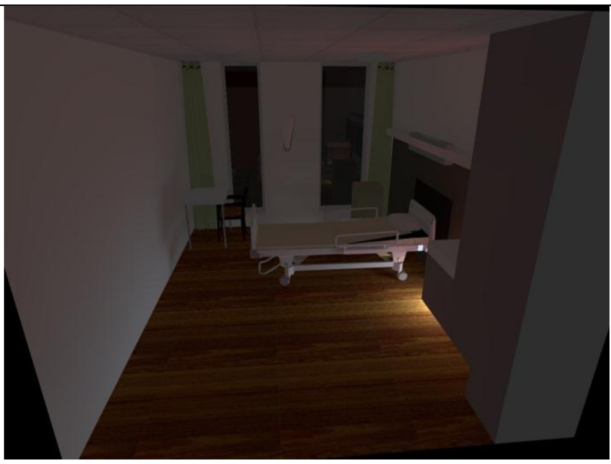
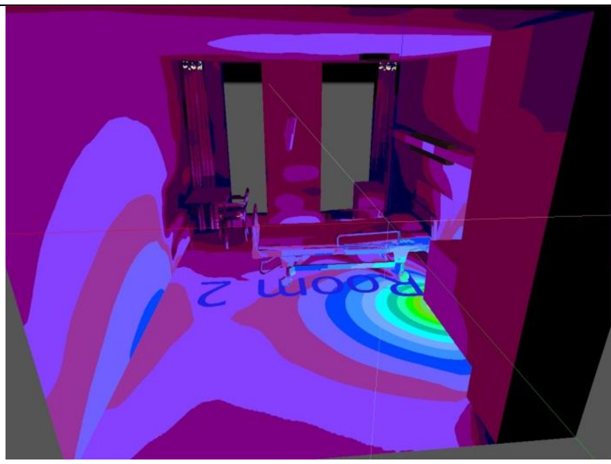
Table 38. Specification measurement grids in DIALux evo			
Name	Positiong	Calculation parameter	Setting
Grid bed	8.575; -21.453; h:0.85 m (size: 1.622*2.510 m)	Horizontal illuminance	Distance x: 0.2 m Distance y: 0.1 m
Grid desk	10.364; -22.747; h:0.750 m (size: 0.6*0.9m)	Horizontal illuminance	Quantity x: 3 Quantity y: 3
Grid total room (h:0.2m)	9.012; -21.063; h: 0.2m (size: 2.5*4.0 m)	Horizontal illuminance	Distance x: 0.5 m Distance y: 0.5 m
Grid total room (h:0.9m)	9.012; -21.063; h: 0.9m (size: 2.5*4.0 m)	Horizontal illuminance	Distance x: 0.5 m Distance y: 0.5 m

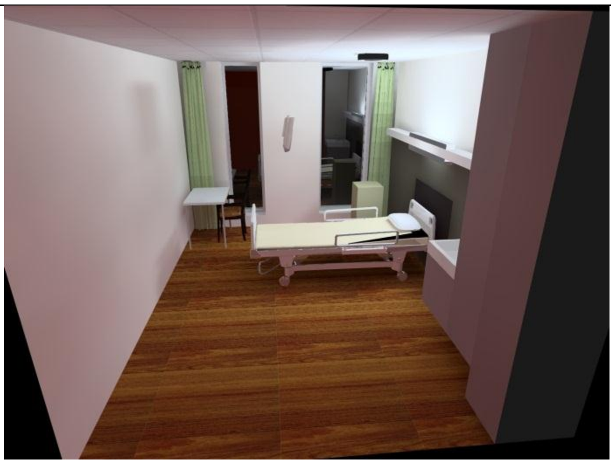
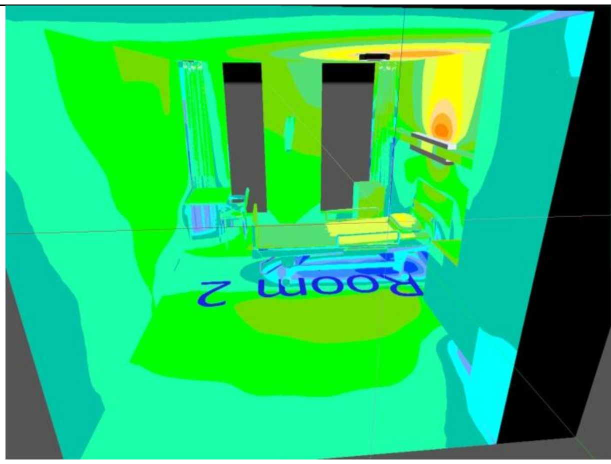
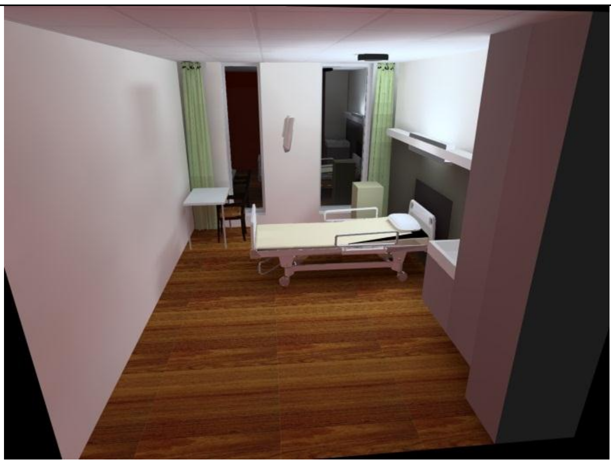
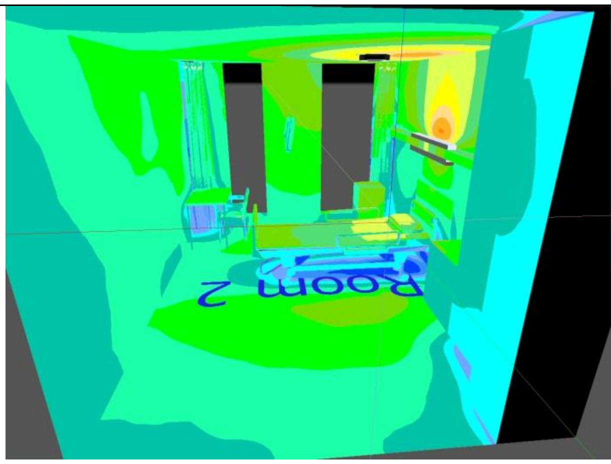
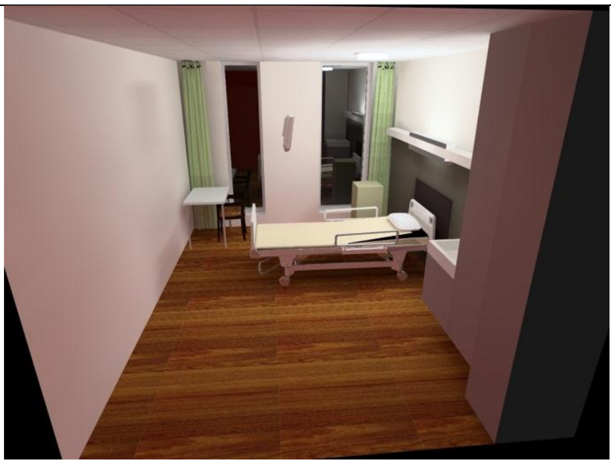
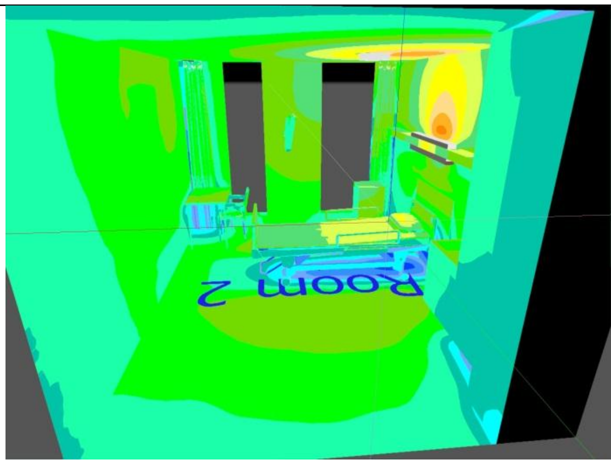
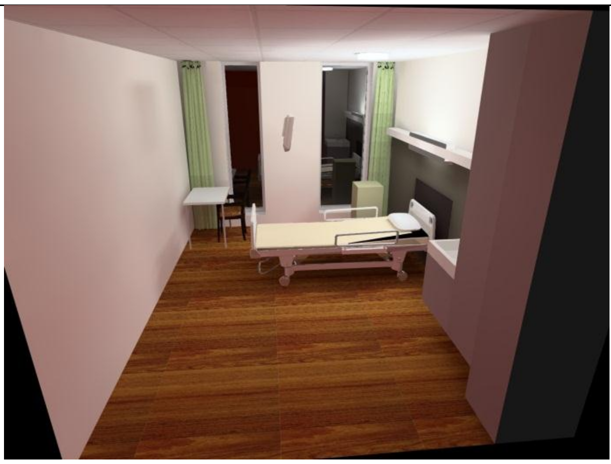
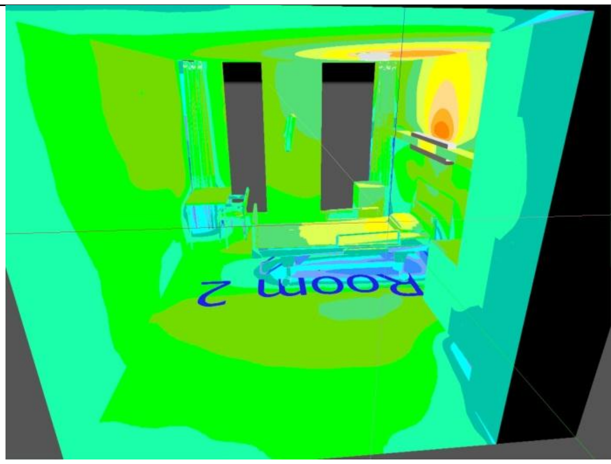
Realistic and colored – illuminance values - pictures simulation model

