EVALUATION OF A CONVENTIONAL OFFICE LIGHTING SYSTEM TO ASSESS ITS CIRCADIAN EFFECTIVENESS

A thesis submitted in partial fulfillment
of the requirement for the degree of
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CERTIFICATE OF RECOMMENDATION

This is to certify that the thesis entitled **"Evaluation of a Conventional Office Lighting System to assess its Circadian Effectiveness"** submitted by **Prasad Chatterjee**, (Exam Roll No - M4ILN24001, Registration number 163494 of 2022-2023) of this University in partial fulfillment of the requirements for the award of degree of Master of Engineering in Illumination Engineering, Electrical Engineering Department, is a bonafide record of the work carried out by him under my guidance and supervision.

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CERTIFICATE OF APPROVAL

The foregoing thesis titled **"Evaluation of a Conventional Office Lighting System to assess its Circadian Effectiveness"** is hereby approved as a credible study in the area of Illumination Engineering carried out and presented by **Prasad Chatterjee** (Exam Roll No. - M4ILN24001) and satisfactorily warrants its acceptance as a per-requisite to the degree for which it has been submitted. It is notified to be understood by this approval, the undersigned does not necessarily endorse or approve statements made, opinion expressed and the conclusion is drawn therein but approved the thesis only for the purpose for which it has been submitted.

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DECLARATION OF ORIGINALITY AND COMPLIANCE OF ACADEMIC ETHICS

I hereby declare that this thesis entitled "Evaluation of a Conventional Office Lighting System to assess its Circadian Effectiveness" contains a simulation based study and original research work by me, Prasad Chatterjee (Exam Roll No - M4ILN24001), as a part of my Master of Engineering in Illumination Engineering studies.

All information in this document has been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by thesis rules and conduct, I have fully cited and referenced all material and information which are not original to this work.

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ABSTRACT

In the field of designing an indoor lighting environment, it has been seen that along with the visual stimulation part of emitted radiation by a light source, the non visual part of it is affecting the very core of living a healthy life through regulating the circadian system. Hence, the non-visual attribute of emitted radiation from a light source on human health has been explored through extensive research. In view of recent applications, how to make an indoor environment circadian supportive and in how many ways a particular type of lighting distribution can affect overall human health are growing much more interest among researchers and lighting professionals. This thesis work aims to evaluate how far a conventional office lighting system is circadian supportive. Moreover a number of related issues are explained, viz. (i) why a particular model (CS model) is chosen to work with, (ii) what kinds of application benefits are observed through pioneer research, (iii) the possible challenges a lighting designer may face on how maintaining all the conventional lighting design goals a circadian effective lighting environment can be created in office spaces while being in compliance with all the circadian effective design guidelines, along with possible solutions to overcome these design challenges.

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Chapter 1

It focuses on Introduction to the thesis, then the literature review that deals with what problems can arise when the lighting environment is circadian non-supportive, models of circadian phototransduction and how application of circadian effective lighting can benefit, then a research gap followed by problem statement and scope or objectives of the project.

1.1 Introduction

Due to the modern lifestyle and demand of the time, days are spent mostly in closed indoors and where at the end of the day nights are not dark but well illuminated with artificial lighting. This modern day situation to live a life far from circumstances that nature has provided, leads to problems at different levels physically and mentally. Though there could be many aspects to why human beings are not physically and mentally that resilient than its previous generations, here in this thesis work we have tried to discuss and explore the relationship between lighting environment and human health and well-being and how changing the lighting environment can help in living a better life.

As a great percentage of professional work happens in typical office indoors, this thesis work particularly focuses on office lighting environment to study how far a typical conventional office lighting design is circadian supportive, what challenges are there and what could be done to make it happen through investigations with the help of simulation software, following proper design guidelines. This thesis work has been presented in five chapters here, as follows,

Chapter 1: It focuses on literature review that deals with what problems can arise when the lighting environment is circadian non-supportive, models of circadian phototransduction and how application of circadian effective lighting can benefit, then a research gap followed by problem statement and scope or objectives of the project.

Chapter 2: It deals with all the relevant background theory needed for the circadian phototrasnduction model, that we have chosen to work with and the design guidelines to make an indoor lighting design circadian supportive for its occupants.

Chapter 3: It discusses the project execution process in details which consists of experiments conducted, simulation work, design parameters, required calculation and execution flowchart.

Chapter 4: It deals with the results and graphical analysis.

Chapter 5: It deals with the discussion and conclusion

The liminaire IES file and the report from the simulation software (DIALux Evo 12.0) is attached in the Appendix section towards the end.

1.2 Literature Review

These days we, human beings, live, typically in such indoor environments, as far the lighting is concerned it is actually very unnatural. Normally we live in an environment where the artificial lighting levels are fixed through out the day and night, thus deviating from natural light-dark phenomenon happening in nature. The Suprachiasmatic Nuclei, better known as SCN in human brain, is responsible for operating a biological master clock, that is responsible for regulating and maintaining all kinds of biological functions in the body and in turn it affects our overall health, sleep wake cycle, mood, cognitive ability and daily performance levels. This, operation of master clock through SCN, known as circadian entrainment, is found to be synchronized with the natural day night cycle. So, lighting environment, specifically in indoor, affects our health and well being. Hence, in recent times, much growing concern has been noticed among the researchers to study more about this light dependent circadian entrainment to provide design recommendations and lighting designers to design lighting environments that is circadian supportive.

This literature review will be divided in three parts. First, how circadian non-supportive working environment can be detrimental. Second, which model of circadian phototransduction is more reliable to judge and quantify circadian effectiveness present in a given lighting scene or environment. Third, benefits of the application of circadian supportive lighting design using CS model.

1.2.1 Research on how circadian non-supportive working environment can be detrimental:

The best way to be in a circadian supportive lighting environment is to have sufficient amount of day light exposure in day time and chronological reduction in amount of light as the day ends and night begins.

A paper published by, Angus C. Burns, Richa Saxena and colleagues in December, 2021 did a study over 400000 participants in UK Biobank cohort, who helped the researchers with self reported time spent in outdoor lighting during the day and provided individual subjective assessments on how good or bad they are perceiving it in view of different factors and that assessment led to a large scale statistical analysis.

They examined the associations between self-reported time spent in outdoor light during the day and mood, sleep, and circadian-related outcomes. After adjusting for demographic, employment, and lifestyle covariates it was observed that greater time spent in outdoor light during the day was associated with fewer depressive symptoms, lower odds of using antidepressant medication and lower odds of lifetime recurrent major depressive disorder, greater ease of getting up in the morning, less tiredness, better sleep, and earlier chronotype. A longitudinal relationship was found, such that greater time spent in outdoor light during the day, predicted less frequent depressive symptoms, lower odds of using antidepressant medications, greater ease of getting up in the morning, less tiredness, and better sleep at night. It was concluded that these results could be associated and be explained by the impacts of light on the circadian system as well as non-circadian, direct effects of light on mood centers in the brain [40]

A paper published by Lunn RM, Blask DE, Coogan AN, Figueiro MG, and 14 others on health consequences of electric lighting practices in the modern world [41], has found, that unnatural exposures to light, as either light at night (LAN) or dim indoor lighting during the day, lead to changes in the expression of clock genes and proteins in the SCN, as well as melatonin and other hormones, which in turn lead to effects on sleep duration and quality and to disruption of central and peripheral circadian clocks.

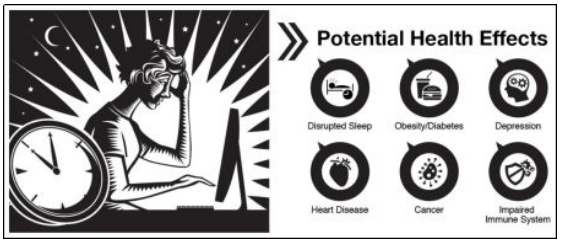


Figure 1.1: graphical representation of adverse effects of light at night [41]

As the graphical representation of adverse effects of significant exposure to light at night (LAN) is shown in figure 1.1, can lead to Disturbed sleep, Obesity and Diabetes, Chronic depression, Heart disease, impaired immune system and even cancer. Some of these problems are outlined in communiqués from the World Health Organization, American Medical Association, and the United States National Toxicology Program.

Chellappa et al. in 2011 has found that apart from the direct effects of light on physiology, light also indirectly impacts daily rhythms by affecting hunger cues,

acute behavior, and cognitive arousal levels. Thus, exposure to light at night may alter timing of food intake and the downstream effects of hormones and molecular signaling pathways [42].

So like this, there are numerous researches have happened and still happening, showing the direct relation of how living a life style that is synchronized with daily day-night natural cycles is the best way to be, while breaking natural circadian clock can lead to bizarre physical and mental complications.

1.2.2 Which model of Circadian Phototransduction is more reliable?

As we have seen in this previous section 1.2.1 of literature review, that breaking of natural biological clock can lead to various levels of health complications, research shows that application of circadian supportive lighting design in indoor environment can lead to better physical an mental health situations.

Till date there are two major school of thought that tries to model the circadian phototransduction mechanism in human beings.

One is Circadian Stimulus or CS model proposed by Rea et al. in 2005 for the first time and later updated with new research findings on understanding the complex neural network of human eye for circadian phototransduction [22 - 24]. Enormous care has been taken to understand the biophysics, complex arrangements of retinal circadian phototransduction based on modern day neurological and neuroanatomical understanding of human eye and then a model is built to characterize the relationship between photic stimulus (irradiance on eye level) and circadian response that is validated with downstream melatonin suppression, circadian phase response and alertness levels.

Second one is Melanopic Equivalent Daylight Illuminance or mEDI model proposed by TM Brown and colleagues [43] and supported by Commission Internationale de l'Éclairage (CIE) [44,45]. Large amount of datasets having a relationship between irradiance (equivalent to D-65 daylight illuminance)and melatonin suppression are taken, then a global 4 parameter curve fitting has been done (validated with downstream melatonin suppression) and conclusions are drawn that melanopsin based curve fitting best supports the melatonin suppression, circadian phase resetting and alertness than any other photoreceptors.

Table 1.1: Comparison between mEDI model and CS model

Parameters	mEDI model	CS model
Basis of modelling	Through 4 parameter curve fitting on large amount of input (equivalent day light illuminance) to output (melatonin suppression) data.	Through understanding and modelling retinal circadian phototransduction circuit that is validated with the relationship of photic stimulus incident on retina to melatonin suppression
The sub-additive nature of color and brightness perception in human eye	Not taken in calculation	Taken in calculation with in detail understanding.
The contribution of all five photoreceptor in circadian phototransduction	Not taken in consideration while being focused only on melanopsin based iPRGCs	All five photoreceptor contributions are well taken care of based on modern neurological and neuroanatomical understanding of eye
Model generalization	Low, as it fails in predicting circadian responses based on monochromatic light sources	High, as it can predict circadian responses based on both monochromatic and polychromatic light sources.
Conversion to relative light source to measure circadian impact	Yes, conversion from any other spectral distribution to equivalent day light illuminance (w.r.t CIE D-65) is done.	No such conversions are taken place.
Pupil dilatation	Taken in consideration	Not taken in consideration

In this above comparison (Table 1.1) or rather difference between two models of circadian phototransduction, CS model given by Rea et al. [22-24] makes it self a

far better model that judges the circadian responses on photic stimulus based on modern day understanding of human eye than CIE recommended just mere curve fitting based mEDI model that has no intentional understanding of circadian neural circuits in eye in its model.

Thus, in this project work, we consider to work to CS model.

1.2.3 Application of circadian effective lighting design using CS model:

Complying with other standards of indoor lighting design, the Underwriters Laboratories (UL) in it's 24480 design guidelines (DG) has provided in detailed information on how to apply circadian effective lighting design based on CS model and the required design goals to achieve circadian effective lighting environment [46].

The basic recommendation is to design a lighting scheme that can provide CS=0.30 (equivalent to 30% nocturnal melatonin suppression) at least for 2 hours in day time, preferably in morning hours.

There is empirical evidence and support that just designing indoor lighting with above mentioned criterion has provided positive effects on people in terms of promoting better sleep at night, reducing sleepiness during the day and reduction in depressive symptoms.

Laboratory studies using self-luminous displays by Figueiro et al. in 2011 [49], Wood et al. in 2013 [50], Figueiro and Overington in 2016 [52], specialized field studies like Young et al. in 2015 [54] in nuclear submarines, studies with senior facilities for persons with Alzheimer's disease by Figueiro et al. in 2014 [47], in 2016 [51], office lighting studies by Figueiro, Steverson et al. in 2015 [48], Figueiro and Rea 2016 [53] in all of these studies and researches the specified amount of circadian effective lighting has been used successfully and clinically relevant positive health outcomes has been measured in all of them.

Figueiro and colleagues showed that exposing older adults with Alzheimer's disease to a dose equivalent to, or higher than CS = 0.30 from the time of waking to 6:00 PM improved sleep quality, increased sleep duration, and reduced symptoms of depression and agitation [47,51].

Similarly, Young et al. showed that exposing submariners to a lighting installation delivering a similar light dose increased measures of circadian entrainment (increased total melatonin in first morning urine void), increased sleep efficiency (as measured by actigraphy) and reduced self-reports of sleepiness during the shift [54].

Research data from Figueiro and Rea (2016) showed that office workers in summer months had greater sleep duration and efficiency than in winter months. During the summer months, the average measured light values were close to those equivalent to CS= 0.30 while the average light exposure in winter months was very near threshold. Data from close to 200 subjects working in four different buildings in Europe, Iceland, and North America showed that, compared to those receiving light exposures of CS = 0.15 or less in the morning hours (between 8:00 AM and noon), office workers who receive a CS = 0.30 or more during the morning hours reported having better subjective feelings of vitality (measured in Subjective Vitality Scale [SVS]) and were less sleepy at work (measured in Karolinska Sleepiness Scale [KSS]).

These sleep related outcome measures are very important to employers and employees alike, suggesting that "bright" circadian-effective light during the day can help people sleep better at night and perhaps, because they are less sleepy, it can enhance productivity during the day.

Though so much of application has been done and clinically proven positive health benefits has been measured, there is no fixed guidelines on how the lighting scheme should be to achieve circadian supportive design goals.

In a very recent study by Figueiro et al. [55] Such an attempt to provide more insights on what kind of lighting setup and what types of luminaire can be used to design an office lighting environment has been taken in a paper published in October, 2023.

They used six different types of lighting schemes with individual or a combination of luminaire types (like direct, indirect) while proving same amount of circadian effective light to judge in which lighting setup there is least amount of energy consumption and discomfort glare along with assessment of subjective preference of lighting scheme by the participants.

On a subjective measure, ceiling mounted downlighting (direct type) has been re-

ported to be least preferred by the participants (having higher levels of discomfort glare among the provided lighting schemes, though well below the recommended highest permissible level) and a setup where individual blue light boxes were provided along with direct type of pendent luminaire (having one of the lowest levels of discomfort glares among the provided lighting schemes) was reported to be most preferred. Overall, a combination of direct indirect type of luminaire or a hybrid type where local light sources are used to effectively deliver the required CS value is more preferred because of lower levels of perceived discomfort glare by participants.

The results showed no such significant statistical difference among to lighting schemes in terms nocturnal melatonin suppression levels associated with the active lighting distributions employed in the study[55].

Identifying the limitations of the study it has been stated that,

- There could be recall biases as the lighting distribution preference assessments were done after the study was over.

- The hybrid light solution that employed local lightings was most unique among all provided lighting distributions, and it was that first scheme where the participants were put in tests, probably that is why it was chosen as most preferred lighting scheme.

- To measure the melatonin suppression the study was conducted in night time, so among the experimental conditions daylight was not considered and preference might not be same in presence of daylight.

- The study was done in the span of 1.5 hours, that mostly discards the possibilities of habituation that could occur after several hours of light exposures.

1.3 Research Gap:

So, there are a lot of uncertainties because of many real life situations could not be held account for controlled studies. Keeping the conclusions and the limitations in mind it can be stated that there is still much more research is needed to understand what kind of lighting set up can have significant impact on human

circadian responses such as melatonin suppression, circadian phase responses and alertness levels while providing the same recommended CS levels.

Hereby, understanding recent pioneer research and a gap that seeks answers to what kinds of lighting schemes can provide required CS values while keeping all other indoor lighting standards intact in the design and also, while keeping the CS value same along with other indoor lighting standards what kind of lighting setup can provide better circadian effective responses, in this presented thesis work, it is intended to study that even with most common but least preferred lighting design preference (as mentioned in the study [55]) that is with direct type ceiling mounted luminaires, if the circadian supportive lighting design goals can be achieved or not in conventional office lighting, through software simulation.

1.4 Problem Statement:

Is conventional office lighting design, circadian supportive, while following prescribed indoor lighting standards ?

1.5 Scope or objectives of the project :

- To study how far the conventional lighting system is satisfying the CS requirement while maintaining other prescribed indoor lighting standards.