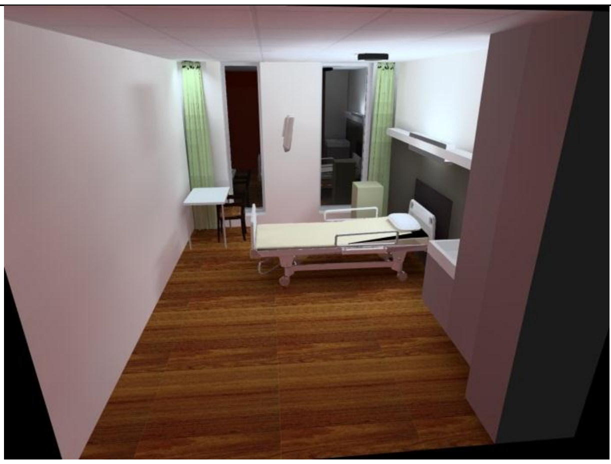
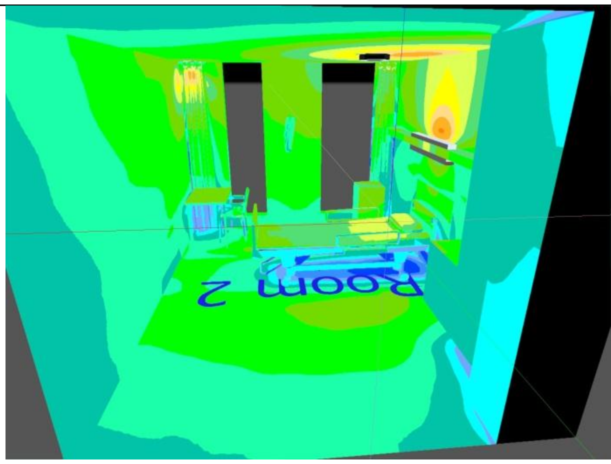
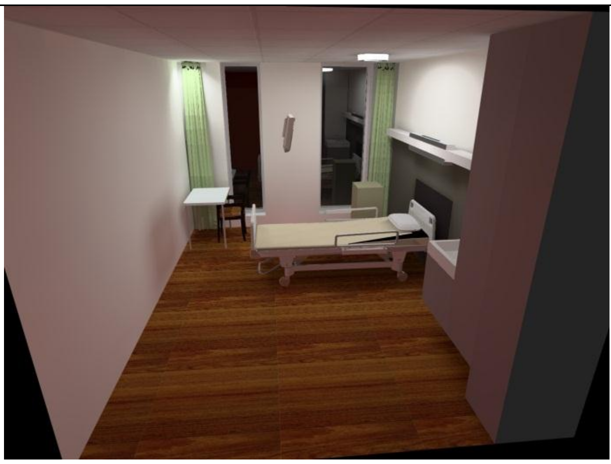
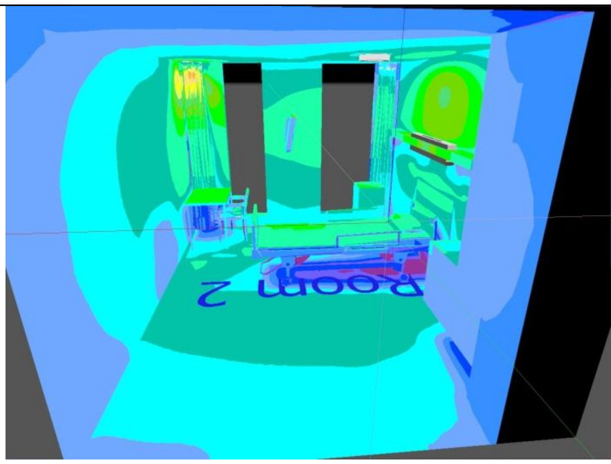
	Realistic	Colored- illuminance distribution values
3		
4		
5		

6		
7		
12		
14		

15		

	Realistic	Colored- illuminance distribution values
3		
4		

5		
6		
7		
12		

14		
15		

Appendix E: Validation simulation model

Table 39. Technical specification lamp and armature in DIALux evo 6

Luminaire	Lamps	Luminous flux [lm]	Power [W]	Collerated Color Temperature [K]	Color rendering
Belia ID – zumtobel	Indirect 2x 39W	4450	54	3033	83
		4450	54	3033	83
	Direct 1x T16/24W	1	0	300	83
Belia ID – zumtobel	Indirect 2x 39W	1	0	300	83
		1	0	300	83
	Direct 1x T16/24W	1752	24	3033	83
EVG – D(1) Polaron WD2 Trilux	2x TR40W LIS ULD interface	3400	40	3000	100
		1	0	300	100
TEE 200 INFÄLLD 2X18W HF X-REFLEKTOR	2x FSM	1200	18	3000	83
		1200	18	3000	83

Validation of simulation model, Table 20, 21 and 22 shows the values of the measurement, simulation model and a comparison between these two. In addition, comparison = measurement – simulation, therefore positive value and negative values occur. For each table, colored values (extreme values) will be further explained.