- If the conventional lighting setup is not meeting the recommended CS value, how to make lighting design circadian supportive with least changes in design.

Chapter 2

It deals with all the relevant background theory needed for the circadian phototrasnduction model, that we have chosen to work with and the design guidelines to make an indoor lighting design circadian supportive for its occupants.

2.1 Background Theory

2.1.1 The link between Light, Circadian Rhythm and our Health:

The SCN or Suprachiasmatic Nuclei located in hypothalamus region in the brain, acts as a master clock that organizes and controls the timing of all daily biological functions, starting from functionality of complex coordination between organs to cellular level operation.

It is found that this cyclical pattern of biological functionality that is governed by SCN in human beings has an intrinsic time period of slightly grater than 24 hours and this biological clock is modulated by temporal pattern of light and dark due to earth's rotation on its axis. Hence, there is synchronization between the functionality of SCN and the natural day-night cycle [1,2], this is what is recognized as human circadian rhythm.

It has been found from many researches that disruption of the natural 24 hours of light and dark cycle can have adverse effects on overall health, cognitive ability, daily day to day activities starting from loss of adequate sleep[9,10], gain in weight, poor performance levels, diabetes[8], cardio vascular diseases[5,6,7] and even cancer [3,4]. This disruption of circadian rhythm mainly happens because of staying in different levels of non-circadian supportive lighting conditions throughout the day and night.

2.1.2 Understanding Circadian Light:

The term "Light" that is basically understood in terms of that which makes us capable to see. In language of scientific literature it is defined as optical radiation capable of producing a visual sensation in human beings often with the typical range of 380nm to 780nm without any of it's correlation with different biological consequences. So, our understanding of light as per the definition is only related to human visual perception. With this definition it is not possible to define optical radiation that produces non-visual effects in human beings and visual sensations to other species.

So, light as a stimulus to human visual system was derived from the response that came from human visual system with different experimentation. The same way, Circadian light can be defined as a stimulus to the circadian system only in correlation with response coming from circadian system.

In a very broad understanding it can be said that circadian light is effectiveness of a natural or artificial lighting system to stimulate the human circadian system. So, it rises the necessity to measure response of human circadian system to optical radiation incident on retina to define and quantify stimulus to human circadian system [1].

2.1.2.1 Photometry and the $V(\lambda)$:

This is 2024 and it has been a century now from the foundation of $V(\lambda)$, the photopic luminous efficiency function. Through conducting psychophysical experiments and and following a consensus process, the data from these experiments were combined to form $V(\lambda)$.

Thereby, $V(\lambda)$ is a bridge between Radiometry and Photometry, where Radiometry is the measurement of radiant energy and photometry is the measurement of light.

Depending upon different geometric properties of interest the $V(\lambda)$ is weighted with different radiometric properties to have corresponding photometric measurements [11]. These are as follows,

$V(\lambda)$ weighted radiant flux (radiant energy per unit time) became luminous flux.

$V(\lambda)$ weighted radiant intensity (radiant energy per unit solid angle) became luminous intensity.

$V(\lambda)$ weighted irradiance (radiant flux incident upon per unit area) became illuminance.

$V(\lambda)$ weighted radiance (radiant intensity per unit surface area) has become luminance.

Hence forth, Circadian light, as a bridge between radiometry to circadian photometry can be described with parallel definitions as above with same geometrical considerations [1].

Depending upon different experimental conditions, many spectral response

functions can be obtained from human visual system and $V(\lambda)$ is one among many such spectral response functions. To name a few, there are photopic and scotopic luminous efficiency function[12], mesopic response function given by Rea et al[13], glare response function given by Bullogh et al[15], brightness central response function given by CIE[12], Brightness response function at peripheral region given by Weale et al[14].

The property because of which $V(\lambda)$ has been in extensive use in every measurement of photometric parameters is Additivity. It can be described as, when two light sources with different spectral power distributions but of equal luminance, when combined by unit fractional amounts, they will continue to have same luminance[1].

In a very broad understanding it can be stated that when two light sources are set to provide a combined response the resultant photometric parameters along with the brightness level should increase in all levels. Now this does not happen always.

For example, when Red and Green light sources are combined together the resultant colour appears to be Yellow. It has been seen with experiments that the brightness perception of Yellow is lesser than the individual amount of Red and Green that was combined to form Yellow. This phenomenon where the resultant brightness perception becomes lesser and the either of the individual source brightness is called sub-additivity and with $V(\lambda)$ this phenomenon can never be described.

The problem with $V(\lambda)$ is its use is very limited but still because of commercial forces and government regulations for the purpose of common trade across the globe till date whatever photometric parameters we use to specify a light source is based on $V(\lambda)$ even though this spectral response function describes the functionality of human eye in a very limited zone.

If we dig a little deeper on the formation of $V(\lambda)$, we can see that it is formed only through the combined spectral responses of large(L) and medium (M) cones which focuses only on foveal region and that contributes to only 2% of the entire retina, completely discarding the effects or functionality of rods and short (S) cones in the response characteristics, where as S-cones are extremely vital for brightness perception.

2.1.2.2 Colorimetry and Perception of Brightness in Human Eye:

Colorimetry, originated from the 19th century's controlled observations and later through biological understanding of 3 different photo receptors (L,M & S cones) established that there are only three primary colors, Red, Green and Blue, perceived by human eye and any other colour can be matched through the combination of these three primaries. Later it was discovered that, Some very saturated color stimuli cannot be matched using a set of three physical primaries without slightly changing the color of the test light by adding one of the physical primaries to it. Mathematically, this is equivalent to using a negative amount of primary to make the match.

To avoid the use of negative amounts of primaries, the CIE color system [16] makes use of imaginary primaries that are mathematically defined, but not physically realizable.

Thus, the color of any test light can be quantified in terms of the relative amounts of the primary lights needed to match its appearance. The radiant powers in the three primaries are typically normalized with a linear transformation so that their sum is unity. By knowing two of the normalized values, the third value is also known. That is how the two dimensional graphical representation of colour was established in CIE (x,y) 1931 chromaticity system and later with many other mathematical modifications (x,y) took the form of (x',y'), than (u,v) and later (u',v').

This system of quantifying the relative amounts of three primaries to match the test source does not fully characterize it's colour appearance. For example, a stimulus that is recognized as orange and another that is recognized as brown can have the same chromaticities, but factors such as the objects' relative luminances against their surrounding luminances will influence their perceived colors.

So, where $V(\lambda)$ atleast represents spectral sensitivity of fovea, representing the achromatic channel, the colorimetry neither represents any one visual channel or the combination of visual channels.

Since brightness is influenced by both chromatic and achromatic visual channels, additional mechanisms are needed to measure apparent brightness. One of common methods to describe the relative brightness described by Guth et al.[17]

through B/L luminance ratio method where B is luminance of the reference light source and L is the Luminance of the test light source. From his B/L ratio, it can be quantitatively established that the luminance of the color Yellow is lesser than the individual luminance of Red and Green [1], thus justifying the existence of sub-additivity.

So, what sub-additivity actually is and why is this so stressed upon while narrating the background of creating Circadian light ? The answer lies in human eye!

It has been seen in researches that the Intrinsically photosensitive retinal ganglion cells (ipRGCs) provide direct input to the SCN [18,19], before discoveries it was thought that the neural signals only from this cells are responsible to activate the biological clock governed by SCN. It was first suggested by Figuero et al. [20] that not only iPRGCs but multiple photoreceptors present in human eye actually contribute together to human Circadian Phototransduction (How retina converts light into neural signals to stimulate SCN and in turn to operate the master clock) via spectral opponent processes distal to the ipRGCs in the retina.

Spectral opponency is an inherent attribute of the human retina, initiated distal to the ipRGCs in the outer plexiform layer of the retina, and underlies both color perception and the subadditive nature of apparent brightness perception.

There are three different visual channels present in human eye. One is one is achromatic channel and other two are chromatic channels.

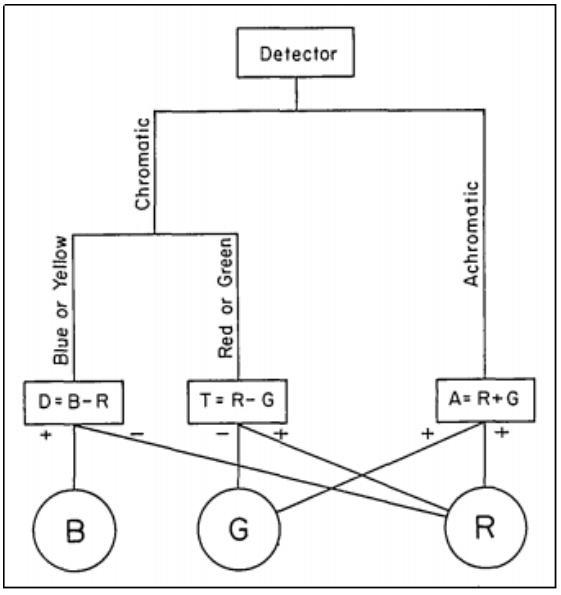


Figure 2.1: Schematic diagram of ATD vector model taken from Guth et al.[17]

where A refers to the nonopponent achromatic system, 'T' is the tritanopic system, and 'D' is the deuteranopic system[17]. This vector model presented in 1980 by Guth et al. describes the perception of brightness very effectively. Where the achromatic channel is additive in nature responsible for the perception of whiteness, as spectrally opponent systems, 'T' and 'D' channels can signal either "red" or "green" and either "blue" or "yellow" to the brain. Moreover, a spectrally opponent system is inherently a subadditive system because the addition of, say, a "green" light to a "red" light can decrease the response of the r-g system cell. Since the two spectral opponent channels contribute to brightness perception, two lights added together can actually appear less bright than either light alone.

For one type of "r-g" channel, excitatory input is provided by the 'L' cones and inhibitory input is provided by the M cones. For example, when the 'L' cone provides relatively more input to the "r-g" channel than the M cone, the "r-g" channel signals "red" to the brain. Similarly, for one type of "b-y" channel, excitatory input is provided by the 'S' cones and inhibitory input is provided by both the 'L' cones and the M cones. When a light stimulates the 'S' cones more than the combined input from the 'L' and 'M' cones, the b-y channel signals "blue" to the brain, this is called spectral opponency.

It has be demonstrated by Figueiro and colleagues that the subadditive response to light by the circadian system is formed from spectral opponent mechanisms in retina [21].

So, the limitation of photopic luminous efficiency function, the associated photometric system, the contemporary understanding of colorimetry is incapable of describing the sub-additive response to light by the human eye and that led to an urgency of developing models that can comply with the circadian system response to the modern neurological and neuroanatomical understanding of human eye and perception of vision.

With these complicated neural connections as per the current research, a mathematical model has been developed to define "Circadian Light" and "Circadian Stimulus" by Rea et al. [22] in 2005 and later as more progress has been made in understanding the complex mechanisms of human eye this model is being revised and also encouraged to implement it practically.

Currently Rea MS, Nagare R and Figueiro MG, together have published two papers on "Modeling circadian phototransduction" in 2021, one dealing with modern

neurological and neuroanatomical understanding of human eye [23] and other one presents the most tuned and updated mathematical model [24] of circadian response to light in accordance to it. The practical implementation guidelines are provided by UL 24480 DG.

2.1.3 The Evolution of modelling Circadian Phototransduction by MS Rea and colleagues:

The first model of circadian phototransduction was published in 2005 based upon psychophysical studies relating optical radiation on the retina and its effect on suppressing the synthesis of melatonin by the pineal gland [22].

Two minor revisions were published in 2012 and in 2018 through "Modelling the spectral sensitivity of the human circadian system"[26] and "Light as a circadian stimulus for architectural lighting" [27] respectively. The 2005 model and subsequent revisions were constrained by orthodox retinal neuroanatomy, taking into account published photoreceptor action spectra by Smith and Pokorny [28] in 1975 and documented pre-retinal filtering by Wyszecki and Stiles [30] in 1982 together with well-established principles of retinal neurophysiology through Kolb et al.[29] in 2004.

The model was able to predict nocturnal melatonin suppression from both monochromatic and polychromatic light spectra of different amounts without having to evoke post hoc fitting functions unrelated to retinal neurophysiology and neuroanatomy. Since the publication of the model in 2005, however, new insights into the neurophysiology of the retina have emerged. For example, en passant synapses between S-cone bipolar (SB) neuron and the "M1 ipRGC" in the most distal, OFF, sublayer of the inner plexiform layer (IPL) of the retina have now been identified [31,32] and incorporating such new findings it was tried to provide an updated physiological foundation for the revised model of circadian phototransduction circuit by Rea et al.[23,24] In 2021.

2.1.4 Understanding retinal neurology of circadian phototransduction:

In this section it is tried to draw a picture on why the current modelling of circadian phototransduction is modeled in a certain way. Not going in much

details of the medical researches this section will be restricted in the modelling of complex neural connections in the human eye as presented in the paper "Modelling Circadian Phototransduction: Retinal Neurophysiology and Neuroanatomy" by Rea et al. [23] in compliance with the understanding of the mathematical model presented later.

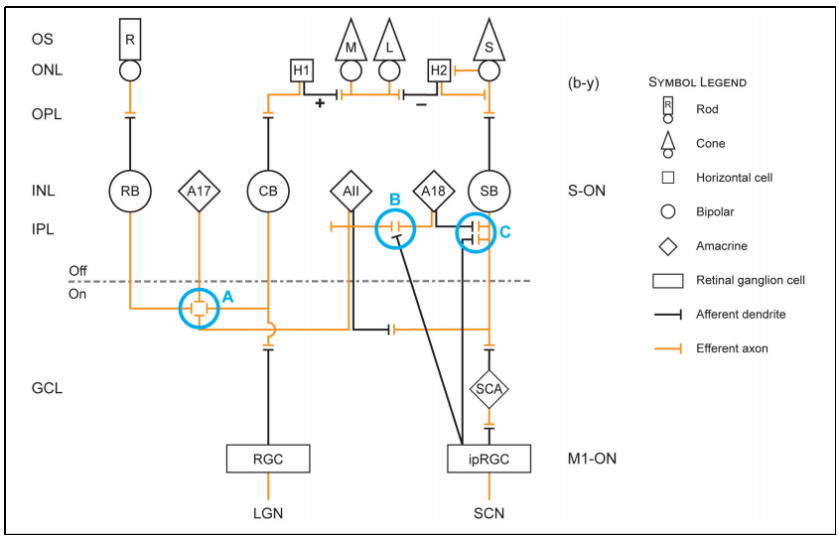


Figure 2.2: Retinal mechanisms for Circadian Phototransduction by Rea et al. [23]

In figure 2.2, a Retinal circuit diagram is used to illustrate the revised model of circadian phototransduction.

On the left side of the figure are the conventional labels for the different layers of the retina: OS, outer segment of the rod (R) and cone [L (long-wavelength sensitive), M (middle-wavelength sensitive), and S (short-wavelength sensitive)] photoreceptors.

ONL, outer nuclear layer containing the cell bodies of the rod and cone photoreceptors and two types of horizontal cells (H1 and H2).

OPL, outer plexiform layer containing the distal plexus of the photoreceptor (efferent, orange lines) axons and the (afferent, black lines) dendrites of the horizontal and bipolar neurons.

INL, inner nuclear layer containing the cell bodies of the rod bipolar (RB) and two cone bipolar neurons, one achromatic cone bipolar (CB) and one S-cone bipolar (SB) neuron and amacrine neurons (AII, A17, A18).

IPL, inner plexiform layer containing the plexus of axons and dendrites of the bipolar, amacrine, and ganglion neurons, which is divided into OFF and ON sublayers.

GCL, ganglion cell layer containing the cell bodies of the conventional retinal ganglion cells (RGCs) and the intrinsically photosensitive retinal ganglion cells (ipRGCs) as well as a displaced S-cone amacrine (SCA). At the bottom of the figure are the two targets for ganglion cell axons, the RGC axons reaching the lateral geniculate nucleus (LGN) and the ipRGC axons reaching the suprachiasmatic nucleus (SCN).

Also shown in the diagram are blue circles (Processes A–C) that represent important processes in the revised model. Process A represents cone inhibition of rods and thereby a reduction in shunting inhibition of the ipRGC by AII amacrine cells in process B. Process B also includes decoupling of shunting inhibition of AII amacrine cells via the A18 amacrine cells when the spectrally opponent SB signals "yellow." Process C represents the "en passant" complex involving the SB, ipRGC, and A18 neurons.

From application point of view, understanding the nature of each cell stated in above information is beyond the scope of this project, so, for more details on working of each individual cells mentioned above it is requested to go through the paper "Modelling Circadian Phototransduction: Retinal Neurophysiology and Neuroanatomy" by Rea et al. [23].

2.1.5 What is expected to be done to build a model for circadian stimulus?

The circadian phototransduction mechanism can be conceived as a unique neural circuit in the retina with a spectral sensitivity to optical radiation and a circadian response characteristic to different amounts of that optical radiation.