Table 40. Validation illuminance values for lighting setting A1 (indirect + direct + general, h=0.2)

Measurement						Simulation						Comparison					
	125	140	134	125	106		105	112	111	104	97		20	28	23	21	9
	184	171	169	149	136		148	150	145	136	119		36	21	24	13	17
183	237	224	206	183	170	157	207	204	186	161	143	26	30	20	20	22	27
288	289	262	230	203	173	244	285	262	230	193	160	44	4	0	0	10	13
					153						142						11
					139						137						2
346	294	263	226	184	146	240	167	200	243	196	149	106	127	63	-17	-12	-3
	290	265	221	175			191	259	230	173			99	6	-9	2	
108	180	216	196	154		102	158	211	198	142		6	22	5	-2	12	
E_{min}:	106 lx	E_{max}	346 lx			E_{min}:	97 lx	E_{max}	285 lx			$E_{min,diff}$	0 lx	$E_{max,diff}$	127 lx		
$\bar{E}$:	196 lx	U_o	0,54			$\bar{E}$:	169 lx	U_o	0,56								

Further explanation Table 20: reflection bed is not sufficient enough.

Table 41. Validation illuminance values for lighting setting A2 (indirect, direct, general, h=0.9)

Measurement						Simulation						Comparison					
	146	151	143	133	125		108	111	105	95	89		38	40	38	38	36
	220	210	143	161	147	181	164	159	145	127	111		56	51	-2	34	36
	302	271	225	191	167	242	243	228	190	156	135		59	43	35	35	32
434	405	336	265	217	185	347	383	318	248	189	155	87	22	18	17	28	30
730	580	430	330	219	181	742	569	406	278	207	143	-12	11	24	52	12	38
830	548	431	298	199	176	970	536	426	293	210	147	-140	12	5	5	-11	29
530	464	382	295	205	172	549	505	381	279	211	164	-19	-41	1	16	-6	8
382	340	296	243	195	140	278	322	299	247	190	160	104	18	-3	-4	5	-20
239	255	254	218	171	100	195	227	242	211	161	143	44	28	12	7	10	-43
E_{min}	100 lx	E_{max}	830 lx			E_{min}	89 lx	E_{max}	970 lx			$E_{min,diff}$	2 lx	$E_{max,diff}$	140 lx		
$\bar{E}$	283 lx	U_o	0.35			$\bar{E}$	263 lx	U_o	0.34								

Further explanation Table 21:

Table 42. Validation illuminance values for lighting setting B1 (general, h=0.2)

Measurement						Simulation						Comparison					
	32	33	30	27	26		27	28	27	26	24		5	5	3	1	2
	37	38	35	32	33		36	36	34	32	29		1	2	1	0	4
36	45	45	42	38	34	38	45	45	43	38	34	-2	0	0	-1	0	0
48	51	51	48	42	37	49	52	53	49	43	38	-1	-1	-2	-1	-1	-1
					30						39						-9
					17						39						-22
48	49	51	44	30	16	40	37	56	52	46	38	8	12	-5	-8	-16	-22
	46	45	40	32			52	54	50	40			-6	-9	-10	-8	
11	36	40	35	30		14	44	49	46	34		-3	-8	-9	-11	-4	

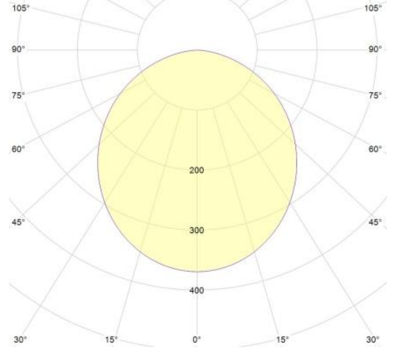
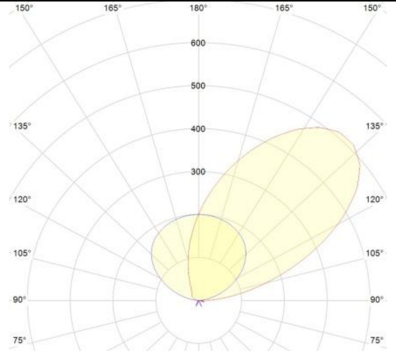
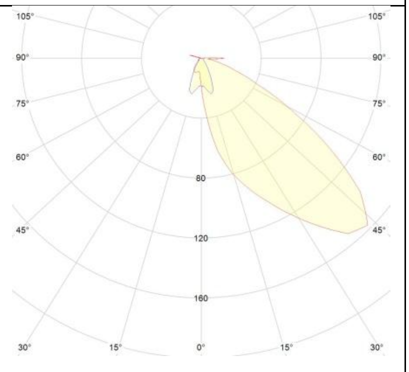
Measurement				Simulation				Comparison			
E_{min}:	11 lx	E_{max}	57 lx	E_{min}:	10 lx	E_{max}	56 lx	$E_{min,diff}$:	0 lx	$E_{max,diff}$:	22 lx
$\bar{E}$:	37 lx	U_o	0.30	$\bar{E}$:	39 lx	U_o	0.26				

Further explanation Table 22:

Appendix F: New situation

Table 43. New situation, reflection factors		
Surface	**Color**	**Reflection factor [%]**
Wall, Wand vinyl VesCom, color	soft white (167.027) | RGB: 213-211-204	80
	orange (01-A) | RGB: 185-65-4	13
	wall behind bed | RGB: 108-106-94	10
	Board behind the bed | RGB: 53-46-46	3
Floor	PVC Armstrong, Timberline PUR color: medium wenge (331-022)	20
Ceiling	OWA Stembild (mineral fiber panels), color: RAL 9010 | (ceiling panels)	70
Furniture		
Closet	RGB: 162-152-151	29
	RGB: 241-236-225 | white	76
Night closet	RGB: 174-173-139	37
Head wall panel	RGB: 237-235-231	75
Bed	RGB: 237-226-195	69
Chair	RGB: 237-207-123	58
Desk	RGB: 230-236-236	70
Sink	RGB: 248-247-244	80
Curtain	RGB: 193-213-162	55
Television		

Table 44. Specification calculation point E_{oog}		
	Position	Calculation parameter
E_{oog} lying patient in bed	7.618; -21.456; h:0.873 m	Horizontal illuminance Unified Glare Rating (UGR)
E_{oog} sitting patient in bed	7.720; -21.461; h:1.123 m	Vertical illuminance Unified Glare Rating (UGR)

Table 45. Technical specification lamp and armature in simulation model					
Luminaire type - manufactur	Lamp type	Luminous flux [lm]	Power [W]	Color Temperature [K]	
Glamox C90085820	LED	1.000-11.000	31	3000-6000	
Zumtobel – sinus 4283399	LED, indirect	6395	64	3000-6000	
	LED, direct	940	11	3000-6000	

Raw data general

- General lighting
  - Position: 9.114 / -21.264 / h= 2.7m

Simulation model - general scenario [lux], h=0.2 m

	65	72	75	73	67
	89	100	104	99	90
	118	135	141	134	119
110	144	165	174	163	146
				69	165
				63	163
51	55	127	145	113	142
	119	124	133	115	70
	91	110	114	93	

Min [lux]	51
Max [lux]	174
E_m [lux]	111
U_o [-]	0,5

Simulation model - general scenario [lux], h=0.9 m

	59	67	69	66	60
86	92	106	110	102	89
120	141	171	178	158	129
133	188	256	270	231	176
153	241	295	311	287	200
151	237	257	252	282	207
127	190	210	218	224	174
98	137	162	170	158	133
71	94	125	129	108	101

Min [lux]	59
Max [lux]	311
E_m [lux]	161
U_o [-]	0,4

Raw data treatment

Simulation model, treatment 1000 lux General 11.000 lm, Indirect (rotated 75°) 6395 lm, direct 904lm											
680	924	1083	1145	1165	1157	1127	1109	1082	1037	987	924
707	1037	1206	1552	1258	1225	1150	1070	1091	1032	1030	973
740	1095	1273	1314	1311	1246	1114	943	1019	1007	1038	994
738	1107	1282	1315	1307	1221	1050	841	936	936	1003	981
717	1066	1235	1266	1255	1162	990	800	890	890	954	943
671	985	1137	1169	1158	1076	928	778	842	825	888	880
670	853	996	1034	1032	978	880	805	828	797	818	806

min	670
max	1552
average	1019
uo	0,7

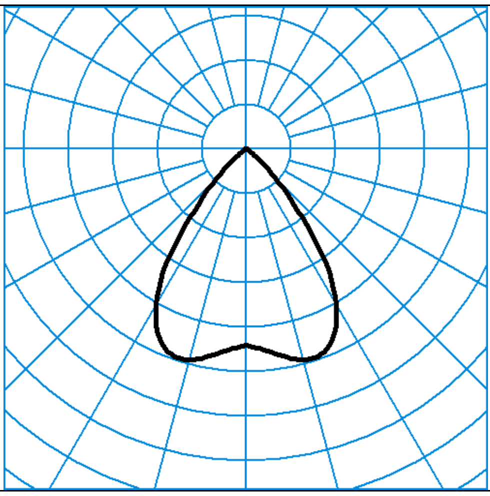
Simulation model, treatment 500 lux General 3500 lm, Indirect (rotated 75°) 6395 lm, direct 904lm											
400	592	686	680	633	582	532	496	465	436	409	390
424	690	790	765	698	627	555	495	476	446	426	409
453	744	851	817	739	650	554	462	459	436	432	418
457	759	867	828	746	647	538	433	435	415	423	415
445	734	838	801	722	624	519	418	419	400	408	404
413	672	767	738	669	582	408	405	401	378	386	383
400	567	658	645	594	529	459	406	392	366	362	362

min	362
max	867
average	545
uo	0,7

Simulation model, treatment 300 lux General 3500lm, indirect (rotated 30°) 6395 lm, direct 904 lm											
223	260	284	302	306	322	336	344	346	340	330	314
246	268	310	318	323	337	343	340	351	346	342	329
256	300	323	331	337	346	339	313	339	340	347	336
254	305	329	328	336	346	327	294	322	326	342	334
249	294	315	321	326	328	315	285	313	316	332	328
239	276	298	303	306	309	299	279	301	303	319	314
221	247	269	277	284	289	289	285	299	294	302	296

min	221
max	351
average	309
uo	0,7

Specifications luminaire above sink

Type	InperlaL G2 C07 BR19 1000-840 ET 01 TOC: 6865440
Lighting distribution	
CCT	4000K
Ra	80
Position	In ceiling, above sink
Luminous flux [lm]	1000

Raw data, relax

Indirect											
183	199	211	213	207	198	189	173	159	146	133	124
188	204	222	221	213	206	192	179	164	154	138	124
193	212	227	220	224	210	200	101	168	152	138	126
200	216	233	220	222	215	205	106	175	159	141	130
195	212	227	220	219	216	204	100	172	158	141	128
188	209	225	225	218	213	201	107	170	160	145	133
192	202	218	210	214	208	199	104	169	155	144	132

min	100
max	233
average	182
uo	0,55

Indirect, direct											
226	242	247	237	222	206	194	178	161	148	135	125
247	261	269	252	231	216	198	184	167	153	140	126
257	275	278	263	245	222	207	186	171	159	140	128
264	280	286	264	243	227	210	190	176	161	143	132
259	275	279	263	239	227	211	193	175	160	143	130
246	266	271	256	236	223	207	191	173	162	147	134
234	244	252	242	228	216	205	188	171	157	146	134

min	125
max	286
average	207
uo	0,61

											General, indirect
275	310	343	365	384	389	384	376	366	348	326	299
281	320	360	382	399	406	394	371	369	350	342	311
299	328	365	391	410	408	386	342	354	346	340	318
292	327	370	391	406	402	370	322	337	331	335	317
284	325	361	383	401	392	361	312	327	317	322	308
275	312	348	367	381	376	345	312	320	307	309	296
263	299	328	346	358	357	336	316	315	296	292	277

min	263
max	410
average	342
uo	0,77

Direct, indirect, general											
318	352	379	399	398	398	389	380	368	350	328	300
341	378	407	414	417	416	400	375	372	352	344	313
363	391	417	426	430	420	393	347	358	349	342	320
356	390	422	427	427	414	377	326	340	333	337	319
348	388	412	418	421	403	368	317	330	320	324	310
333	369	394	398	398	386	351	316	323	310	311	298
305	341	363	370	372	365	342	320	318	298	294	278

min	278
max	430
average	362
uo	0,77

Indirect, desk											
191	209	222	225	220	211	204	189	177	166	154	146
197	214	234	233	226	222	209	198	185	174	164	153
202	223	239	242	224	227	219	204	194	181	172	165
209	228	247	243	239	235	225	212	201	197	187	184
205	225	241	244	238	238	230	220	212	209	207	210
199	222	240	242	239	237	231	224	219	228	237	251
204	216	233	236	235	235	233	228	232	246	268	291

min	146
max	291
average	216
uo	0,68

Illuminance desk: desk, indirect				
281	309	281	min	254
329	422	385	max	422
277	277	254	average	313
			uo	0,81

General, desk											
98	121	143	157	190	205	214	221	224	220	214	200
103	125	150	175	201	215	216	211	226	226	228	218
104	128	152	180	207	216	207	183	213	220	236	232
103	127	153	178	205	211	199	161	199	213	240	244
101	123	146	171	196	202	186	160	198	214	249	262
97	116	139	161	184	189	178	162	197	218	260	285
91	109	128	148	168	176	174	178	209	235	276	309

min	91
max	309
average	186
uo	0,49

Illuminance desk: desk, general					
318	334	324		min	254
319	406	407		max	407
254	301	272		average	326
				uo	0,81