Modeling human circadian phototransduction requires a systematic and converging approach to understand how a retinal circuit might perform this conversion. No model of circadian phototransduction can be justified by the results of a single experiment. Rather, such a model must be able to quantitatively characterize the photic stimulus incident on the retina such that the circadian system response can be accurately and consistently predicted.

Moreover, any model of circadian phototransduction should be consistent with

retinal neurophysiology and neuroanatomy.

In short, a system of photometry is to be designed or modeled in such a way that the photic circadian stimulus is quantified in terms of both spectrum and amount. Where the responses include,

- light-induced nocturnal melatonin suppression,

- phase shifting as measured by changes in melatonin concentrations,

- changes in minimum core body temperature.

Though it should comply with the very closely linked circadian system responses, the model of circadian stimulus, like other photometric quantities, is not a complete specification of the photic stimulus to the circadian system and is not necessarily the only determinate of a circadian system outcome as there are many other responses that are linked with it, such as sleep, alertness, cortisol concentration etc [24].

2.1.6 The process of modelling the neural circuit spectral sensitivity:

Spectral sensitivity functions can be generated from data relating nocturnal melatonin suppression to log photon rate densities (photons $cm^{-2}s^{-1}$) for each of a set of narrowband spectra.

A functional relationship is then to be experimentally developed relating the stimulus magnitude (here it is photic stimulus) to the response magnitude (here it is melatonin suppression) for all wavelengths.

In a biological non-linear system, two things are common and will be always there, one is a threshold and other one is saturation. So, to obtain the responses for different photic stimulus on same scale. a constant criterion response is to be established.

Here the half-saturation value from the functional relationship and the amount of photon rate density (or irradiance) needed to produce that criterion response is determined for each wavelength.

Maximum spectral sensitivity is going to be that wavelength, needing the least amount of photon rate density (or irradiance) to reach the constant criterion response.

It has been seen through researches that the saturation level of melatonin suppression is at 70%. As a constant criterion method wavelengths were tested to reach the half saturation level, that is 35% of melatonin suppression.

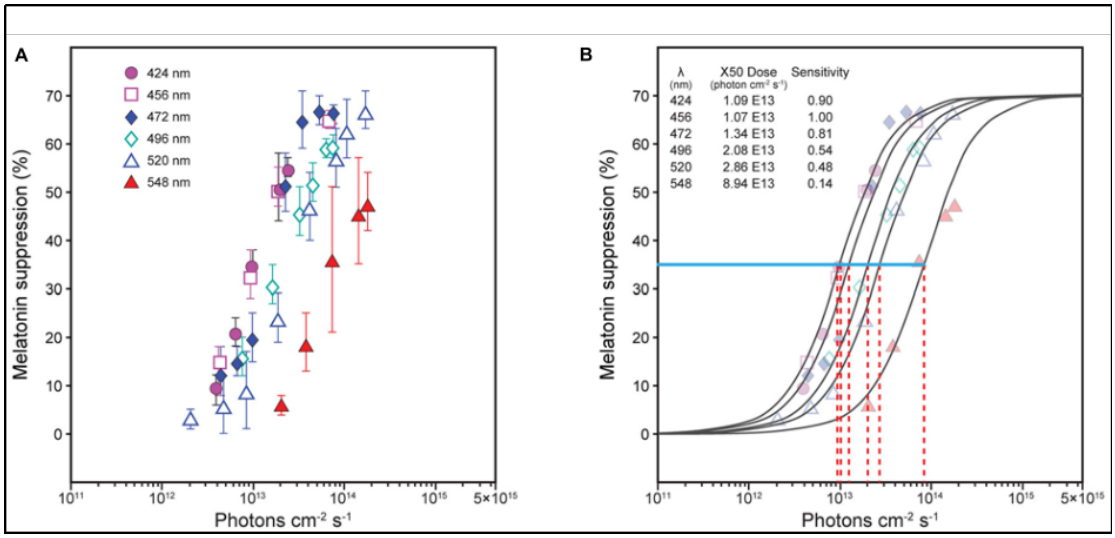


Figure 2.3: Nocturnal melatonin suppression at each narrowband spectra, taken from Real et al. [24]

To determine spectral sensitivity, the amount of photon rate density (photons $cm^{-2}s^{-1}$) needed at each wavelength [(B), red dashed lines] to reach half-saturation [(B), blue solid line, $\approx$ 35% suppression] is plotted [Figure 2.3] relative to the wavelength requiring the least amount of energy to reach half-saturation (maximum sensitivity).

Following this above mention procedure, two spectral sensitivity estimates were made to measure spectral responses of circadian phototransduction from monochromatic photic stimulus by Brainard et al. [33] and Thapan et al. [34] separately in 2001 and that became the basis of developing and proposing a model on circadian stimulus by Rea et al. [22] in 2005.

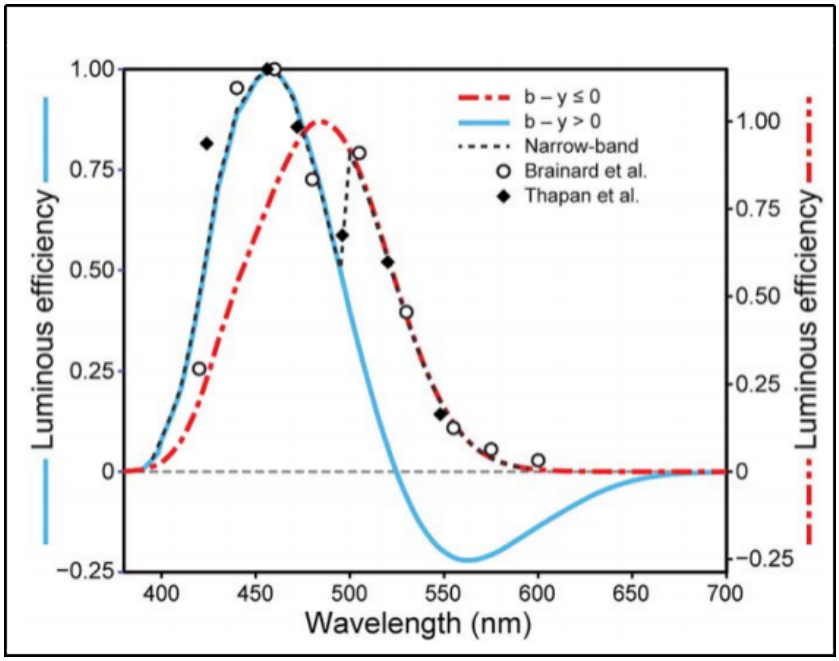


Figure 2.4: spectral responses of circadian phototransduction from monochromatic photic stimulus by Brainard et al. [33] and Thapan et al. [34]

The relative sensitivity of different narrowband wavelengths for suppressing nocturnal melatonin from Brainard et al. [33] and Thapan et al. [34] are shown in Figure 2.4. Also shown are the predictions from the two-state circadian phototransduction model[22], for narrowband (achromatic dashed line) and for "warm" polychromatic lights where b-y$\leq$0 (red dot/dash line) and for "cool" polychromatic lights where b-y$>$0 (blue solid line) when the overall flux density on the retina is 300 scotopic lux.

light level of 300 scotopic lx was chosen for illustration because rod inhibition is modeled to control threshold for ipRGC activation, thereby providing a common basis for comparing different spectral sensitivity functions and because, empirically, this light level is approximately equal to that producing the half-saturation response levels of nocturnal melatonin suppression.

Here the b-y is the chromatic channel where if the mathematical result is less than zero it is perceived as warm light and if the result is grater than zero it is perceived as cool light in case pf polychromatic light.

2.1.6.1 The later modified (2012) two state model proposed by Rea et al. In 2005:

$$CL_A = 1548\Bigg\{ \int Mc_\lambda E_\lambda d\lambda + a_{b-y}\Bigg(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda} \Bigg)$$

$$\text{- a}_{rod}\Bigg(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\Bigg)\Bigg\}$$

[When, b-y > 0]

$$= 1548 \int Mc_\lambda E_\lambda d\lambda$$

[When, b-y ≤ 0]

$\ldots(1)$

Where,

$$b - y = (\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k \int \frac{V_\lambda}{mp_\lambda})$$

CL_A= Circadian Light equivalent to 1000 photopic lux with respect to CIE standard illuminant A.
E_λ = Light source spectral irradiance .
Mc_λ = Melanopsin sensitivity (corrected for crystalline lens).
S_λ= S-cone fundamental.
mp_λ= Macular pigment transmittance.
V_λ = Photopic luminous efficiency function.
V'_λ = Scotopic luminous efficiency function.
k = 0.2616
a_{by} = 0.7
arod = 3.3
RodSat = 6.5 W/m^2

$$CS = 0.7 * \left[1 - \frac{1}{1 + (\frac{CL_A}{355.7})^{1.1026}} \right]$$

$$\ldots (2)$$

Where, CS = Circadian Stimulus.

Circadian Stimulus(CS) is equivalent to percentage of melatonin suppression.

2.1.6.2 Brief explanation of equation (1) and (2):

Not every wavelength of optical radiation is effective to evoke a circadian response in human eye, for example, infrared or ultraviolet optical radiation.So, to establish a neural circuit response characteristic, all effective radiations are to be considered simultaneously, specially to account for sub-additivity. The two state non linear model of circadian light in equation (1) was used for that purpose.

The sigmoidal logistic function in equation (2) was used to describe the response characteristic of the neural circuit underlying circadian phototransduction and to predict the nocturnal melatonin suppression.

The parameters in equation (2) were determined from mathematical modeling nocturnal melatonin suppression data from a variety of experiments using 1-h exposures to polychromatic lights.

All known photoreceptors contribute to the spectral sensitivity of the circadian system. Rod bleaching controls the threshold for absolute sensitivity of cone contributions to the ipRGCs, so absolute light levels are expressed in units of CIE scotopic illuminance.

As rods saturate, cones begin to provide input to the ipRGCs. However, cone signals are processed by the outerplexiform layer of the retina before reaching the ipRGCs. In particular, cone signals must be converted into spectrally opponent, blue versus yellow (b-y) or red versus green (r-g) signals by bipolar (depolarizing and hyperpolarizing) neurons before they can reach the next stage of neural processing.

To fit the nocturnal melatonin suppression data from Brainard et al. (2001) and Thapan et al. (2001) and to be consistent with orthodox retinal neural physiology

(Kolb et al. 2004), the modeled S-ON cone response (Kolb 2004) adds to the self-generated ipRGC response only if the b-y bipolar neuron depolarizes, signaling "blue" to the innerplexiform layer of the retina. This phenomenon has been expressed through the first part of the equation when the condition satisfies to, b-y > 0 in Eq. (1).

If the b-y bipolar neuron generates a hyperpolarizing "yellow" response, the signal cannot be processed by the ipRGCs. This phenomenon has been expressed through the second part of the equation when the condition satisfies to, b-y$\leq$0 in Eq. (1).

The spectral response of the b-y mechanism is modeled by the difference between S-cone fundamental (Smith and Pokorny 1975) and the sum of the L- and Mcone response (i.e.,$V(\lambda)$) after the spectral transmittance of the pre-retinal screening pigment, the macula lutea (mp). This is expressed by the equation of , b-y in Eq. (1).

2.1.6.3 Limitations of 2005, CS model:

The sigmoidal function parameters become fixed for defining the circadian stimulus, abbreviated as CS, following 1-h exposure. Importantly, for any set of stimulus conditions the neural circuit response characteristic (CS, Eq. (2)) is assumed to be fixed except for the half-saturation constant (355.7 in Eq. (2)).

Later it is found that CL_A can affect the halfsaturation constant due to the spectral power distribution's impact on rod-cone interactions affecting absolute threshold.

Further, the half-saturation constant would be affected by stimulus conditions not included in the CL_A and CS formulations, for example, exposure durations other than 1 h.

With regard to this latter point it is found that, CS is not, therefore, a complete specification of the photic stimulus.

Since 2005, the results from a number of experiments aimed specifically at testing the model have been published. Melatonin suppression after 1 h of light exposure during the early biological night was always measured. And over the years of study and experimentation has found that the ability of the 2005 CS model (Eq. (1) and (2)) to predict nocturnal melatonin suppression following 1-h exposures

to the different spectra was good, but not perfect, with an overall coefficient of determination, r^2 , of 0.69.

Over the years, the model has consistently been able to predict nocturnal melatonin suppression of "cool," polychromatic light sources, but has not been able to accurately predict suppression from "warm" light sources.

Nocturnal melatonin suppression was systematically overestimated for "warm" LED light sources that produced radiant energy throughout the spectrum in a study by Nagare et al. [35] Conversely, a second study by Nagare et al. [36] revealed that nocturnal melatonin suppression was systematically underestimated for "warm" LED light sources with a discontinuity in spectral energy around 480nm. The original model used an in vivo estimate of ipRGC-melanopsin spectral sensitivity alone to characterize the spectral sensitivity of the circadian phototransduction circuit to "warm" sources, so this simple assumption for determining CL_A for "warm" sources was clearly inadequate.

This model of circadian phototransduction is, however, silent with respect to different exposure durations and the distributions of light exposures across the retina. Clearly the duration and distribution of light exposure will affect the total amount of melatonin suppressed at night. For a fixed spectrum and amount, exposures of longer durations and covering more area of the retina will produce greater attenuation (and vice versa) [24,37]

Thus, to predict the total amount of nocturnal melatonin suppression from light exposures of different durations and spatial extent, CL_A and CS must be augmented by other aspects of the luminous stimulus, exposure duration and light distribution across the retina.

2.1.7 The updated CS model of 2021:

In the updated model of circadian stimulus, Rea et al. [24] modified the model with recent research findings of retinal neural circuit for circadian phtotransduction with the introduction of exposure duration (t) and light distribution (f) parameters across retina as shown in equation (4) below.

The 2005 two-state CL_A formulation (Eq. (1)) did not include a physiologically based threshold term for the ipRGC-melanopsin response. In the revised formulation (CL_A2.0, Eq. (3)), the ipRGC-melanopsin response is directly modulated by

a threshold term involving both rods and cones that, through the AII amacrine neuron, elevates the threshold response of the M1 ipRGCs to light [24].

$$CL_A 2.0 = 1548\Bigg\{\Bigg(\int Mc_\lambda E_\lambda d\lambda - a_{rod1}\Bigg(\frac{V'_\lambda E_\lambda d\lambda}{\int Vc_\lambda E_\lambda d\lambda + g_1 \int Sc_\lambda E_\lambda d\lambda}\Bigg)$$

$$\Bigg(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\Bigg)\Bigg) + \Bigg(a_{b-y}\Bigg(\int Sc_\lambda E_\lambda d\lambda - k \int Vc_\lambda E_\lambda d\lambda\Bigg)$$

$$\text{- a}_{rod2}\Bigg(\frac{V'_\lambda E_\lambda d\lambda}{\int Vc_\lambda E_\lambda d\lambda + g_2 \int Sc_\lambda E_\lambda d\lambda}\Bigg)\Bigg(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\Bigg)\Bigg)\Bigg\}$$

[When $b-y > 0$]

$$= 1548\Bigg\{\Bigg(\int Mc_\lambda E_\lambda d\lambda - a_{rod1}\Bigg(\frac{V'_\lambda E_\lambda d\lambda}{\int Vc_\lambda E_\lambda d\lambda + g_1 \int Sc_\lambda E_\lambda d\lambda}\Bigg)$$

$$\Bigg(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\Bigg)\Bigg)\Bigg\}$$

[When $b-y \leq 0$]

. . . (3)

Where,

$$b - y = \int Sc_\lambda E_\lambda d\lambda - k \int Vc_\lambda E_\lambda d\lambda$$

$$\text{Sc}_\lambda = \int \frac{\frac{S_\lambda}{mp_\lambda}}{max\frac{S_\lambda}{mp_\lambda}}$$

$$\text{Vc}_\lambda = \int \frac{\frac{V_\lambda}{mp_\lambda}}{max\frac{V_\lambda}{mp_\lambda}}$$

CL_A= Circadian Light equivalent to 1000 photopic lux with respect to CIE standard illuminant A.

E_λ = Light source spectral irradiance .

Mc_λ = Melanopsin sensitivity (corrected for crystalline lens).
S_λ = S-cone fundamental.
mp_λ = Macular pigment transmittance.
V_λ = Photopic luminous efficiency function.
V'_λ = Scotopic luminous efficiency function.
k = 0.2616; aby = 0.21; arod1 = 2.30; arod2 = 1.60; g1 = 1.00; g2 = 0.16; RodSat = 6.50 Wm^2

$$CS_{t,f} = 0.7 * \left[1 - \frac{1}{1 + (\frac{t*f*CL_A 2.0}{355.7})^{1.1026}}\right] \ldots (4)$$

Where,

t = Duration of exposure
f = Spatial distribution

2.1.7.1 A brief description of the modified CS model(Eq. (4)):

The primary purpose of the revised model (Eqs. 3 and 4) was to improve the characterization of the circadian phototransduction circuit to different spectra and amounts of optical radiation on the human retina.