Additional results - general lighting situation

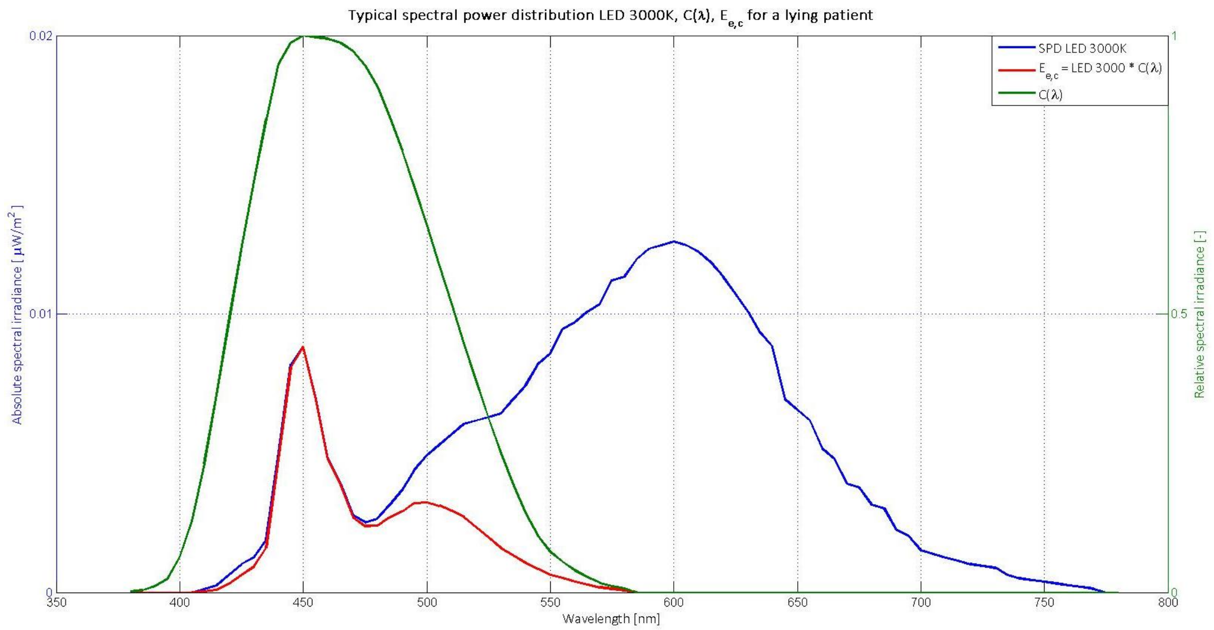


Figure 47. The Red line indicates the vertical effective irradiance in μW/m^{2}nm on patient eye, when the patient in lying in bed. Which is an outcome of relative spectral power distribution of LED 3000K multiple with the sensitivity function of ipRGC.

Additional results – treatment lighting situations

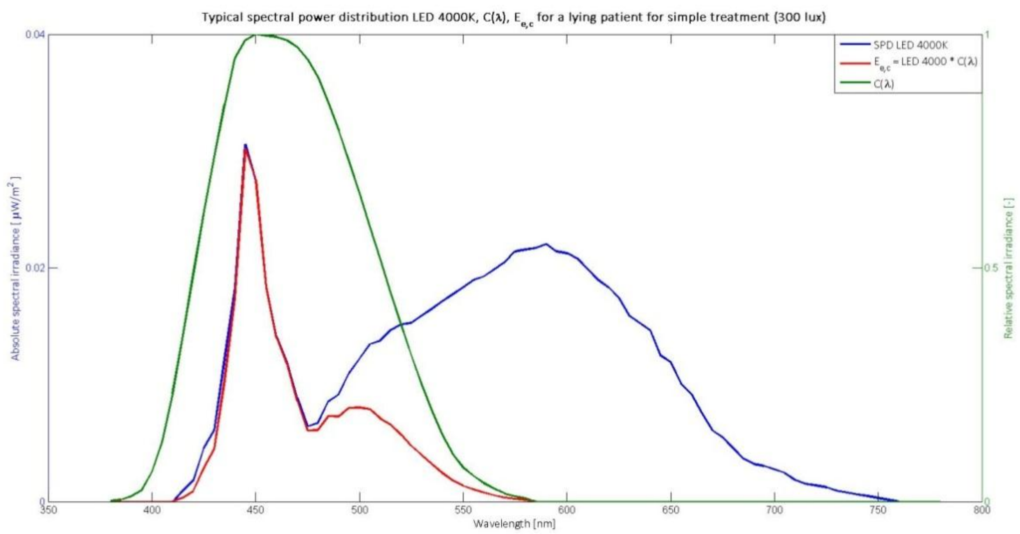


Figure 48. The Red line indicates the vertical effective irradiance in μW/m^{2}nm on patient eye, when the patient in lying in bed and a simple treatment is performed. Which is an outcome of relative spectral power distribution of LED 4000K multiple with the sensitivity function of ipRGC.

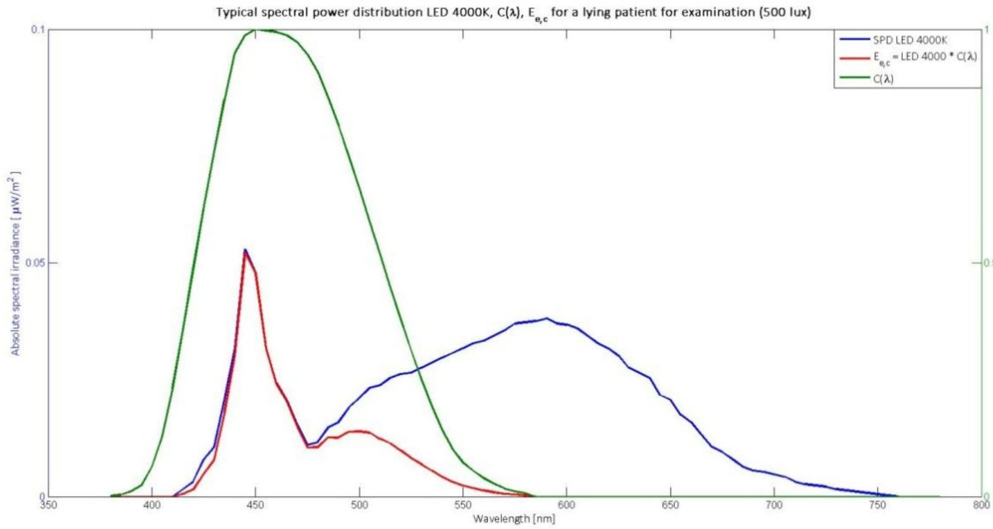


Figure 49. The Red line indicates the vertical effective irradiance in μW/m^{2}nm on patient eye, when the patient in lying in bed and a complex treatment is performed. Which is an outcome of relative spectral power distribution of LED 4000K multiple with the sensitivity function of ipRGC.