In limitations of 2005 CS model it is discussed that the saturation constant can be seen to get modified when the exposure duration is other than 1 hour. So, in the modified model it is tried to overcome that limitation by introducing a new Half-saturation constant, augmented with duration of exposure.

In effect, 't' can simply modify the half saturation constant to predict absolute nocturnal melatonin suppression for any continuous light exposure duration from 0.5 to 3 h without any modifications to the CS formulation itself.

$$Half - satconstant 2.0 = 355.7 * t^{-1} \ldots (5)$$

where, 't' serves the purpose of a scalar representing light exposure duration in hours. The coefficient of determination,r^2, for the simplified allometric fit became

equal to 0.93, just by introducing 't' in calculation [24].

Following this same logic used to model the duration of light exposure, the possibility that a single parameter, 'f', representing the spatial distribution of circadian light exposure is explored through augmenting it to CS formulation to predict nocturnal melatonin suppression.

In that way the half saturation constant can be further represented as,

$$Half - satconstant2.0 = 355.7 * t^{-1} * f^{-1} \quad \ldots(6)$$

This above formulation can be seen in implementation in Eq. (4). Now as the spatial distribution of the circadian phototransduction circuit across retina is still not well understood and there are controversies in research that which part of the retina is more sensitive to circadian phototransduction (for example, somewhere it is told that the nasal retina is more sensitive than the temporal retina and the opposite is found in some other studies [24]), the augmentation of a term related to spatial distribution of circadian light exposure in retina, is of low precision.

For modeling purposes, here, only three levels of spatial distribution of the luminous stimulus were assumed,

- (a)Full visual field, as with a Ganzfeld, f = 2.0.

  The full visual field or the ganzfeld is associated with an uniform light distribution or a diffused lighting system.

- Central visual field, as with a discrete light box on a desk, f = 1.0

  The central visual field is associated with a light source that is placed at on-axis visual field, as mentioned above, having a separate light source on desk.

- Superior visual field, as from ceiling mounted down-light fixtures, f = 0.5.

2.1.7.2 Limitations of the revised CS model ($CS_{t,f}$):

So, as the first limitation of the model, can be identified as, $CL_A2.0$ and CS, as measures of photic stimulus to the circadian system, are independent of the temporal dynamics of the phototransduction circuits and are silent with respect to the distribution of these circuits across the retina. Independent, because it can not measure or predict melatonin suppression for an intermittent exposure of radiation.

Second, when the occupant is made to stay in certain lighting condition for long duration, definitely the eye gets an adaptation as per the environment of light exposure. This adaptation mechanism, unaccounted for in the model, which is responsible for discounting the absolute flux density on the retina in favor of adjusting the system gain (visual system), perhaps to maintain brightness and color constancy by the visual system.

Third, the model can predict melatonin suppression for upto 3 hours of continuous light exposure not beyond that.

Fourth, The spatial distribution of phototransduction circuits, as it would affect values of, 'f', are not very well known as discussed earlier during the augmentation of , 'f' in Eq. (4).

Understanding the spatial distribution of circadian phototransduction circuits is of particular interest for clinical and architectural applications. Subsequent research is needed to address questions based on spatial distribution, such as,

- should a light box designed to improve circadian entrainment be placed above or to the side of the patient? or
- are architectural lighting fixtures in the ceiling plane more or less effective than a window in the wall? or
- is natural daylight exposure more like a Ganzfeld or more like a ceiling fixture?

A study by phillips [38] suggests that the operating characteristic of the modeled circadian phototransduction circuit is subjected to change upon earlier light exposure.

Because nocturnal melatonin suppression exhibits some habituation to a prolonged light stimulus and as the current model of circadian stimulus is not tuned to measure such habituation, a perfect downstream measure of the output from the circadian phototransduction mechanisms in the retina, is not possible. But still, nocturnal melatonin suppression can be predicted, to a first approximation, from 0.5 to 3 hours of light exposure.

2.1.8 The Design Recommendation and The Circadian Effective Dose:

Despite having so many limitations to the latest model of circadian stimulus given by Rea et al. [24], the application research has found that the practical implementation of it showed remarkable improvements in overall sleep quality and reducing depression.

The most elaborate circadian effective lighting design has been provided by the UL 24480 design guidelines.

The basic recommendation is to provide circadian effective lighting that amounts to CS = 0.3 which is equivalent to $CL_A2.0 = 274$ (W/m^2), for 2 hours, during the morning hours, that is 8:00 am to 12:00 pm [39].

As far the model is concerned, $CL_A2.0$ and CS, it is subjected to give instantaneous values of circadian effective light and the capability of melatonin suppression. When the exposure duration factor, 't', is augmented in CS formulation, it became a time dependent melatonin suppression.

Now, upon closer observation it can be seen that introduction of the factor, 't', in CS formulation gives a reciprocal relation between the circadian effective light and the duration of exposure. Thus to provide more design flexibility a term, "circadian effective dose" has been introduced in the system.

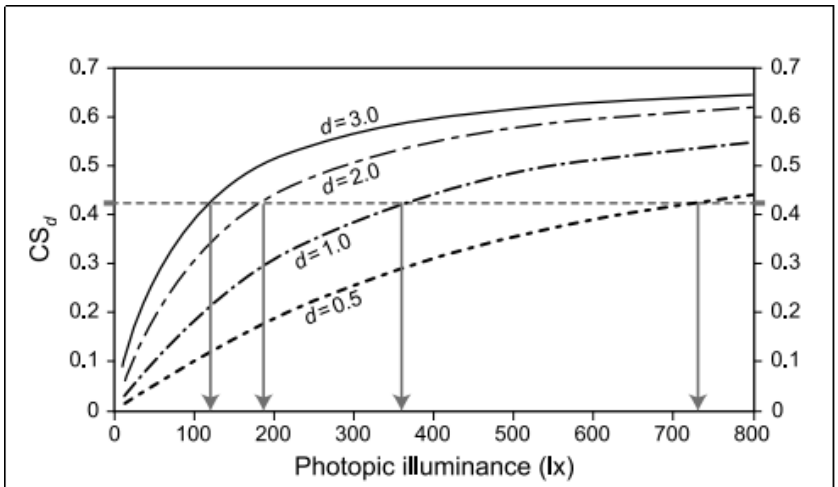
The circadian effective dose, CS_d is absolutely similar to CS_t where the time duration factor is replaced in representation. What it tells is, in the CS_t formulation (in Eq. (4) for $CS_{t,f}$, not considering the spatial distribution factor, f, or by considering, f = 1, it becomes CS_t), if we calculate considering $CL_A2.0 = 274$ (W/m^2) and t = 2 (as per the UL 24480 DG recommendations) we get value of the circadian effective dose, CS_d=0.43

$$CS_d = CS_t = 0.7 * \left[1 - \frac{1}{1 + (\frac{t * CL_A2.0}{355.7})^{1.1026}}\right] \quad \ldots (7)$$

$$= 0.43$$

[where, $CL_A2.0 = 274$ (W/m^2) and t = 2]

If at any given point of time this circadian effective dose is fixed then, according to the reciprocal relation, there is a huge design flexibility, like the designer can have high circadian effective light $CL_A2.0$ level and short exposure duration (t) or vise versa.



Duration (*d*, h)	0.5	1.0	2.0	3.0
Photopic illuminance (lx)	736	377	190	127
CS	0.54	0.43	0.30	0.23
CL_A 2.0	1097	550	274	183

Figure 2.5: Circadian-effective light dose, CS_d, as function of photopic illuminance (Lux) for CIE standard illuminant D65 following 0.5 hour, 1 hour, 2 hours (base case from UL 24480) and 3 hours exposure durations (d or t), taken from Rea et al. [39].

From the example, effective dose response curve with respect to photopic illuminance, given in figure 15, the reciprocal relation between circadian effective light level ($CL_A2.0$) and the exposure duration (d or t) is clearly visible.

Certainly, while designing with different types of luminaire this response curve may change but with fixing the effective dose, it can be judged by the designer that for what duration a certain type of lighting scheme can be applied to reach the circadian effective lighting design goal, provided, light levels should be in synchronization with the natural sunrise and sunset, thus very high light levels in the early morning hours is no recommend.

2.2 Design Guidelines:

The standard that is rigorously followed throughout this thesis work is UL 24480 DG, this documentation of standards provided by Underwriters Laboratories that has provided guidelines on how much amount of circadian effective value should be achieved through a given lighting distribution for the building occupants. It also provided steps to involve in judging the Circadian effectiveness of a given light source with a bunch of practical examples of implementations [56].

2.2.1 A few declarations by UL 24480 DG :

- It helps specifiers and lighting designers to implement lighting design schemes that promotes circadian entrainment for day active and night inactive people occupying commercial, educational and industrial spaces.
- These design guidelines contain only non mandatory provisions. It is not intended for conformity assessment or to create compliance.
- It describes how lighting specifications of circadian effective light are to be accomplished and verified using current knowledge.
- This document does not describe light for vision and it is expected that lighting design is already being done with other specifications mentioned by standards.
- All the recommendations for circadian effectiveness in this design guideline are made using vertical photopic illuminance (Ev) at the occupant's eyes.

2.2.2 Steps to establish a circadian effective lighting design:

Step-1: Setting up the circadian effective design goal

A minimum of two hours of circadian effective light equivalent to that which would suppress melatonin production at night by 30% should be provided at the observer's eyes during occupied daytime hours that is from 7:00 am to 4:00 pm.

In the evening that is from 5:00 pm to 7:00 pm and during night after 8:00 pm, levels of circadian light at occupant's eyes should be limited, while still sufficient for performing visual tasks at these times.

Based upon these,

$CS \geq 0.30$ is the primary design goal (7:00 am to 4:00 pm)
$CS \leq 0.20$ should be in the evening (5:00 pm to 7:00 pm)
$CS \leq 0.10$ should be at night after 8:00 pm

Step-2: Selection of a luminaire type

Intensity distribution of the selected luminaire must be known.

Higher vertical to horizontal ratio of illuminance is preferred for a selected luminaire for better and uniform distribution of light. Generally it is preferred to have 0.5 or above of (E_V/E_H) ratio.

Step-3: selection of proper spectral power distribution

SPDs can be obtained from the manufacturer or can be manually measured directly with a spectroradiometer. SPD of a given light source is a must be known for further steps to follow.

Light sources of same CCT can differ in SPDs, so proper SPD of a light source in use has to be known either from manufacturer or from manual measurement.

Step-4: The use of a photometrically realistic software for calculations:

To obtain vertical illuminance levels at observer's eyes a photometrically realistic software is to be used to calculate it accurately and to give a prior estimation of visual appearance for a given lighting distribution in a building space.

The eye plane that is defined for vertical illuminance measurements is to be set between 0.9 m to 1.3 m above the floor plane and extended throughout the occupied space.

At least 10 representative sample values of E_V should be obtained.

Step-5: Calculation of CS value from the E_V and SPD:

With the help of previously obtained SPD and E_V obtained from photometrically realistic software the CS value needs to be calculated for each E_V using the publicly available CS calculator and it is to be averaged to find out average CS value of the lighting distribution for a specific design.

without the SPD andE_V values, the CS calculator can not be operated.

Step-6: Determination of circadian effectiveness of a selected light distribution in a given space:

If the circadian effective lighting design criterion is not met i.e. CS$\geq$0.30, the previous steps are needed to be repeated after changing the luminaire.

Local lighting such as lighting from work stations can be added.

Reflectance values for different room surfaces can also be adjusted in photmetrically realistic software.

2.2.2.1 Key things to remember:

- A minimum of 2 hours of circadian effective light exposure should be provided to building occupants duting 7 am to 4 pm.
- If a minimum duration of exposure is desired, circadian effective light should be provided to the occupants in the morning hours.
- A wide variety of controlling mechanisms could be used from manual switching to automatic color tuning of the system to control the timing of change and duration of exposure.

Chapter 3

It discusses the project execution process in details which consists of experiments conducted, simulation work, design parameters, required calculation and execution flowchart.

3.1 Project Execution Process:

3.1.1 Experiments to measure SPD of emitted radiation and to make luminaire IES file:

The data that is essential in this work is SPD of emitted radiation by luminaire, and its IES file to proceed for further steps. The luminaire details as given by the manufacturer are given below,

Table 3.1: Luminaire details

Luminaire Type	Maker's name	Voltage(Volt) and Frequency(Hz)	Power Consumption (Watt)	CCT (K)
Circular LED (Diffused)	Havells India Limited	230 and 50	15	6000

Figure 3.1: Havells, Circular LED (Diffused)

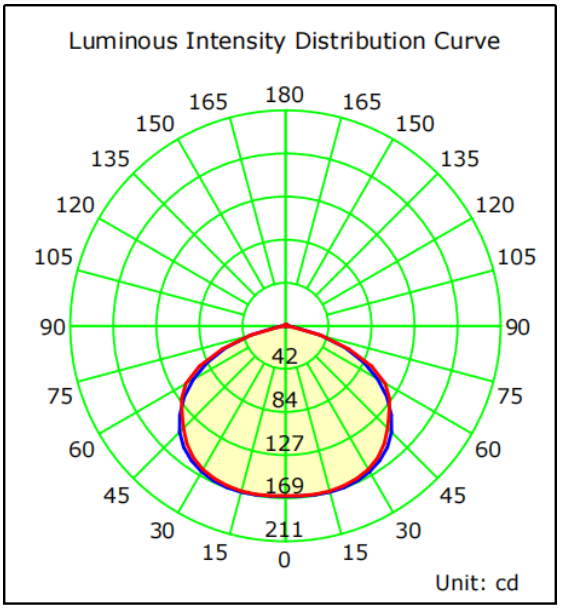


Figure 3.2: Luminaire luminous intensity distribution curve.

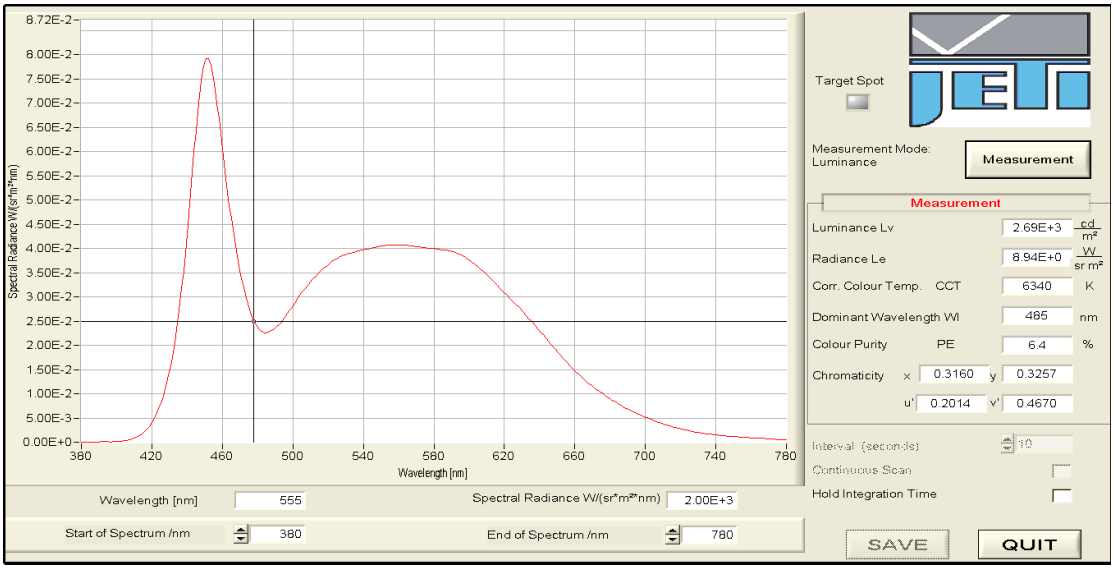


Figure 3.3: SPD of emitted radiation by luminaire (Figure 17) as measured by Specbos-1200 Spectroradiometer (measured in Illumination Engineering Laboratory, Jadavpur University)

"Lisun Electronics" made fully automatic "LSG-1700B" Goniophotometer (Figure 3.4) is used to prepare IES file and "JETI Technische Instrumente" made "Specbos 1200" Spectroradiometer (Figure 3.5) is used to have SPD data of emitted radiation of the above luminaire (Figure 3.1) available in the Illumination Engineering laboratory of Jadavpur University.