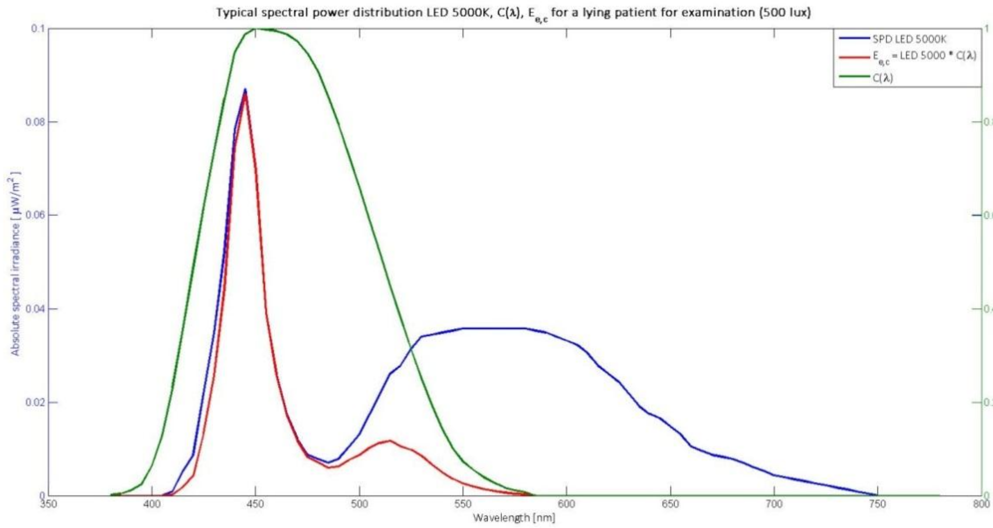
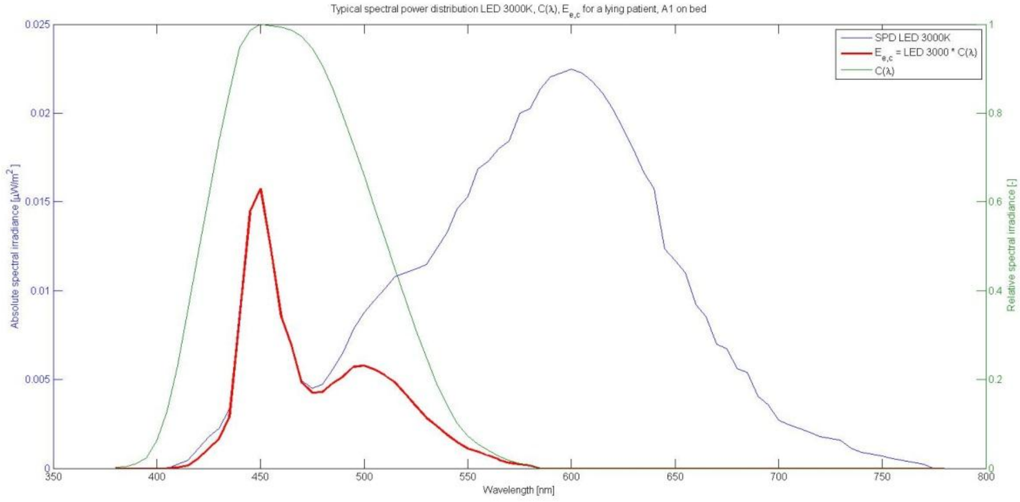
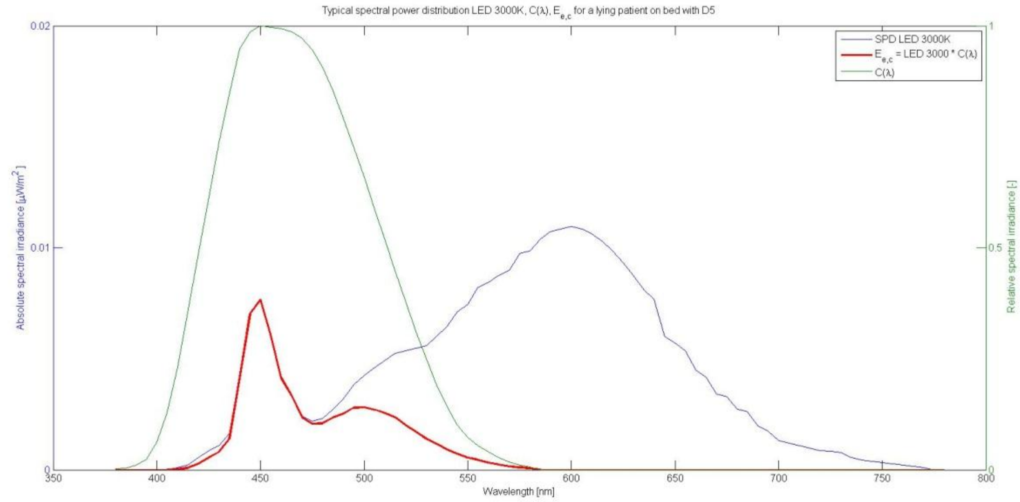
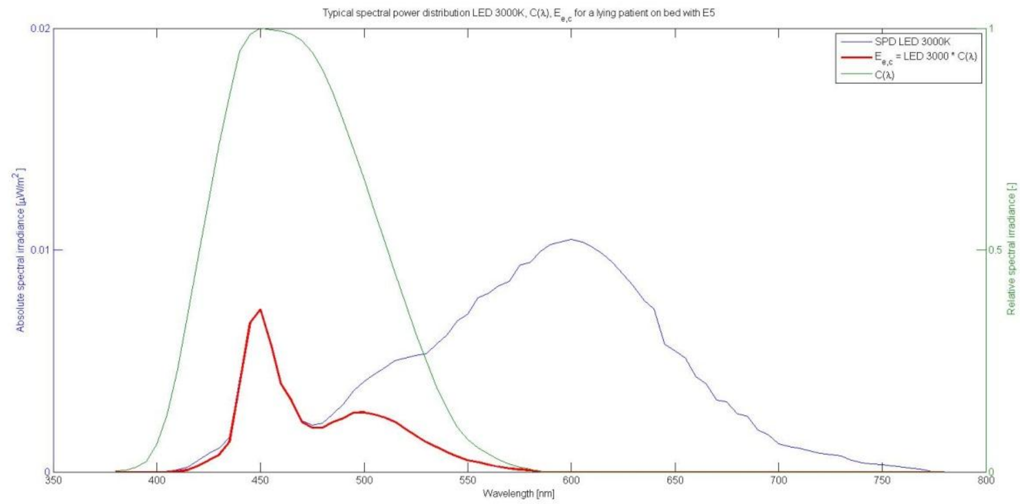


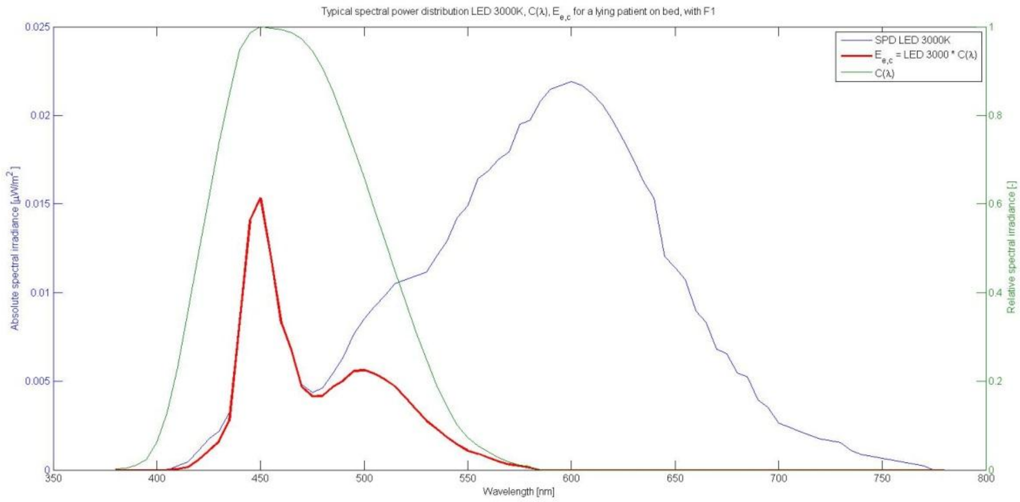
Figure 50. The Red line indicates the vertical effective irradiance in μW/m^{2}nm on patient eye, when the patient in lying in bed and an complex treatment is performed. Which is an outcome of relative spectral power distribution of LED 5000K multiple with the sensitivity function of ipRGC.