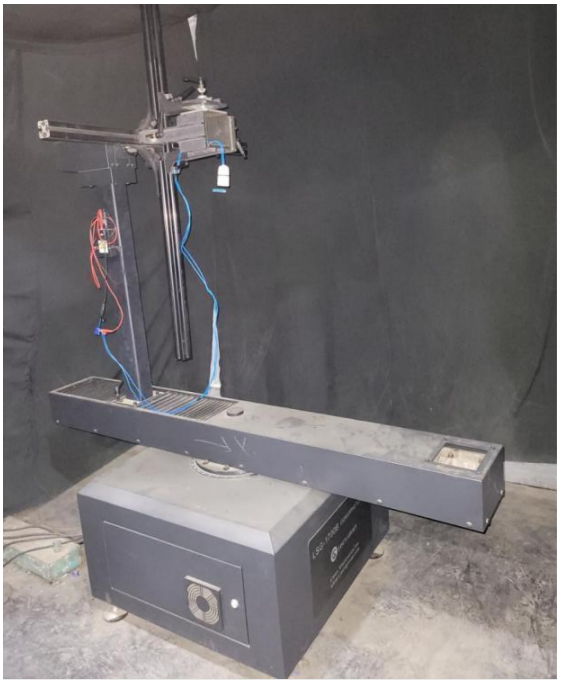


Figure 3.4: LSG-1700 Goniophotometer

Figure 3.5: Specbos-1200 Spectroradiometer

3.2 The simulation work:

The software that has been chosen for the simulation work of this thesis work is is DIALux Evo.

A room dimension of $(6 * 4 * 3.2)m^3$ has been equipped with six tables to imply six work stations. Tables are at a height of 0.8m.

A calculation grid has been taken at a height of 0.825m to measure horizontal illuminance levels and to calculate unified glare rating (UGR).

There are nine calculation grids along the length and nineteen calculation grids along the width of the room a. Grids along the length of the room are named as "Long Grid 1, 2, 3 . . . " like this as they are in longitude and grids along the width of the room are named as "Lat Grid 1, 2, 3 . . . " like this, as they are in latitude of the room.

At first the vertical grids were positioned in the same location but facing opposite directions to calculate vertical illuminance and unified glare ratings in all four cardinal directions. As it is theoretically comprehensible that as the room is and all the room elements are symmetrically positioned, it is not needed to calculate for four cardinal directions, only two is enough.

These vertical grids, Long grids and Lat grids are located at a spread of 0.9m to 1.3m through out the length and breath of the occupied space in the room respectively, at a equal interval of distances. These intervals are 0.3m and 0.4m for the Lat-Grids and Long-Grids respectively.

These vertical grids are placed in such a way that the overall circadian effective lighting of the room can be achieved irrespective of the position of work stations.

3.2.1 Design Parameters to be achieved:

On the working plane ,

Illuminance$\geq$ 500Lux; Overall Uniformity$(E_{Min}/E_{Avg}) \geq 0.7$;
Uniformity $(E_{Min}/E_{Avg}) \geq 0.6$; Unified Glare Rating , $(UGR) \leq 19$.

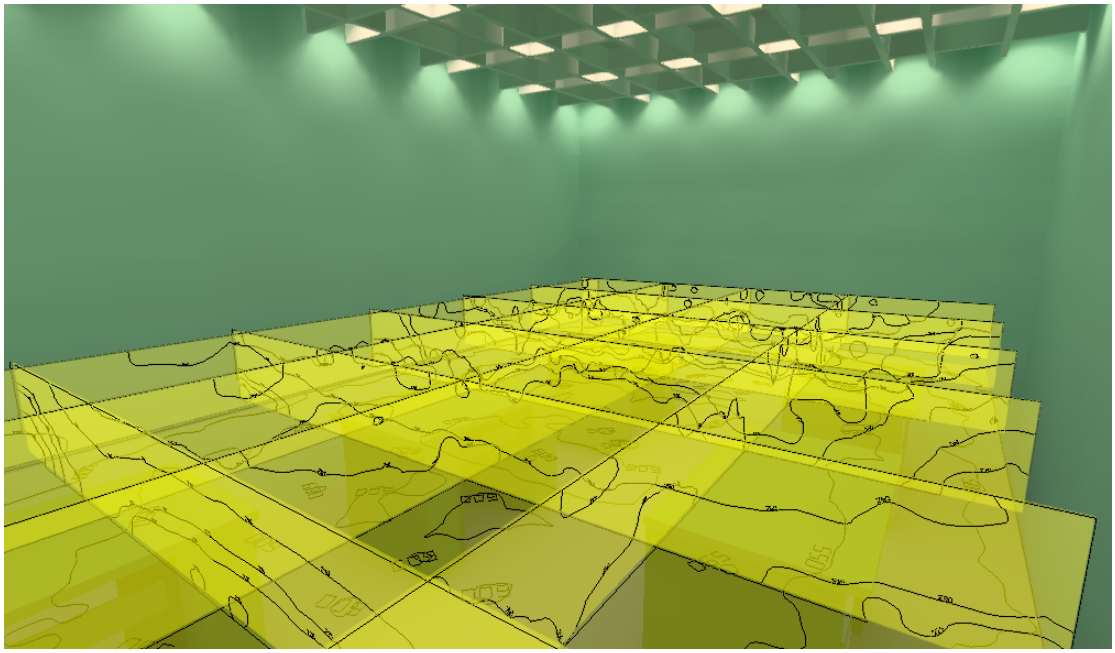


Figure 3.6: Room interior: making the grid layout better understandable by keeping the intermediate vertical grid visibility off [A picture from DIALux Evo 12.0 software]

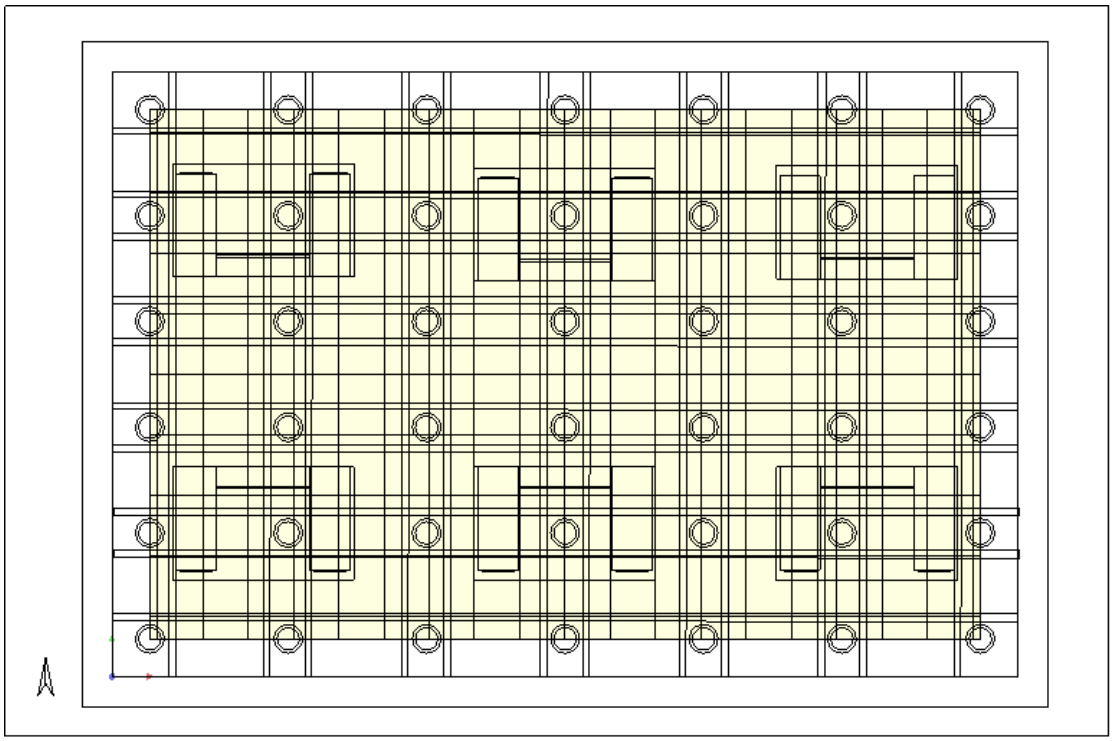


Figure 3.7: Top view of room plan [A picture from DIALux Evo 12.0 software]. For better understanding of the calculation grid layout a few longitudinal and latitudinal grids are coloured with different colours. Here "Blue" coloured grids are Long (longitudinal) grids and "Red" coloured grids are Lat (Latitudinal) grids.

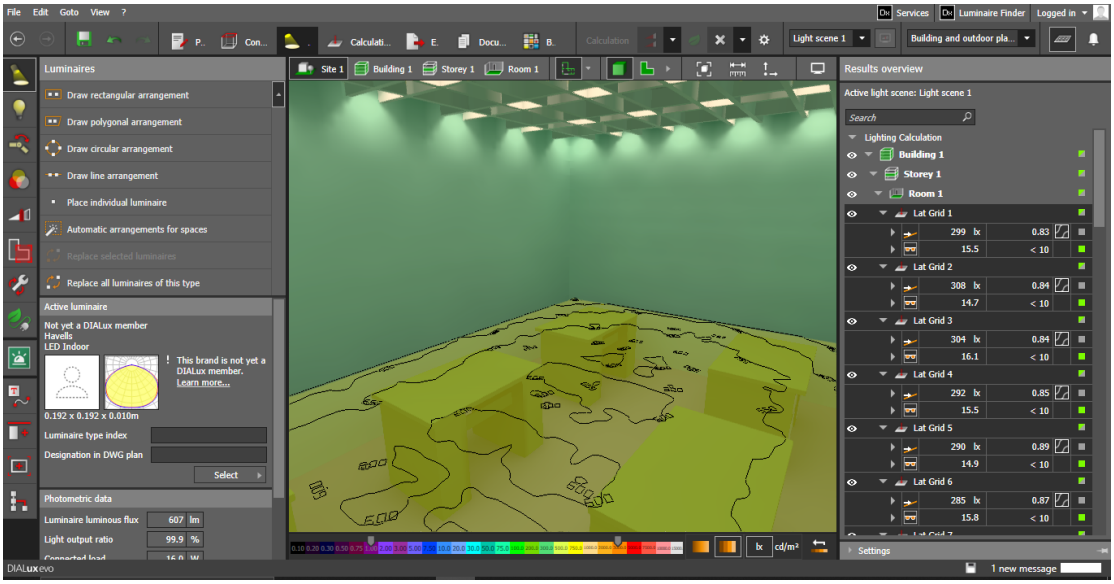


Figure 3.8: A picture of DIALux Evo 12.0 user interface while doing this project

3.2.2 Calculation to find out required number of luminaires:

The objective of this calculation is to find out how many luminaires are required to properly illuminate the room as per the recommendations in standards.

From the Gonio-photometer provided IES file data the luminaire lumen output has been found as 608 lumen (lm).

The DIAlux mentioned maintenance factor (MF) is 0.8 for indoor lighting. In DIALux this is termed as Light Loss Factor (LLF).

The typical value of coefficient of utilization (CU) for indoor spaces is considered as 0.6.

The required horizontal illuminance level is set to be 500 Lux.

From standard definition we know,

$$E = \frac{\phi}{A}$$

Where,

E = Average Illuminace (Lux)
ϕ = Luminous Flux (Lumen)
A = Area (m^2)

Now, let N be the number of luminaires required,

And as found,

MF = 0.8; CU = 0.6; Ø = 608 lm; A = 6 X 4 m^2 ; E = 500 Lux

As,

$$E = \frac{\phi * CU * MF * N}{A}$$

$$N = 41.118$$

$$\approx 42$$

So, approximately we need to use 42 number of luminaires to achieve the required horizontal illuminance level of 500 Lux.

In DIALux Evo, these 42 number of luminaires are arranged in a field arrangement having 6 rows and 7 columns, hence in a 6 x 7 matrix.

Then the results are observed.

Later, these vertical average illuminances, as found in results after calculation in DIAlux Evo, are fed in the freely available online CS Calculator 2.0 (https://cscalc.light-health.org/) to figure out if the circadian effective design goal is reached or not.

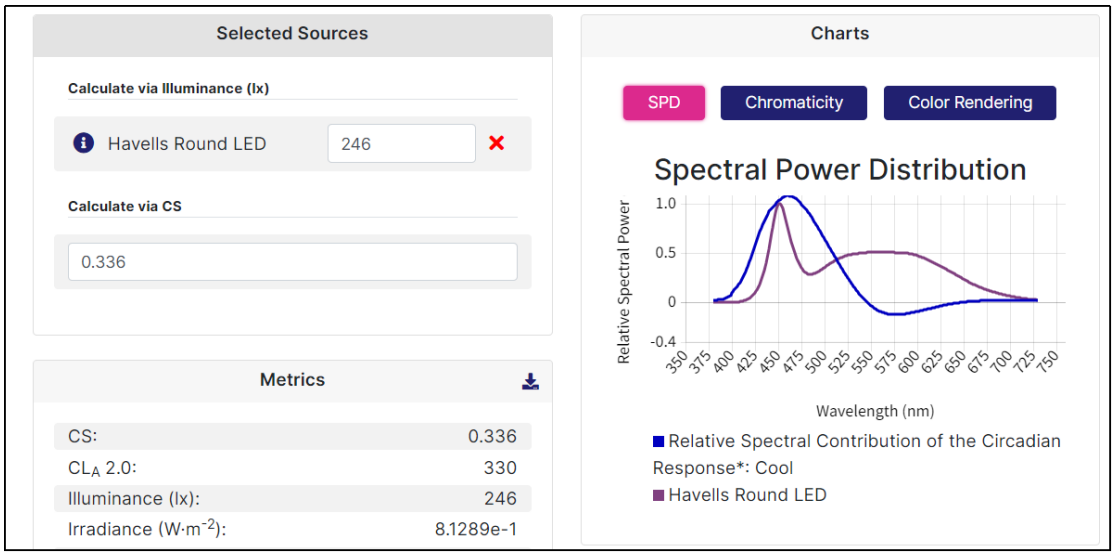
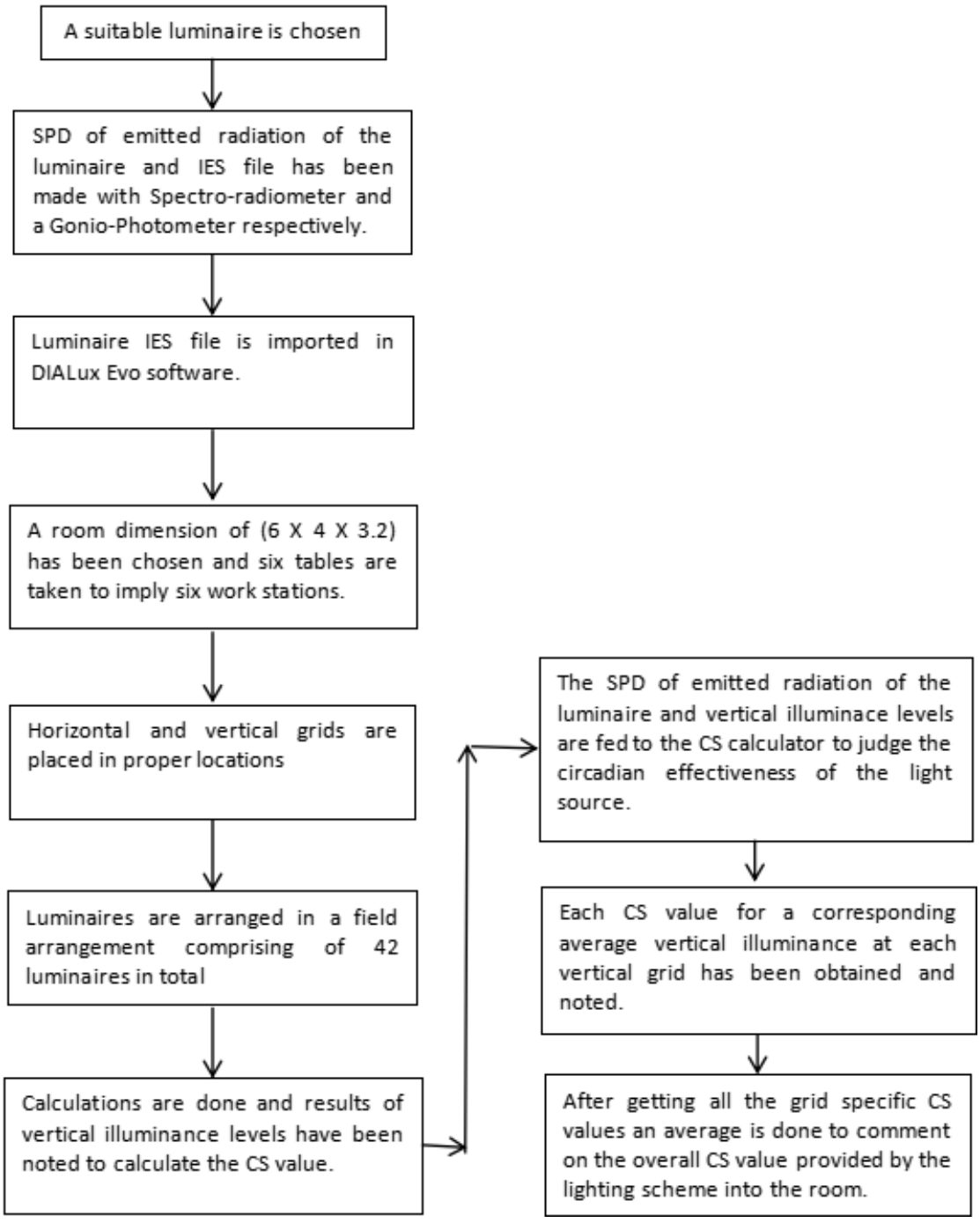