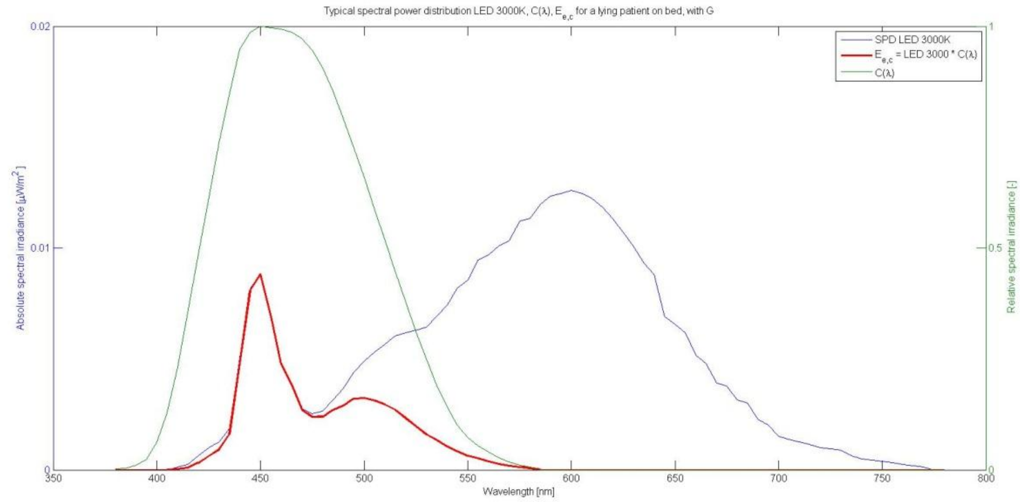
Additional results – treatment lighting situations

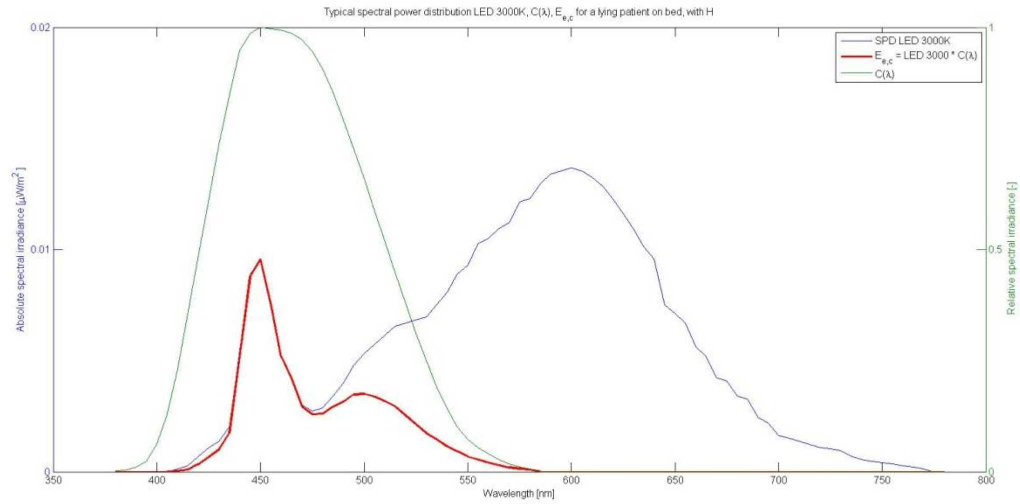


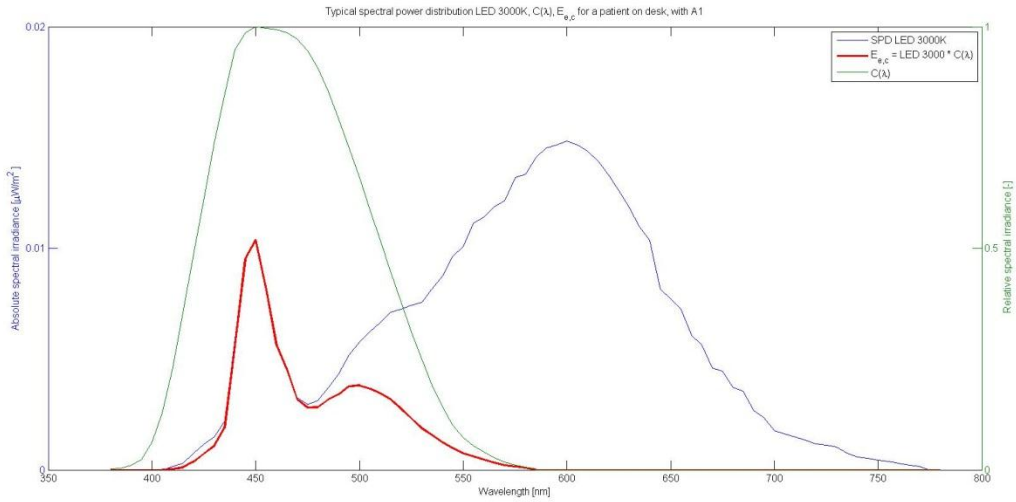


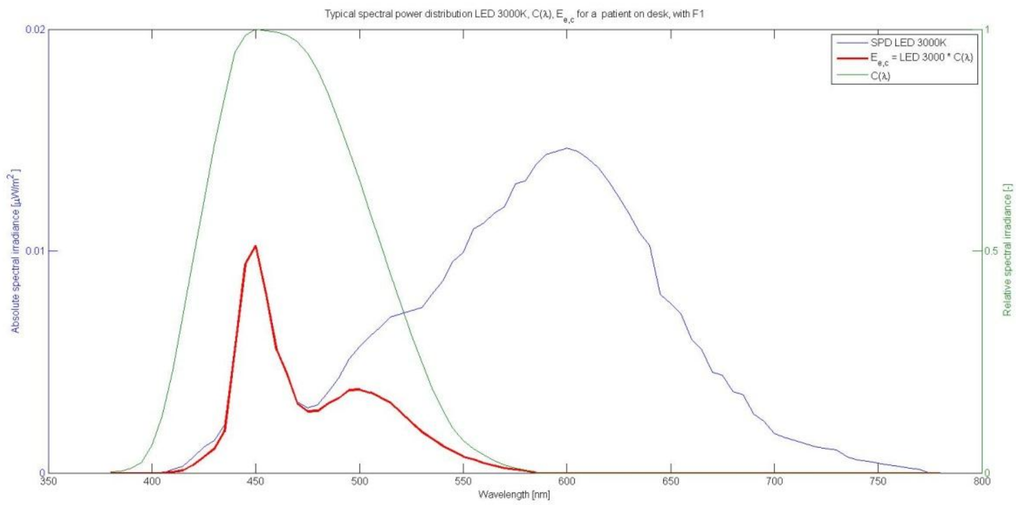


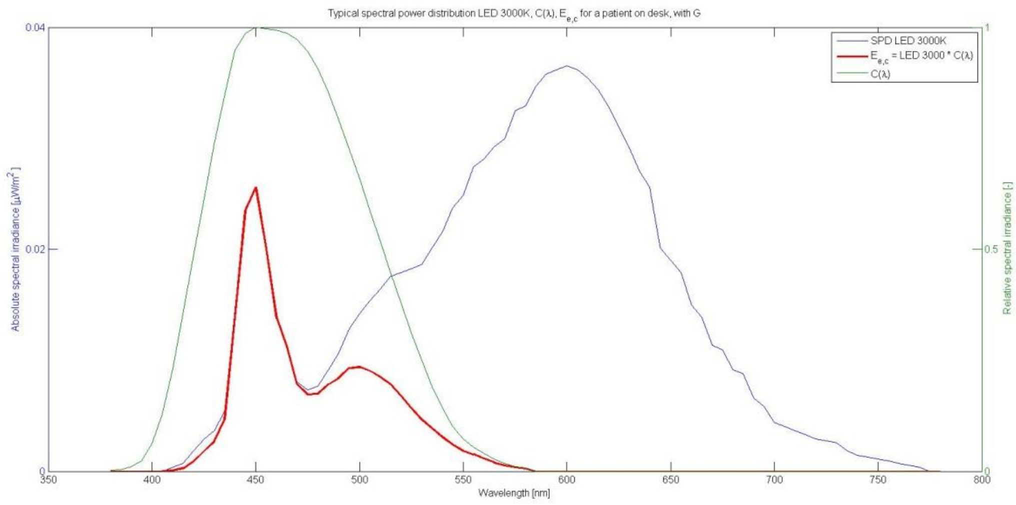

Typical spectral power distribution LED 3000K, C(λ), E_e,c for a lying patient on bed, with F1
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m^2]
Relative spectral irradiance [-]
Wavelength [nm]