Figure 3.9: A picture of User Interface of freely available online CS calculator 2.0

3.3 Execution flow chart:



Chapter 4

It deals with the results and graphical analysis

4.1 Results:

Table 4.1: Long Grid Values Achieved

Long Grid Serial Number	Vertical Illuminance (Lux)	Overall Uniformity (E_{Min}/E_{Avg})	Uniformity (E_{Min}/E_{Avg})	Unified Glare Rating	CL_A2.0 Value (W/m^2)	CS Value
1	246	0.68	0.56	16.3	330	0.336
2	264	0.65	0.53	16.3	355	0.349
3	272	0.66	0.53	16.2	365	0.355
4	269	0.68	0.54	16.5	361	0.353
5	267	0.69	0.56	16.4	359	0.352
6	269	0.68	0.56	16.3	361	0.353
7	273	0.65	0.52	16.2	367	0.356
8	265	0.65	0.53	15.9	356	0.350
9	247	0.67	0.54	16.3	331	0.336

Table 4.2: Lat Grid Values Achieved

Long Grid Serial Number	Vertical Illumi-nance (Lux)	Overall Unifor-mity (E_{Min}/ E_{Avg})	Unifor-mity (E_{Min}/ E_{Avg})	Unified Glare Rating	CL_A2.0 Value (W/m^2)	CS Value
1	299	0.83	0.76	15.5	402	0.374
2	308	0.84	0.78	14.7	415	0.379
3	304	0.84	0.76	16.1	409	0.377
4	292	0.85	0.77	15.5	393	0.369
5	290	0.89	0.81	14.9	390	0.368
6	285	0.87	0.77	15.8	383	0.364
7	275	0.87	0.78	15.6	370	0.357
8	283	0.84	0.78	16.5	380	0.363
9	283	0.85	0.79	16.3	380	0.363
10	269	0.86	0.79	15.5	361	0.353
11	265	0.88	0.81	16.3	356	0.350
12	262	0.88	0.80	16.4	352	0.348
13	249	0.87	0.79	15.7	334	0.338
14	254	0.85	0.77	15.8	341	0.342
15	247	0.84	0.77	15	331	0.336
16	227	0.85	0.77	15.5	304	0.320
17	217	0.85	0.78	16.2	291	0.311
18	203	0.86	0.78	14.7	272	0.298
19	187	0.87	0.80	15.5	250	0.283

Table 4.3: Work plane values achieved:

Type of illuminance	Illuminance (Lux)	Overall Unifor-mity (E_{Min}/ E_{Avg})	Unifor- mity (E_{Min}/ E_{Avg})
Horizontal	541	0.73	0.64
Cylindrical	234	0.84	0.71

& Unified glare rating (UGR) = 16.4

Average CLA2.0 value of the room =353.54 (W/m^2)
Average CS value of the room = 0.3476

4.2 Calculation of minimum required light exposure duration with respect to current lighting design:

From equation (7), we know,

$$CS_d = CS_t = 0.7 * \left[1 - \frac{1}{1 + (\frac{t * CL_A 2.0}{355.7})^{1.1026}} \right]$$

Where the prescribed minimum circadian effective dose (CS_d) is fixed to be 0.43, and as the average $CL_A 2.0$ value of the room is found to be 274 (W/m^2),

The duration of exposure, to achieve the minimum circadian effective dose, can be found from the above equation as,

$$t = 1.53$$

So, the minimum exposure duration (t) should be 1.53 hours to achieve the prescribed circadian effective lighting dose ($CS_d = 0.43$), with our existing lighting design.

4.3 Graphical Analysis:

4.3.1 Relationship of Vertical Illuminance with Grid positions:

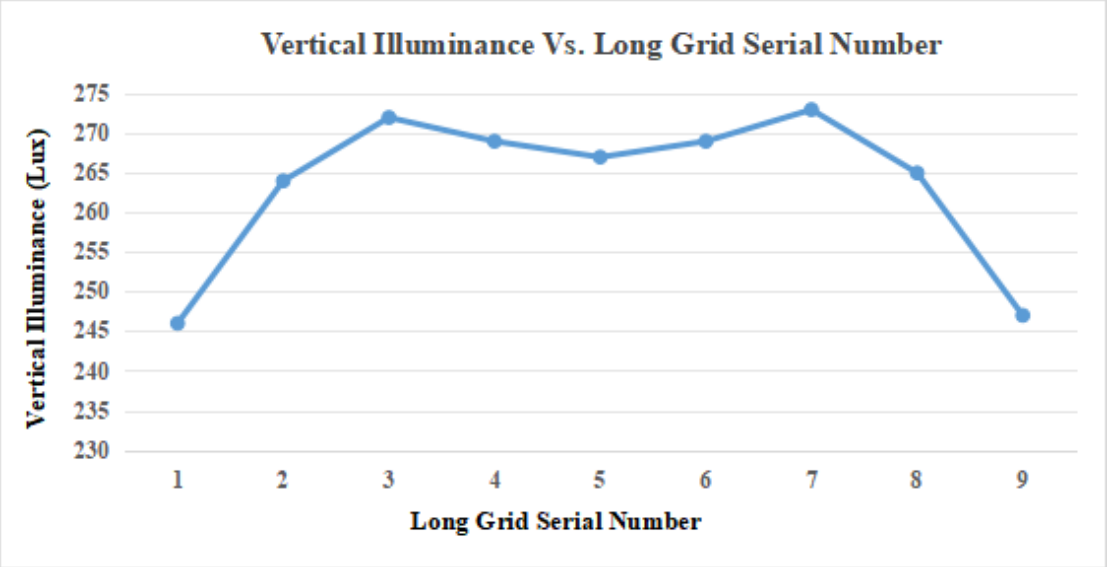


Figure 4.1: Relationship of Vertical Illuminance with Long Grid positions

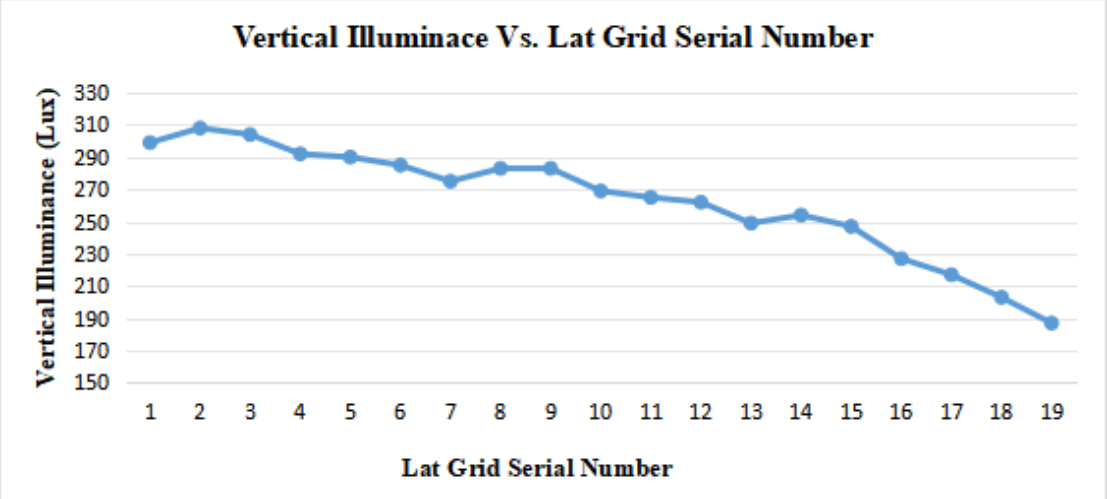


Figure 4.2: Relationship of Vertical Illuminance with Lat Grid positions

In Long Grids, [see Figure 3.7] grids from top to bottom wall, having more light in the middle compared to near wall grids [Figure 4.1] Where in Lat-Grids, the grids with first few serial numbers are getting more light exposure and as the grid progresses from left wall to right wall the light exposure drops [Figure 4.2]. Hence the latitudinal cross sections is more illuminated compared to longitudinal cross sections of the room.

4.3.2 Relationship of Overall Uniformity (E_{Min}/E_{Avg}) with Grid positions:

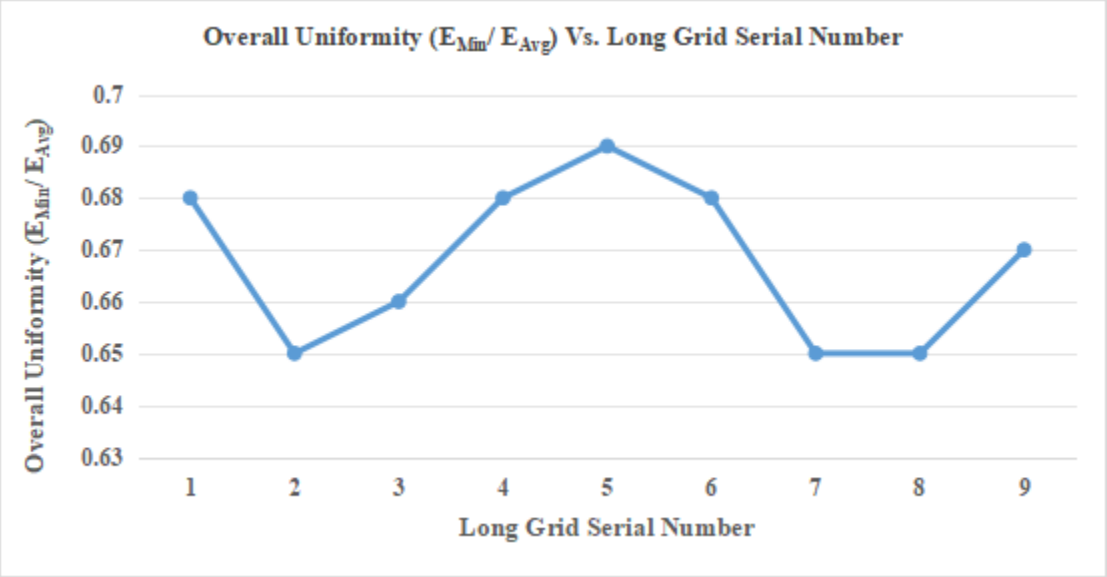


Figure 4.3: Relationship of Overall Uniformity (E_{Min}/E_{Avg}) with Long-Grid positions.

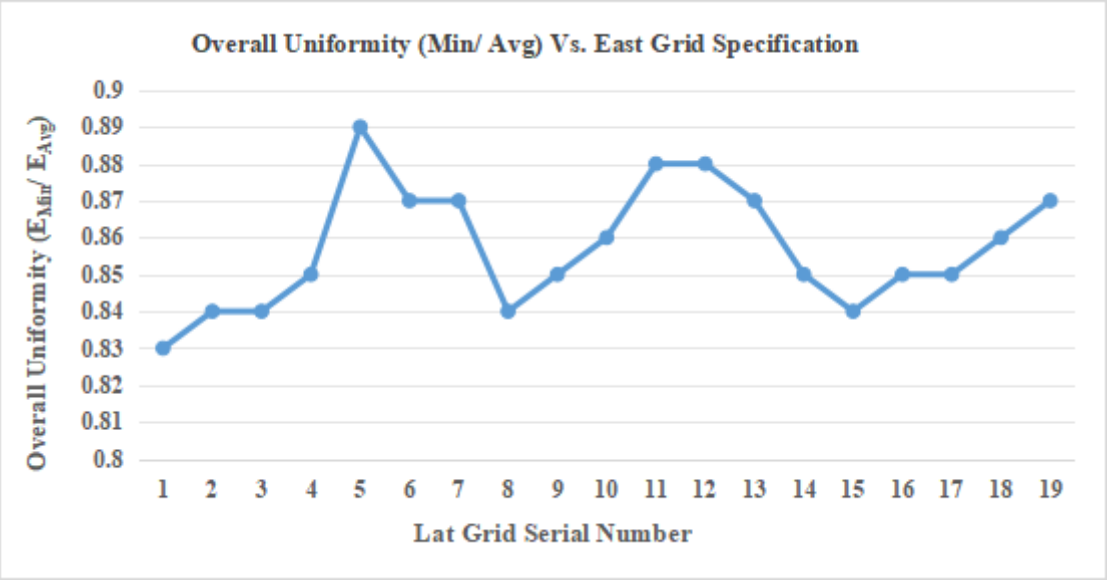


Figure 4.4: Relationship of Overall Uniformity (E_{Min}/E_{Avg}) with Lat-Grid positions.

In Longitudinal vertical grids (Long Grids) overall uniformity ranges from 0.65 to 0.69 [Figure 4.3] and in latitudinal vertical grids (Lat Grids) the overall uniformity level ranges from 0.83 to 0.89 [Figure 4.4], suggesting good overall uniformity of light distribution levels along the latitudinal cross section compared to longitudinal cross section of the room.

4.3.3 Relationship of Uniformity (E_{Min}/E_{Avg}) of illuminance with Grid positions

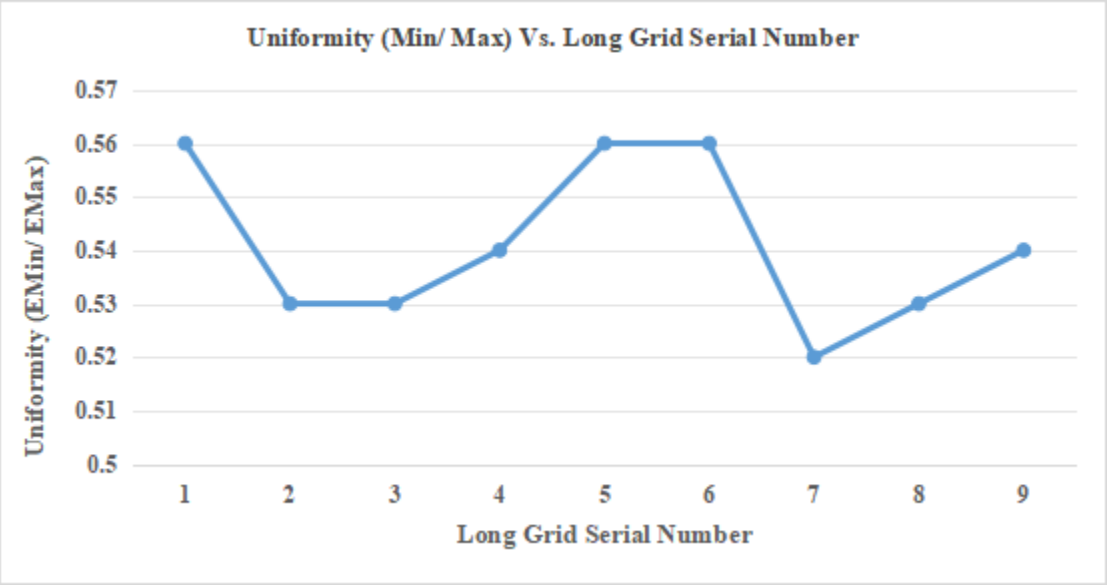


Figure 4.5: Relationship of Uniformity (E_{Min}/E_{Avg}) of illuminance with Long Grid positions

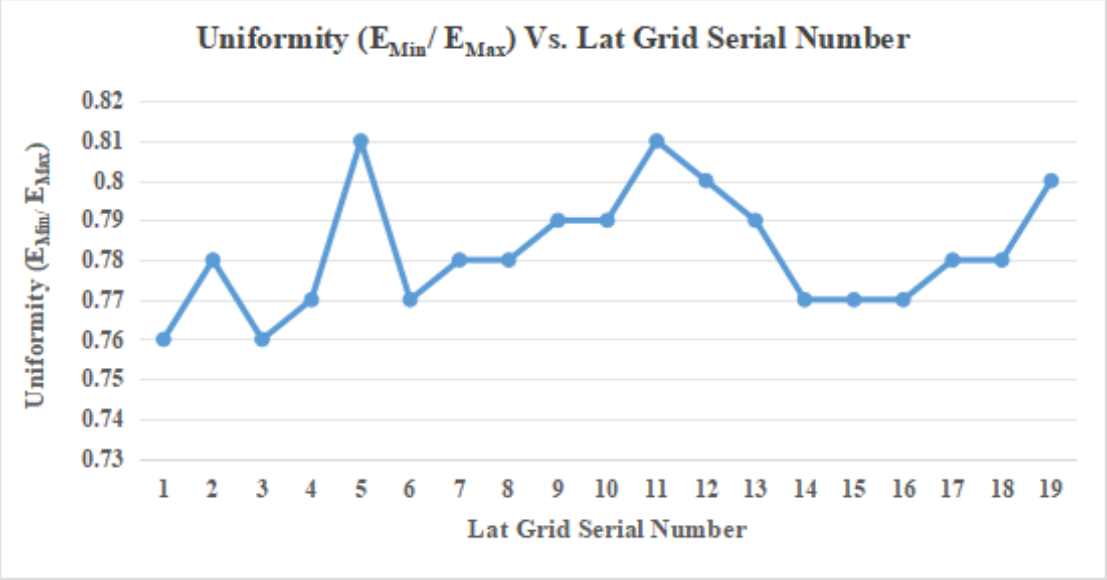


Figure 4.6: Relationship of Uniformity (E_{Min}/E_{Avg}) of illuminance with Lat Grid positions

Similar to overall uniformity (E_{Min}/E_{Avg}, the Uniformity (E_{Min}/E_{Avg}, though a tougher standard to maintain, here it is found to be poor (but satisfactory as grater than 0.5) along the longitudinal cross section of the room, having a range from 0.52 to 0.56 [Figure 4.5] and good while having a range 0.76 to 0.81 along the latitudinal cross sections [Figure 4.6].

4.3.4 Relationship of Unified Glare Rating (UGR) with Grid positions

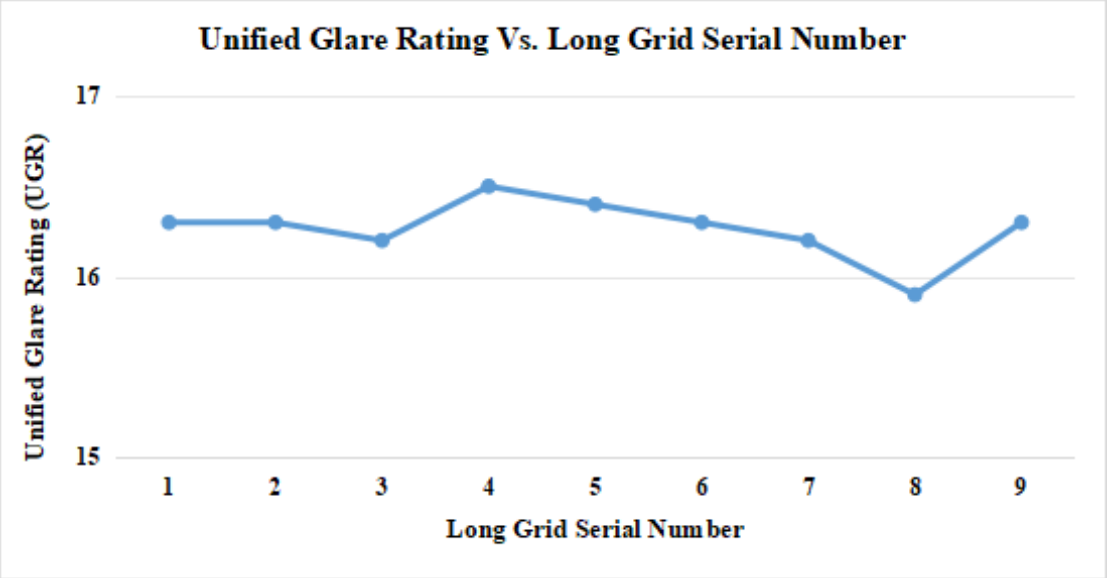


Figure 4.7: Relationship of Unified Glare Rating (UGR) with Long Grid positions

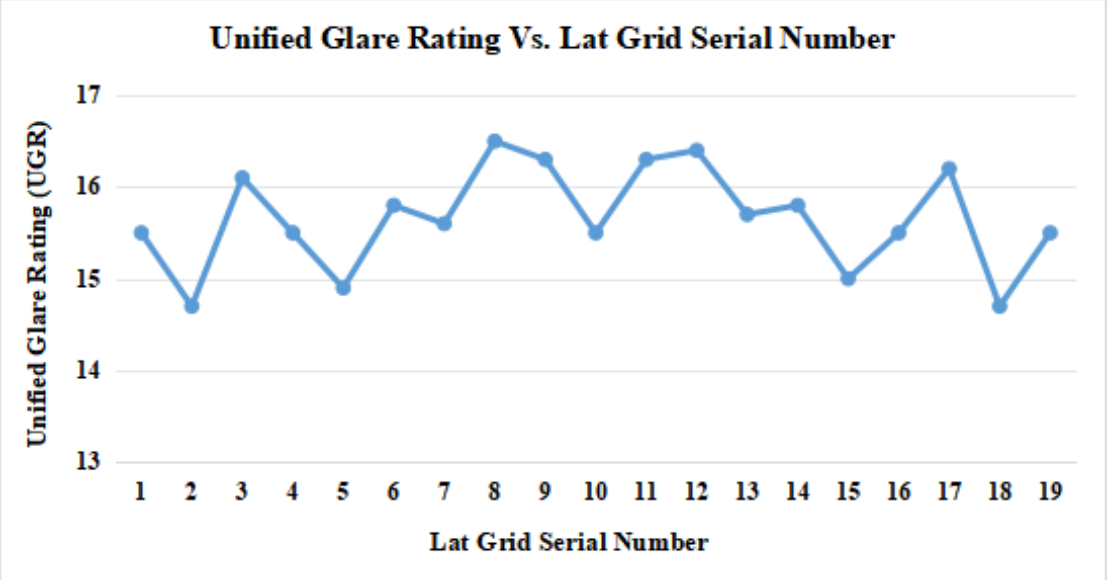


Figure 4.8: Relationship of Unified Glare Rating (UGR) with Lat Grid positions

Both from Figure 4.7 and Figure 4.8 it is noticeable that in no where the UGR value exceeded the mark of 17. So, in terms of glare the lighting design is good in all vertical grids (specifying all four cardinal directions).

4.3.5 Relationship of Circadian Light ($CL_A2.0$) with Grid positions

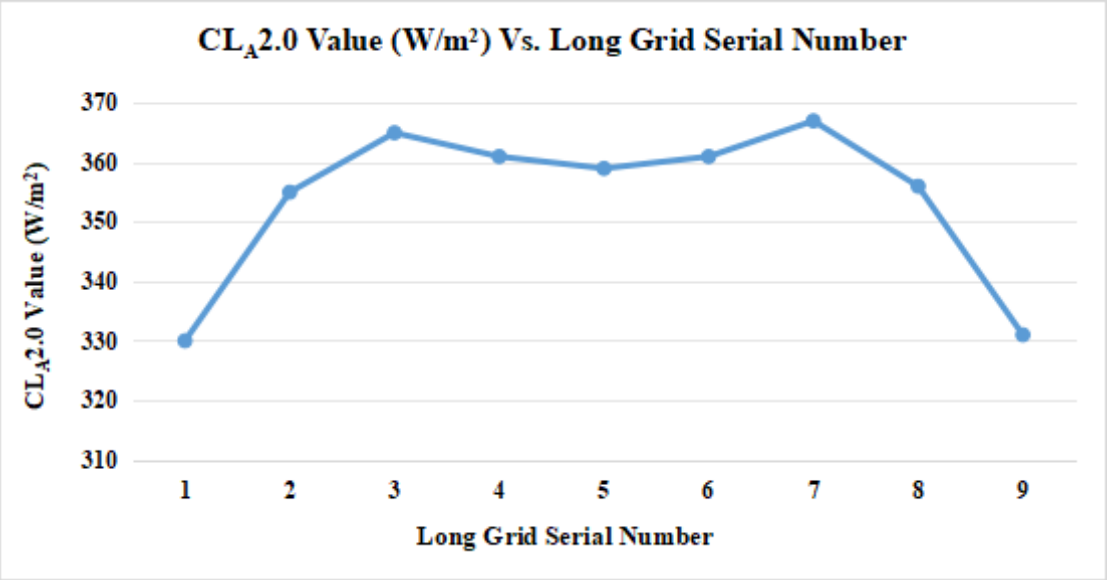


Figure 4.9: Relationship of Circadian Light ($CL_A2.0$) with Long Grid positions

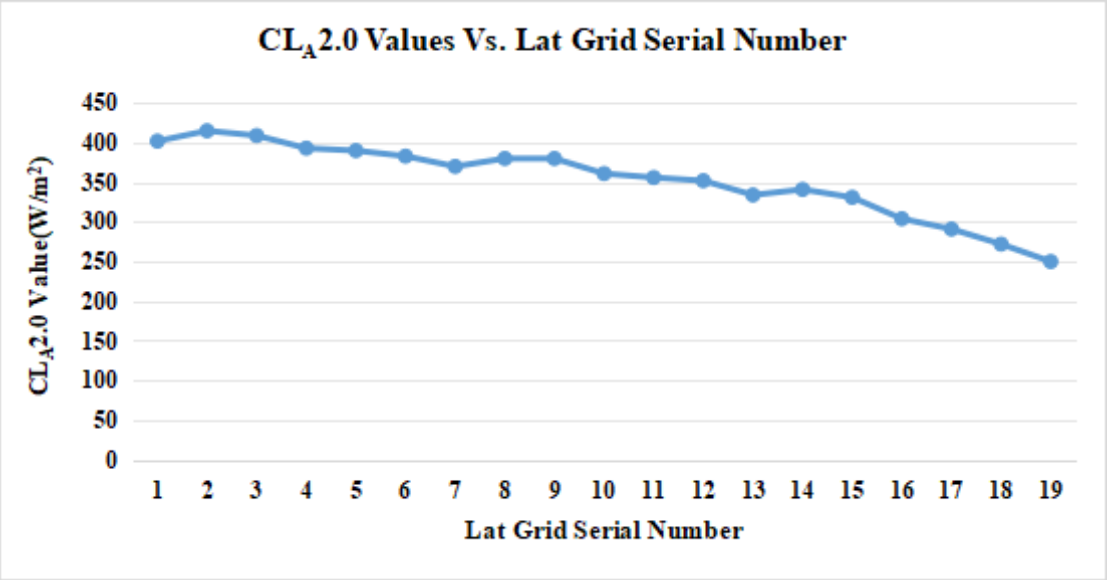


Figure 4.10: Relationship of Circadian Light ($CL_A2.0$) with Lat Grid positions

As we can see, the curvature of graph holding relationship of Circadian Light ($CL_A2.0$) with Grid positions in Figure 4.9 and Figure 4.10 is exactly similar to curvature of graph holding relationship of Vertical Illuminance with Grid positions in figure Figure 4.1 and Figure 4.2 respectively, suggesting that there is a positive correlation between amount of lux incident on eye and the amount of amount of Circadian Light received, while keeping the source constant.

4.3.6 Relationship of Circadian Stimulus (CS) with Grid positions

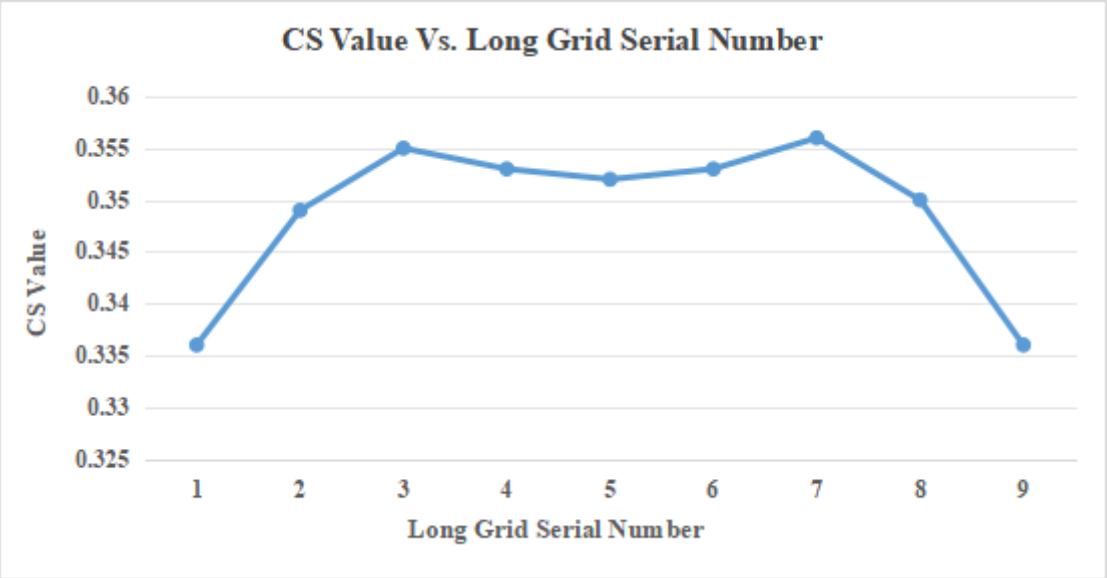


Figure 4.11: Relationship of Circadian Stimulus (CS) with Long Grid positions

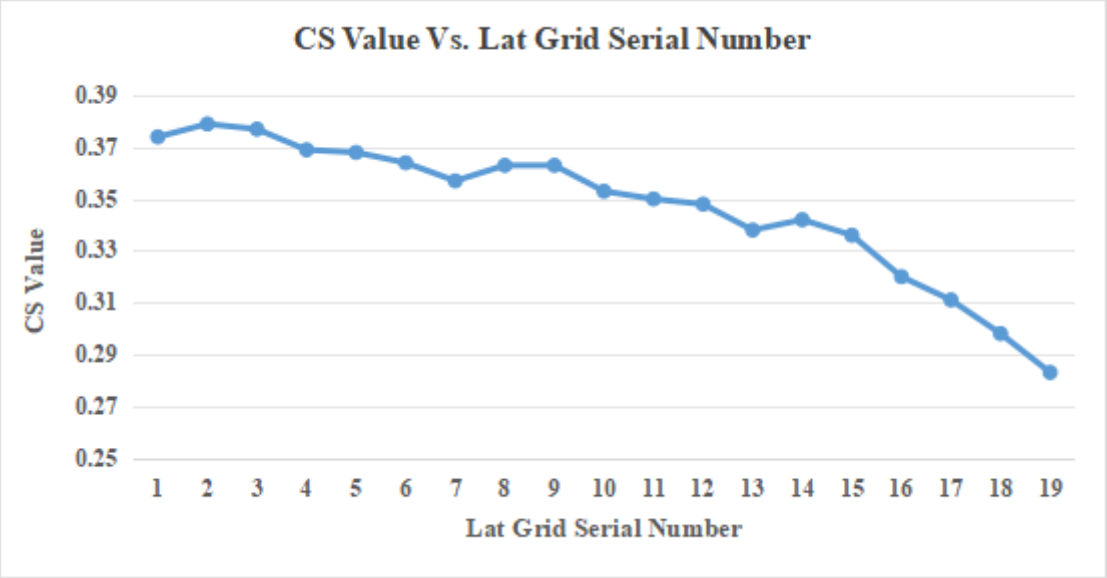


Figure 4.12: Relationship of Circadian Stimulus (CS) with Lat Grid positions

As it can be observed that Figure 4.11 and 4.12 is exactly similar with Figure 4.9 & 4.10 and Figure 4.1 & 4.2 in terms of nature of curvature, suggesting a positive correlation between amount of $CL_A2.0$ received in eye level and the CS Value and of-curse with amount of vertical illuminance received at eye level with the CS value respectively.

Chapter 5

It deals with the discussion and conclusion

5.1 Discussion:

It is found from the results [Section 4.1, Table 4.3] that, as far the conventional design parameters are concerned, the current lighting design is satisfactory, while achieving all the conventional design goals as follows,

Table 5.1: Results obtained as per the conventional design parameters

Conventional design parameters (on working plane)	Required	Achieved
Illuminance (Lux)	≥ 500	541
Overall Uniformity (E_{Min}/E_{Avg})	≥ 0.7	0.73
Uniformity (E_{Min}/E_{Avg})	≥ 0.6	0.64
Unified Glare rating (UGR)	≤ 19	16.4

It is found from the graphical analysis [Section 4.3, Figure 4.11 and 4.12] that illuminance received at eye level has a positive correlation with the amount of circadian light (CL_A2.0) and the value of circadian stimulus (CS), while keeping the source constant. Hence, more the illuminance, better is the amount of (CL_A2.0) and CS. We also found that the required CS value of 0.3 is achieved through out the vertical grids except Lat Grid 18 & 19 (though they are very close to 0.3) and average CS value of the room to be 0.3476 which indicates well achieving of the required CS value [Section 4.1].

From the minimum circadian effective dose (CS_d) requirement criterion of, 0.43, it is found that with the average, CL_A2.0 of , 353.54(W/m^2), if we apply the current lighting design only for approximately 1.53 hours [Section 4.1], the CS_d =0.43 can be achieved very easily in the morning hours (i.e. 8:00 am to 12:00 pm [38]).

As per the circadian effective lighting design recommendation from UL 24480 DG, the lighting design presented in this thesis work, should not be applied after 4:00 pm. After 4:00 pm to 5:00 pm CS value should be slowly transited from 0.3 to 0.2 and should be kept at $\leq$0.2 from 5:00 pm to 7:00 pm. After that there should be a slow transition of CS value from 0.2 to 0.1 in the time span of 7:00 pm to 8:00 pm and after 8:00 pm the CS value should be kept at $\leq$0.1. As per recommendation this transition of light level should not be grater than 5% per second.