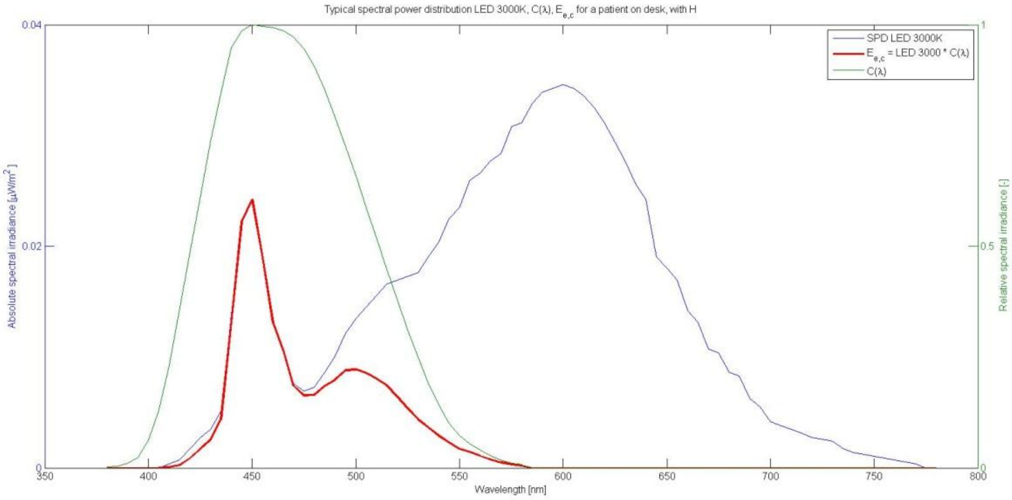

Typical spectral power distribution LED 3000K, C(λ), E_e,c for a lying patient on bed, with G
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m^2]
Relative spectral irradiance [-]
Wavelength [nm]


Typical spectral power distribution LED 3000K, C(λ), E_e,c for a lying patient on bed, with H
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m^2]
Relative spectral irradiance [-]
Wavelength [nm]


Typical spectral power distribution LED 3000K, C(λ), E_e,c for a patient on desk, with A1
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m2]
Relative spectral irradiance [-]
Wavelength [nm]


Typical spectral power distribution LED 3000K, C(λ), E_e,c for a patient on desk, with F1
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m2]
Relative spectral irradiance [-]
Wavelength [nm]


Typical spectral power distribution LED 3000K, C(λ), E_e,c for a patient on desk, with G
SPD LED 3000K
E_e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m2]
Relative spectral irradiance [-]
Wavelength [nm]


Typical spectral power distribution LED 3000K, C(λ), E e,c for a patient on desk, with H
SPD LED 3000K
E e,c = LED 3000 * C(λ)
C(λ)
Absolute spectral irradiance [μW/m2]
Relative spectral irradiance [-]
Wavelength [nm]
0.04
0.02
0
1
0.5
350
400
450
500
550
600
650
700
750
800

Literature used as starting point

Experimental information Brainard 2001, 2008 and 2015			
	Brainard		
year	2001	2008	2015
Lighting stimulus	Monochromatic light stimulus	Monochromatic light stimulus	Polychromatic lamplight
Timing and exposure duration	2:00-3:30 – 90 min	2:00-3:30 – 90 min	2:00-3:30 – 90 min
Exposure to lighting	Subject sat quietly, kept their eye open, and gazed at a fixed target dot in the centre of the ganzfeld dome	Subject sat quietly with his or her eyes open and his or her head resting in an ophthalmologic heald holder facing a paternless, white ganzfeld apparatus encompassing the entire visual field.	Subject sat quietly with their eyes open and facing a 119*120 cm flat panel of fluorescent light with their eyes 30 cm from the central portion of the light – emitting surface.
Experimental light stimuli	450 or 1200 W xenon arc lamp (photon Technology Inc., Princeton, NJ	Arc lamps collimated in a grating monochromator	Philips lighting: 4000K: TL5 HO 54W/830 17000K: prototype blue-enriched fluorescent lamp Prototype SEB flueorescent lamps housed in strato luminaires (model TPH 710)
Measurement irradiance	Tektronix J16 Radiometer/photometer with a J6512 irradiance probe	Same	International light radiometer/photometer 1400A (Newport, MA) with an SEL033 #6857
Measurement melatonin	Radioimmunoassay (RIA) procedure Minimum detection limit of the assay is 0.5-2.0 pg/ml	Radiaimmunossay (RIA) with a minimum detection limit of 0.5 to 5.0 pg/ml	RIA had a minimum detection limit of 0.5-2.0 pg/ml

Appendix G: Matlab scripts

```
%run plot different graph in 1 figure

clear all
close all

load spd_v.mat
load spd_ipRGC.mat
load spd_3000D.mat
load spd_4000D.mat
load spd_5000D.mat

% T = spd_4000D

for X = 380:780  ;

   Erel_v= spd_3000D .* spd_v;
end

Erel_opp = sum(Erel_v) % oppervlakte grafiek is optelling alle
getallen, integraal


Km = 683;
Eoog = 153; %Eoog dialux, specific luminaire (spd_...);

Erel = Km * Erel_opp ;

K = Eoog / Erel

% K = Eoog / (Km * Erel_opp);

%///////////////////////////////////////////////

Ee_3000D  =  spd_3000D  *  K  ;  %SPD_3000  relative  waarde  naar
absolute waarde

for X = 380:780  ;

   Ee_c= Ee_3000D .* spd_iprgc1;
end

Ee_c_opp  =  sum(Ee_c)  %  oppervlakte  grafiek  is  optelling  alle
getallen, integraal

Hthres = 0.2655;

Int_time = Hthres./Ee_c_opp

Hec = Int_time * Ee_c_opp
```

```
iprgc1_opp = sum(spd_iprgc1);

%////////////////////////////////////////
for X = 380:780  ;

   flux= Ee_3000D .* spd_v;
end

flux2  =  sum(flux);  %  oppervlakte  grafiek  is  optelling  alle
getallen, integraal


luminous_flux = Km * flux2 % terug koppeling dat het klopt



figure(2) %dubbele y-as
% x = 380:780;
%
% xmin = 380;
% xmax = 780;
% ymin = 0;
% ymax = 1;
% axis([xmin xmax ymin ymax]);
% subplot(2,1,1);
x = 380:5:780;
y1 = Ee_3000D;
y2 = spd_iprgc1;
[AX,H1,H2] = plotyy(x,y1,x,y2),


hold on
plot( spectrum_3000,Ee_c, 'r', 'LineWidth',2)

set(get(AX(1),'Ylabel'),'String','Absolute  spectral  irradiance
[ \muW/m^2 ]')
set(get(AX(2),'Ylabel'),'String','Relative  spectral  irradiance
[-]' )

% set(gca,'xlim',[380 780],'yticklabel','')
% set(gca,'xtick',[])

xlabel ('Wavelength [nm]')
% ylabel ('Spectral irridiance ')
title   ('Typical   spectral   power   distribution   LED   3000K,
C(\lambda), E_e_,_c for a lying patient')
legend({'SPD    LED    3000K',    'E_e_,_c    =    LED    3000    *
C(\lambda)','C(\lambda)'},'FontSize',10,'LineWidth')
```