Thus complying with the CS requirement if we would have designed our office room with working plane illuminance of $\geq$300 Lux, would we be able to achieve the required CS value of $\leq$0.2 after 4:00pm ?

If we see, the max(vertical illuminance/ horizontal illuminance) in our current design it is, (308/541) = 0.5693. using this ratio, we can say that if we would have designed our office room with ≥300 lux of horizontal working plane illuminance then the maximum vertical plane illuminance would have been, (300/0.5693) = 170.79 Lux. Putting this value in the CS calculator we found the CS value of 0.266. Similarly if we see min(vertical illuminance/ horizontal illuminance), it is (187/541) = 0.3456, then in corresponding design of ≥300 lux of horizontal working plane illuminance, the lowest average vertical illuminance level is (300∗0.3456) = 103.68 Lux. Putting this value in the CS calculator we found the CS value of 0.182. So, we can say that with design of ≥300 lux of horizontal working plane illuminance we can achieve the average CS value of the room a little higher than 0.2.

Now, if we change the CCT level, will the recommended CS value of ≤0.2 be achieved for the duration of 5:00 pm to 7:00 ? In quest to find out this answer, considering the same lux values in vertical grids assuming the exact same light distribution, we opted to see what will be the CS values when we use some other luminaire having a CCT in the warm white range, assuming that this kind of SPD of emitted radiation can be possible to deliver through change in CCT. Here an LED "Lumileds Luxeon Rebel LXM3_PW81LED 2700K" luminaire is used (available in the data base of freely available CS calculator), And the results are,

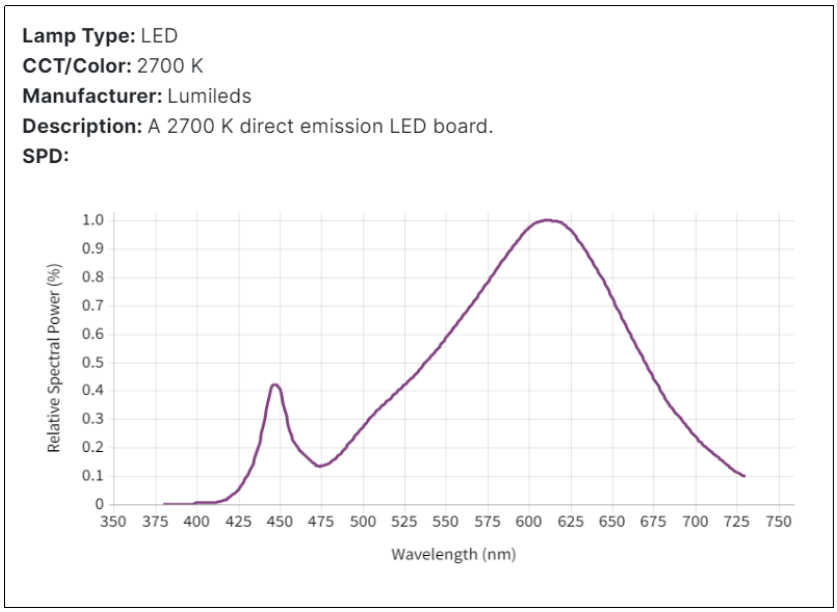


Figure 5.1: SPD information of "Lumileds Luxeon Rebel LXM3_PW81LED 2700K" as provided in the database of freely available CS calculator.

Table 5.2: Longitudinal grid values while using"Lumileds Luxeon Rebel LXM3_ PW81LED 2700K" luminaire

Long Grid Serial Number	Vertical Illuminance levels (Lux)	CS Value
1	246	0.209
2	264	0.220
3	272	0.225
4	269	0.223
5	267	0.222
6	269	0.223
7	273	0.226
8	265	0.221
9	247	0.209

Table 5.3: Latitudinal grid values while using "Lumileds Luxeon Rebel LXM3_ PW81LED 2700K" luminaire

Lat Grid Serial Number	Vertical Illuminance levels (Lux)	CS Value
1	299	0.241
2	308	0.247
3	304	0.244
4	292	0.237
5	290	0.236
6	285	0.233
7	275	0.227
8	283	0.232
9	283	0.232
10	269	0.223
11	265	0.221
12	262	0.219
13	249	0.211
14	254	0.214
15	247	0.209
16	227	0.196
17	217	0.189
18	203	0.179
19	187	0.167

The average CS value achieved in this case is 0.219 which is very close to 0.2. Now in conventional office lighting design a range of, 300-500-700 lux levels has been given depending upon the nature of task performed in the office spaces. Though we have chosen to design our office having a work plane illuminance of $ge500$ lux, considering the requirement of the CS recommendation if we take the provision of changing the illuminance level in between the provided range, then along with a lighting control mechanism where illuminance and the CCT can be varied in a wide range, we can very easily achieve the required recommend CS value of $le0.2$ after 4:00 pm.

Hence we need a dynamic lighting control mechanism to achieve all the time specific CS recommendations for a circadian effective lighting design.

5.2 Conclusion:

We found that vertical illuninace level has a positive correlation with the circadian light received at eye level and the corresponding CS value [Section 4.3, Figure 4.11 and 4.12].

We found that how by changing illuminance and CCT values can directly impact the CS value [Section 5.1].

We found that the conventional office lighting system presented in this thesis work is only applicable for the temporal duration of 7:00am to 4:00pm and after that with the help of lighting control mechanisms we need to vary the CCT from cool white to warm white range and by dimming the light level we need to achieve the circdian effective design goals after 4:00pm [Section 5.1].

So, we conclude that if we use a dynamic lighting control mechanism where luminaire CCT and illuminance levels can be changed, we can very easily achieve the time specific recommended CS values to design a circadian supportive lighting design while keeping all the conventional lighting design parameters.

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Appendix

Lisun Electronics Inc.
http://www.Lisungroup.com
Tel: +86(21)51083341
Fax: +86(21)51083342

Report No.: Recessed CWLED Test Time: 2024-03-21 14:15

Luminaire Property

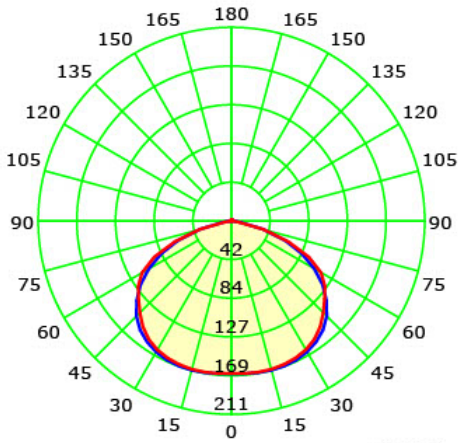
Luminaire Manufacturer:
Luminaire Category: LED Indoor
Luminaire Description: Havells
Lamp Catalog: CWLED, 15 watt
Lamp Description: 220-240 V
Number of Lamps: 1
Voltage: 220.3 V
Current: 0.076 A
Power: 16.03 W
Power Factor: 0.956

Photometric Results

CIE Class: Direct
Total Rated Lamp Lumens: 607.7 lm
Measurement Flux: 607.7 lm
Efficiency: 100%
Downward Ratio: 99%
Upward Ratio: 1%
Field Angle(C0/C180,C90/C270,C45/C225,C135/315): 157.7, 156.9, 158.5, 158.5
Beam Angle(C0/C180,C90/C270,C45/C225,C135/315): 130.3, 133.5, 134.1, 134.1
Luminaire Efficacy Rating (LER): 37.96
Central Intensity: 167.38 cd
Max. Intensity: 169.5 cd
Pos of Max. Intensity: H22.5 V15
S/MH(C0/C180): 1.47
S/MH(C90/C270): 1.45

Picture Of Luminaire

Luminous Intensity Distribution Curve

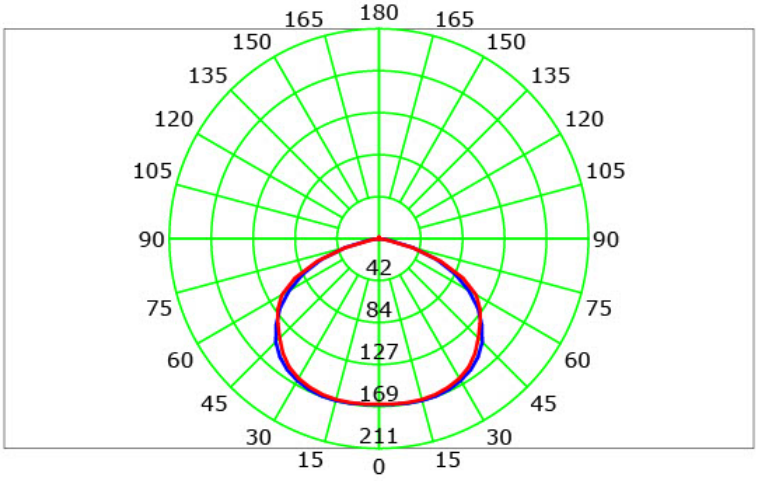


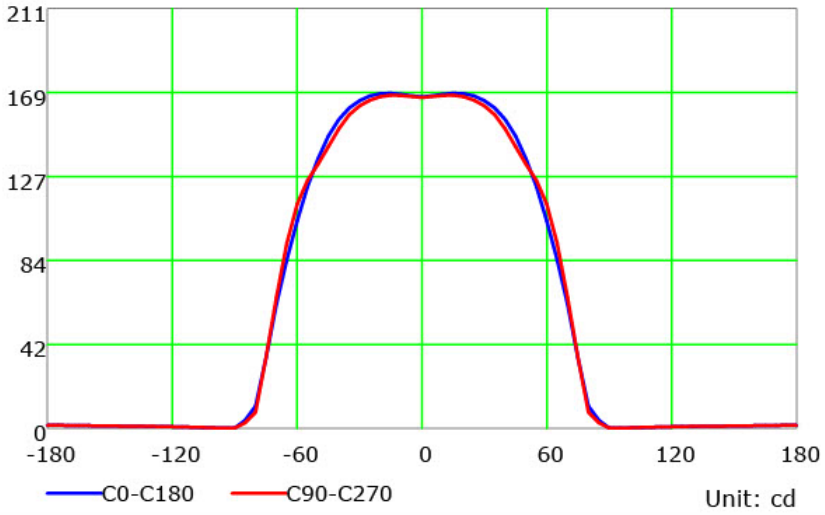
Unit: cd

C Plane (°):0.0-90.0: 22.5
Gamma Plane (°):0.0-180.0:5.0
Test Lab: Illumination Engineering Laboratory , ETest Device: LSG-1700Bartment , Jadavpur University
Test Type: TYPE C
Distance: 7.470 m
Temperature: 25 DEGREE
Humidity:
Operator: Prasad
Inspector:

Lisun Electronics Inc.
http://www.Lisungroup.com
Tel: +86(21)51083341
Fax: +86(21)51083342

Luminous Intensity Distribution Curve





C Plane (°):0.0-90.0: 22.5
Gamma Plane (°):0.0-180.0:5.0
Test Lab: Illumination Engineering Laboratory , ETest Device: LSG-1700Bartment , Jadavpur University
Test Type: TYPE C
Distance: 7.470 m
Temperature: 25 DEGREE
Humidity:
Operator: Prasad
Inspector:

Zonal Lumen

Gamma [°]	Imean [cd]	Zonal Flux [lm]	Sum Zonal Flux [lm]	Rel Zonal Flux [%]	Sum Rel Zonal Flux [%]
0.0-5.0	167.7	4.0	4.0	0.66	0.66
5.0-10.0	168.4	12.0	16.1	1.98	2.64
10.0-15.0	168.9	20.0	36.1	3.30	5.94
15.0-20.0	168.7	27.8	63.9	4.58	10.52
20.0-25.0	167.6	35.2	99.1	5.79	16.30
25.0-30.0	165.5	41.9	140.9	6.89	23.19
30.0-35.0	162.1	47.7	188.7	7.86	31.05
35.0-40.0	157.1	52.4	241.1	8.62	39.67
40.0-45.0	150.1	55.6	296.7	9.15	48.82
45.0-50.0	141.5	57.2	353.9	9.41	58.23
50.0-55.0	131.7	57.3	411.1	9.42	67.65
55.0-60.0	119.6	55.3	466.4	9.10	76.75
60.0-65.0	102.8	50.0	516.4	8.22	84.98
65.0-70.0	79.7	40.4	556.8	6.64	91.62
70.0-75.0	51.3	26.8	583.6	4.41	96.03
75.0-80.0	23.9	12.8	596.3	2.10	98.13
80.0-85.0	8.0	4.3	600.7	0.71	98.85
85.0-90.0	2.3	1.2	601.9	0.20	99.05
90.0-95.0	0.4	0.2	602.1	0.04	99.09
95.0-100.0	0.4	0.2	602.4	0.04	99.13
100.0-105.0	0.5	0.3	602.6	0.05	99.17
105.0-110.0	0.7	0.3	603.0	0.06	99.23
110.0-115.0	0.8	0.4	603.4	0.06	99.29
115.0-120.0	0.9	0.4	603.8	0.07	99.36
120.0-125.0	1.0	0.4	604.2	0.07	99.44
125.0-130.0	1.0	0.5	604.7	0.07	99.51
130.0-135.0	1.1	0.5	605.2	0.07	99.59
135.0-140.0	1.2	0.4	605.6	0.07	99.66
140.0-145.0	1.3	0.4	606.0	0.07	99.73
145.0-150.0	1.3	0.4	606.4	0.06	99.79
150.0-155.0	1.4	0.4	606.8	0.06	99.85
155.0-160.0	1.5	0.3	607.1	0.05	99.90
160.0-165.0	1.5	0.3	607.3	0.04	99.94
165.0-170.0	1.6	0.2	607.5	0.03	99.97
170.0-175.0	1.6	0.1	607.6	0.02	99.99
175.0-180.0	1.7	0.0	607.7	0.01	100.00

C Plane (°):0.0-90.0: 22.5
Gamma Plane (°):0.0-180.0:5.0
Test Lab: Illumination Engineering Laboratory , Electrical Engineering Department , Jadavpur University
Test Type: TYPE C
Distance: 7.470 m
Temperature: 25 DEGREE
Humidity:
Operator: Prasad
Inspector:

Candlepower Table

Unit: cd

G\C	C0.0	C22.5	C45.0	C67.5	C90.0					
G0.0	167.4	167.3	167.4	167.3	167.1					
G5.0	167.9	168.2	168.1	167.9	167.6					
G10.0	168.7	169.0	169.0	168.7	168.1					
G15.0	169.2	169.5	169.1	168.6	168.2					
G20.0	169.0	168.9	168.5	168.2	167.4					
G25.0	167.9	167.4	166.8	166.1	165.7					
G30.0	165.5	165.1	164.1	163.3	162.9					
G35.0	161.7	161.1	160.0	158.9	158.3					
G40.0	156.0	155.5	154.6	152.7	151.2					
G45.0	147.6	147.0	147.9	144.7	142.2					
G50.0	136.1	136.1	139.5	137.0	133.3					
G55.0	122.0	123.8	129.4	129.1	125.2					
G60.0	104.9	109.6	115.8	116.3	113.4					
G65.0	85.2	91.3	95.7	95.2	93.5					
G70.0	62.7	66.4	68.3	67.3	66.2					
G75.0	35.6	34.4	36.3	37.2	35.9					
G80.0	11.3	9.0	13.5	14.8	8.3					
G85.0	4.2	3.4	4.4	5.2	2.9					
G90.0	0.3	0.5	0.3	0.5	0.3					
G95.0	0.3	0.5	0.4	0.5	0.3					
G100.0	0.4	0.5	0.5	0.5	0.4					
G105.0	0.5	0.6	0.6	0.6	0.6					
G110.0	0.7	0.7	0.7	0.7	0.7					
G115.0	0.8	0.8	0.9	0.8	0.8					
G120.0	0.9	0.9	0.9	0.9	0.9					
G125.0	1.0	1.0	1.0	1.0	1.0					
G130.0	1.1	1.1	1.1	1.1	1.1					
G135.0	1.2	1.2	1.1	1.1	1.2					
G140.0	1.2	1.3	1.2	1.2	1.3					
G145.0	1.3	1.3	1.3	1.3	1.3					
G150.0	1.3	1.4	1.3	1.4	1.4					
G155.0	1.4	1.4	1.4	1.5	1.4					
G160.0	1.5	1.5	1.5	1.5	1.5					
G165.0	1.5	1.5	1.6	1.6	1.6					
G170.0	1.6	1.6	1.6	1.6	1.6					
G175.0	1.7	1.7	1.7	1.7	1.7					
G180.0	1.7	1.7	1.7	1.7	1.7					

C Plane (°):0.0-90.0: 22.5
Gamma Plane (°):0.0-180.0:5.0
Test Lab: Illumination Engineering Laboratory , Electrical Engineering Department , Jadavpur University
Test Type: TYPE C
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Inspector: