STUDIES ON LUMINANCE OF VISUAL ADAPTATION FIELD IN MESOPIC PHOTOMETRY SYSTEM

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of the requirements of the degree of

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in
Illumination Engineering

Submitted by

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CERTIFICATE OFRECOMMENDATION

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CERTIFICATE OF APPROVAL

This foregoing thesis is hereby approved as a creditable study in the area of Illumination Engineering, carried out and presented by **DIPENDRANATH KISKU**, in a manner of satisfactory warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is notified to be understood that by this approval, the undersigned do not necessarily endorse or approved the thesis only for the purpose for which it has been submitted.

FINAL EXAMINATION FOREVALUATION OF THESIS.

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DECLARATION OF ORIGINALITY AND OF ACADEMIC ETHICS

I hereby declare that this thesis contains literature survey and original research work by the undersigned candidate, as part of my **Master of Engineering in Illumination Engineering** studies.

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

I also declare that, as required by these rules and conduct, I have fully cited and referenced all materials and results that are not original to this work.

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CHAPTER :1

INTRODUCTION

INTRODUCTION

The basis of all lighting technology and practice lies in photometry, the measurement of visible light.Photometry provides a method to assess light in terms of human visual spectral sensitivity. The mesopic luminance region covers a range of luminances between the scotopic and photopic regions. Mesopic lighting applications include road and street lighting, outdoor area lighting and other night-time traffic environments. In the mesopic region the spectral sensitivity of the human visual system is not constant and changes with light level. This is due to the changing contribution of the rods and cones on the retina. Thus, not only one mesopic spectral sensitivity function is needed but instead several functions are needed, together with a defined procedure for using these functions in a photometric measurement system .

In 2010, the Commission Internationale de l'Eclairage (CIE) published a system for visual performance-based mesopic photometry, which is valid between the luminances 0.005 cd/m^2 and 5 cd/m^2. In night-time driving conditions, the luminances in the visual scene are in the mesopic range; thus, mesopic photometry should be adopted when assessing lighting in outdoor areas and other night-time traffic environments.

Humans see differently at different light levels. This is because under high light levels typical during the day (photopic vision), the eye uses cones to process light. Under very low light levels, corresponding to moonless nights without electric lighting (scotopic vision), the eye uses rods to process light. At many night-time levels, a combination of both cones and rods supports vision. Photopic vision facilitates excellent colour discrimination ability, whereas colours are not discriminable under scotopic vision. Mesopic vision falls between these two extremes. In most night-time environments, there is enough ambient light at night to prevent true scotopic vision.

Mesopic photometry aims to measure light in a way which correlates with the mesopic vision. In mesopic photometry, adaptation luminance is needed to derive the Mesopic luminance for the measurement field. Adaptation luminance is the average luminance (or brightness) of those objects and surfaces in the immediate vicinity of an observer estimating the visual range.

The adaptation luminance has a marked influence on an observer's estimate of the visual range because, along with the visual angle of the object under observation, it determines the observer's threshold contrast. High adaptation luminance tends to produce a high threshold contrast, thus reducing the estimated visual range. This effect of the adaptation luminance is to be distinguished from the influence of background luminance.

1.1 Literature Survey

- **Roman Dubnièka, DionýzGašparovský , "Classification system for lighting design under condition of mesopic photometry". 2016 IEEE Lighting Conference of the Visegrad Countries**

From this paper we can understand that amount of adaptation luminance which is required for the computation or determination of the mesopic photometric quantity for example luminance or illuminance in mesopic photometry system. This is mainly dependent on visual field of observer and also value of this photometric quantity is different for various situations in scene of the visual field of observer. The paper deals with various situations which occur on the road under public lighting to analyse of possibility of assessment of adaptation luminance. The results can be used for creation of appropriate classification system for practice and lighting designer to allow calculation of the photometric parameters at roadlighting design .

- **M Maksimainen, M Puolakka, E Tetri and L Halonen, "Veiling luminance and visual adaptation field in mesopic photometry" . Lighting Res . Technol. 2017;Vol.49 ;743 - 762**

This paper states that, in mesopic photometry, adaptation luminance is needed to derive the Mesopic luminances for the measurement field. The average luminance of the visual adaptation field is considered as the adaptation luminance. The visual adaptation field has yet to be defined in terms of the size, shape, or location within the visual field. A study in three road lighting situations was conducted, in order to determine the practicability of using the road surface as the adaptation field compared to circular or elliptical adaptation fields. Currently, the road surface is used as the measurement field for calculating road lighting. Using the road surface as the adaptation field resulted in 76–113%, higher average luminance than obtained using circular or elliptical adaptation fields when the road was bordered by a park. High luminance sources outside of the visual adaptation field cause veiling luminance. Veiling luminance increases the adaptation state, but not the luminance within the measurement field. The bias veiling luminance can cause on mesopic luminance calculations was estimated to be less than 2%. The estimated bias can be considered negligible in practical road lighting measurements.

- **T Uchida, M Ayama, Y Akashi, N Hara, T Kitano, Y Kodaira, K Sakai, "Adaptation luminance simulation for CIE mesopic photometry system implementation". Lighting Res.Technol.2016 ;Vol.48 ; 14-25**

This paper described a simulation method to determine adaptation luminance is proposed for implementation of the CIE mesopic photometry system. The simulation takes four factors into account: luminance distribution, eye movement of observers, surrounding luminance effect and area of measurement. Each factor is modelled as a two-dimensional geometrical function. The method determines an adaptation luminance for the area of measurement through four calculation steps. The simulation method was applied to examples of luminance distributions of outdoor lit scenes and the results were compared with possible simple predictors of adaptation luminance. The comparisons suggest that the average luminance of the area of measurement can be considered as a good approximation in most of the cases. Exceptions are scenes for pedestrians in which there are many bright sources surrounding the area of measurement.

- **T Uchida, YOhno, "Simplified field measurement methods for CIE mesopicPhotometry System". Lighting Res. Technol .2017 ; Vol.49. ;774- 787**

This paper discussed that , for implementation of the mesopic photometry system in CIE 191:2010 to outdoor lighting, two simplified methods to measure the mesopic luminance are proposed. One of the methods, named the Adaptation Spectral Power Distributionmethod, assumes that the spectral power distributions (SPDs) of reflected light at test points on the road surface are the same as that of the adaptation field. Another method, named the Source SPD method, assumes that the reflected light SPDs are equal to the SPD of the light source. Error simulations with a real road surface spectral reflectance dataset show that the error distributes over an 8% range due to the variation of the road surface spectral reflectance in the worst case. Although the bias due to the road surface spectral reflectances causes a large error with the Source SPD method, a proposed correction can reduce the error sufficiently. Error simulations also show that the Source SPD method is not so sensitive for lighting scenes that include multiple light source types. It has been shown that the SPD methods can measure the mesopic quantities without scotopic/photopicluminance meters having both $V(\lambda)$ and $V'(\lambda)$ detectors when both the adaptation field and test points consist of road surfaces.

- **T Uchida, Y Ohno, "Defining the visual adaptation field for mesopic photometry: Effect of surrounding source position on peripheral adaptation".Lighting Res. Technol .2017 ; Vol.49 ; 763 -773**

This paper states that, in CIE 191:2010, the Commission Internationale de l'Eclairage recommends a mesopic photometry system based on peripheral visual tasks. For implementation of the system, the visual adaptation field needs to be defined, taking into account the surrounding luminance effect on the state of adaptation. A series of vision experiments in the mesopic range has been conducted to measure the surrounding luminance effect with respect to the angle between a peripheral task point and a point source. The results show that the surrounding luminance effect at a peripheral task point decreases with increasing angle at a larger slope than existing models, such as the Stiles-Holladay equation, the Commission Internationale de l'Eclairage general disability glare formula and the Stiles–Crawford equation. A new model for the surrounding luminance effect is proposed.

1.2 Problem Definition

Outdoor lighting installations incorporate different types of white Light Emitting Diode (WLED) lamps. The luminance level generally lies in Mesopic zone for different types of outdoor lighting. Adaptation luminance is also a factor for outdoor lighting. The performance for Cool White LED lamps in outdoor lighting scenario under Mesopic luminance range and adaptation luminance of this lamp are studied here.

1.3 Objectives

The objectives of the thesis are

- To study the behaviour of cool white LED lamps under mesopic conditions.
- Simulation of Adaptation Luminance.
- To compare adaptation luminance & mesopic luminance of cool white LED lamp under different surrounding luminance conditions.

1.4 Methodology

- Determination of photopic luminance from Luminous Intensity table.
- Measurement of photopic luminance and vertical illuminance under cool white LED lamp and adaptation conditions.
- Determination of S/P ratios, CCT & SPD of the lamps.
- Calculation of Mesopic Luminance.
- Simulation of adaptation luminance using MATLAB software.
- Comparison of the obtained results by graphical and analytical comparative studies.

1.5 Chapter Details

Chapter1 of this thesis work states the introduction of the thesis and gives us methodology of this thesis work.

Chapter2 discusses history and evolution of mesopic photometry and gives the details of CIE publication 191:2010, Mesopic Photometry

Chapter3 discusses the importance of Adaptation luminance in Mesopic photometry system.

Chapter4 gives the procedure to conduct the experiment.

Chapter5 of this thesis work determination of theoretical photopic luminance and measurement of photopic luminance and vertical illuminance has done.

Chapter6 deals with calculated values of Mesopic Luminance.

Chapter7 deals with simulated values of Adaptation Luminance.

Chapter8 discuss and analyse the results of the experiment.

Chapter9 states the conclusion and future scope of this thesis work .

CHAPTER :2

MESOPIC PHOTOMETRY

2.1 Mesopic Photometry: CIE 191:2010

The aim of photometry is to measure light in such a way that the results correlate with human vision. Traffic signals and computer displays, for example, are meant for human eyes, and therefore, must be evaluated based on the spectral responsivity of the average human eyes. While radiometry covers all spectral regions from ultraviolet to infrared, photometry deals with only the spectral region from 380 to 780 nm (the visible region) where human eyes are sensitive. Photometry is essential for evaluation of light sources and objects used for lighting, signaling, displays, and other applications where light is seen by the human eye.
In order to achieve the aim of photometry, one must take into account the characteristics of human vision. The relative spectral responsivity of the human eye was first defined by the Commission Internationale de l’E´clairage (CIE), (the International Commission on Illumination), in 1924. It iscalled the spectral luminous efficiency for photopic vision, with a symbol V(λ), defined in the domain from 380 to 780 nm, and is normalized to unity at its peak, 555 nm . The luminance level is very high (luminance levels more than 5 cd/m^2) in the photopic vision and in the eyes cones are the dominant receptors . The spectral responsivity of human eyes deviates significantly at very low levels of luminance (luminance levels less than 0.005 cd/m^2) when the rods in the eyes are the dominant receptors. This type of vision is called scotopic vision. Its spectral responsivity, peaking at 507 nm, as shown in Fig 2.1, is designated as V’(λ) , and was defined by CIE in 1951[CIE 1951]. The human vision in the region between photopic vision and scotopic vision is called mesopic vision.At adaptation luminance levels between approximately 5 and 0.005 cd/m^2 both the cones and the rods are active. In the mesopic vision range, the activity of the rods becomes more important from high to low adaptation levels. As a result, the spectral sensitivity gradually shifts into the direction of small wavelength. In the mesopic vision range, light sources containing more cool white light than warm white light are more efficient for vision[Van Bommel 2015]. Claims are sometimes exaggerated and sometimes made when they are not valid at all. Such claims are valid for peripheral vision but not for on-line vision.

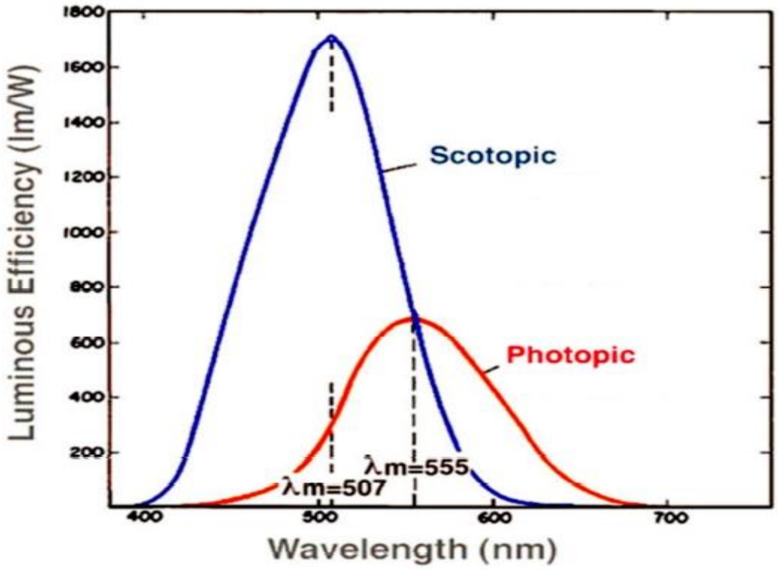


Fig 2.1 The Photopic and Scotopic Luminous Efficiency Functions

2.2 S/P RATIO

The ratio of the luminous flux output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function V’(λ), to the luminous flux output evaluated according to the CIE photopic spectral luminous efficiency function V(λ) is termed as the scotopic to photopic ratio, denoted as S/P ratio.

$$S/P\ Ratio = \frac{K'_m \int S_\lambda(\lambda)V'(\lambda)d\lambda}{K_m \int S_\lambda(\lambda)V(\lambda)d\lambda}$$

Where ,

K'_m = 1700 lm/W is the maximum value of the spectral luminous efficacy for scotopic vision ,V’(λ) .

K_m= 683 lm/W is the maximum value of the spectral luminous efficacy for photopic vision, V(λ) .

$S_\lambda(\lambda)$ is the spectral power distribution of the light source.

‘λ’ is the wavelength.

2.3 MESOPIC VISION : HISTORY

Firstly, spectral luminous efficiency function for photopic vision V(λ) was introduced, then came the spectral luminous efficiency function for scotopic vision V'(λ), but there still existed a condition which is neither photopic nor scotopic. So, to fulfil the visual requirements and visual satisfaction under this condition, mesopic photometry was introduced.

Till the mid-1990s most of the research in this segment was based on brightness matching criterion between the target object and the surface adjacent to it. Seven of the nine initial models of mesopic photometry are based on this criterion. Later with the realization that, detection and recognition of the object is much more relevant than brightness matching, came the criterions based on visual task performance experiments. The first two mesopic models based on task performance show that under off-axis reaction time is dependent on the light spectrum whereas for on-axis the reaction time is independent of the spectrum of light. After that from a few more experiments it was clearly revealed that there exists a strong spectral effect in detection of off-axis target. The most remarkable finding of CIE mesopic system is the formation of a table where values of mesopic luminance corresponding to particular photopic luminance for all relevant S/P ratios are present. Though this table has an enormous importance, there is no clear instructions present to use it for practical application. Research is still going on in this domain to determine the most appropriate criterion of defining mesopic photometry.

The International Commission on Illumination (CIE) has published a recommendation for a performance based mesopic photometry system CIE 191:2010[CIE 2010]. The system provides a bridge between scotopic and photopic photometry. It has been developed with an emphasis on the visual performance in road and street lighting applications. According to the CIE 191 system, mesopic luminous efficiency $V_{mes}(\lambda)$ is a linear combination of the photopic $V(\lambda)$ and scotopic V (λ) luminous efficiency functions.

2.3.1 BRIEF DESCRIPTION OF MESOPIC MODELS

In the past many attempts were made to develop a model for mesopic vision. Several authors have measured the spectral sensitivity functions in the mesopic domain (Walters and Wright, 1943; Kinney, 1958; Palmer, 1968; Kokoschka and Bodmann, 1975; Ikeda and Shimozono, 1981; Yaguchi and Ikeda, 1984; Sagawa and Takeichi, 1986; Sagawa and Takeichi, 1987; He et al., 1998)[CIE 2001]. All these studies proposed a specific spectral sensitivity as a function of the adaptation light level in the mesopic range. However, it appeared to be difficult to establish a consistent mesopic model. In 1989 the CIE published are port on the status of mesopic photometry, without actually establishing a standard model for mesopic vision (CIE, 1989). After that publication new methods and refinements of the existing models were proposed. In 2001 a new CIE report was published (CIE, 2001), updating the CIE publication of 1989. Seven mesopic models were addressed in this publication, which are based on 100 visual field and heterochromatic brightness matching (HCBM). Table 2.1 lists these mesopic models and their most important parameters, together with four mesopic models based on reaction time (RT) which were published elsewhere. With these models it is possible to calculate the so-called equivalent luminance, using various types of input variables. The equivalent luminance is defined as the luminance of the reference stimulus (formally with wavelength of nearly 555 nm, but also often a broadband white light) that appears equal to the test stimulus in brightness (CIE, 2001). The equivalent luminance has a better correlation to the visual impression or task performance than the common photopic luminance based on the $V(\lambda)$ function. Instead of the more formal term equivalent luminance, the term mesopic luminance will be used in this study to designate the output of mesopic models. The seven models are based on HCBM experiments in which the task of the subjects was to match the brightness of two parts of a static stimulus with a diameter of 10 degrees. The currently widely-used luminous efficiency function for photopic vision, $V(\lambda)$, is mainly based on flicker photometry using a 2-degreefield in which the two parts of the stimulus are compared by presenting them in an alternating mode. These differences in the tasks and conditions result in different shapes of the spectral sensitivity function in photopic conditions. A stimulus with a saturated colour (e.g. monochromatic blue or red) that has the same luminance as a white stimulus is perceived as brighter than the white stimulus. This effect is known as the Helmholtz–Kohlrausch effect (Wyszecki and Stiles, 1982). Therefore the spectral sensitivity functions based on photopic brightness matching are wider than the luminous efficiency function $V(\lambda)$ which is incorporated in the vast majority of all luminance meters and illuminance meters. The spectral luminous efficiency function for scotopic vision, $V'(\lambda)$, is determined by HCBM using a 20-degree field (CIE, 1983).Thus, because of differences in task and stimulus diameter, it is difficult to merge the sensitivity functions to a single model. There is no smooth connection between the existing spectral sensitivity data in the mesopic domain and the current spectral sensitivity standards for scotopic, $V'(\lambda)$, at the lower end of the mesopic range, and for photopic vision, $V(\lambda)$, at the higher end of the mesopic range. The problem of the difference in the field size can be solved by applying the spectral luminous efficiency function for the 10 degree CIE-observer,V_{10}(λ),for the photopic domain, instead of the more generally used spectral luminous efficiency function for the 2-degree CIE-observer, V(λ).Another problem is that the spectral sensitivity functions based on brightness matching suffer from a failure of additive feature. Additive feature is essential for photometry (Abney's law). The additive problem can be tackled by using flicker photometry or a similar method. The V(λ) and V_{10}(λ)functions are based on flicker photometry and have been shown to obey Abney's law (Wyszecki and Stiles, 1982). The models 8 and 9 are based on RT. The authors claim that these models do not suffer from the problems of models which are based on brightness matching (He et al., 1997, 1998).They state that in a reaction time task, just as in flicker photometry, the fast magnocellular channel, rather than the slow parvocellular channel, is being used. It is thought that the magnocellular channel is used for the fast transportation of the brightness signal; the parvocellular channel is slower and transports both the brightness and colour signals. Only the magnocellular channel appears to obey Abney's law of additivity. Therefore, the results of the reaction time experiments can be directly compared with luminance data obtained with the spectral luminous efficiency functions for photopic vision, V(λ) and V10(λ). As both He models include peripheral measurements these models make use of the wide field V_{10}(λ) rather than the V(λ) for describing the luminance at photopic light levels. Foveal vision measured by reaction times might be modelled by V(λ) for any light level (He et al., 1997).

The reaction time task is directly linked to the performance task of driving a vehicle. One of the tasks of driving a vehicle is avoiding a potential hazard on the road and therefore a fast reaction is essential. Potential hazards, such as cars, pedestrians, and animals, do not always appear in front of the car, often they can come into view from the side. For that reason, off-axis detection is also important.The rods play an important role for off-axis detection, so the photopic luminance based on the V(λ) function is inadequate. It should be noted that the first seven models in Table 3.a. do not account for the eccentricity of the stimulus, i.e. eccentricity is not a parameter in the model.Models 8, 9, 10, and 11 are all based on reaction time measurements of two studies (He et al., 1997, 1998) .

$$V_{mes}(\lambda, L_{mes}) = k\{x(L_{mes})V_{10}(\lambda) + [1 - x(L_{mes})]V'(\lambda)\}$$

Which ensures that the maximum value of V_{mes}(λ) is unity. The mesopic luminance, L_{mes}, is calculated by applying the calculated spectral luminous efficiency function for mesopic vision in the integration over the visual part of the spectrum

$$L_{mes} = K_{mes} \int V_{mes}(\lambda, L_{mes}) L_e(\lambda) d\lambda$$

The factor K_{mes} is equal to 683 lm/W divided by the value of V_{mes}(λ) for a wavelength of λ= 555 nm and L_e(λ) is the spectral radiance in W m^{-2} s^{-1}. Note that the light level used to calculate the weighting factor x in turn is used as mesopic luminance. Hence, the calculation of the mesopic luminance is a complicated iterative algorithm that must be repeated until a sufficiently accurate value of L_{mes} is obtained.

Model 9 differs from model 8 because of a slightly different function for the weighting factor. The algorithm is also iterative and more complicated because the light level is expressed as mesopic retinal illuminance rather than as mesopic luminance. Model 9 also determines the spectral luminous efficiency function for mesopic vision, $V_{mes}(\lambda)$, by weighting the spectral luminous efficiency functions $V'(\lambda)$ and $V_{10}(\lambda)$.Model 10 is designed according to the same weighting principle as applied in models 8 and 9. The difference is that now the more common efficiency function for photopic vision for a 2-degree field size, $V(\lambda)$, is used instead of $V_{10}(\lambda)$. The second simplification is that the weighting factor is a function of the photopic luminance L and the ratio of scotopic and photopic luminance, S/P(2-degree observer). Therefore, the calculation procedure is not iterative. Model 11, the unified luminance model, is the simplest model (Rea et al., 2004), which only needs the photopic luminance and scotopic luminance as input, rather than the spectral radiance data as in previous models. The model consists of a closed form equation and the calculation is not iterative. As the reaction time task is highly relevant for traffic, and additivity is preserved, it can be concluded that spectral Model 8 is based on the calculation of the spectral luminous efficiency function for mesopic vision, $V_{mes}(\lambda)$,by weighting the spectral luminous efficiency function for scotopic vision, $V'(\lambda)$, and the spectral luminous efficiency function for photopic vision with 10 degrees' field size, $V_{10}(\lambda)$ according to equation:

The weighting factor, x, depends on the light level. The factor k is a normalization constant sensitivity determined with a reaction time task would seem to be a promising candidate for a mesopic model.

Table 2.1 A list of Mesopic models in the 2001 CIE report (No. 1–7) and the models of He and Rea (No. 8–11) [Eloholma 2005]

No.	Model	Field diameter (degrees)	Task	Eccentricity (degrees)	Input variables	References
1.	Palmer 1	10	HCBM	0	L_{10} ,L'	Palmer,1968
2.	Palmer 2	10	HCBM	0	L_{10} ,L'	CIE,1989,2001
3.	Sagawa-Takeichi	10	HCBM	0	L_{10} ,L', X,Y,Z	Ikeda and Shimozono,1981; CIE 1989
4.	Nakano-Ikeda	10	HCBM	0	L', X_{10},Y_{10},Z_{10}	Sagawa and Takeichi,1987,1992
5.	Kokoschka-Bodmann	10	HCBM	0	L', X_{10},Y_{10},Z_{10}	Kokoschka and Bodmann,1975; Kokoschka 1980
6.	Trezona	10	HCBM	0	L', X_{10},Y_{10},Z_{10}	Trezona, 1987,1990
7.	Ashizawa	10	HCBM	0	$V_{10}(\lambda)$,$V'(\lambda)$	Ashizawa et al,1985
8.	He 1	2	RT	15	$L_e(\lambda)$	He et al 1997
9.	He 2	2	RT	12	$L_e(\lambda)$	He et al 1998
10	Rea	2	RT	Non-foveal	$L_e(\lambda)$	Rea et al 2003
11	Unifl	2	RT	Non-foveal	L_e ,L	Rea et al 2004

2.4 RECOMMENDED SYSTEM FOR PERFORMANCE BASED MESOPIC PHOTOMETRY

The recommended system for visual performance based mesopic photometry describes spectral luminous efficiency, $V_{mes}(\lambda)$, in the mesopic region as a linear combination of the photopic spectral luminous efficiency function, $V(\lambda)$, and the scotopic spectral luminous efficiency function, $V'(\lambda)$, and establishes a gradual transition between these two functions throughout the mesopic region. The system is of the form:

$$M(m)V_{mes}(\lambda) = mV(\lambda) + (1-m)V'(\lambda) \text{for } 0 \leq \text{m} \leq 1$$

$$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} \int V_{mes}(\lambda) L_e(\lambda) d\lambda$$

Where,

M(x) is a normalizing function such that $V_{mes}(\lambda)$ attains a maximum value of 1

$V_{mes}(\lambda_0)$ is the value of $V_{mes}(\lambda)$ at 555 nm

L_{mes} is the mesopic luminance

$L_e(\lambda)$ is the spectral radiance in $W \cdot m^{-2} \cdot sr^{-1} \cdot nm^{-1}$

if$L_{mes} \geq 5.0$ cd·m^{-2}, then m = 1

if$L_{mes} \leq 0.005$ cd·m^{-2}, then m = 0

The coefficient m and the mesopic luminance, L_{mes}, can be calculated using an iterative approach as follows:

$m_0 = 0.5$

$$L_{mes,n} = \frac{m_{(n-1)} L_p + (1 - m_{(n-1)}) L_s V'(\lambda_0)}{m_{(n-1)} + (1 - m_{(n-1)}) V'(\lambda_0)}$$

$$m_n = a + b \log_{10}(L_{mes,n}) \text{for} 0 \leq \text{m} \leq 1$$

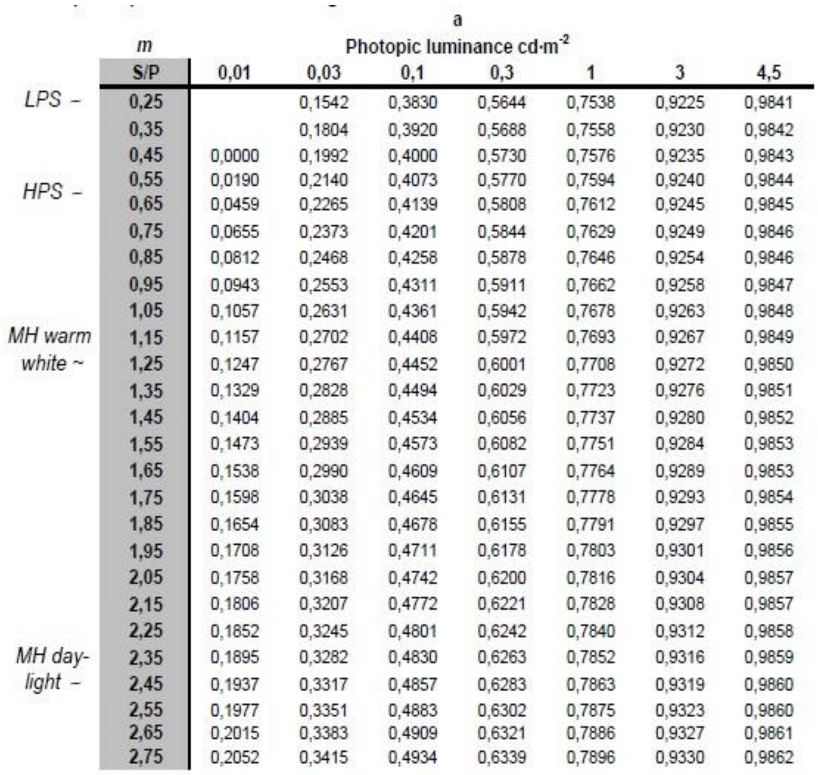
Where L_p is the photopic luminance, L_s is the scotopic luminance, and $V'(\lambda_0) = 683/1699$ is the value of scotopic spectral luminous efficiency function at λ_0=555 nm, a and b are parameters which have the values a = 0.7670 and b = 0.3334, and n is the iteration step.

The values of m and L_{mes} for this system as a function of photopic luminance and light source S/P-ratio (ratio of scotopic-to-photopic luminous output) are given in Table 2.2.

The system is proposed for evaluation of lighting for visual tasks in the peripheral region of the visual field in the mesopic region; it is recommended that on-axis tasks, where foveal vision is dominant, should be evaluated using the photopic spectral luminous efficiency function, V(λ).

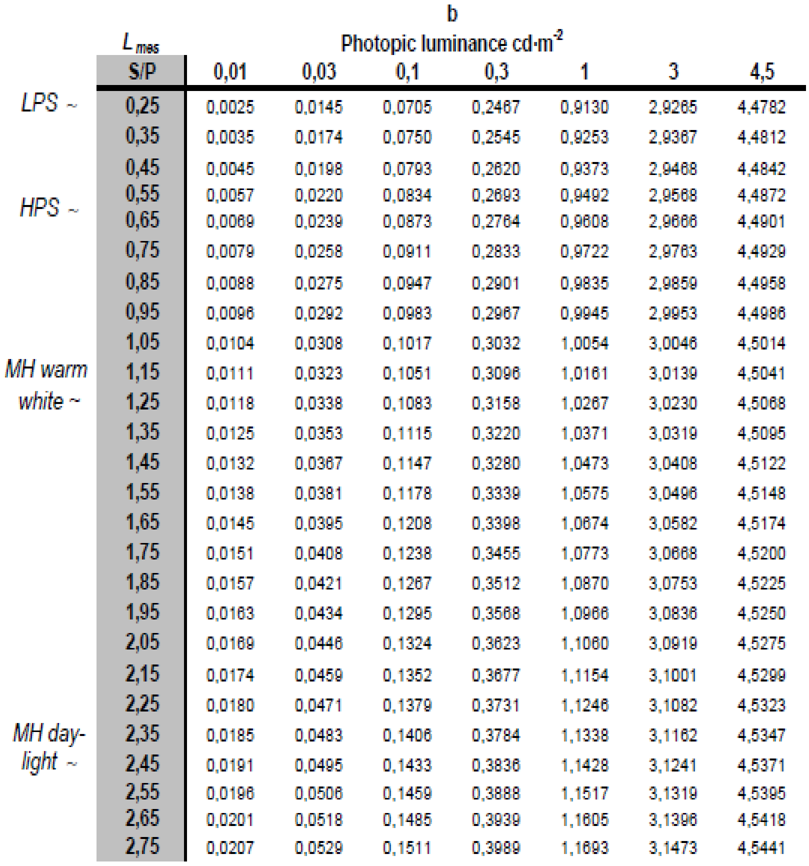
A requirement of the recommended system is that it should (within limits) provide a result that is meaningful in relation to human visual psychophysics and provide a correlation with visual performance under a range of different conditions. The degree of correlation with task performance was used as one criterion in determining the recommended system. The other criteria were the practical utility of the system and the requirement that it should maintain additivity, which is an underlying requirement of CIE photometry. The recommended system is an intermediate between the USP- (Rea et al 2004) and MOVE-systems (Goodman et al 2007) and (similarly to them) describes mesopic spectral luminous efficiency in terms of a linear combination of the photopic and scotopic spectral luminous efficiency functions that provides a gradual transition between these functions through the mesopic region. The mesopic spectral luminous efficiency functions derived using this system are additive in nature and provide a bridge between the current photopic and scotopic functions, with the further advantage of being relatively easy to implement in a practical measurement system, as well as providing a meaningful correlation with actual task performance. Thus this recommended system represents an effective and practical solution to mesopic photometry, based upon more than a decade of visual psychophysical studies and nearly a century of photometric metrology principles.

Table:2.2 a) Adaptation Coefficient *m* and b) L_{mes} of the recommended mesopic system as a function of photopic luminance and S/P-ratio of light source.



a

	m	Photopic luminance cd·m^{-2}						
	S/P	**0,01**	**0,03**	**0,1**	**0,3**	**1**	**3**	**4,5**
LPS –	**0,25**		0,1542	0,3830	0,5644	0,7538	0,9225	0,9841
	0,35		0,1804	0,3920	0,5688	0,7558	0,9230	0,9842
	0,45	0,0000	0,1992	0,4000	0,5730	0,7576	0,9235	0,9843
HPS –	**0,55**	0,0190	0,2140	0,4073	0,5770	0,7594	0,9240	0,9844
	0,65	0,0459	0,2265	0,4139	0,5808	0,7612	0,9245	0,9845
	0,75	0,0655	0,2373	0,4201	0,5844	0,7629	0,9249	0,9846
	0,85	0,0812	0,2468	0,4258	0,5878	0,7646	0,9254	0,9846
	0,95	0,0943	0,2553	0,4311	0,5911	0,7662	0,9258	0,9847
	1,05	0,1057	0,2631	0,4361	0,5942	0,7678	0,9263	0,9848
MH warm white ~	**1,15**	0,1157	0,2702	0,4408	0,5972	0,7693	0,9267	0,9849
	1,25	0,1247	0,2767	0,4452	0,6001	0,7708	0,9272	0,9850
	1,35	0,1329	0,2828	0,4494	0,6029	0,7723	0,9276	0,9851
	1,45	0,1404	0,2885	0,4534	0,6056	0,7737	0,9280	0,9852
	1,55	0,1473	0,2939	0,4573	0,6082	0,7751	0,9284	0,9853
	1,65	0,1538	0,2990	0,4609	0,6107	0,7764	0,9289	0,9853
	1,75	0,1598	0,3038	0,4645	0,6131	0,7778	0,9293	0,9854
	1,85	0,1654	0,3083	0,4678	0,6155	0,7791	0,9297	0,9855
	1,95	0,1708	0,3126	0,4711	0,6178	0,7803	0,9301	0,9856
	2,05	0,1758	0,3168	0,4742	0,6200	0,7816	0,9304	0,9857
	2,15	0,1806	0,3207	0,4772	0,6221	0,7828	0,9308	0,9857
	2,25	0,1852	0,3245	0,4801	0,6242	0,7840	0,9312	0,9858
MH day-light –	**2,35**	0,1895	0,3282	0,4830	0,6263	0,7852	0,9316	0,9859
	2,45	0,1937	0,3317	0,4857	0,6283	0,7863	0,9319	0,9860
	2,55	0,1977	0,3351	0,4883	0,6302	0,7875	0,9323	0,9860
	2,65	0,2015	0,3383	0,4909	0,6321	0,7886	0,9327	0,9861
	2,75	0,2052	0,3415	0,4934	0,6339	0,7896	0,9330	0,9862



	L_{mes}	b Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	0,25	0,0025	0,0145	0,0705	0,2467	0,9130	2,9265	4,4782
	0,35	0,0035	0,0174	0,0750	0,2545	0,9253	2,9367	4,4812
	0,45	0,0045	0,0198	0,0793	0,2620	0,9373	2,9468	4,4842
HPS ~	0,55	0,0057	0,0220	0,0834	0,2693	0,9492	2,9568	4,4872
	0,65	0,0069	0,0239	0,0873	0,2764	0,9608	2,9666	4,4901
	0,75	0,0079	0,0258	0,0911	0,2833	0,9722	2,9763	4,4929
	0,85	0,0088	0,0275	0,0947	0,2901	0,9835	2,9859	4,4958
	0,95	0,0096	0,0292	0,0983	0,2967	0,9945	2,9953	4,4986
	1,05	0,0104	0,0308	0,1017	0,3032	1,0054	3,0046	4,5014
MH warm white ~	1,15	0,0111	0,0323	0,1051	0,3096	1,0161	3,0139	4,5041
	1,25	0,0118	0,0338	0,1083	0,3158	1,0267	3,0230	4,5068
	1,35	0,0125	0,0353	0,1115	0,3220	1,0371	3,0319	4,5095
	1,45	0,0132	0,0367	0,1147	0,3280	1,0473	3,0408	4,5122
	1,55	0,0138	0,0381	0,1178	0,3339	1,0575	3,0496	4,5148
	1,65	0,0145	0,0395	0,1208	0,3398	1,0674	3,0582	4,5174
	1,75	0,0151	0,0408	0,1238	0,3455	1,0773	3,0668	4,5200
	1,85	0,0157	0,0421	0,1267	0,3512	1,0870	3,0753	4,5225
	1,95	0,0163	0,0434	0,1295	0,3568	1,0966	3,0836	4,5250
	2,05	0,0169	0,0446	0,1324	0,3623	1,1060	3,0919	4,5275
	2,15	0,0174	0,0459	0,1352	0,3677	1,1154	3,1001	4,5299
	2,25	0,0180	0,0471	0,1379	0,3731	1,1246	3,1082	4,5323
MH daylight ~	2,35	0,0185	0,0483	0,1406	0,3784	1,1338	3,1162	4,5347
	2,45	0,0191	0,0495	0,1433	0,3836	1,1428	3,1241	4,5371
	2,55	0,0196	0,0506	0,1459	0,3888	1,1517	3,1319	4,5395
	2,65	0,0201	0,0518	0,1485	0,3939	1,1605	3,1396	4,5418
	2,75	0,0207	0,0529	0,1511	0,3989	1,1693	3,1473	4,5441

2.5 SYSTEMS FOR MESOPIC PHOTOMETRY BASED ON VISUAL TASK PERFORMANCE

The foundations for any system of photometry must lie in empirical visual performance data using human subjects. Photometry has always had its roots in human visual psychophysics. Significantly, however, the current system of photometry is truly representative of the spectral sensitivity of human vision for only a very limited number of visual tasks. The spectral sensitivity of the visual system for mesopic vision is not well represented by either of the spectral luminous efficiency functions, V(λ) and V′(λ), that currently underlie photometry.

It is worth noting that no single system can ever hope to provide a complete prediction of visual performance for all tasks and lighting conditions. Vision is a hugely complicated process and the spectral luminous efficiency of the eye is influenced by a large number of factors. These factors include size and location of the stimulus in the visual field, ambient light level and spectrum, stimulus contrast and spectrum, and speed of response required by the task being conducted. Changing any of these parameters will change the efficiency of the visual system and the ability to perform the requisite task (Rea and Bullough 2007, Eloholma 2005).

Instead of trying to describe the detailed performance of the eye under a given set of conditions, the emphasis in this Technical Committee has been on developing a system of photometry for the mesopic region which can be readily implemented in practice, but which may not provide a precise description of visual performance. This places two important constraints on the system:

- It must be additive
- It must tend to V(λ) at the upper end of the mesopic region and to V′(λ) a the lower end

The simplest form of a system for mesopic photometry that satisfies these constraints is a linear combination of the photopic and scotopic spectral luminous efficiency functions, of the form:

$$V_{mes} = yV(\lambda) + (1-y)V'(\lambda) \text{y being a function of luminance}$$

The mesopic spectral sensitivity functions, $V_{mes}(\lambda)$, defined by such a system are, by definition, additive in nature (since both V(λ) and V′(λ) are additive), but it must be remembered that due to the dependence of mesopic spectral sensitivity on the state of adaptation of the eye, additivity applies only within a given adaptation level.

The two recently proposed visual performance based systems for mesopic photometry, namely the USP-system (Rea et al. 2004) and the MOVE-system (Goodman et al., 2007), both take the form presented above, thus bridging the photopic and scotopic domains and preserving the fundamental requirement of additivity. The different experimental conditions underlying these two systems result in differences between the systems, a major difference being the transition point between the mesopic and photopic regions. Also, the different characteristics of the adaptation coefficient (designated X in the USP-system, and x in the MOVE-system), result in different predictions of mesopic values calculated with the two systems. In addition to the USP- and MOVE-systems, an Intermediate system is also considered in this report. The Intermediate system has the form presented above, and like the MOVE-system has a log-linear relationship between 'y' and mesopic luminance, but has adjusted upper and lower luminance limits for the mesopic region .

2.5.1 USP-SYSTEM

Two investigations by He et al. (1997, 1998) form the experimental basis of the USP-system. In the first work of He et al. (1997) reaction times were measured monocularly under two light sources (HPS and MH) at eight luminance levels between 0.003 cd/m^2 and 10 cd/m^2. A target contrast of C = 2.3, was used in the experiments. The spectral power distributions of the test target and the adaptation backgrounds were the same i.e. the only information available to the visual system was the achromatic content of the stimulus. (More specifically, the tasks involved luminance contrast with no colour contrast.) The resultant system was a linear combination of the scotopic V′(λ) and the 10^0photopic $V_{10}(\lambda)$ functions. The system is based on reaction time data for two subjects. According to He et al. (1997) visual inspection of the two subjects' off-axis reaction time data showed a separation between the two light sources below 0.3 cd/m^2, but no clear separation was observed above 1 cd/m^2. As the midpoint between these luminances in log units is 0.6 cd/m^2, and the paper described that the rod-cone discontinuity at about this luminance, the 0.6 cd/m^2 luminance value was chosen by

He et al. as a convenient point of bifurcation on fitting the data curves. Based on the reaction time data, He et al. concluded that there is no rod contribution above 0.6 cd·m^{-2} to the reaction time task investigated. An independent study of Bierman et al. (1998) confirmed the reaction time data of He et al. (1997) by using reaction time differences of the two eyes as the criterion.

In the second work by He et al. (1998) mesopic spectral luminous efficiency functions of one subject were measured using a method of reaction time differences between the two eyes. In this binocular simultaneity method, luminous efficiencies for five quasi-monochromatic stimuli (half bandwidth of 10 nm, peaks at 436 nm, 470 nm, 510 nm, and 630 nm) were measured against a yellow reference field (monochromatic 589 nm) at three light levels (0.3 Td, 3 Td, 10 Td). Thus in this experimental study the spectral power distribution of the reference field was different from that of the test field and each eye was adapted to a different condition (i.e. light level and wavelength).The derived mesopic spectral luminous efficiency functions were fitted with the linear model developed in the earlier work of He et al. (1997). The transition point between mesopic and photopic regions was not reached within the retinal illuminance range studied (0.3 Td, 3 Td, 10 Td). Using a relationship between adaptation coefficient and retinal illuminance, the transition point for the data of the one subject in question was estimated to occur at 21 Td, corresponding to a luminance level of 1.7 cd/m^2. The latter study of He et al. (1998) resulted in an iterative computational procedure for calculating mesopic light levels. In this procedure, the transition point between mesopic and photopic regions occurs at 21 Td. When the monocular viewing used in the previous study by He et al. (1997) is transferred to correspond to binocular viewing conditions, the transition point of 0.6 cd/m^2 corresponds to a retinal illuminance value of 25 Td as remarked by He et al. (1998).

Table 2.3: The experimental conditions underlying the USP-system (He et al. 1997, He et al. 1998)

Method	Stimuli	Contrast	Luminance	Subject	
RT	MH and HPS	2.3	0.003-10 cd/m^2	2	3
RT	470,510,546,630 nm	2.3	0.3,3,10 Td	1	

Half bandwidth = 10 nm $C = (L_t - L_b)/L_b$

The USP formulation is proposed by Rea et al. (2004) as a unified system of photometry. In the mesopic region the parameter X is used to calculate mesopic luminous efficiency $V_{mes}(\lambda)$ as a linear transition between the scotopic V'(λ) and the photopic V(λ) functions and is of the form

$$V_{mes}(\lambda) = XV(\lambda) + (1 - X)V'(\lambda) \qquad \text{for } 0 \leq X \leq 1$$

where $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function under the given conditions, V(λ) is the photopic spectral luminous efficiency function, V'(λ) is the scotopic spectral luminous efficiency function, and X is a parameter characterizing the relative proportions of the photopic and scotopic luminous efficiency at any luminance level. In the scotopic region the USP-system is equivalent to current scotopic photometry and in the photopic region it is equivalent to current photopic photometry, as also are the other systems described in this report.

In proposing the USP-system Rea et al. (2004) made several simplifications to the approaches of the works of He et al. Firstly, since the pupil size is large and essentially constant below 1 cd/m^2, it was assumed that a constant pupil diameter of 7 mm could be taken to apply, so that the transition point between the mesopic and photopic regions determined from each of the two studies (He et al. 1997, He et al. 1998) are in substantial agreement. This led to the choice of 0.6 cd/m^2 as the transition point between the mesopic and photopic regions. Secondly, the relationship between the coefficient X and mesopic luminance was assumed to be linear between 0.001 cd/m^2 and 0.6 cd/m^2 in order to develop a closed-form solution for X. And thirdly, in the final form of the USP-system, $V_{10}(\lambda)$ was substituted by $V(\lambda)$, based on the observation that for most practical conditions photometric quantities based on $V(\lambda)$ and $V_{10}(\lambda)$ do not differ substantially.

Below equations give the closed-form expression for calculating the mesopic luminance L_{mes} and the corresponding coefficient X.

$$L_{mes} = 0.834L_p - 0.335L_s - 0.2 + \sqrt{0.696L_p^2 - 0.333L_p - 0.56L_pL_s + 0.113L_s^2 + 0.537L_s + 0.04}$$

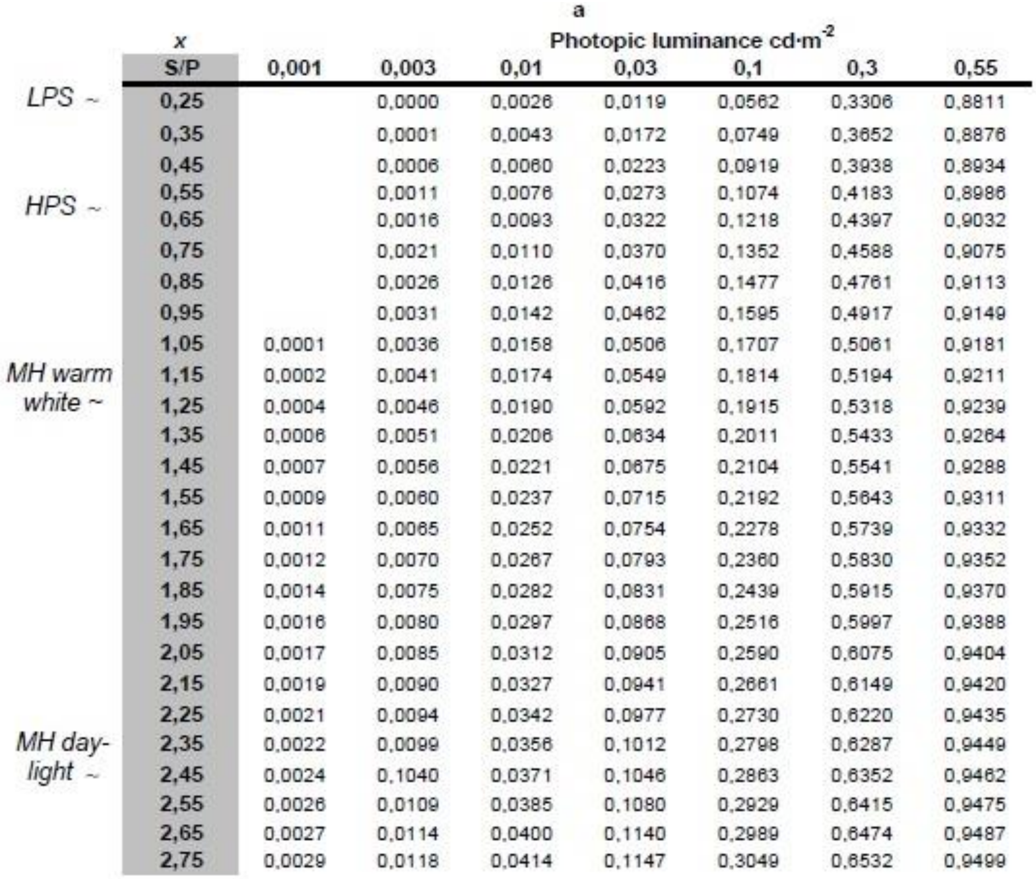
For $0.001<L_{mes}<0.6$

$X = mL_{mes} + \beta$ for $0 \leq X \leq 1$

Where L_p is the photopic luminance, L_s is the scotopic luminance, and m and β are coefficients given by m = 1/0.599 and β = -0.001/0.599 (Rea et al 2004).

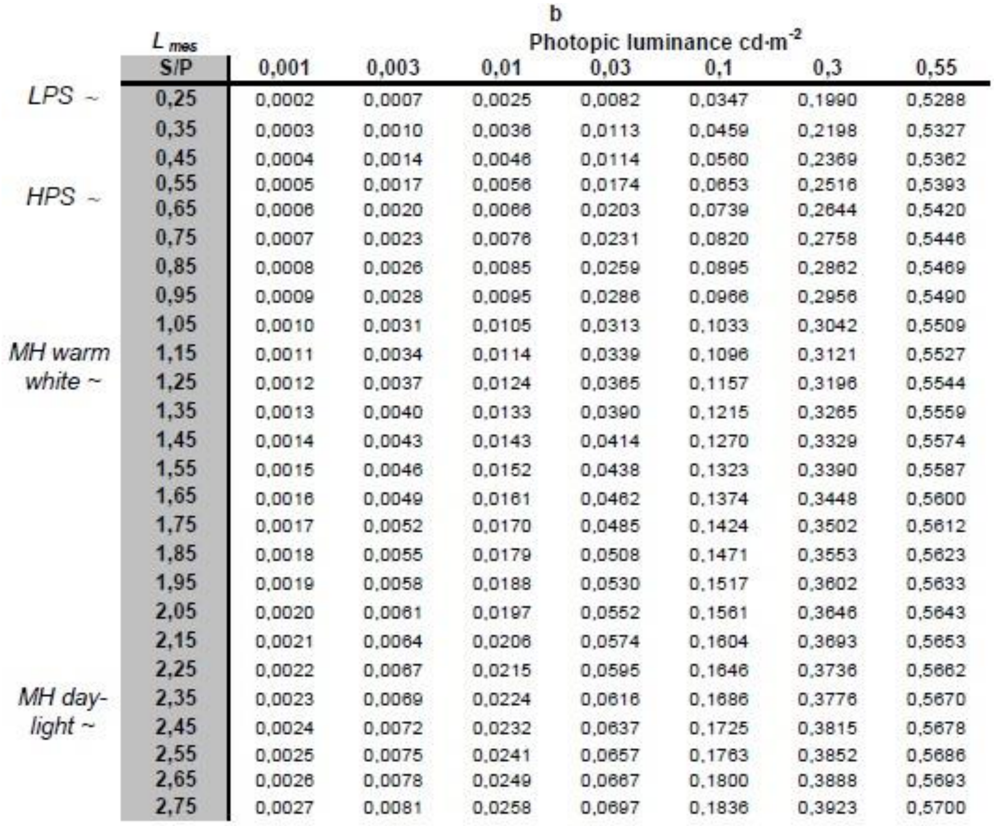
The values of X and L_{mes} given by the USP-system as a function of photopic luminance and light source S/P-ratio are presented in Table 2.3. The lamp notations LPS (low pressure sodium), HPS (high pressure sodium) and MH (metal halide) on the left side of the table refer to the typical regions of S/P-ratios of these lamp types.

Table 2.4 a) The values of X given by the USP-system as a function of photopic luminance and S/P-ratio, b)values of L_{mes} given by the USP-system as a function of photopic luminance and S/P-ratio (Rea et al. 2004).



a

	x	Photopic luminance cd·m^{-2}						
	S/P	**0,001**	**0,003**	**0,01**	**0,03**	**0,1**	**0,3**	**0,55**
LPS ~	**0,25**		0,0000	0,0026	0,0119	0,0562	0,3306	0,8811
	0,35		0,0001	0,0043	0,0172	0,0749	0,3652	0,8876
	0,45		0,0006	0,0060	0,0223	0,0919	0,3938	0,8934
HPS ~	**0,55**		0,0011	0,0076	0,0273	0,1074	0,4183	0,8986
	0,65		0,0016	0,0093	0,0322	0,1218	0,4397	0,9032
	0,75		0,0021	0,0110	0,0370	0,1352	0,4588	0,9075
	0,85		0,0026	0,0126	0,0416	0,1477	0,4761	0,9113
	0,95		0,0031	0,0142	0,0462	0,1595	0,4917	0,9149
	1,05	0,0001	0,0036	0,0158	0,0506	0,1707	0,5061	0,9181
MH warm white ~	**1,15**	0,0002	0,0041	0,0174	0,0549	0,1814	0,5194	0,9211
	1,25	0,0004	0,0046	0,0190	0,0592	0,1915	0,5318	0,9239
	1,35	0,0006	0,0051	0,0206	0,0634	0,2011	0,5433	0,9264
	1,45	0,0007	0,0056	0,0221	0,0675	0,2104	0,5541	0,9288
	1,55	0,0009	0,0060	0,0237	0,0715	0,2192	0,5643	0,9311
	1,65	0,0011	0,0065	0,0252	0,0754	0,2278	0,5739	0,9332
	1,75	0,0012	0,0070	0,0267	0,0793	0,2360	0,5830	0,9352
	1,85	0,0014	0,0075	0,0282	0,0831	0,2439	0,5915	0,9370
	1,95	0,0016	0,0080	0,0297	0,0868	0,2516	0,5997	0,9388
	2,05	0,0017	0,0085	0,0312	0,0905	0,2590	0,6075	0,9404
	2,15	0,0019	0,0090	0,0327	0,0941	0,2661	0,6149	0,9420
	2,25	0,0021	0,0094	0,0342	0,0977	0,2730	0,6220	0,9435
MH day-light ~	**2,35**	0,0022	0,0099	0,0356	0,1012	0,2798	0,6287	0,9449
	2,45	0,0024	0,1040	0,0371	0,1046	0,2863	0,6352	0,9462
	2,55	0,0026	0,0109	0,0385	0,1080	0,2929	0,6415	0,9475
	2,65	0,0027	0,0114	0,0400	0,1140	0,2989	0,6474	0,9487
	2,75	0,0029	0,0118	0,0414	0,1147	0,3049	0,6532	0,9499



b

	L_{mes}	Photopic luminance cd·m^{-2}						
	S/P	0,001	0,003	0,01	0,03	0,1	0,3	0,55
LPS ~	**0,25**	0,0002	0,0007	0,0025	0,0082	0,0347	0,1990	0,5288
	0,35	0,0003	0,0010	0,0036	0,0113	0,0459	0,2198	0,5327
	0,45	0,0004	0,0014	0,0046	0,0114	0,0560	0,2369	0,5362
HPS ~	**0,55**	0,0005	0,0017	0,0056	0,0174	0,0653	0,2516	0,5393
	0,65	0,0006	0,0020	0,0066	0,0203	0,0739	0,2644	0,5420
	0,75	0,0007	0,0023	0,0076	0,0231	0,0820	0,2758	0,5446
	0,85	0,0008	0,0026	0,0085	0,0259	0,0895	0,2862	0,5469
	0,95	0,0009	0,0028	0,0095	0,0286	0,0966	0,2956	0,5490
	1,05	0,0010	0,0031	0,0105	0,0313	0,1033	0,3042	0,5509
MH warm white ~	**1,15**	0,0011	0,0034	0,0114	0,0339	0,1096	0,3121	0,5527
	1,25	0,0012	0,0037	0,0124	0,0365	0,1157	0,3196	0,5544
	1,35	0,0013	0,0040	0,0133	0,0390	0,1215	0,3265	0,5559
	1,45	0,0014	0,0043	0,0143	0,0414	0,1270	0,3329	0,5574
	1,55	0,0015	0,0046	0,0152	0,0438	0,1323	0,3390	0,5587
	1,65	0,0016	0,0049	0,0161	0,0462	0,1374	0,3448	0,5600
	1,75	0,0017	0,0052	0,0170	0,0485	0,1424	0,3502	0,5612
	1,85	0,0018	0,0055	0,0179	0,0508	0,1471	0,3553	0,5623
	1,95	0,0019	0,0058	0,0188	0,0530	0,1517	0,3602	0,5633
	2,05	0,0020	0,0061	0,0197	0,0552	0,1561	0,3646	0,5643
	2,15	0,0021	0,0064	0,0206	0,0574	0,1604	0,3693	0,5653
	2,25	0,0022	0,0067	0,0215	0,0595	0,1646	0,3736	0,5662
MH day-light ~	**2,35**	0,0023	0,0069	0,0224	0,0616	0,1686	0,3776	0,5670
	2,45	0,0024	0,0072	0,0232	0,0637	0,1725	0,3815	0,5678
	2,55	0,0025	0,0075	0,0241	0,0657	0,1763	0,3852	0,5686
	2,65	0,0026	0,0078	0,0249	0,0667	0,1800	0,3888	0,5693
	2,75	0,0027	0,0081	0,0258	0,0697	0,1836	0,3923	0,5700

2.5.2 MOVE – SYSTEM

The MOVE-system proposed by the MOVE consortium (Eloholma et al. 2005, Goodman et al. 2007) is based on an empirical multi-technique approach, where the task of night-time driving was divided into three visual subtasks, which are related to the detection of a visual target, the speed of detection, and the identification of the details of the target. Both chromatic and achromatic targets were included. Thus, unlike the approach taken for the USP- system, the MOVE- system is based on data from tasks that do not inherently obey the laws of additivity. This approach was taken in an attempt to provide a reasonably accurate characterisation of visual effectiveness for a wide range of ‘realistic’ visual tasks, i.e. tasks involving the chromatic as well as the achromatic channels of the human visual system. Like the USP-system, however, a major constraint on the system was that it should be able to be readily implemented in practice, and it was therefore recognised that it could not provide a precise description of visual response for any of the tasks considered.

The detection of a visual target is related to the achromatic threshold (Freiding et al. 2007), i.e. to increments and/or decrements of the visual target’s intensity around the threshold. Achromatic detection thresholds were measured using three experimental setups: modified Goldman perimeter (TKK Helsinki University of Technology, Finland), large homogenous screen (TUD Darmstadt University of Technology, Germany), and screen with computer controlled projector (UP University of Pannonia, Hungary).

The speed of detection is related to reaction times (Walkey et al. 2007). Reaction time data were measured using four different experimental setups: large uniform hemisphere (TKK, Finland), computer controlled CRT display (CU City University, UK), driving simulator (TNO Human Factors, The Netherlands), and large homogenous screen (TUD, Germany).

The identification of the targets is related to achromatic recognition threshold (Várady et al. 2007). These data were measured using a screen with computer-controlled projector (UP, Hungary).

A common set of parameter values were used as the basis of each particular data set generated at each of the different test locations. The joint parameters were: background photopic luminances 0.01 cd/m^2, 0.1 cd/m^2, 1 cd/m^2, and 10 cd/m^2(some experiments also used 0.3 $cd/m^2$and 3 cd/m^2), target eccentricities 0° and 10°, target size 2° (and 0.29°), and nearly steady presentation $\Delta t \geq 3s$ (or $\Delta t \leq 500$ ms for some of the reaction time experiments). The contrasts were at or near threshold and both quasi-monochromatic (half bandwidth = 10 nm) and broadband light sources were used. For some of the experiments the target and background had the same spectral characteristics (achromatic conditions) whereas the majority used different colours for the target and background (chromatic conditions). Altogether 109 subjects participated in the experiments. Table 2.4 summarises the parameters and experimental conditions underlying the MOVE-system.

Table:2.5 The experimental conditions underlying the contrast threshold (CT), reaction time (RT) and recognition threshold (RGT) experiments of the MOVE-system (Eloholma 2005, Goodman et al., 2007). The experiments were carried out in different laboratories.

Method	**Stimuli**	**Contrast**	**Luminance(cd/m^2)**	**Subject**	
CT	380-700 nm steps	At threshold	0.01-10	6	109
	450-700 nm steps	At threshold	0.01-1	10	
	blue,green,red(100 nm bands)	At threshold	0.01-10	19	
RT	466, 503, 522, 594, 638 nm	0.05-3	0.01-10	23	
	various broadband	Varied	0.01-10	11	
	broadb. white, yellow, red, blue	0.14	0.01-10	23	
	380-700 nm, 10 nm steps	Near threshold	0.3-1	7	
RGT	450-700 nm ,10 nm steps	At threshold	0.01-1	10	

It was foreseen in the MOVE work that the spectral response for each visual sub-task might require a distinct description of mesopic spectral sensitivity. Results from each of the three visual sub-tasks were therefore initially modelled separately, with each background level taken in turn. It was subsequently found, however, that an acceptably good fit to all the data sets was obtained with a single model.

The data from the vision experiments of the MOVE project resulted in a linear system for mesopic photometry characterizing the mesopic spectral sensitivity of peripheral vision (Goodman et al. 2007):

$$M(x)V(\lambda) = xV(\lambda) + (1-x)V'(\lambda) \text{for } 0 \le x \le 1$$

where M(x) is a normalizing function such that the $V_{mes}(\lambda)$ function attains a maximum value of 1, $V_{mes}(\lambda)$ is the mesopic spectral luminous efficiency function under the given conditions, V(λ) is the photopic spectral luminous efficiency function, V’(λ) is the scotopic spectral luminous efficiency function, and x is a coefficient dependent on the luminance level and spectrum.

The experimental data generated within the MOVE project indicated that mesopic vision extends to approximately 10cd/m^2, although the differences between mesopic and photopic spectral sensitivity become smaller with increasing luminance. The MOVE-system places the transition between the mesopic and photopic regions at approximately 10 cd/m^2, and the transition between the mesopic and scotopic at approximately 0.01cd/m^2, though both the upper- and lower limits are dependent on the S/P-ratio as well.

The coefficient x and mesopic luminance L_{mes} of the MOVE-system are determined iteratively as follows

$$x_{n+1} = a + b\log_{10}[\frac{1}{M(x_n)}(x_n\frac{L_p}{K_p} + (1 - x_n)\frac{L_s}{K_s}] \text{for } 0 \leq x \leq 1$$

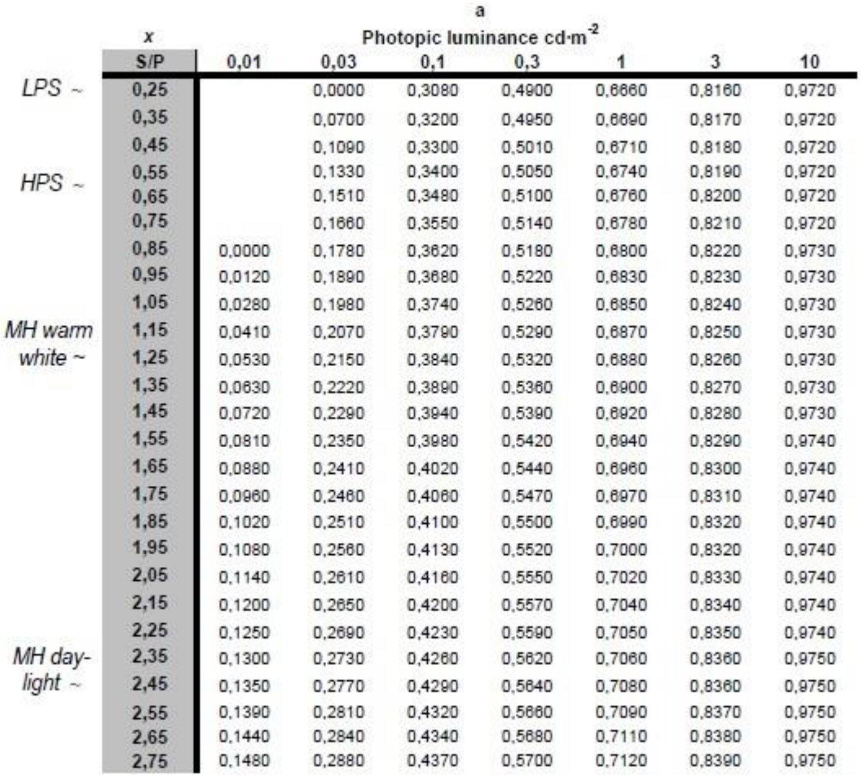
$$L_{mes} = \frac{xL_p + (1 - x)L_sV'(\lambda_0)}{x + (1 - x)V'(\lambda_0)}$$

where a and b are parameters which have the values a = 1.49 and b = 0.282, L_p is the photopic luminance, L_s is the scotopic luminance, K_p is the photopic maximum luminous efficacy (K_p = 683 lm·W^{-1}), K_s is the scotopic maximum luminous efficacy (K_s =1699lm/W), L_{mes} is the mesopic luminance, and $V'(\lambda_0)$ = 683/1699 is the value of scotopic spectral sensitivity function at λ_0=555 nm, which is the wavelength where photopic spectral sensitivity function attains its maximum $V(\lambda_0)$ = 1. The normalizing function M(x) can be approximated as follows:

$$M(x) = \max[xV(\lambda) + (1 - x)V'(\lambda)] \approx 1 - 0.65x + 0.65x^2$$

The values of x and L_{mes} given by the MOVE-system as a function of photopic luminance and light source S/P-ratio are presented in Table 2.6

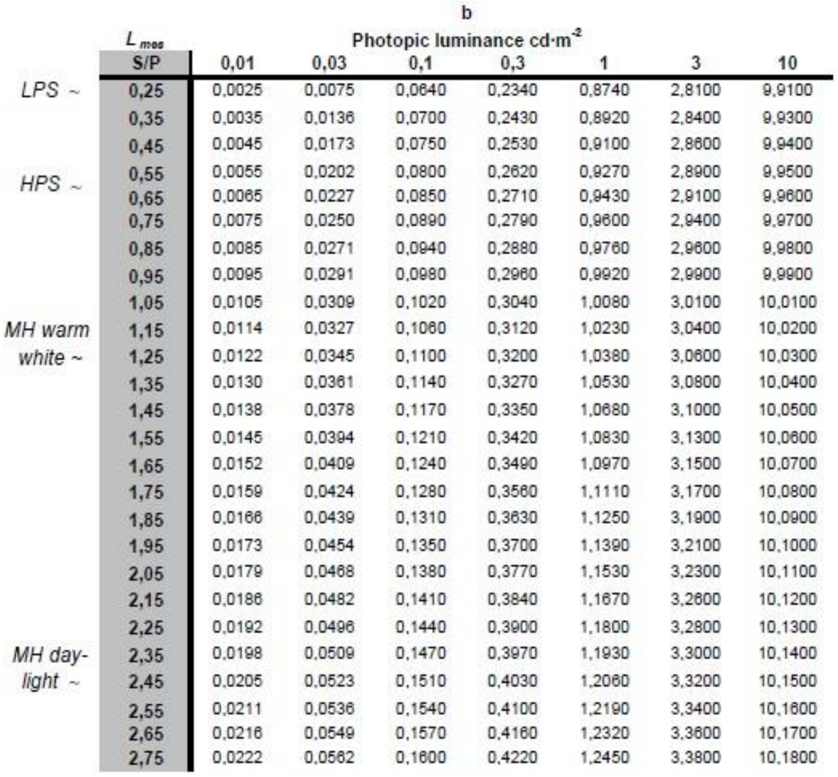
Table 2.6 a) The values of *x* given by the MOVE-system as a function of photopic luminance and S/P-ratio, b) values of L_{mes} given by the MOVE-system as a function of photopic luminance and S/P-ratio.



a

Photopic luminance cd·m^{-2}

	x S/P	0,01	0,03	0,1	0,3	1	3	10
LPS ~	0,25		0,0000	0,3080	0,4900	0,6660	0,8160	0,9720
	0,35		0,0700	0,3200	0,4950	0,6690	0,8170	0,9720
	0,45		0,1090	0,3300	0,5010	0,6710	0,8180	0,9720
HPS ~	0,55		0,1330	0,3400	0,5050	0,6740	0,8190	0,9720
	0,65		0,1510	0,3480	0,5100	0,6760	0,8200	0,9720
	0,75		0,1660	0,3550	0,5140	0,6780	0,8210	0,9720
	0,85	0,0000	0,1780	0,3620	0,5180	0,6800	0,8220	0,9730
	0,95	0,0120	0,1890	0,3680	0,5220	0,6830	0,8230	0,9730
	1,05	0,0280	0,1980	0,3740	0,5260	0,6850	0,8240	0,9730
MH warm white ~	1,15	0,0410	0,2070	0,3790	0,5290	0,6870	0,8250	0,9730
	1,25	0,0530	0,2150	0,3840	0,5320	0,6880	0,8260	0,9730
	1,35	0,0630	0,2220	0,3890	0,5360	0,6900	0,8270	0,9730
	1,45	0,0720	0,2290	0,3940	0,5390	0,6920	0,8280	0,9730
	1,55	0,0810	0,2350	0,3980	0,5420	0,6940	0,8290	0,9740
	1,65	0,0880	0,2410	0,4020	0,5440	0,6960	0,8300	0,9740
	1,75	0,0960	0,2460	0,4060	0,5470	0,6970	0,8310	0,9740
	1,85	0,1020	0,2510	0,4100	0,5500	0,6990	0,8320	0,9740
	1,95	0,1080	0,2560	0,4130	0,5520	0,7000	0,8320	0,9740
	2,05	0,1140	0,2610	0,4160	0,5550	0,7020	0,8330	0,9740
	2,15	0,1200	0,2650	0,4200	0,5570	0,7040	0,8340	0,9740
	2,25	0,1250	0,2690	0,4230	0,5590	0,7050	0,8350	0,9740
MH day-light ~	2,35	0,1300	0,2730	0,4260	0,5620	0,7060	0,8360	0,9750
	2,45	0,1350	0,2770	0,4290	0,5640	0,7080	0,8360	0,9750
	2,55	0,1390	0,2810	0,4320	0,5660	0,7090	0,8370	0,9750
	2,65	0,1440	0,2840	0,4340	0,5680	0,7110	0,8380	0,9750
	2,75	0,1480	0,2880	0,4370	0,5700	0,7120	0,8390	0,9750



b

Photopic luminance cd·m^{-2}

	L_{mes} S/P	0,01	0,03	0,1	0,3	1	3	10
LPS ~	0,25	0,0025	0,0075	0,0640	0,2340	0,8740	2,8100	9,9100
	0,35	0,0035	0,0136	0,0700	0,2430	0,8920	2,8400	9,9300
	0,45	0,0045	0,0173	0,0750	0,2530	0,9100	2,8600	9,9400
HPS ~	0,55	0,0055	0,0202	0,0800	0,2620	0,9270	2,8900	9,9500
	0,65	0,0065	0,0227	0,0850	0,2710	0,9430	2,9100	9,9600
	0,75	0,0075	0,0250	0,0890	0,2790	0,9600	2,9400	9,9700
	0,85	0,0085	0,0271	0,0940	0,2880	0,9760	2,9600	9,9800
	0,95	0,0095	0,0291	0,0980	0,2960	0,9920	2,9900	9,9900
	1,05	0,0105	0,0309	0,1020	0,3040	1,0080	3,0100	10,0100
MH warm white ~	1,15	0,0114	0,0327	0,1060	0,3120	1,0230	3,0400	10,0200
	1,25	0,0122	0,0345	0,1100	0,3200	1,0380	3,0600	10,0300
	1,35	0,0130	0,0361	0,1140	0,3270	1,0530	3,0800	10,0400
	1,45	0,0138	0,0378	0,1170	0,3350	1,0680	3,1000	10,0500
	1,55	0,0145	0,0394	0,1210	0,3420	1,0830	3,1300	10,0600
	1,65	0,0152	0,0409	0,1240	0,3490	1,0970	3,1500	10,0700
	1,75	0,0159	0,0424	0,1280	0,3560	1,1110	3,1700	10,0800
	1,85	0,0166	0,0439	0,1310	0,3630	1,1250	3,1900	10,0900
	1,95	0,0173	0,0454	0,1350	0,3700	1,1390	3,2100	10,1000
	2,05	0,0179	0,0468	0,1380	0,3770	1,1530	3,2300	10,1100
	2,15	0,0186	0,0482	0,1410	0,3840	1,1670	3,2600	10,1200
	2,25	0,0192	0,0496	0,1440	0,3900	1,1800	3,2800	10,1300
MH day-light ~	2,35	0,0198	0,0509	0,1470	0,3970	1,1930	3,3000	10,1400
	2,45	0,0205	0,0523	0,1510	0,4030	1,2060	3,3200	10,1500
	2,55	0,0211	0,0536	0,1540	0,4100	1,2190	3,3400	10,1600
	2,65	0,0216	0,0549	0,1570	0,4160	1,2320	3,3600	10,1700
	2,75	0,0222	0,0562	0,1600	0,4220	1,2450	3,3800	10,1800

2.5.3 INTERMEDIATE-SYSTEM

Although the USP- and MOVE-systems do show significant differences in the calculated mesopic luminance as a function of photopic luminance, particularly for highly coloured sources at low luminance levels, these differences become smaller at all levels for the majority of ‘white light’ sources used in typical lighting applications, such as roadway lighting at night. In practical terms, therefore, the results obtained using either of the two systems are similar. The principal difference between the systems lies in the form of the transition from the mesopic to photopic regimes. The USP-system has a transition from mesopic (mixed scotopic and photopic) functions to the single, photopic spectral luminous efficiency function at 0.6 cd/m^2. The MOVE-system includes a contribution from the scotopic spectral luminous efficiency function, albeit an ever-diminishing one, until about 10 cd/m^2. The upper luminance limit of the mesopic region has been regarded to be too high for the MOVE-system (Rea and Bullough 2007) and too low for the USP-system (Eloholma and Halonen 2006).

In some respects the USP- and MOVE-systems can be considered as representing two extremes. In the one case (USP), only reaction times were measured and chromatic effects were removed from consideration, with the result that this may limit the applicability to achromatic tasks only; in the other case (MOVE) a broad range of tasks is considered, but this introduces a greater degree of variability (or uncertainty) into the results, since the transition from the scotopic to the photopic condition is complicated by non-linear interactions between the chromatic and achromatic channels which may be different for each individual task. In the USP-system a small number (3) of observers were used to minimize ‘noise’ and in the MOVE-system a large number (119) of observers were used to minimize effects of inter-observer variability. It is also worth noting that although the MOVE-experiments included achromatic as well as chromatic tasks, the chromatic tasks dominated. Real-life situations, such as driving on a road at night, involve both achromatic and chromatic tasks, and the achromatic tasks may be slightly under-weighted in the MOVE analysis.

An Intermediate system between the USP- and MOVE-systems was therefore also considered. This system was intended to ensure reasonably wide applicability while also giving increased weight to achromatic tasks as compared with the MOVE-system. Although being an Intermediate system, it is not an average of the USP- and MOVE-systems. There is a significant degree of freedom in the choice of the precise form of the transition and the following points have been considered in deciding this:

- It is advantageous, in terms of practical implementation of a new system of photometry, for there to be a definite upper and lower limit above and below which no change to the current system of photometry is necessary. This makes it clear, for example, whether a particular lighting specification standard needs to be changed to refer to the new system and avoids complicating unnecessarily general lighting applications where peripheral vision plays a less significant role. (It has been shown that $V(\lambda)$ applies at all levels for tasks involving foveal vision only.)

- Based on the argument that the different experimental conditions underlying the USP-system and the MOVE-system explain the difference between the luminance level for the photopic mesopic transition in the two systems, the transition point for the Intermediate-system would be expected to lie between the USP-system value of 0.6 cd/m^2 and the MOVE-system value of 10 cd/m^2. Two different upper limits for the Intermediate-system, 3 cd/m^2 and 5 cd/m^2, have therefore been considered in the report.
- A log-linear relationship between the mesopic luminance and the adaptation coefficient 'y' value was selected, since this provides a better match to the data gathered within the MOVE project than a linear-linear relationship of the form used in the USP-system, and therefore provides a better approximation to actual visual performance for a wider range of tasks.

The Intermediate system with upper and lower limits of 3 cd/m^2 and 0.01 cd/m^2 , respectively, is denoted as the MES1-system and takes the form:

$$M(m_1)V_{mes}(\lambda) = m_1V(\lambda) + (1 - m_1V'(\lambda)$$

where M(m_1) is a normalizing function such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, attains a maximum value of 1.

If $L_{mes} \geq 3.0$ cd/m^2 , then $m_1 = 1$

If $L_{mes} \leq 0.01$ cd/m^2 , then $m_1 = 0$

If 0.01 cd·m^{-2}<L_{mes}< 3.0 cd/m^2 then $m_1 = 0.404 \log L_{mes} + 0.807$

where L_{mes} is the mesopic luminance.

The coefficient m_1 and the mesopic luminance L_{mes} obtained using the MES1-system can be iteratively calculated as follows:

$m_{1,0} = 0.5$

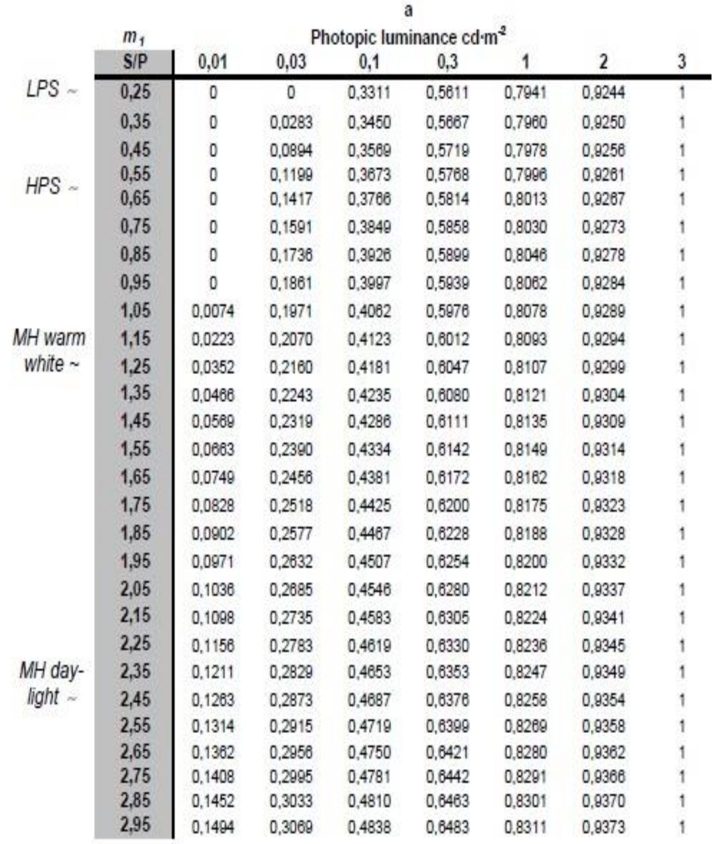
$$L_{mes,n} = \frac{m_{1,(n-1)}L_p + (1 - m_{1,(n-1)})L_sV'(\lambda_0)}{m_{1,(n-1)} + (1 - m_{1,(n-1)})V'(\lambda_0)}$$

$$m_{1,n} = a + b\,log_{10}(L_{mes,n}) \text{ for } 0 \leq m_{1,n} \leq 1$$

Where L_p is the photopic luminance, L_s is the scotopic luminance, $V'(\lambda_0) = 683/1699$ is the value of scotopic spectral sensitivity function at $\lambda_0 = 555$ nm, a and b are parameters which have the values a = 0.807 and b = 0.404, and n is an iteration step

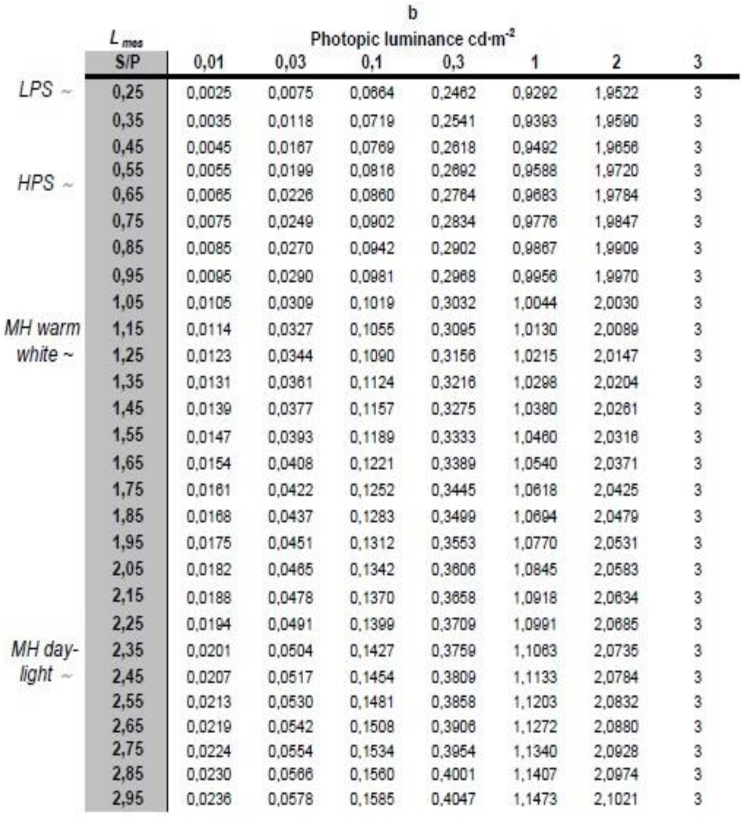
The values of m_1 and L_{mes} given by the MES1-system as a function of photopic luminance and light source S/P-ratio are presented in Table2.7

Table 2.7 a) The values of$m_1$given by the MES1-system as a function of photopic luminance and S/P-ratio, b) values of L_{mes} given by the MES1-system as a function of photopic luminance and S/P-ratio.



a

	m_1	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	0	0	0,3311	0,5611	0,7941	0,9244	1
	0,35	0	0,0283	0,3450	0,5667	0,7960	0,9250	1
	0,45	0	0,0894	0,3569	0,5719	0,7978	0,9256	1
HPS ~	0,55	0	0,1199	0,3673	0,5768	0,7996	0,9261	1
	0,65	0	0,1417	0,3766	0,5814	0,8013	0,9267	1
	0,75	0	0,1591	0,3849	0,5858	0,8030	0,9273	1
	0,85	0	0,1736	0,3926	0,5899	0,8046	0,9278	1
	0,95	0	0,1861	0,3997	0,5939	0,8062	0,9284	1
	1,05	0,0074	0,1971	0,4062	0,5976	0,8078	0,9289	1
MH warm white ~	1,15	0,0223	0,2070	0,4123	0,6012	0,8093	0,9294	1
	1,25	0,0352	0,2160	0,4181	0,6047	0,8107	0,9299	1
	1,35	0,0466	0,2243	0,4235	0,6080	0,8121	0,9304	1
	1,45	0,0569	0,2319	0,4286	0,6111	0,8135	0,9309	1
	1,55	0,0663	0,2390	0,4334	0,6142	0,8149	0,9314	1
	1,65	0,0749	0,2456	0,4381	0,6172	0,8162	0,9318	1
	1,75	0,0828	0,2518	0,4425	0,6200	0,8175	0,9323	1
	1,85	0,0902	0,2577	0,4467	0,6228	0,8188	0,9328	1
	1,95	0,0971	0,2632	0,4507	0,6254	0,8200	0,9332	1
	2,05	0,1036	0,2685	0,4546	0,6280	0,8212	0,9337	1
	2,15	0,1098	0,2735	0,4583	0,6305	0,8224	0,9341	1
	2,25	0,1156	0,2783	0,4619	0,6330	0,8236	0,9345	1
MH day-light ~	2,35	0,1211	0,2829	0,4653	0,6353	0,8247	0,9349	1
	2,45	0,1263	0,2873	0,4687	0,6376	0,8258	0,9354	1
	2,55	0,1314	0,2915	0,4719	0,6399	0,8269	0,9358	1
	2,65	0,1362	0,2956	0,4750	0,6421	0,8280	0,9362	1
	2,75	0,1408	0,2995	0,4781	0,6442	0,8291	0,9366	1
	2,85	0,1452	0,3033	0,4810	0,6463	0,8301	0,9370	1
	2,95	0,1494	0,3069	0,4838	0,6483	0,8311	0,9373	1



b

	L_{mes}	Photopic luminance cd·m^{-2}						
	S/P	0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	0,0025	0,0075	0,0664	0,2462	0,9292	1,9522	3
	0,35	0,0035	0,0118	0,0719	0,2541	0,9393	1,9590	3
	0,45	0,0045	0,0167	0,0769	0,2618	0,9492	1,9656	3
HPS ~	0,55	0,0055	0,0199	0,0816	0,2692	0,9588	1,9720	3
	0,65	0,0065	0,0226	0,0860	0,2764	0,9683	1,9784	3
	0,75	0,0075	0,0249	0,0902	0,2834	0,9776	1,9847	3
	0,85	0,0085	0,0270	0,0942	0,2902	0,9867	1,9909	3
	0,95	0,0095	0,0290	0,0981	0,2968	0,9956	1,9970	3
	1,05	0,0105	0,0309	0,1019	0,3032	1,0044	2,0030	3
MH warm white ~	1,15	0,0114	0,0327	0,1055	0,3095	1,0130	2,0089	3
	1,25	0,0123	0,0344	0,1090	0,3156	1,0215	2,0147	3
	1,35	0,0131	0,0361	0,1124	0,3216	1,0298	2,0204	3
	1,45	0,0139	0,0377	0,1157	0,3275	1,0380	2,0261	3
	1,55	0,0147	0,0393	0,1189	0,3333	1,0460	2,0316	3
	1,65	0,0154	0,0408	0,1221	0,3389	1,0540	2,0371	3
	1,75	0,0161	0,0422	0,1252	0,3445	1,0618	2,0425	3
	1,85	0,0168	0,0437	0,1283	0,3499	1,0694	2,0479	3
	1,95	0,0175	0,0451	0,1312	0,3553	1,0770	2,0531	3
	2,05	0,0182	0,0465	0,1342	0,3606	1,0845	2,0583	3
	2,15	0,0188	0,0478	0,1370	0,3658	1,0918	2,0634	3
	2,25	0,0194	0,0491	0,1399	0,3709	1,0991	2,0685	3
MH day-light ~	2,35	0,0201	0,0504	0,1427	0,3759	1,1063	2,0735	3
	2,45	0,0207	0,0517	0,1454	0,3809	1,1133	2,0784	3
	2,55	0,0213	0,0530	0,1481	0,3858	1,1203	2,0832	3
	2,65	0,0219	0,0542	0,1508	0,3906	1,1272	2,0880	3
	2,75	0,0224	0,0554	0,1534	0,3954	1,1340	2,0928	3
	2,85	0,0230	0,0566	0,1560	0,4001	1,1407	2,0974	3
	2,95	0,0236	0,0578	0,1585	0,4047	1,1473	2,1021	3

The Intermediate system with upper and lower limits of 5 cd/m² and 0.005 cd/m², respectively, is denoted as the MES2-system and takes the form:

$$M(m_2)V_{mes}(\lambda) = m_2V(\lambda) + (1 - m_2V'(\lambda)$$

Where M(m_2) is a normalizing function such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, attains a maximum value of 1.

If $L_{mes} \geq 5.0$ cd/m^2, then $m_2 = 1$

If $L_{mes} \leq 0.005$ cd/m^2, then $m_2 = 0$

If 0.005 cd·m^{-2}<L_{mes}< 5.0 cd/m^2 , then $m_2 = 0.3334 \log L_{mes} + 0.767$

Where L_{mes} is the mesopic luminance .

The coefficient m_2 and the mesopic luminance L_{mes} obtained using the MES2-system can be iteratively calculated as follows:

$m_{2,0} = 0.5$

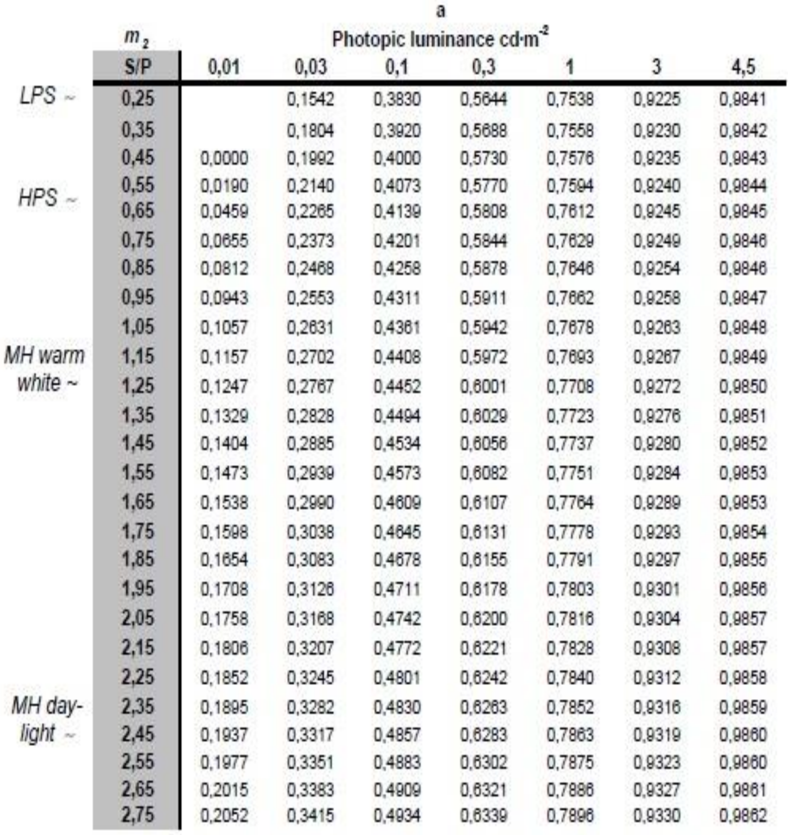
$$L_{mes,n} = \frac{m_{2,(n-1)}L_p + (1 - m_{2,(n-1)})L_sV'(\lambda_0)}{m_{2,(n-1)} + (1 - m_{2,(n-1)})V'(\lambda_0)}$$

$m_{2,n} = a + b\, log_{10}(L_{mes,n})$ for $0 \leq m_{2,n} \leq 1$

Where L_p is the photopic luminance, L_s is the scotopic luminance, and $V'(\lambda_0) = 683/1699$ is the value of scotopic spectral sensitivity function at $\lambda_0 = 555$ nm, a and b are parameters which have the values a = 0.7670 and b = 0.3334, and n is an iteration step.

The values of m_2 and L_{mes} given by the MES2-system as a function of photopic luminance and light source S/P-ratio are presented in Table2.7

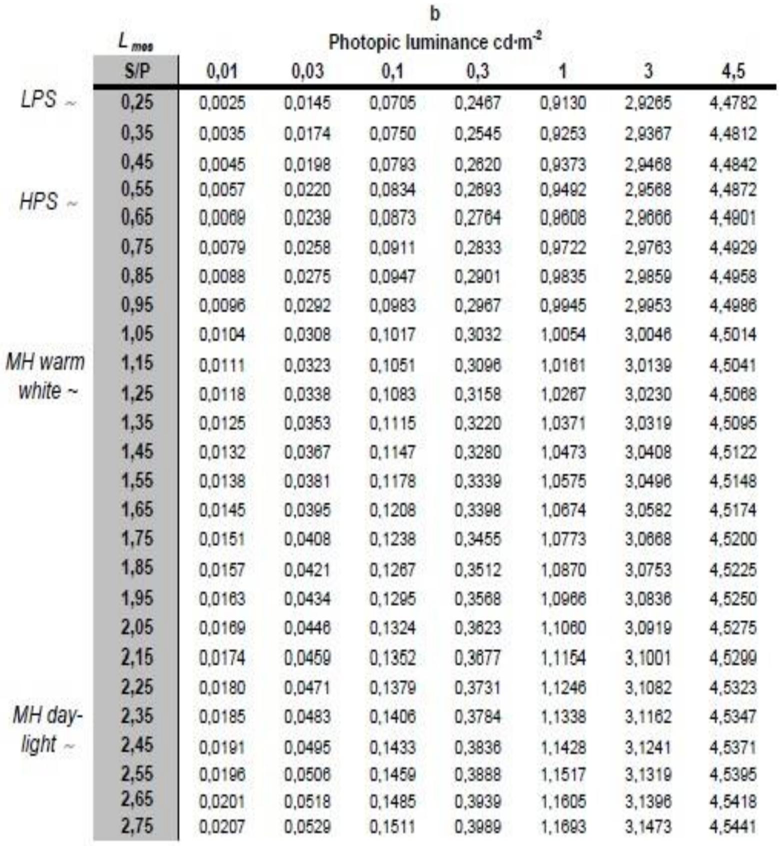
Table 2.8 a) The values of$m_2$given by the MES2-system as a function of photopic luminance and S/P-ratio, b) values of L_{mes} given by the MES2-system as a function of photopic luminance and S/P-ratio. (At photopic luminances of 5 cd/m^2 the coefficient m_2 has a value of 1 and the mesopic luminance is therefore 5 cd/m^2, thus the photopic luminance 4.5 cd/m^2 is more informative and is given in the table 2.8



a

m_2 — Photopic luminance cd·m^{-2}

	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	**0,25**		0,1542	0,3830	0,5644	0,7538	0,9225	0,9841
	0,35		0,1804	0,3920	0,5688	0,7558	0,9230	0,9842
	0,45	0,0000	0,1992	0,4000	0,5730	0,7576	0,9235	0,9843
HPS ~	**0,55**	0,0190	0,2140	0,4073	0,5770	0,7594	0,9240	0,9844
	0,65	0,0459	0,2265	0,4139	0,5808	0,7612	0,9245	0,9845
	0,75	0,0655	0,2373	0,4201	0,5844	0,7629	0,9249	0,9846
	0,85	0,0812	0,2468	0,4258	0,5878	0,7646	0,9254	0,9846
	0,95	0,0943	0,2553	0,4311	0,5911	0,7662	0,9258	0,9847
	1,05	0,1057	0,2631	0,4361	0,5942	0,7678	0,9263	0,9848
MH warm white ~	**1,15**	0,1157	0,2702	0,4408	0,5972	0,7693	0,9267	0,9849
	1,25	0,1247	0,2767	0,4452	0,6001	0,7708	0,9272	0,9850
	1,35	0,1329	0,2828	0,4494	0,6029	0,7723	0,9276	0,9851
	1,45	0,1404	0,2885	0,4534	0,6056	0,7737	0,9280	0,9852
	1,55	0,1473	0,2939	0,4573	0,6082	0,7751	0,9284	0,9853
	1,65	0,1538	0,2990	0,4609	0,6107	0,7764	0,9289	0,9853
	1,75	0,1598	0,3038	0,4645	0,6131	0,7778	0,9293	0,9854
	1,85	0,1654	0,3083	0,4678	0,6155	0,7791	0,9297	0,9855
	1,95	0,1708	0,3126	0,4711	0,6178	0,7803	0,9301	0,9856
	2,05	0,1758	0,3168	0,4742	0,6200	0,7816	0,9304	0,9857
	2,15	0,1806	0,3207	0,4772	0,6221	0,7828	0,9308	0,9857
	2,25	0,1852	0,3245	0,4801	0,6242	0,7840	0,9312	0,9858
MH day-light ~	**2,35**	0,1895	0,3282	0,4830	0,6263	0,7852	0,9316	0,9859
	2,45	0,1937	0,3317	0,4857	0,6283	0,7863	0,9319	0,9860
	2,55	0,1977	0,3351	0,4883	0,6302	0,7875	0,9323	0,9860
	2,65	0,2015	0,3383	0,4909	0,6321	0,7886	0,9327	0,9861
	2,75	0,2052	0,3415	0,4934	0,6339	0,7896	0,9330	0,9862



b

L_{mes} — Photopic luminance cd·m^{-2}

	S/P	0,01	0,03	0,1	0,3	1	3	4,5
LPS ~	**0,25**	0,0025	0,0145	0,0705	0,2467	0,9130	2,9265	4,4782
	0,35	0,0035	0,0174	0,0750	0,2545	0,9253	2,9367	4,4812
	0,45	0,0045	0,0198	0,0793	0,2620	0,9373	2,9468	4,4842
HPS ~	**0,55**	0,0057	0,0220	0,0834	0,2693	0,9492	2,9568	4,4872
	0,65	0,0069	0,0239	0,0873	0,2764	0,9608	2,9666	4,4901
	0,75	0,0079	0,0258	0,0911	0,2833	0,9722	2,9763	4,4929
	0,85	0,0088	0,0275	0,0947	0,2901	0,9835	2,9859	4,4958
	0,95	0,0096	0,0292	0,0983	0,2967	0,9945	2,9953	4,4986
	1,05	0,0104	0,0308	0,1017	0,3032	1,0054	3,0046	4,5014
MH warm white ~	**1,15**	0,0111	0,0323	0,1051	0,3096	1,0161	3,0139	4,5041
	1,25	0,0118	0,0338	0,1083	0,3158	1,0267	3,0230	4,5068
	1,35	0,0125	0,0353	0,1115	0,3220	1,0371	3,0319	4,5095
	1,45	0,0132	0,0367	0,1147	0,3280	1,0473	3,0408	4,5122
	1,55	0,0138	0,0381	0,1178	0,3339	1,0575	3,0496	4,5148
	1,65	0,0145	0,0395	0,1208	0,3398	1,0674	3,0582	4,5174
	1,75	0,0151	0,0408	0,1238	0,3455	1,0773	3,0668	4,5200
	1,85	0,0157	0,0421	0,1267	0,3512	1,0870	3,0753	4,5225
	1,95	0,0163	0,0434	0,1295	0,3568	1,0966	3,0836	4,5250
	2,05	0,0169	0,0446	0,1324	0,3623	1,1060	3,0919	4,5275
	2,15	0,0174	0,0459	0,1352	0,3677	1,1154	3,1001	4,5299
	2,25	0,0180	0,0471	0,1379	0,3731	1,1246	3,1082	4,5323
MH day-light ~	**2,35**	0,0185	0,0483	0,1406	0,3784	1,1338	3,1162	4,5347
	2,45	0,0191	0,0495	0,1433	0,3836	1,1428	3,1241	4,5371
	2,55	0,0196	0,0506	0,1459	0,3888	1,1517	3,1319	4,5395
	2,65	0,0201	0,0518	0,1485	0,3939	1,1605	3,1396	4,5418
	2,75	0,0207	0,0529	0,1511	0,3989	1,1693	3,1473	4,5441

2.6 APPLICATIONS OF MESOPIC SYSTEM

Mesopic photometry provides the means to compare light sources at low levels using a common criterion. It is foreseen that there will be a strong motivation within the lighting community to adopt and use a photometric method that is valid and justified in the mesopic applications.

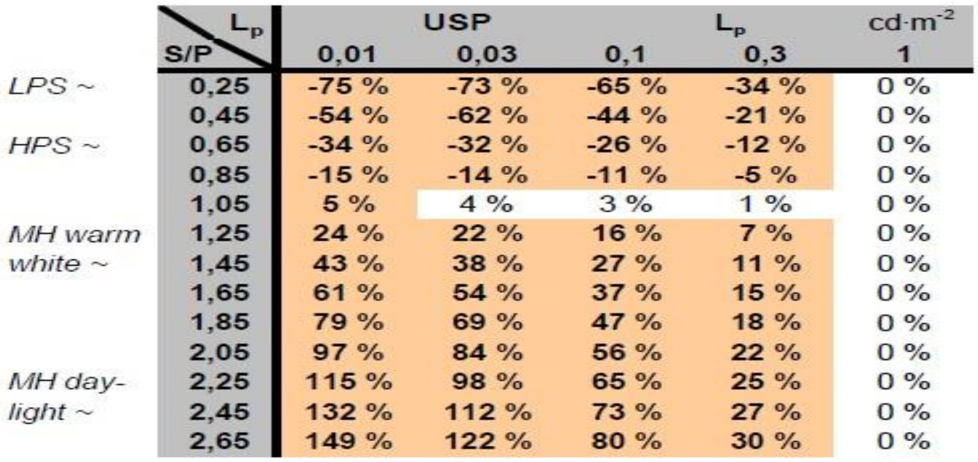
The mesopic design will provide means to optimize outdoor lighting both in terms of human visual performance and energy use. The use of mesopic photometry will promote the development of mesopically optimized lighting products. It will give the manufacturers foundations on which to develop light sources that are optimized for low light level applications. This will result in better energy efficiency and visual effectiveness in outdoor lighting conditions.

2.7 CALCULATION OF MESOPIC LUMINANCE

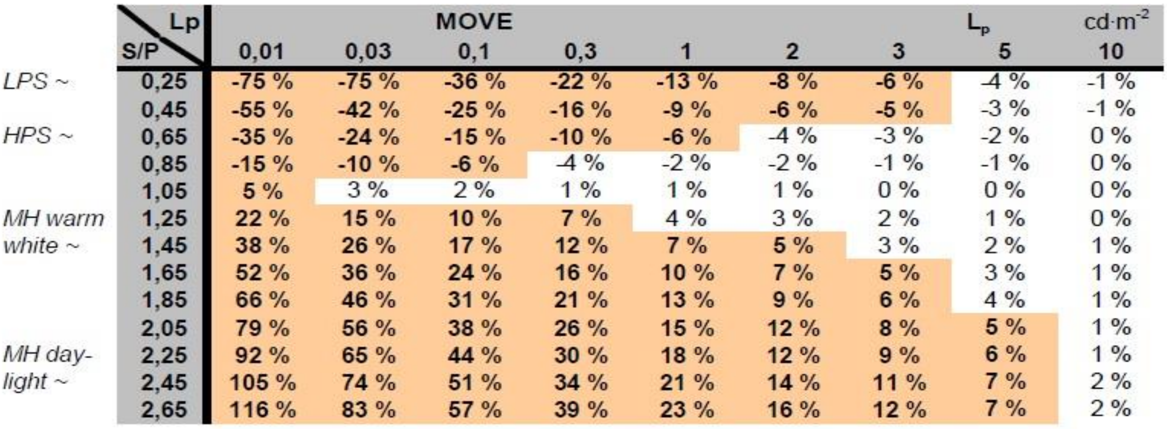
For the calculation of the mesopic luminance, the S/P ratio of the light source is needed. The higher the S/P ratio, the higher is the luminous efficacy of the light source in terms of mesopic design.

Table 2.9 shows the difference between the luminance values calculated using the recommended mesopic system and those calculated with the photopic spectral luminous efficiency function, for light sources with a range of S/P ratio values. Differences higher than 5% are highlighted in colour.

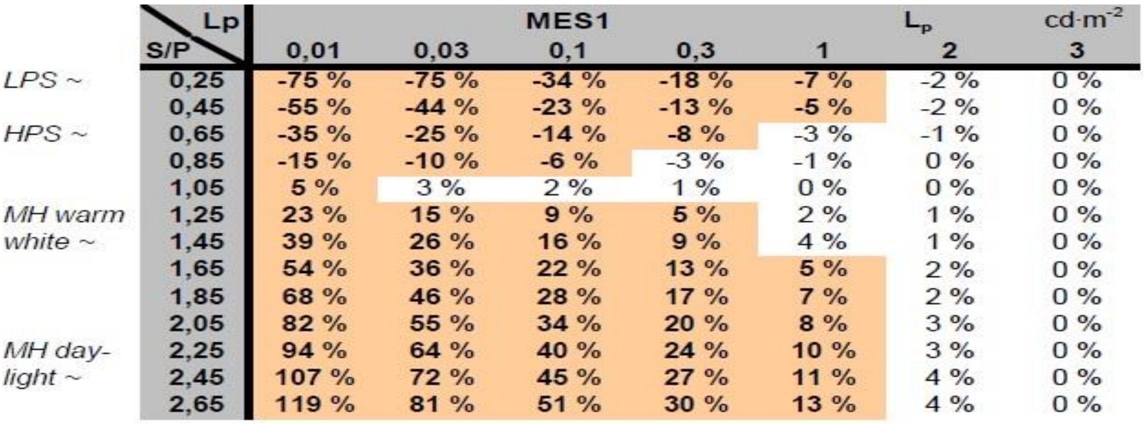
Table 2.9 Differences between mesopic and photopic luminances (%) calculated with the USP-, MOVE- and Intermediate (MES1 and MES2) systems for different photopic luminances L_p and light source S/P-ratios.



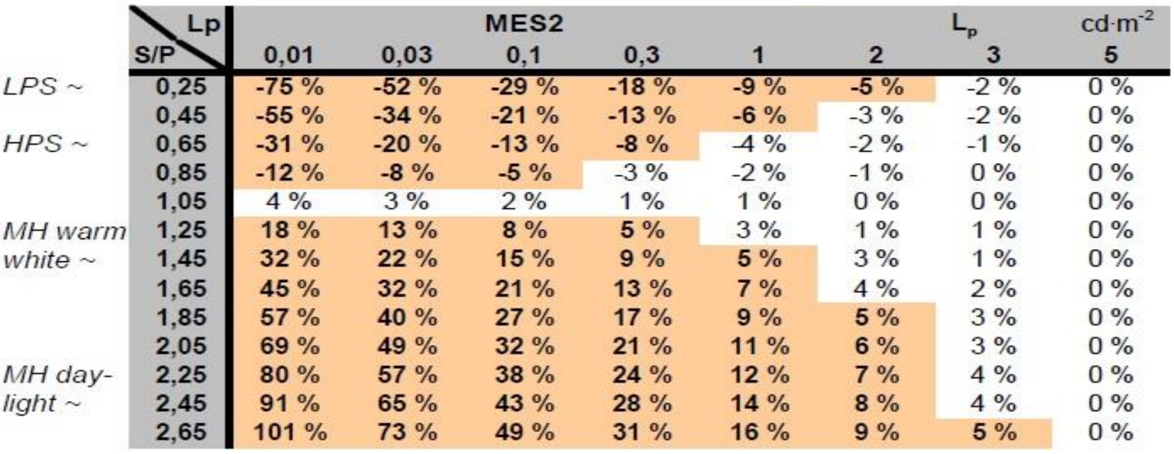
	L_p	USP			L_p	$cd \cdot m^{-2}$
	S/P	0,01	0,03	0,1	0,3	1
LPS ~	0,25	-75 %	-73 %	-65 %	-34 %	0 %
	0,45	-54 %	-62 %	-44 %	-21 %	0 %
HPS ~	0,65	-34 %	-32 %	-26 %	-12 %	0 %
	0,85	-15 %	-14 %	-11 %	-5 %	0 %
	1,05	5 %	4 %	3 %	1 %	0 %
MH warm white ~	1,25	24 %	22 %	16 %	7 %	0 %
	1,45	43 %	38 %	27 %	11 %	0 %
	1,65	61 %	54 %	37 %	15 %	0 %
	1,85	79 %	69 %	47 %	18 %	0 %
	2,05	97 %	84 %	56 %	22 %	0 %
MH day-light ~	2,25	115 %	98 %	65 %	25 %	0 %
	2,45	132 %	112 %	73 %	27 %	0 %
	2,65	149 %	122 %	80 %	30 %	0 %



	Lp			MOVE					L_p	$cd \cdot m^{-2}$
	S/P	0,01	0,03	0,1	0,3	1	2	3	5	10
LPS ~	0,25	-75 %	-75 %	-36 %	-22 %	-13 %	-8 %	-6 %	-4 %	-1 %
	0,45	-55 %	-42 %	-25 %	-16 %	-9 %	-6 %	-5 %	-3 %	-1 %
HPS ~	0,65	-35 %	-24 %	-15 %	-10 %	-6 %	-4 %	-3 %	-2 %	0 %
	0,85	-15 %	-10 %	-6 %	-4 %	-2 %	-2 %	-1 %	-1 %	0 %
	1,05	5 %	3 %	2 %	1 %	1 %	1 %	0 %	0 %	0 %
MH warm white ~	1,25	22 %	15 %	10 %	7 %	4 %	3 %	2 %	1 %	0 %
	1,45	38 %	26 %	17 %	12 %	7 %	5 %	3 %	2 %	1 %
	1,65	52 %	36 %	24 %	16 %	10 %	7 %	5 %	3 %	1 %
	1,85	66 %	46 %	31 %	21 %	13 %	9 %	6 %	4 %	1 %
	2,05	79 %	56 %	38 %	26 %	15 %	12 %	8 %	5 %	1 %
MH day-light ~	2,25	92 %	65 %	44 %	30 %	18 %	12 %	9 %	6 %	1 %
	2,45	105 %	74 %	51 %	34 %	21 %	14 %	11 %	7 %	2 %
	2,65	116 %	83 %	57 %	39 %	23 %	16 %	12 %	7 %	2 %



	Lp			MES1			L_p	$cd \cdot m^{-2}$
	S/P	0,01	0,03	0,1	0,3	1	2	3
LPS ~	0,25	-75 %	-75 %	-34 %	-18 %	-7 %	-2 %	0 %
	0,45	-55 %	-44 %	-23 %	-13 %	-5 %	-2 %	0 %
HPS ~	0,65	-35 %	-25 %	-14 %	-8 %	-3 %	-1 %	0 %
	0,85	-15 %	-10 %	-6 %	-3 %	-1 %	0 %	0 %
	1,05	5 %	3 %	2 %	1 %	0 %	0 %	0 %
MH warm white ~	1,25	23 %	15 %	9 %	5 %	2 %	1 %	0 %
	1,45	39 %	26 %	16 %	9 %	4 %	1 %	0 %
	1,65	54 %	36 %	22 %	13 %	5 %	2 %	0 %
	1,85	68 %	46 %	28 %	17 %	7 %	2 %	0 %
	2,05	82 %	55 %	34 %	20 %	8 %	3 %	0 %
MH day-light ~	2,25	94 %	64 %	40 %	24 %	10 %	3 %	0 %
	2,45	107 %	72 %	45 %	27 %	11 %	4 %	0 %
	2,65	119 %	81 %	51 %	30 %	13 %	4 %	0 %



	Lp			MES2				L_p	$cd \cdot m^{-2}$
	S/P	0,01	0,03	0,1	0,3	1	2	3	5
LPS ~	0,25	-75 %	-52 %	-29 %	-18 %	-9 %	-5 %	-2 %	0 %
	0,45	-55 %	-34 %	-21 %	-13 %	-6 %	-3 %	-2 %	0 %
HPS ~	0,65	-31 %	-20 %	-13 %	-8 %	-4 %	-2 %	-1 %	0 %
	0,85	-12 %	-8 %	-5 %	-3 %	-2 %	-1 %	0 %	0 %
	1,05	4 %	3 %	2 %	1 %	1 %	0 %	0 %	0 %
MH warm white ~	1,25	18 %	13 %	8 %	5 %	3 %	1 %	1 %	0 %
	1,45	32 %	22 %	15 %	9 %	5 %	3 %	1 %	0 %
	1,65	45 %	32 %	21 %	13 %	7 %	4 %	2 %	0 %
	1,85	57 %	40 %	27 %	17 %	9 %	5 %	3 %	0 %
	2,05	69 %	49 %	32 %	21 %	11 %	6 %	3 %	0 %
MH day-light ~	2,25	80 %	57 %	38 %	24 %	12 %	7 %	4 %	0 %
	2,45	91 %	65 %	43 %	28 %	14 %	8 %	4 %	0 %
	2,65	101 %	73 %	49 %	31 %	16 %	9 %	5 %	0 %

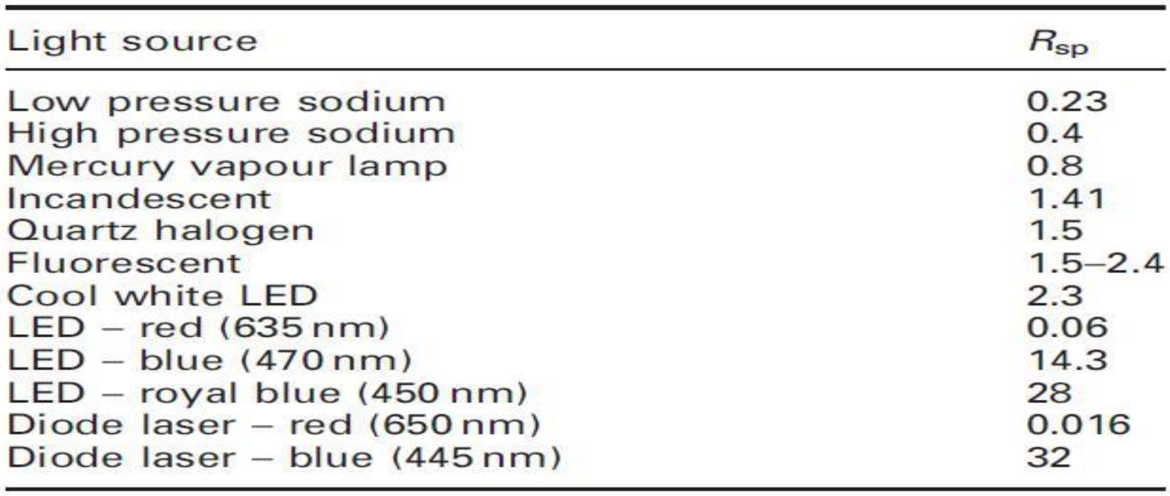
The MES-2 table shows that lamps with a relatively high output in short wavelength region (S/P ratio>1) result in the increased luminance values when measured using the recommended system, whereas lamps using with relatively high output in the long wavelength region result in the decreased luminance values. The impact of using the recommended system increases with the decreasing light level. Currently recommended road surface luminances, which are within the range $0.3 cd/m^2$ to $2 cd/m^2$ [CEN, 2003], [CIE, 1995], [Rea 2000], are indicated with a rectangle in the table. Many of the white light sources currently used for the applications such as road lighting have S/P ratios between about 0.65 (high pressure sodium) and 2.50 (certain metal halides).

2.8 COMPARISON OF LIGHT SOURCES

The use of mesopic dimensioning changes the luminous output and consequently the luminous efficacy orders of lamps.

Table 2.10 lists shows the S/P ratios of light sources used in outdoor lighting. Light sources with S/P>1 have higher content of their spectral output in the short wavelength region and are thus mesopically more efficient than light sources with S/P<1.

Table 2.10 Typical S/P ratios of different light source.[Shpak 2017]



Light source	R_{sp}
Low pressure sodium	0.23
High pressure sodium	0.4
Mercury vapour lamp	0.8
Incandescent	1.41
Quartz halogen	1.5
Fluorescent	1.5–2.4
Cool white LED	2.3
LED – red (635 nm)	0.06
LED – blue (470 nm)	14.3
LED – royal blue (450 nm)	28
Diode laser – red (650 nm)	0.016
Diode laser – blue (445 nm)	32

2.9 LIMITATIONS OF MESOPIC PHOTOMETRY

Although the mesopic photometry system is intended to predict visual task performance, it is not applicable to all tasks. There are some limitations due to simplification for modeling or limits of the underpinning visual evidences.

Firstly, the mesopic photometry system cannot be applied to tasks at all area on the retina. Since the density of the cones and the rods changes throughout the retina, and since the mesopic photometry system is based on visual tasks at 10^{o} eccentricity and more or less, visual task performances at the other retinal area may be different from those predicted by the system. The MOVE project chose the 10^{o} eccentricity because it is likely related to driving tasks. CIE 191 recommends to use the V (λ) function for foveal task performance prediction at all adaptation levels because the fovea is occupied only by the cones .

Secondly, it is not known whether it can be used for situations where observers are adapted to high-saturated colors. This is because the experiments underpinning the CIE 191 system mainly used white light, which closes to the black-body locus on the chromaticity diagram, for adaptation and background of the tasks. Applying the mesopic photometry system to extremely high-S/P-ratio sources should be avoided.

CHAPTER :3

ADAPTATION LUMINANCE

3.1 INTRODUCTION

Mesopic photometry has emerged as an improvement to lighting measurement. Road lighting will be one of the main application areas for mesopic photometry. The commission Internationale de l'Eclairage (CIE) 191:2010 system for mesopic photometry requires knowledge of the adaptation luminance, L_a , of the visual environment . The adaptation luminance is represented by the average luminance of the visual adaptation field, an unspecified area in the visual scene. Moreover, the visual adaptation field has yet to be defined in terms of the size, shape, or location within the visual field. Another component in mesopic photometry is the adaptation state, the luminance the retina is adapted to. The adaptation state defines the spectral sensitivity of the retina. In this study, the adaptation state is defined as the sum of the average photopic luminance of the visual adaptation field, L_p and the veiling luminance, L_{veil}. The veiling luminance, L_{veil}, is an increment to the adaptation state caused by high-luminance sources due to intra-ocular scatter[M Maksimainen et al].

3.2 ADAPTATION LUMINANCE &MESOPIC LUMINOUS EFFICIENCY FUNCTION

The mesopic photometry system recommended in CIE 191:2010 defines mesopic luminous efficiency functions, the spectral efficiency of which changes depending on the observers' adaptation luminance. The absence of methods to determine the adaptation luminance for real lit scenes is the most critical. An adaptation luminance for a lit scene has to be determined to obtain the mesopic luminous efficiency function that can predict task performances in the scene appropriately. The adaptation luminance should be determined on the basis of the peripheral adaptation state of observers' eyes since the mesopic photometry system was developed based on peripheral task performance.[T Uchida et al.2016].

3.3 FACTORS RELATED TO THE ADAPTATION LUMINANCE

It is difficult to determine an adaptation luminance for a real outdoor lit scene because scenes usually have complex luminance distributions (LDs), while laboratory experiments underpinning the mesopic photometry system were basically conducted with uniform LDs. The LDs for real lit scenes contain not only non-uniform lit road surfaces but also the dark sky or high-luminance sources such as luminaires. Their luminance ranges are extremely wide and to what luminance the observers' eyes adapt has been a big question[T Uchida et al.2016].

Earlier studies have pointed out some factors that influence the adaptation state of observers. Here those factors are categorized into four types: LD, EMs, SLEs and AOM. To model the four factors and their derivatives as distribution functions in the field of view, two coordinate systems are introduced[T Uchida et al.2016].One co-ordinate system is a spherical coordinate system (θ,φ) where θ is the horizontal angle and φ is the vertical angle, to basically present the position on the retina. This will be referred to as the 'retinal coordinate system'. Another coordinate system is also a spherical coordinate system that has the same structure with different symbols (θ', φ'), but fixed to the world outside the observer, not to the observer's visual system. This will be referred as the ‘object coordinate system’. Both coordinate systems share the origin at the observer’s eye position as shown in Figure 3.1

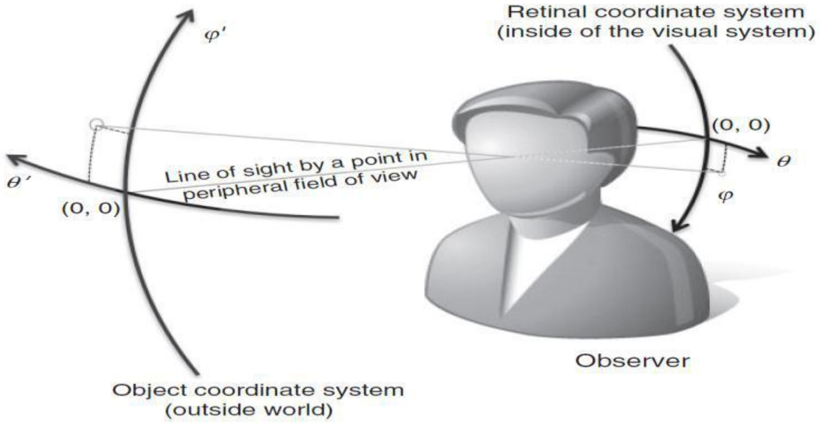


Fig 3.1Object coordinate system and retinal coordinate system[T Uchida et al.2016]

When discussing the adaptation state of an arbitrary peripheral point in the field of view, the point $(\theta,\varphi)=(0,0)$ in the retinal coordinate system corresponds to a peripheral point, not the fovea. The point $(\theta',\varphi')=(0,0)$ in the object coordinate system is a point corresponding to the point $(\theta,\varphi)=(0,0)$ in the retinal coordinate system when the observer looks at an ‘original point’ in the object coordinate system. Since the position of the original point does not matter for the simulation process, it is not given specifically. When the observer moves his/her line of sight, the retinal coordinate system follows the movement while the object coordinate system does not.

3.3.1LUMINANCE DISTRIBUTIONS

The LD of a lit scene is a fundamental factor for the adaptation luminance. Usually, the luminance range for outdoor lighting at night is much wider than that for indoor lighting. According to outdoor lighting recommendations, such as CIE 115:2010, average luminance of 0.3 to 2.0 cd/m^{2}is recommended. Since a certain level of non-uniformity is allowed in the recommendations, the minimum luminance, usually at the end of lit areas, may be 0.1cd/m$^{2.}$ On the other hand, there may be various bright light sources, such as luminaires, headlamps of oncoming cars or luminous signs, in the same scene. For example, some luminaires have a luminance of more than 10,000 cd/m^2. In this study, LD is expressed as a luminance level function $L(\theta',\varphi')$ with respect to the object coordinate system (θ',φ').

3.3.2EYE MOVEMENTS

In a study[Uchida at el2016] , the Eye Movements are modeled as a two-dimensional(2D) Gaussian probability density distribution $f_{EM}(\theta',\varphi')$ with no co-relation expressed as

$$f_{EM}(\theta',\varphi') = \frac{1}{2\pi\sigma_{\theta'}\sigma_{\varphi'}} \times e^{[-\frac{1}{2}\left\{\left(\frac{\theta'}{\sigma_{\theta'}}\right)^2 + \left(\frac{\theta'}{\sigma_{\varphi'}}\right)^2\right\}]} d\theta' d\varphi'$$

Where, $\sigma_{\theta'}$,$_,\sigma_{\varphi'}$ are standard deviations (SD) for the horizontal and vertical directions. This function is defined with respect to the object coordinate system. It should be noted that the EM function is centered at the origin of the object coordinate system so that it just expresses relative movement of the line of sight.[T Uchida et al.2016]

3.3.3SURROUNDING LUMINANCE EFFECT

The SLE is an increment of the adaptation luminance at a point in the field of view caused by the surrounding luminance. It is due to stray light within the human eye and/or lateral neural interactions. For foveal vision, this factor is called as ‘veiling luminance’ and has been investigated for many years. The angular characteristic, which is the luminance increment as a function of the visual angle between a source causing the veiling luminance and the task point (fovea), is modeled as some equations, such as Stiles-Holladay formula or CIE general disability glare equation. Since the mesopic photometry system is based on peripheral task performances, SLE for peripheral vision should be characterized and be taken into account.

3.3.4AREA OF MEASUREMENT

In this study[Uchida at el2016] , takes an approach to determine an average adaptation luminance for an area of measurement (AOM). AOM is an area that is illuminated by a lighting installation and is measured photometrically to verify the installation. For example, a road surface that the lighting design intends to illuminate is the AOM. The road surface is usually seen as a trapezoidal area from the drivers’ view point.

For the adaptation luminance simulation, AOM is modeled as a 2D function $f_{AOM}(\theta',\varphi')$with respect to the object coordinate system(θ',φ').This function takes a value of one for inside the AOM and zero for outside the AOM.[T Uchida et al.2016]

3.4 SIMULATION METHOD FOR ADAPTATION LUMINANCE

A Simulation Method for calculation of adaptation luminance based on analysis of luminance distribution of light scene consists of four step:

1. Effective LD calculation
2. Adaptation LD calculation
3. AOM hit probability distribution calculation
4. Adaptation luminance calculation

3.4.1Effective LD

Effective luminance is the luminance after taking the SLE into account. It is the adaptation LD when the observer’s line of sight is fixed. In this case, if there were no SLE, then each point of the retina would adapt to a nominal luminance from each direction. However, light from each direction slightly scatters to an area surrounding the corresponding point in the retinal coordinate system, as characterized as SLE. As a result, SLEs due to the light from each direction overlap each other and slightly diffuse the projected LD.

Since the observer’s line of sight is assumed to be fixed at the original point for the effective LD, the LD projected to the retinal coordinate system, L(θ,φ) is determined from LD L(θ’,φ’) by substituting as (θ,φ) =(θ’,φ’).

Then the effective LD $L_{effective}$(θ,φ)can be calculated by convolution of the projected LD
and the SLE as

$$L_{effective}(\theta,\varphi) = (L * f_{SLE})(\theta,\varphi)$$

3.4.2 Adaptation LD

Although the effective LD is the adaptation LD when the line of sight is fixed, actually the observers’ line of sight moves as expressed by EM. If a point in the retinal coordinate system looks at two points with 50–50 probability due to the EM, the adaptation luminance can be considered the average of the effective luminances for the two points. Generalizing this concept, each point of the retinal coordinate system adapts to an average effective luminance weighted by the EM. This process can be expressed as

$$L_a(\theta,\varphi) = (L_{effective} * f_{EM})(\theta,\varphi)$$

Where, L_a(θ,φ) is the adaptation LD. The f_{EM}(θ,φ) is derived from f_{EM}(θ’,φ’) just by substituting as (θ,φ) =(θ’,φ’).

3.4.3AOM hit probability distribution

Each point on the retinal coordinate system has different probability to look inside the AOM, depending on the EM. For instance, a pedestrian’s lower parts of the retinal coordinate system more probably look at a street surface (AOM) than the upper parts of the retinal coordinate system. The probability for each point on the retinal coordinate system to look inside AOM. P_{AOM}(θ,φ) can be calculated as

$$P_{AOM}(\theta,\varphi) = (f_{AOM} * f_{EM})(\theta,\varphi)$$

3.4.4Adaptation luminance of AOM

Finally, the adaptation luminance of the AOM, which is the average adaptation luminance weighted with the AOM hit probability distribution, is derived as

$$L_{a,AOM} = \frac{\int\int L_a(\theta,\varphi).P_{AOM}(\theta,\varphi)d\theta d\varphi}{\int\int P_{AOM}(\theta,\varphi)\,d\theta d\varphi}$$

Where, $L_{a,AOM}$ is the adaptation luminance of AOM

CHAPTER :4

EXPERIMENTAL PROCEDURE

As discussed in Chapter 3, Adaptation luminance depends on four factors:

- LD : Luminance Distribution
- EM : Eye Movement
- SLE : Surrounding Luminance Effect
- AOM: Area of Measurement

In this Thesis Luminance Distribution, Surrounding Luminance Effect and Area of Measurement have been considered. To calculate Surrounding Luminance Effect three veiling luminance models were used in this study:

Uchida and Ohno equation [M Maksimainen et al] :

$$L_{veiling}=E_v\frac{260}{\theta^3}$$

Fry equation [M Maksimainen et al] :

$$L_{veiling}=9.2\sum\frac{E_{gl}}{\theta(\theta+1.5)}$$

CIE general disability glare equation [M Maksimainen et al] :

$$L_{veiling}=E_{gl}\{\frac{10}{\theta^3}+\left[\frac{5}{\theta^2}+\frac{0.1p}{\theta}\right]\left[1+\left(\frac{A}{62.5}\right)^4\right]+0.0025p\}$$

Where $L_{veiling}$ is the veiling luminance caused by a high-luminance light source; θ is the angle in degree between the line of fixation and the high-luminance source ; A(43 years) is the age in years ; p(0.9) is the eye pigmentation factor ; E_v is the illuminance on a plane perpendicular to a straight line between the observer’s eye and the light source. E_{gl} is the illuminance on a vertical plane at the observer’s eye. Consequently, E_{gl} is E_v multiplied by the cosine of θ.

4.1 CALCULATION METHOD

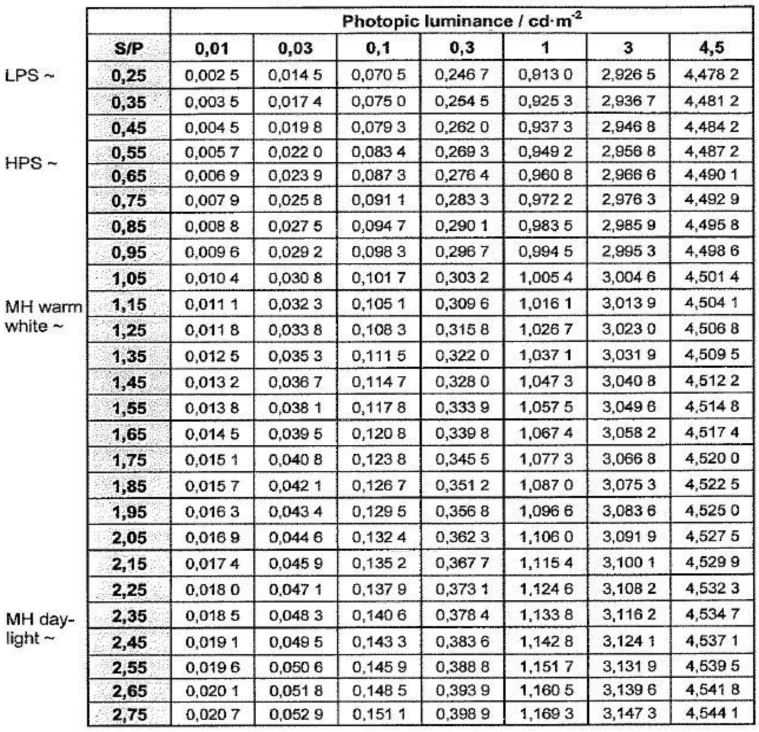
4.1.1DETERMINATION OF PHOTOPIC LUMINANCE

Total area of measurement is divided into 66 grid (0.5m x 0.5m) points under main light source as shown in Fig. 4.6. Point specific luminance values are measured using Luminance Meter for all the grid points.

4.1.2DETERMINATION OF MESOPIC LUMINANCE

STEP 1. S/P ratio values of the lamps are determined by Scotopic/Photopic meter.

STEP 2.Mesopic luminance values are interpolated from the known photopic luminance values and s/p ratios using CIE191-2010 table(Table 4.1).The table is shown below.



		Photopic luminance / cd·m^{-2}						
	S/P	**0,01**	**0,03**	**0,1**	**0,3**	**1**	**3**	**4,5**
LPS ~	**0,25**	0,002 5	0,014 5	0,070 5	0,246 7	0,913 0	2,926 5	4,478 2
	0,35	0,003 5	0,017 4	0,075 0	0,254 5	0,925 3	2,936 7	4,481 2
	0,45	0,004 5	0,019 8	0,079 3	0,262 0	0,937 3	2,946 8	4,484 2
HPS ~	**0,55**	0,005 7	0,022 0	0,083 4	0,269 3	0,949 2	2,956 8	4,487 2
	0,65	0,006 9	0,023 9	0,087 3	0,276 4	0,960 8	2,966 6	4,490 1
	0,75	0,007 9	0,025 8	0,091 1	0,283 3	0,972 2	2,976 3	4,492 9
	0,85	0,008 8	0,027 5	0,094 7	0,290 1	0,983 5	2,985 9	4,495 8
	0,95	0,009 6	0,029 2	0,098 3	0,296 7	0,994 5	2,995 3	4,498 6
	1,05	0,010 4	0,030 8	0,101 7	0,303 2	1,005 4	3,004 6	4,501 4
MH warm white ~	**1,15**	0,011 1	0,032 3	0,105 1	0,309 6	1,016 1	3,013 9	4,504 1
	1,25	0,011 8	0,033 8	0,108 3	0,315 8	1,026 7	3,023 0	4,506 8
	1,35	0,012 5	0,035 3	0,111 5	0,322 0	1,037 1	3,031 9	4,509 5
	1,45	0,013 2	0,036 7	0,114 7	0,328 0	1,047 3	3,040 8	4,512 2
	1,55	0,013 8	0,038 1	0,117 8	0,333 9	1,057 5	3,049 6	4,514 8
	1,65	0,014 5	0,039 5	0,120 8	0,339 8	1,067 4	3,058 2	4,517 4
	1,75	0,015 1	0,040 8	0,123 8	0,345 5	1,077 3	3,066 8	4,520 0
	1,85	0,015 7	0,042 1	0,126 7	0,351 2	1,087 0	3,075 3	4,522 5
	1,95	0,016 3	0,043 4	0,129 5	0,356 8	1,096 6	3,083 6	4,525 0
	2,05	0,016 9	0,044 6	0,132 4	0,362 3	1,106 0	3,091 9	4,527 5
	2,15	0,017 4	0,045 9	0,135 2	0,367 7	1,115 4	3,100 1	4,529 9
	2,25	0,018 0	0,047 1	0,137 9	0,373 1	1,124 6	3,108 2	4,532 3
MH day-light ~	**2,35**	0,018 5	0,048 3	0,140 6	0,378 4	1,133 8	3,116 2	4,534 7
	2,45	0,019 1	0,049 5	0,143 3	0,383 6	1,142 8	3,124 1	4,537 1
	2,55	0,019 6	0,050 6	0,145 9	0,388 8	1,151 7	3,131 9	4,539 5
	2,65	0,020 1	0,051 8	0,148 5	0,393 9	1,160 5	3,139 6	4,541 8
	2,75	0,020 7	0,052 9	0,151 1	0,398 9	1,169 3	3,147 3	4,544 1

Table 4.1 Values of $L_{mes}$of the recommended Mesopic system as a function of photopic luminance and s/p ratio [CIE191].

4.1.3DETERMINATION OF ADAPTATION LUMINANCE

STEP 1 .The visual angles between the source and task points(here grid points) in degreesare calculated using MATLAB.

STEP 2 . Vertical Illuminance values on all grid points for surrounding sources are measured using Luxmeter.

STEP 3 . Veiling Luminance is calculated using the equations given below

Uchida and Ohno equation:

$$L_{veiling}=E_v\frac{260}{\theta^3}$$

Fry equation:

$$L_{veiling}=9.2\sum\frac{E_{gl}}{\theta(\theta+1.5)}$$

CIE general disability glare equation:

$$L_{veiling}=E_{gl}\{\frac{10}{\theta^3}+\left[\frac{5}{\theta^2}+\frac{0.1p}{\theta}\right]\left[1+\left(\frac{A}{62.5}\right)^4\right]+0.0025p\}$$

STEP 4 .Local luminance (L_{local}) values (here photopic luminance values on the grid points for all individual sources) are already measured using Luminancemeter.

STEP 5 . The values of Local Luminance and Veiling Luminance of each grid points are added to get Adaptation Luminance (L_a).

4.1.4DETERMINATION OF THEORITICAL PHOTOPIC LUMINANCE

STEP 1. Luminous Intensity values (I-Table) of the lamp are determined by Goniophotometer.

STEP 2. C ,γ angle of all grid points are calculated.

STEP 3. Luminous Intensity values are interpolated from the known I-Table values for all grid point.

STEP 4. Calculation of illuminance (E) by using Inverse square law , using MATLAB.

STEP 5. Reflectance (q) values of all grid points are measured by using Luxmeter and Luminance meter.

STEP 6. We multiplied the illuminance (E) values by reflectance (q) values to get the theoretical photopic luminance.

$$L_P = qE$$

4.2 EXPERIMENTAL SETUP

4.2.1 EQUIPMENT

- **SCOTOPIC/PHOTOPIC METER**

Scotopic/Photopic Ratio for a particular source was measured using Scotopic/Photopic Meter of “SOLAR Light”, Sl. No. 3101 as shown in figure 4.1. This meter has two sensors equipped with CIE V(λ) and V’(λ) sensitivity functions respectively. It evaluates and shows scotopic and photopic illuminance as seen by the sensor. The S/P ratio of a source can be obtained by dividing the measured scotopic illuminance with photopic illuminance

RANGE: Photopic Detector (PMA 2130):0 to 150000 1ux

Scotopic Detector (PMA 2131): 0 to 150000 lux

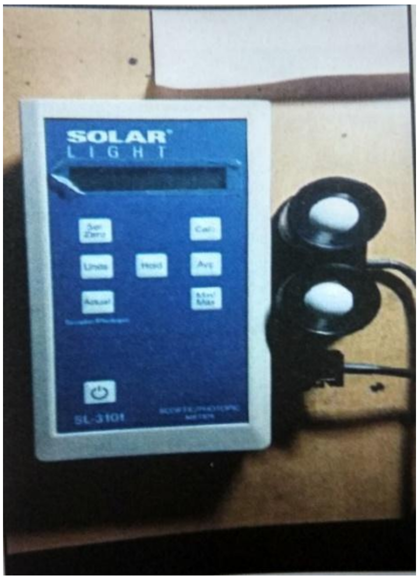


Fig 4.1 Scotopic/Photopic Meter

- **CHROMOMETER**

For measurements of CCT of the lamps, a Chromameter of “Konica Minolta” Make, Model: CL-200Awas used as shown in fig

RANGE: 0.1 to 99990lux, 2000K to 10000K

Fig 4.2 Chromameter

- **SPECTRORADIOMETER**

“JETI” made Specbos 1200Spectroradiometer, which is used to measure the SPD of the light sources.

RANGE: Spectral range-380-780nm.

Calculated wavelength step- 1nm.

Digital electronic resolution- 16Bit ADC (15Bit used).

Viewing angle-1.8^{0}.

Measuring distance/diameter- 20cm- 6mm; 100cm- 31mm.

Measuring values- Spectral radiance, Total luminance/total radiance, Total illuminance / total irradiance, Chromaticity coordinates x,y,u',v', CCT, Color purity, CRI.
Measuring range luminance- 2…7x10^{4}cd/m^{2}.

Measuring range illuminance- 20…5x10^{5}lux.

Luminance accuracy- ±2%(@100cd/m^{2} and illuminant (A).

Luminance reproducibility- ±1%.

Chromaticity accuracy- ±0.001 x,y(@ illuminant (A).

Color reproducibility- ±0.0005x,y.

CCT reproducibility- ±20K(@illuminant(A).

Wavelength accuracy- ±0.5nm.

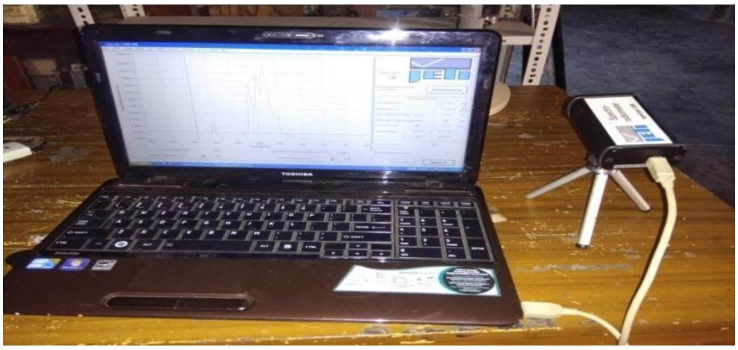


Fig 4.3 SPECTRORADIOMETER

- **LUXMETER**

The Luxmeter was used to measure the illuminance level. The details of the Luxmeter are given below:

Maker’s name: METRAVI

Model number: Light Meter 1332A

Range: 200/2K/20K/200K

Resolution: 0.1lux

- **LUMINANCE METER**

The Luminance Meter of “Konica Minolta” & Model –LS100 used for measurement of luminance.

RANGE: Fast: 0.001 to 299900cd/m^2 , Slow : 0.001 to 49990 cd/m^2.

Fig 4.4 Luminance meter

- **TRIPOD**

A tripod was used for mounting the luminance meter at a fixed position.

- **MARKING THE FIELD**

The measurement fields were marked using chalk marker.

- **MEASURING TAPE**

Marking distance measured by a standard 50m measuring tape.

- **PROGRAMMABLE AC/DC POWER SOURCE**

Variation in input voltage affects the luminous output of a lamp. To maintain a constant voltage throughout the experimental procedure, a programmable AC/DC power supply was used. The line voltage was first fed to this machine and from there the output taken as input to the luminaire under the experiment.

RANGE: AC I/P :750VA(100 to 180V),1000VA(180 to 250V)

DC I/P: 750VA (100 to 180V), 1000VA (180 to 250V)

AC O/P Voltage: 0 to 155 V_{rms}(100V), 0 to 310 V_{rms} (200V)

DC O/P Voltage: -220V to +220 V(100V), - 440V to +440V(200V)

AC O/P Current: 10 A(100V),5A(200V)

DC O/P Current: 10A(100V),5A(200V)

Frequency: 1Hz to 550Hz.

- **GONIOPHOTOMETER**

For measurements of Luminous Intensity (I-Table) of the lamp , High Precision Rotation Luminaire Goniophotometer (LSG – 1700B) were used .

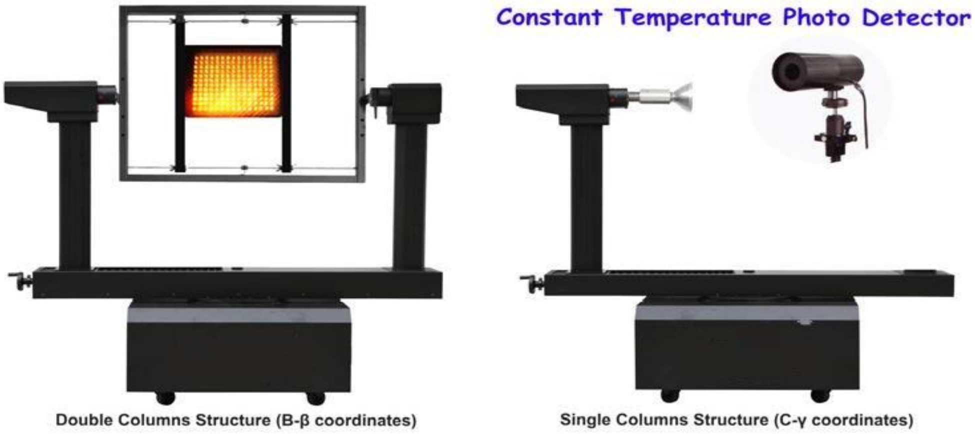


Fig 4.5 Goniophotometer

SPECIFICATION:

- Meets the requirements of CIE, IEC, IES LM-79 & GB standards
- Reaching many measurement ways such as B-βand C-γ
- The tested luminaries rotates around an angle of (γ)±180°(or 0-360°) and the tested luminaries rotates around itself with an angle of (C)±180°(or 0-360°)
- Luminosity Testing Range: Illuminance 0.001lx~99,999lx; Light Intensity 1.0cd ～107cd(detector)
- The accuracy of angle: 0.01°
- Accuracy of photometry: CIE Class A
- Testing Accuracy: 2%(Under Standard lamp); Stray Light: less than 0.1%

4.2.2 LAMP DETAILS

The lamp that is used as light source in this Thesis work is

1. COOL WHITE LED (CWLED)

1. COOL WHITE LED

COOL WHITE LED lamp was the main light source in this thesis work experiment. The details of the lamp are shown below

MAKE: UNILUX LED Lighting Technologies

OPERATING VOLTAGE: 230V AC

CURRENT: 0.32A

POWER: 72W

FREQUENCY: 50Hz

POWER FACTOR: 0.98

CCT: 5064K

CRI: 88.35

S/P RATIO: 2.09

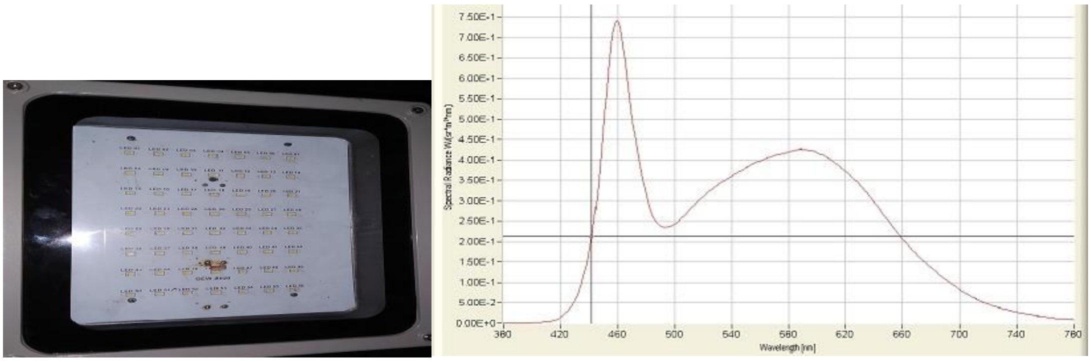


Fig 4.6 SPD curve for 72W White Cool LED

4.2.3 SURROUNDINGLIGHT SOURCES

Two types of Fluorescent Tube lights (FTL) lamps are used as surrounding light source

1. COOL WHITE FTL
2. WARM WHITE FTL

1. COOL WHITE FTL

Details of the COOL WHITE FTL lamps that are used in this experiment are shown below

MAKE: Philips

OPERATING VOLTAGE: 220V AC

POWER: 36W

FREQUENCY: 50Hz

CURRENT: 0.44A

LUMINOUS FLUX: 2500 lm

CCT: 6200K

LUMINOUS EFFICACY: 70 lm/W
CRI: 72

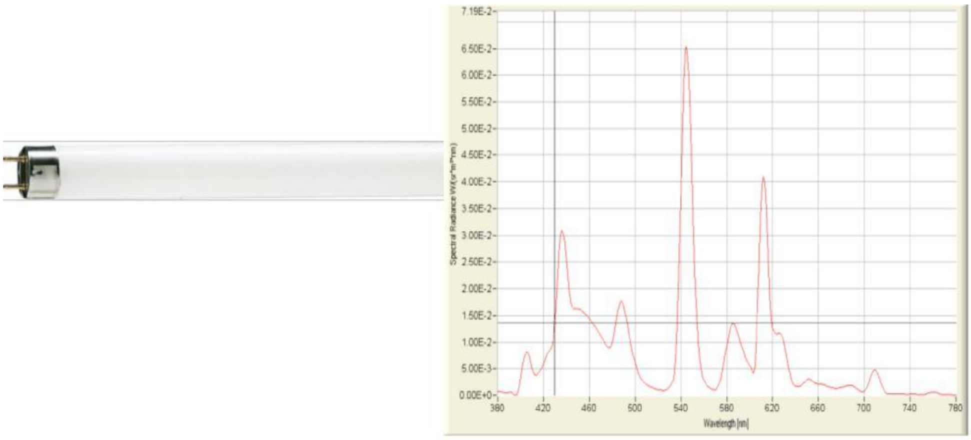


Fig 4.7 SPD curve for 36W Cool White FTL

2. WARM WHITE FTL

Details of the WARM WHITE FTL lamps that are used in this experiment are shown below

MAKE: Philips

OPERATING VOLTAGE: 220V AC

POWER: 36W

FREQUENCY: 50Hz

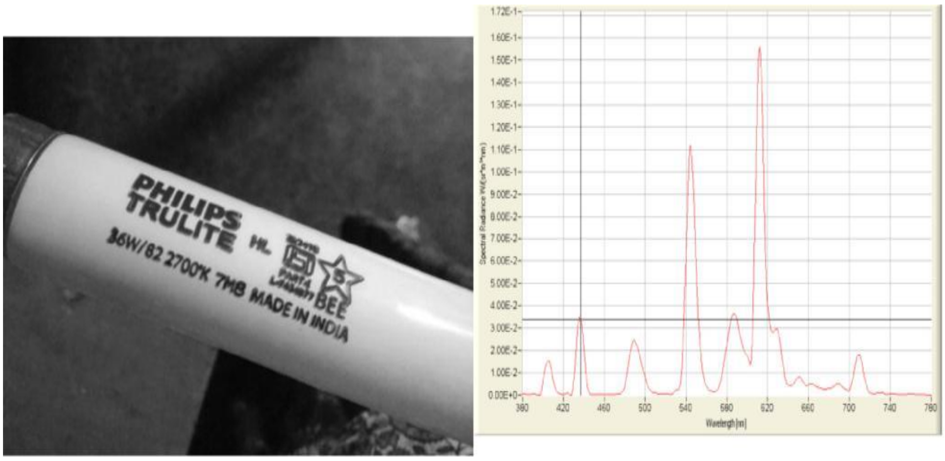
CURRENT: 0.44A

LUMINOUS FLUX: 3250 lm

CCT : 2700K

LUMINOUS EFFICACY: 90 lm/W

CRI: 82



SPD Fig

Fig 4.8 curve for 36W Warm White FTL

4.2.4 MEASUREMENT SET-UP

Figure 4.6shows a diagram of the experimental set-up used to carry out the experiment in the Dark Room of Illumination Engineering Laboratory, Electrical Engineering Department of Jadavpur University. Mounting height of Luminaires on pole was 3.6 meter .The measurement grid was of 11x6 points with both length and breadth wise separation of 0.5m.Length wise the grids were marked as 1,2,….11. Breadth wise the grids were marked as A,B,…F. The points are shown in figure. The luminance meter was fixed at height of 1.4m at a distance of 6m from the point (D,6). In this figure the surrounding light source positions are shown as pos1, pos2 and pos3. Pos3 is 0.7m away from grid point (F,1). Pos2 is 0.7m away from grid point (F,8). Pos1 is 2.9m away from pos2. Mounting height of the surrounding light sources is 2.5m. The nadir point of the main light source is at grid point (B,6). All height and distances were measured using a standard 50m measurement tape. Figure shows a photograph of the experimental setup.

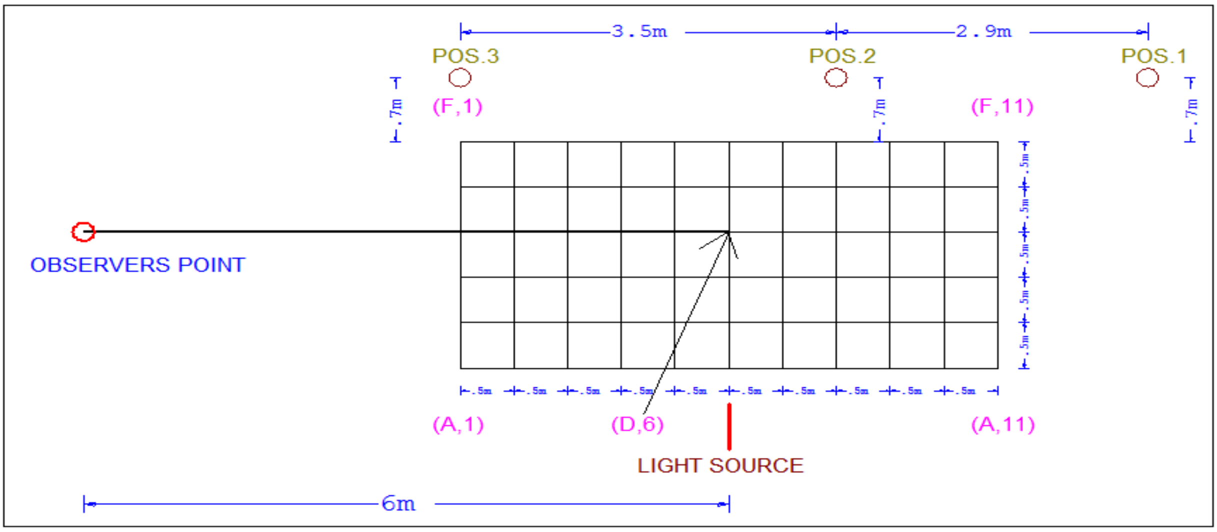


Fig 4.9 Layout of grid

Fig 4.10 Experimental set-up

CHAPTER :5

DETERMINATION OF PHOTOPIC LUMINANCE

5.1 DETERMINATION OF THEORITICAL PHOTOPIC LUMINANCE ($L_{p,t}$) OF COOL WHITE LED

To determine the theoretical photopic luminance ($L_{p,t}$) the intensity value (i.e. I-Table) of the cool white LED lamp were measured using Goniophotometer. The measured intensity values of the lamp are shown in the table 5.1

Table:5.1 I-Table(in candela) of the COOL WHITE LED lamp

	H(-90)	**H(-60)**	**H(-30)**	**H(0)**	**H(30)**	**H(60)**	**H(90)**
V(-90)	0.9	0.8	0.8	0.8	0.8	0.7	0.8
V(-45)	0.9	144.3	613.2	852.8	646.6	203.2	1
V(0)	1.5	448.4	1248.4	1486.7	1287.8	492.6	1.8
V(45)	3.4	151.3	643.2	903.7	679.3	209.1	5.5
V(90)	5	4.2	4.2	4.2	4.2	3.8	4.9

Then the C ,γ angle of each grid points are calculated of the area of measurement and the measured angles are shown in table 5.2 and table 5.3 respectively.

Table:5.2 C angle (in degree) of the grid points

	A	**B**	**C**	**D**	**E**	**F**
1	168.69	180	168.69	158.2	149.03	141.34
2	165.96	180	165.96	153.43	143.13	135
3	161.56	180	161.56	146.31	135	126.86
4	153.44	180	153.44	135	123.69	116.56
5	135	180	135	116.56	108.43	104.03
6	90	90	90	90	90	90
7	45	0	45	63.43	71.56	75.96
8	26.56	0	26.56	45	56.31	63.43
9	18.43	0	18.43	33.69	45	53.13
10	14.03	0	14.03	26.56	36.87	45
11	11.31	0	11.31	21.8	30.96	38.65

Table:5.3 γ angle (in degree) of the grid points

	A	**B**	**C**	**D**	**E**	**F**
1	35.30602	34.77783	35.30602	36.79427	39.00244	41.64742
2	29.79776	29.0546	29.79776	31.84566	34.77783	38.15581
3	23.71133	22.61986	23.71133	26.60038	30.50896	34.77783
4	17.25297	15.52411	17.25297	21.44674	26.60038	31.84566
5	11.11249	7.907163	11.11249	17.25297	23.71133	29.79776
6	7.907163	0	7.907163	15.52411	22.61986	29.0546
7	11.11249	7.907163	11.11249	17.25297	23.71133	29.79776
8	17.25297	15.52411	17.25297	21.44674	26.60038	31.84566
9	23.71133	22.61986	23.71133	26.60038	30.50896	34.77783

10	29.79776	29.0546	29.79776	31.84566	34.77783	38.15581
11	35.30602	34.77783	35.30602	36.79427	39.00244	41.64742

Angles in C-plane (C,γ) have been calculated from the measured data in B-plane(B,β) using the conversion equations for photometry plane systems .

Orientation Plane		**For conversion of Angles**	
Given	Required	For Planes	For Angles
C,γ	B,β	tanB = sinC× tanγ	Sinβ = sinC×sinγ

After the conversion we got the B-plane (B,β) angles and the value of these angles are shown in the table 5.4 and table 5.5 respectively.

Table:5.4 B-angle (in degree) of the grid points

	A	**B**	**C**	**D**	**E**	**F**
1	7.907209	0	7.907209	15.5232	22.62356	29.05471
2	7.90921	0	7.90921	15.52666	22.61991	29.0546
3	7.909227	0	7.909227	15.52408	22.61986	29.05776
4	7.905786	0	7.905786	15.52411	22.61988	29.05568
5	7.907163	0	7.907163	15.52476	22.62045	29.05527
6	7.907163	0	7.907163	15.52411	22.61986	29.0546
7	7.907163	0	7.907163	15.52347	22.61927	29.05421
8	7.905786	0	7.905786	15.52411	22.61988	29.05355
9	7.90514	0	7.90514	15.52408	22.61986	29.05457
10	7.90376	0	7.90376	15.52151	22.61991	29.0546
11	7.907209	0	7.907209	15.5232	22.61764	29.0494

Table:5.5 β-angle (in degree) of the grid points

	A	**B**	**C**	**D**	**E**	**F**
1	6.508158	0	6.508158	12.8517	18.89643	24.52811
2	6.924266	0	6.924266	13.65089	20.0133	25.9032
3	7.307702	0	7.307702	14.38137	21.03751	27.15349
4	7.620795	0	7.620795	14.98368	21.87379	28.16095
5	7.832921	0	7.832921	15.38423	22.42687	28.82368
6	7.907163	0	7.907163	15.52411	22.61986	29.0546
7	7.832921	0	7.832921	15.38285	22.4255	28.82231
8	7.620795	0	7.620795	14.98368	21.87379	28.15827
9	7.303856	0	7.303856	14.38137	21.03751	27.14964
10	6.91941	0	6.91941	13.64604	20.0133	25.9032
11	6.508158	0	6.508158	12.8517	18.89073	24.52241

Now from the I-Table of COOL WHITE LED lamp and B-Plane (B,β) angle, the intensity value were interpolated by using the bilinear interpolation method for all grid points of area of measurement .

The interpolated intensity value of the lamp are shown in the table5.6

Table:5.6 Intensity value (cd) of the grid points

	A	**B**	**C**	**D**	**E**	**F**
1	1348.986	1486.7	1348.986	1213.512	1083.817	962.8307
2	1343.52	1486.7	1343.52	1202.9	1068.896	944.2617
3	1338.495	1486.7	1338.495	1193.24	1055.189	927.3549
4	1334.415	1486.7	1334.415	1185.26	1043.997	913.7646
5	1331.626	1486.7	1331.626	1179.948	1036.591	904.8177
6	1330.653	1486.7	1330.653	1178.099	1034.013	901.704
7	1331.626	1486.7	1331.626	1179.975	1036.618	904.8439
8	1334.415	1486.7	1334.415	1185.26	1043.997	913.8159
9	1338.573	1486.7	1338.573	1193.24	1055.189	927.4295
10	1343.62	1486.7	1343.62	1203	1068.896	944.2617
11	1348.986	1486.7	1348.986	1213.512	1083.935	962.9453

Now from this intensity values, the illuminance (E) value for all grid points were calculated using the Inverse Square Law of illumination. The calculated illuminance values are shown in the table5.7

Table:5.7 Illuminance value (in lux) for all grid points

	A	**B**	**C**	**D**	**E**	**F**
1	58.12091	69.27773	66.74846	62.3593	56.41942	49.47742
2	64.09923	77.39198	74.80622	69.8954	63.0245	54.86704
3	69.67698	85.14891	82.57216	77.18238	69.37469	59.98414
4	74.29927	91.71499	89.19886	83.41024	74.7849	64.30433
5	77.37512	96.16429	93.71047	87.66332	78.4702	67.22271
6	78.4583	97.7449	95.31897	89.1824	79.78493	68.2592
7	77.37512	96.16429	93.71047	87.66533	78.47223	67.22466
8	74.29927	91.71499	89.19886	83.41024	74.7849	64.30795
9	69.68104	85.14891	82.57698	77.18238	69.37469	59.98897
10	64.10402	77.39198	74.81182	69.9012	63.0245	54.86704
11	58.12091	69.27773	66.74846	62.3593	56.42554	49.48332

To get the theoretical photopic luminance ($L_{p,t}$) value this illuminance (E) value multiplied with measured luminance coefficient (q) value as shown in Table 5.8 .

Table:5.8 Measured Luminance co-efficient value for all grid points

	A	**B**	**C**	**D**	**E**	**F**
1	0.03689	0.0455	0.084615	0.0414	0.036243	0.026391
2	0.031881	0.03657	0.043366	0.03137	0.026802	0.026
3	0.024912	0.03055	0.03295	0.028795	0.021933	0.031966
4	0.02387	0.023655	0.03245	0.024324	0.026183	0.02878
5	0.02237	0.02282	0.023448	0.022253	0.019869	0.027669
6	0.023689	0.019538	0.021939	0.02412	0.020071	0.023383
7	0.021556	0.02024	0.021214	0.0195	0.019808	0.02386
8	0.028255	0.019912	0.018937	0.019203	0.022644	0.028924
9	0.0285	0.023021	0.02264	0.024975	0.021461	0.03047
10	0.021507	0.026141	0.025775	0.023389	0.024451	0.034421
11	0.02522	0.031288	0.03221	0.032894	0.039205	0.037794

Then theoretical photopic luminance ($L_{p,t}$) as shown in Table 5.9 are determined by multiplying illuminance (E) value with measured luminance coefficient (q) value .

Table:5.9 Theoretical photopic luminance ($L_{p,t}$) (in cd/m^2)

	A	**B**	**C**	**D**	**E**	**F**
1	2.557251	3.521335	5.865595	2.485868	1.830434	1.094789
2	2.488837	3.205697	3.38542	2.101056	1.491324	1.171317
3	2.156829	2.986107	2.852743	2.119638	1.325513	1.543146
4	2.241554	2.51919	3.047274	1.927156	1.686301	1.464262
5	2.213111	2.568243	2.31971	1.847811	1.332214	1.454722
6	2.38621	2.241292	2.209931	2.035513	1.364441	1.243192
7	2.13258	2.277881	2.098745	1.619248	1.328159	1.254458
8	2.653335	2.120592	1.778265	1.521426	1.458369	1.471671
9	2.467615	2.250185	1.960239	1.838443	1.296982	1.471045
10	1.679096	2.291499	2.012292	1.566646	1.360519	1.550671
11	1.748275	2.42144	2.232829	1.975124	1.980226	1.568016
Average Theoretical Photopic Luminance Value = 2.05562						

5.2 MEASUREMENT OF PHOTOPIC LUMINANCE

In all the grid points the photopic luminance values are measured by Luminance meter. Luminance level were measured when only main light source is on. Point specific photopic luminance (**L_p)** values for COOL WHITE LED source are shown below in the table 5.10.

Table:5.10 Measurement of L_P (cd/m^2) when only COOL WHITE LED is on.

	A	**B**	**C**	**D**	**E**	**F**
1	2.35	2.74	2.8	2.13	1.6	1.14
2	4.25	3.54	4.3	3.21	2.2	1.3
3	3.55	3.78	2.24	3.8	2.3	1.58
4	4.7	3.53	3.38	2.63	2.33	1.57
5	4.31	5.07	2.86	3.42	2.28	1.94
6	4.08	4.44	2.88	3.11	2.36	1.4
7	4.34	4.05	3.06	2.95	2.54	1.6
8	2.64	2.87	2.02	2.37	2.64	1.17
9	3.42	3.01	3.5	2.28	1.56	1.08
10	2.08	1.87	2.64	2.79	1.36	1.3
11	1.717	1.6	1.6	1.61	1.45	1.24
Average Photopic Luminance = 2.628136						

Also there are 2 SETs of experiments performed in this work for measurement of photopic luminance for two different types of Surrounding Light Sources (SLE). At first three Cool white fluorescent tube light have been used as surrounding source (CWSLE). Then all the three tube lights have been replaced by three warm white fluorescent tubes as surrounding sources (WWSLE).

The table shows the conditions in which the photopic luminance values are measured:

		Surrounding Light Source (SLE)	
		SET-1 FOR CWSLE	**SET-2** FOR WWSLE
Main Light Source :CWLED	CWLED: ON	ON	-
		-	ON
	CWLED: OFF	ON	
		-	ON

5.2.1 FOR COOL WHITE SLE (SET-1)

In this case the photopic luminance values were measured on the grid when the surrounding light sources are cool white FTL. Point specific photopic luminance (**L_p**) values are measured for different two conditions:

1. Measurement of L_P when CWLED and all SLEs of all positions are on.
2. Measurement of L_P when only SLEs are on.

Table:5.11 Measurement of L_P (in cd/m^2) when CWLED and all SLEs of all positions are on.

	A	**B**	**C**	**D**	**E**	**F**
1	2.89	4.6	4.71	2.84	1.14	0.94
2	4.18	4.52	4.92	3.43	2.15	1.52
3	4.37	5.33	4.2	4.19	2.77	2.06
4	4.68	4.36	4.87	3.71	2.69	1.37
5	5.63	3.83	4.48	3.5	3.33	1.85
6	4.33	4.34	3.62	3.44	2.71	2.02
7	3.73	3.37	4.26	2.99	3.02	1.65
8	3.69	3.02	2.95	2.36	2.18	1.18
9	2.57	2.43	3.33	2.91	1.63	1.32
10	2.32	2.15	2.41	2.09	1.53	1.21
11	1.71	1.94	1.43	2.13	1.79	1.07
Average Photopic Luminance = 2.96803						

Table:5.12 Measurement of L_P (cd/m^2) when only CWSLEs are on.

	A	**B**	**C**	**D**	**E**	**F**
1	0.429	0.677	1.46	1.857	0.576	0.058
2	0.83	0.857	1.05	1.222	0.541	0.049
3	0.632	0.722	1.209	1.345	0.386	0.048
4	0.515	0.851	0.926	1.088	2.029	0.056
5	0.79	0.68	0.91	1.075	2.1	0.077
6	0.65	0.878	0.903	0.945	0.85	0.087
7	0.732	0.744	0.704	0.943	0.303	0.07
8	1.004	0.68	0.648	0.821	0.408	0.075
9	0.745	0.774	0.932	1.215	0.305	0.073
10	0.73	0.732	0.99	1.082	0.29	0.087
11	0.573	0.645	0.635	1.07	0.342	0.091
Average Photopic Luminance = 0.724258						

5.2.2 FOR WARM WHITE SLE (SET-2)

In this case we measured photopic luminance value when the surrounding light sources are warm white FTL. Point specific photopic luminance **(L_p)** values are measured for different two conditions:

1. Measurement of L_P when CWLED and all SLE of all positions are on.
2. Measurement of L_P when only SLEs are on.

Table:5.13 Measurement of L_P(cd/m^2) when CWLED and all SLE of all positions are on.

	A	**B**	**C**	**D**	**E**	**F**
1	2.08	2.63	4.8	3.83	2	1.24
2	5.1	3.94	3.6	4.75	1.76	1.29
3	4.1	3.87	4.1	3.2	3.12	1.54
4	5.5	4.1	4.3	4.19	3.72	1.31
5	4.8	5.63	3.61	3.59	4.07	1.97
6	4.47	4.27	3.64	4	3.43	1.55
7	4.5	5	4.33	4.5	3.08	1.83
8	4.2	3.24	3.361	3.44	3	1.06
9	4.23	3.46	4.45	4.24	2.25	1.37
10	2.12	2.57	3.93	3.74	1.85	1.46
11	2.26	2.29	2.17	2.51	2.23	1.33
Average Photopic Luminance = 3.259106						

Table:5.14 Measurement of L_P(cd/m^2) when only WWSLEs are on.

	A	**B**	**C**	**D**	**E**	**F**
1	0.66	0.53	1.059	1.3	2.43	0.064
2	0.95	0.56	1.25	1.67	2.52	0.059
3	0.91	0.71	1.075	1.77	2.65	0.069
4	0.65	0.75	1.086	1.41	1.9	0.072
5	0.82	0.81	0.98	1.15	2.19	0.083
6	0.71	0.95	0.91	1.15	0.94	0.068
7	0.82	0.87	0.95	1.2	0.62	0.098
8	0.98	0.79	0.91	1.16	0.53	0.087
9	0.99	0.92	1.342	1.36	0.62	0.094
10	0.69	0.87	1.34	2.33	0.535	0.103
11	0.74	0.97	0.72	1.22	0.584	0.101
Average Photopic Luminance = 0.930439						

5.3 MEASUREMENT OF VERTICAL ILLUMINANCE

Veiling Luminance caused by the surrounding light sources has an impact on the adaptation luminance perceived by the observer. Vertical illuminance (E_V) due to the SLE sources is measured for two different conditions. The table shows the conditions in which the vertical illuminance values are measured.

	SLEs OF ALL POSITION
SET-1: FOR CWFTL	ON
SET-2: FOR WWFTL	ON

5.3.1 FOR COOL WHITE SLE (SET-1)

In this case the vertical illuminance values on the grid when the surrounding light sources are cool white FTL were measured. The measured values of Vertical illuminance are shown in table5.15

Table:5.15 Vertical illuminance value (lux)

	A	**B**	**C**	**D**	**E**	**F**
1	12.89	20.5	26.7	37.3	43.7	26.2
2	12.1	19	24.6	33.2	39.2	23.9
3	10.3	15.5	17.8	22.3	23.1	12
4	9.5	10.9	12.7	14.2	8.7	4.4
5	7.8	8.3	8.9	7.6	4.8	1
6	5.6	5.1	5	4.3	2.3	0.7
7	3.8	3.5	3.4	2.5	1.2	0.4
8	2.8	2.5	2	1.3	0.6	0.1
9	2.2	1.9	1.1	0.9	0.4	0.2
10	1.4	1.1	0.8	0.6	0.3	0.2
11	1	0.7	0.6	0.3	0	0.2

5.3.2 FOR WARM WHITE SLE (SET-1)

In this case the vertical illuminance values on the grid when the surrounding light sources are warm white FTL were measured. The measured values of Vertical illuminance are shown in table5.16

Table:5.16 Vertical illuminance value(lux)

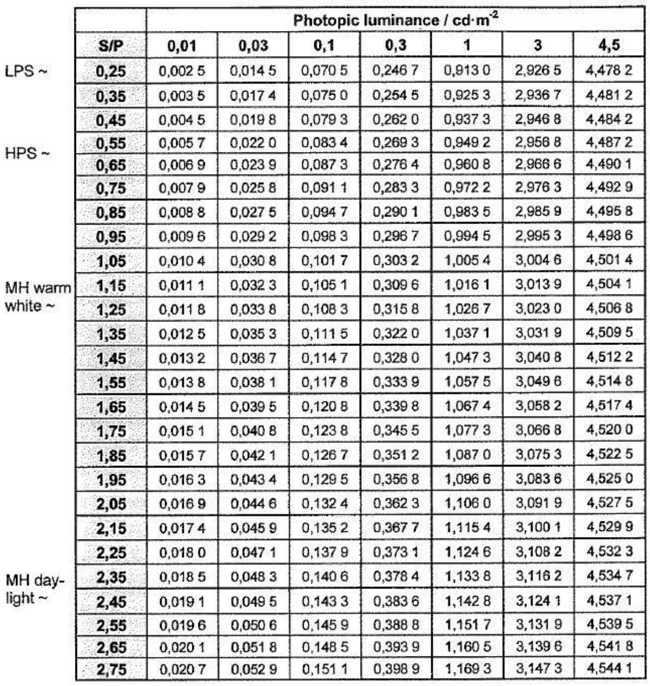
	A	**B**	**C**	**D**	**E**	**F**
1	17.1	23.1	30.7	40.9	47.2	30.6
2	15.5	21.3	27.9	36.6	39.9	26.9
3	14.2	17.6	21	24.3	23.3	15.3
4	11.7	12.6	14.6	14.9	10.9	6.2
5	8.9	9.7	9.5	7.9	5.7	2.1
6	6.4	6.8	6.5	5	3.1	0.4
7	4.9	4.5	3.7	3	1.7	0.3
8	3.4	2.7	2.5	1.6	0.5	0.2
9	2.6	2.1	1.9	1.1	0.2	0.1
10	2.1	1.6	1.2	0.7	0.3	0.1
11	1.4	1	0.9	0.4	0.3	0.1

CHAPTER :6

DETERMINATION OF MESOPIC LUMINANCE

Previously it was studied that mesopic luminance can be calculated from photopic luminance value using the CIE 191-2010 table. After measurement of photopic luminance, corresponding Mesopic luminance (L_M) is calculated using CIE 191:2010 and S/P ratio of the light source .Using Scotopic/Photopic meter the S/P ratio of the light source COOL WHITE LED were determined. Then Mesopic luminance values are interpolated from the known photopic luminance values and s/p ratios using CIE191-2010 as shown in table 6.1.

Table6.1 Values of L_M of the recommended Mesopic system as a function of photopic luminance and s/p ratio [CIE191]



		Photopic luminance / cd·m^{-2}						
	S/P	**0,01**	**0,03**	**0,1**	**0,3**	**1**	**3**	**4,5**
LPS ~	**0,25**	0,002 5	0,014 5	0,070 5	0,246 7	0,913 0	2,926 5	4,478 2
	0,35	0,003 5	0,017 4	0,075 0	0,254 5	0,925 3	2,936 7	4,481 2
	0,45	0,004 5	0,019 8	0,079 3	0,262 0	0,937 3	2,946 8	4,484 2
HPS ~	**0,55**	0,005 7	0,022 0	0,083 4	0,269 3	0,949 2	2,956 8	4,487 2
	0,65	0,006 9	0,023 9	0,087 3	0,276 4	0,960 8	2,966 6	4,490 1
	0,75	0,007 9	0,025 8	0,091 1	0,283 3	0,972 2	2,976 3	4,492 9
	0,85	0,008 8	0,027 5	0,094 7	0,290 1	0,983 5	2,985 9	4,495 8
	0,95	0,009 6	0,029 2	0,098 3	0,296 7	0,994 5	2,995 3	4,498 6
	1,05	0,010 4	0,030 8	0,101 7	0,303 2	1,005 4	3,004 6	4,501 4
MH warm white ~	**1,15**	0,011 1	0,032 3	0,105 1	0,309 6	1,016 1	3,013 9	4,504 1
	1,25	0,011 8	0,033 8	0,108 3	0,315 8	1,026 7	3,023 0	4,506 8
	1,35	0,012 5	0,035 3	0,111 5	0,322 0	1,037 1	3,031 9	4,509 5
	1,45	0,013 2	0,036 7	0,114 7	0,328 0	1,047 3	3,040 8	4,512 2
	1,55	0,013 8	0,038 1	0,117 8	0,333 9	1,057 5	3,049 6	4,514 8
	1,65	0,014 5	0,039 5	0,120 8	0,339 8	1,067 4	3,058 2	4,517 4
	1,75	0,015 1	0,040 8	0,123 8	0,345 5	1,077 3	3,066 8	4,520 0
	1,85	0,015 7	0,042 1	0,126 7	0,351 2	1,087 0	3,075 3	4,522 5
	1,95	0,016 3	0,043 4	0,129 5	0,356 8	1,096 6	3,083 6	4,525 0
	2,05	0,016 9	0,044 6	0,132 4	0,362 3	1,106 0	3,091 9	4,527 5
	2,15	0,017 4	0,045 9	0,135 2	0,367 7	1,115 4	3,100 1	4,529 9
	2,25	0,018 0	0,047 1	0,137 9	0,373 1	1,124 6	3,108 2	4,532 3
MH day-light ~	**2,35**	0,018 5	0,048 3	0,140 6	0,378 4	1,133 8	3,116 2	4,534 7
	2,45	0,019 1	0,049 5	0,143 3	0,383 6	1,142 8	3,124 1	4,537 1
	2,55	0,019 6	0,050 6	0,145 9	0,388 8	1,151 7	3,131 9	4,539 5
	2,65	0,020 1	0,051 8	0,148 5	0,393 9	1,160 5	3,139 6	4,541 8
	2,75	0,020 7	0,052 9	0,151 1	0,398 9	1,169 3	3,147 3	4,544 1

Point specific mesopic luminance (**L_M**) values are calculated for all the grid points for main light source, CWLED from the measured photopic luminance (L_P) data. The calculated mesopic luminance values are shown in table 6.2.

Table:6.2 Determination of L_M(in cd/m^2) when only CWLED is on.

	A	B	C	D	E	F
1	2.4499	2.837	2.8966	2.2315	1.7053	1.2487
2	4.2895	3.6111	4.3373	3.2958	2.301	1.4075
3	3.6207	3.8404	2.3407	3.8595	2.4002	1.6855
4	5	3.6016	3.4582	2.7278	2.43	1.6756
5	4.3469	5	2.9562	3.4964	2.3804	2.0429
6	4.1227	4.4711	2.976	3.2002	2.4598	1.5068
7	4.3755	4.0984	3.1525	3.0455	2.6385	1.7053
8	2.7378	2.9661	2.1223	2.4697	2.7378	1.2785
9	3.4964	3.1047	3.57294	2.3804	1.6656	1.1891
10	2.1818	1.9734	2.7378	2.8867	1.4671	1.4075
11	1.8215	1.7053	1.7053	1.7153	1.5564	1.348
Average Mesopic Luminance = 2.719066						

In this study there are 2 SETs of measurement, i.e. for cool white & warm white SLEs. In SET1 the calculated values of mesopic luminances are shown when the surrounding light sources are cool white FTL. In SET2 same are shown when surrounding light sources are warm white FTL. The table shows the conditions in which the mesopic luminance values are calculated.

		Surrounding Light Source (SLE)	
		SET-1 FOR CWSLE	**SET-2** FOR WWSLE
Main Light Source :CWLED	CWLED: ON	ON	-
		-	ON
	CWLED: OFF	ON	
		-	ON

6.1 FOR COOL WHITE SLE (SET-1)

Point specific mesopic luminance (**L_M**) values are calculated for all the grid points for COOL WHITE LED main light sources from the measured photopic luminance (L_P) data. The point specific mesopic luminances (L_M) were calculated for two different conditions:

1. Determination of L_M when both COOL WHITE LED and all SLEs of all positions are on.
2. Determination of L_M when only SLEs of all position are on.

Table:6.3 Determination of L_M (in cd/m^2) when CWLED and all SLE of all position are on.

	A	**B**	**C**	**D**	**E**	**F**
1	2.9859	5	5	2.9363	1.248	1.0458
2	4.2226	5	5	3.506	2.2513	1.6259
3	4.4042	5	4.2418	4.2322	2.8668	2.162
4	4.7004	4.3946	5	3.7735	2.7874	1.477
5	5	3.8882	4.5	3.5729	3.4105	1.9535
6	4.366	4.3755	3.6876	3.5156	2.8072	2.1223
7	3.7927	3.4487	4.2991	3.0852	3.1142	1.755
8	3.7544	3.1142	3.0455	2.4598	2.2811	1.2884
9	2.6683	2.5293	3.4105	3.0058	1.7351	1.4274
10	2.4201	2.25	2.5094	2.1918	1.6358	1.3182
11	1.8145	2.0429	1.5366	2.2315	1.894	1.1792
Average Mesopic Luminance = 3.049995						

Table:6.4 Determination of L_M (in cd/m^2) when only SLEs of all position are on

	A	B	C	D	E	F
1	0.4544	0.7079	1.4968	1.8928	0.6047	0.06599
2	0.8643	0.8919	1.0879	1.2595	0.5689	0.0561
3	0.6619	0.7539	1.2465	1.3821	0.4105	0.055
4	0.5423	0.8858	0.9624	1.1258	2.0643	0.0638
5	0.8264	0.711	0.9461	1.1129	2.1351	0.0867
6	0.6803	0.9134	0.9389	0.9818	0.8847	0.0976
7	0.7641	0.7764	0.7355	0.9798	0.3256	0.079
8	1.0421	0.711	0.6783	0.8551	0.4329	0.8453
9	0.7774	0.8071	0.9686	1.2525	0.3277	0.08235
10	0.7621	0.7641	1.0278	1.1199	0.312	0.0976
11	0.6016	0.6752	0.665	1.1079	0.3655	0.1019
Average Mesopic Luminance = 0.764526						

6.2 FOR WARM WHITE SLE (SET-2)

Point specific mesopic luminance (**L_M**) values are calculated for all the grid points for COOL WHITE LED main light sources from the measured photopic luminance(L_P) data. The point specific mesopic luminances (L_M) were calculated for two conditions:

1. Determination of L_M when COOL WHITE LED and all SLEs of all positions are on.
2. Determination of L_M when only SLEs of all positions are on.

Table:6.5 Determination of L_M(cd/m^2) when CWLED and all SLE of all position are on

	A	B	C	D	E	F
1	2.1818	2.7278	5	3.8882	2.1024	1.348
2	5	3.9933	3.6684	5	1.8642	1.3976
3	4.1462	3.9264	4.1462	3.2862	3.2098	1.6458
4	5	4.1462	4.3373	4.2322	3.7831	1.4175
5	5	5	3.678	3.6589	4.1175	2.0726
6	4.4997	4.3086	3.7067	4.0507	3.506	1.6557
7	5	5	4.366	5	3.1716	1.9337
8	4.2418	3.3245	3.678	3.5156	3.09518	1.1693
9	4.2704	3.5347	4.4806	4.28	2.3506	1.477
10	2.2215	2.6683	3.9838	3.8022	1.9535	1.5664
11	2.3605	2.3903	2.2712	2.6087	2.3307	1.43735
Average Mesopic Luminance = 3.336158						

Table:6.6 Determination of L_M(cd/m^2) when only SLE of all position are on

	A	**B**	**C**	**D**	**E**	**F**
1	0.6858	0.6539	0.774	0.7929	0.8818	0.3535
2	0.7571	0.6612	0.789	0.822	0.8889	0.3413
3	0.7422	0.6981	0.7752	0.8299	0.8991	0.3657
4	0.6838	0.7079	0.7761	0.8016	0.8401	0.373
5	0.7251	0.7227	0.7644	0.7811	0.8629	0.3998
6	0.6981	0.7571	0.7422	0.7811	0.7546	0.3632
7	0.7251	0.7374	0.7521	0.7851	0.676	0.4363
8	0.7644	0.7177	0.7422	0.7819	0.6841	0.4095
9	0.7669	0.7497	0.7962	0.7977	0.676	0.4265
10	0.6932	0.7374	0.7961	0.874	0.65514	0.4435
11	0.7055	0.762	0.7005	0.7867	0.6671	0.4419
Average Mesopic Luminance = 0.695973						

CHAPTER :7

SIMULATION OF ADAPTATION LUMINANCE

In previous two chapter photopic luminance (L_P) has been measured and corresponding mesopic luminance (L_M) has been calculated. In this chapter the simulation of adaptation luminance (L_a) using MATLAB simulation software has been discussed. There are 2 SETs as discussed in previous two chapters. In SET-1 the simulated values of adaptation luminances are shown when the surrounding light sources are cool white FTL. In SET-2 the simulated values of adaptation luminances are shown when the surrounding light sources are warm white FTL. The visual angles between the source and task points (here grid points) are calculated in degrees using MATLAB. Photopic Luminance (L_P) and Veiling Luminance (L_v) of each grid points are added to get Adaptation Luminance (L_a) .

$$La = Lp + Lveil$$

The table shows the conditions in which the adaptation luminance values are simulated.

	SURROUNDING LIGHT SOURCE (SLE) OF ALL POSITIONS		MAIN LIGHT SOURCE
	COOL WHITE SLEs	WARM WHITE SLEs	COOL WHITE LED (CWLED)
SET-1	ON	X	ON
SET-2	X	ON	ON

Before the simulation of adaptation luminance (La), veiling luminance values were simulated. As discussed earlier in the ‘Experimental Procedure’ chapter, to calculate ‘Surrounding Luminance Effect’ three veiling luminance models were used in this study. Three adaptation luminance values i.e. L_a , L_{a1} ,L_{a2} are simulated from three veiling luminance models Uchida and Ohno model, Fry model , CIE general disability glare equation model respectively .

7.1 FOR COOL WHITE SLE (SET-1)

Point specific adaptation luminance ($\mathbf{L_a}$) values are calculated for all the grid points from the measured photopic luminance (L_P) data while CWLED has been used as main light source and CWFTL has been used as SLEs. For CWLED light source adaptation luminances are simulated for followingcondition:

- Simulation of Adaptation Luminance (L_a) when CWLEDand all SLEs are on .

Adaptation luminance values are simulated (in cd/m^2) for CWLEDlamp along with the effect of SLEs using MATLAB software. The coding in M-file is shown below:

```
x=[1.5:-0.5:-1];
y=[-2.5:0.5:2.5];
[xx,yy]=meshgrid(x,y);
a=(1.4^2+(yy+6).^2).^0.5
b=(((xx+1.7).^2)+((3.9-yy).^2)+(2.15^2)).^0.5
c=((0.75^2)+9.9^2+1.7^2)^0.5
d=((a.^2)-(b.^2)+(c^2))./(2*c)
```

```
e=d./a
theta=acosd(e)
h=theta.^(-3)
i=260*h
filename = 'Ev for Ev cool.xlsx';
Ev = xlsread('Ev cool.xlsx')
size(i)
size(Ev)
L= i.*Ev
filename = 'CWLED Lp for CWLED Lp.xlsx';
Lp = xlsread('CWLED Lp.xlsx')
La=Lp+L
m=theta.^(2)
n=(1.5).*theta
p=m+n
o=Ev./p
Lv=(9.2).*o
La1=Lp+Lv
f=0.9
k=43
u=10*h
v=5./m
w=(0.1*f)./theta
s=(k/62.5)^4
t=0.0025*f
Lv1=Ev.*(u+((v+w)*(1+s))+t)
La2=Lp+Lv1
```

Here ‘Ev Cool ’ and ‘CWLED Lp’ are the name of the excel file for vertical illuminance and photopic luminance respectively. Adaptation luminance (L_a) for all the grid points (in cd/m^2) is listed below:

Table: 7.1 Adaptation Luminance (L_a)(in cd/m^2) from Uchida and Ohno model

	A	**B**	**C**	**D**	**E**	**F**
1	2.411119	2.87309	3.038249	2.583243	2.300508	1.659485
2	4.322028	3.69623	4.58128	3.734509	3.0304	1.935723
3	3.624709	3.936333	2.491898	4.241017	2.920584	1.989784
4	4.781964	3.661414	3.596279	2.970876	2.616572	1.756008
5	4.388492	5.18712	3.038252	3.635922	2.468527	1.990773
6	4.144667	4.522772	2.995557	3.251587	2.465244	1.441619
7	4.389672	4.114387	3.149246	3.043747	2.60274	1.627263
8	2.680955	2.921491	2.07883	2.424702	2.675261	1.177674
9	3.455653	3.053353	3.535848	2.321966	1.586058	1.097021
10	2.104923	1.897555	2.668603	2.820671	1.381409	1.318632
11	1.736411	1.619099	1.623336	1.626658	1.45	1.260172
Average Adaptation Luminance = 2.783745						

Table:7.2 Adaptation Luminance (L_{a1})(in cd/m^2) from Fry model

	A	B	C	D	E	F
1	2.429042	2.894355	3.047358	2.552418	2.192343	1.547542
2	4.33609	3.706894	4.567796	3.655796	2.836402	1.749438
3	3.63337	3.935515	2.462544	4.146299	2.737189	1.845048
4	4.786103	3.652814	3.559028	2.879926	2.517755	1.681464
5	4.388144	5.173577	2.999344	3.569118	2.395991	1.968488
6	4.141354	4.509686	2.965872	3.202776	2.4213	1.422059
7	4.385124	4.101867	3.123392	3.008641	2.574832	1.613753
8	2.675765	2.909856	2.06013	2.402835	2.658768	1.173708
9	3.450032	3.042363	3.523576	2.304278	1.573362	1.08792
10	2.10031	1.8899	2.658199	2.807167	1.370621	1.308389
11	1.732343	1.613381	1.614408	1.61905	1.45	1.248822
Average Adaptation Luminance = 2.75141						

Table:7.3 Adaptation Luminance (L_{a2}) (in cd/m^2) from CIE general disability glare equation model

	A	B	C	D	E	F
1	2.47339	2.964439	3.137402	2.675567	2.332858	1.629691
2	4.377557	3.771244	4.649409	3.762716	2.958248	1.821331
3	3.668447	3.987401	2.520516	4.216242	2.806569	1.879725
4	4.818199	3.688824	3.59959	2.923299	2.543047	1.693733
5	4.414258	5.200616	3.027213	3.591747	2.40954	1.971195
6	4.159919	4.526063	2.981227	3.215278	2.42763	1.423912
7	4.397592	4.112944	3.13364	3.015754	2.578067	1.614796
8	2.684855	2.917656	2.066052	2.406462	2.660359	1.173967
9	3.457098	3.048208	3.52678	2.306748	1.57441	1.088437
10	2.104759	1.893239	2.660493	2.80879	1.371401	1.308907
11	1.735487	1.615479	1.616104	1.619851	1.45	1.249344
Average Adaptation Luminance = 2.779481						

7.2 FOR WARM WHITE SLE (SET-2)

Point specific adaptation luminance (**L_a**) values are calculated for all the grid points for CWLED main light sources from the measured photopic luminance (L_P) data. For CWLED light source adaptation luminances are simulated for following condition:

- Simulation of Adaptation Luminance (L_a) when CWLED and all SLEs are on

Adaptation luminance values are simulated (in cd/m^2) for COOL WHITE LED lamp along with the effect of SLEs using MATLAB software. The coding in M-file is shown below:

```
x=[1.5:-0.5:-1];
y=[-2.5:0.5:2.5];
[xx,yy]=meshgrid(x,y);
```

```
a=(1.4^2+(yy+6).^2).^0.5
b=(((xx+1.7).^2)+((3.9-yy).^2)+(2.15^2)).^0.5
c=((0.75^2)+9.9^2+1.7^2)^0.5
d=((a.^2)-(b.^2)+(c^2))./(2*c)
e=d./a
theta=acosd(e)
h=theta.^(-3)
i=260*h
filename = 'Ev for Ev warm.xlsx';
Ev = xlsread('Ev warm.xlsx')
size(i)
size(Ev)
L= i.*Ev
filename = 'CWLED Lp for CWLED Lp.xlsx';
Lp = xlsread('CWLED Lp.xlsx')
La=Lp+L
m=theta.^(2)
n=(1.5).*theta
p=m+n
o=Ev./p
Lv=(9.2).*o
La1=Lp+Lv
f=0.9
k=43
u=10*h
v=5./m
w=(0.1*f)./theta
s=(k/62.5)^4
t=0.0025*f
Lv1=Ev.*(u+((v+w)*(1+s))+t)
La2=Lp+Lv1
```

Here 'E_v WARM ' and 'CWLED Lp' are the name of the excel file for vertical illuminance and photopic luminance respectively. Adaptation luminance (L_a) for all the grid points (in cd/m^2) is listed below

Table:7.4 Adaptation Luminance (L_a)(in cd/m^2) from Uchida and Ohno model

	A	**B**	**C**	**D**	**E**	**F**
1	2.354742	2.745194	2.802677	2.13243	1.601603	1.141983
2	4.256548	3.544934	4.30343	3.21158	2.202118	1.30266
3	3.56088	3.792103	2.247076	3.805933	2.302687	1.583415
4	4.716393	3.546879	3.393624	2.637202	2.333294	1.574227
5	4.336164	5.096811	2.890042	3.434205	2.283928	1.945077
6	4.119262	4.485443	2.935467	3.152806	2.369152	1.405946
7	4.398823	4.118067	3.149246	3.017498	2.566142	1.606816
8	2.724835	2.968862	2.15825	2.492028	2.734029	1.177674
9	3.541543	3.174286	3.744416	2.401234	1.76195	1.08851
10	2.263364	2.143043	2.97608	3.183614	1.781045	1.309316
11	1.965464	2.031098	2.311758	2.592808	2.471491	1.250086
Average Adaptation Luminance = 2.737141						

Table:7.5 Adaptation Luminance (L_{a1})(in cd/m^2) from Fry model

	A	B	C	D	E	F
1	2.356132	2.746024	2.802779	2.132265	1.601355	1.141556
2	4.257826	3.54527	4.303266	3.211343	2.201623	1.30188
3	3.562141	3.79204	2.246251	3.804659	2.301893	1.582209
4	4.717221	3.545774	3.391277	2.63528	2.332158	1.572533
5	4.336048	5.09371	2.883485	3.42981	2.282416	1.942849
6	4.117251	4.478259	2.921218	3.138049	2.36533	1.403151
7	4.393437	4.10483	3.123392	2.992222	2.554513	1.603438
8	2.714085	2.946523	2.114304	2.443246	2.690047	1.173708
9	3.522382	3.132638	3.660747	2.350137	1.663557	1.08396
10	2.229427	2.06719	2.853841	3.010308	1.568887	1.304194
11	1.91339	1.902032	2.039444	2.14393	1.942079	1.244411
Average Adaptation Luminance = 2.696404						

Table:7.6 Adaptation Luminance (L_{a2}) (cd/m^2) from CIE general disability glare equation model

	A	B	C	D	E	F
1	2.359573	2.748759	2.803791	2.132925	1.601677	1.141869
2	4.261596	3.547302	4.304261	3.211665	2.201934	1.302181
3	3.56725	3.796057	2.24788	3.8056	2.302193	1.582498
4	4.72364	3.550399	3.393832	2.636196	2.332449	1.572812
5	4.344753	5.0999	2.888182	3.431299	2.282699	1.943119
6	4.128522	4.48725	2.928589	3.141828	2.365881	1.403416
7	4.408201	4.116541	3.13364	2.997343	2.555861	1.603699
8	2.732913	2.961499	2.128222	2.451339	2.694289	1.173967
9	3.546469	3.15479	3.682589	2.357271	1.671678	1.084218
10	2.262154	2.100276	2.880797	3.031132	1.584217	1.304453
11	1.953632	1.949374	2.091187	2.191221	1.976218	1.244672
Average Adaptation Luminance = 2.706025						

CHAPTER :8

RESULT ANALYSIS

As the lighting level of many outdoor areas fall under mesopic region, it is necessary to evaluate lighting parameters in mesopic photometry system only. However due to unavailability of mesopic meters, now-a-days photopic quantities are measured first and then corresponding mesopic parameters are calculated. Again in outdoor lighting application areas it is also required to consider adaptation luminance due to wide field of view. Therefore to get an idea about light distribution in the area of measurement, point specific luminance in photopic, mesopic and adaptation conditions are measured and calculated in laboratory environment.

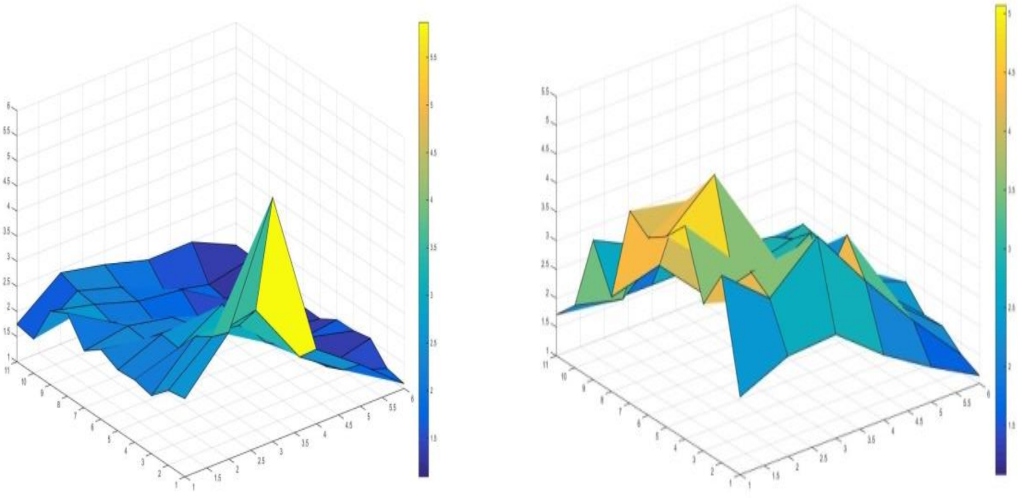
In this thesis work theoretical photopic luminance were evaluated at first from the luminous intensity distribution of a luminaire. Then the photopic luminance for the entire field of measurement were measured and corresponding mesopic luminance values are calculated from CIE 191:2010 Table (Table:4.1) using the S/P ratio of the lamp. Adaptation luminance for the said area of measurement is calculated by the method described in Chapter 4 .The results are compared in different forms as discussed below:

1. Comparison of Average Photopic, mesopic & Adaptation Luminance (L_{avg})
2. Effect of different types of Surrounding Source
3. Surrounding Luminance effect (SLE) in Adaptation luminance

8.1 Comparison of Average Luminance ($L_{average}$)

8.1.1 Photopic Luminance

Theoretical photopic luminances were evaluated at first from the luminous intensity distribution of a luminaire. Then the photopic luminances for the entire field of measurement were measured. Average values of theoretical photopic luminance ($L_{p,t}$) measured photopic luminance (L_P) , are shown in table8.1. The Luminance distribution of theoretical photopic luminance ($L_{p,t}$) and photopic luminance (L_p) are shown below:



$L_{p,t}$ L_p

Figure 8.1 Distribution of theoretical photopic luminance ($L_{p,t}$) and measured photopic luminance (L_p)

Table 8.1: Average Photopic luminance (in cd/m^2)

Only CWLED	**Average Luminance**	
	$L_{p,t}$	**L_p**
	2.05562	2.628136

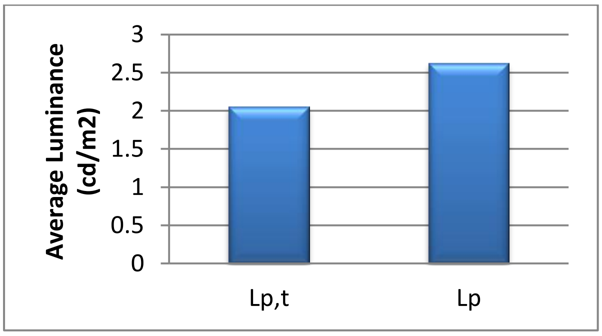
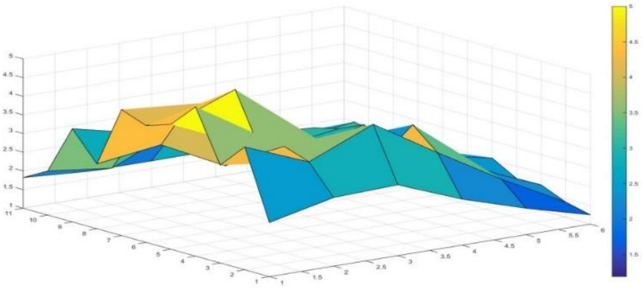


Fig 8.2 Comparison of theoretical ($L_{p,t}$) & measured photopic luminance(L_P)

The determine value of Average theoretical ($L_{p,t}$) photopic luminance is 2.05562 cd/m^2 and measured Average photopic luminance (L_P) is 2.628136 cd/m^2 are shown in table 8.1. There is a difference between these two value of Average theoretical ($L_{p,t}$) & measured Average photopic luminance(L_P) . Here the measured photopic luminance (L_P) value is higher than the theoretical ($L_{p,t}$) photopic luminance because the luminance coefficient value (q) of the grid surface is very poor.

8.1.2 Mesopic Luminance

After measuring photopic luminance for the entire field of measurement corresponding mesopic luminance values are calculated from CIE 191:2010 Table (Table:4.1) using the S/P ratio of the lamp. Average values of theoretical photopic luminance ($L_{p,t}$) measured photopic luminance (L_P), and mesopic luminance (L_M) are shown in table8.2. The Luminance distribution of Mesopic luminance (L_M) is shown below



L_M

Fig 8.3 Distribution of Mesopic luminance (L_M)

Table 8.2: Average luminance (in cd/m^2)

Only CWLED	**Average Luminance**		
	$L_{p,t}$	**L_p**	**L_M**
	2.05562	2.628136	2.719066

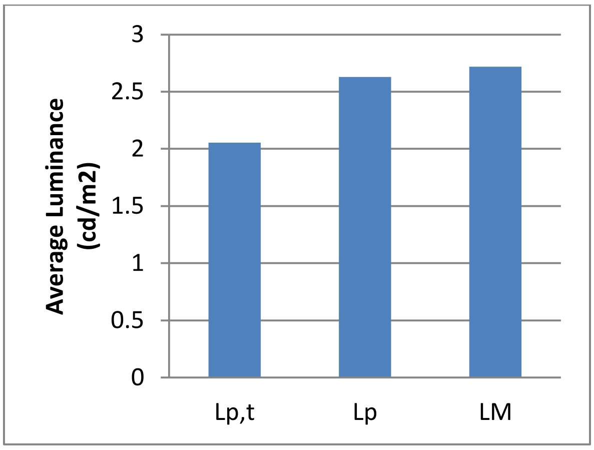


Fig 8.4 Comparison of photopic (L_P) & mesopic luminance

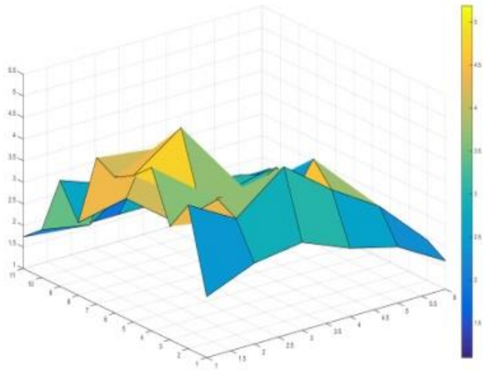
The value of Average theoretical ($L_{p,t}$) photopic luminance is 2.05562 cd/m^2 and measured Average photopic luminance (L_P) is 2.628136 cd/m^2. Here the measured photopic luminance (L_P) value is higher than the theoretical ($L_{p,t}$) photopic luminance because the luminance coefficient value (q) of the grid surface is very poor.

Average Mesopic luminance (L_M) value is higher than measured photopic luminance (L_P) because the S/P ratio of the light source (CWLED) is more than one i.e. 2.09.

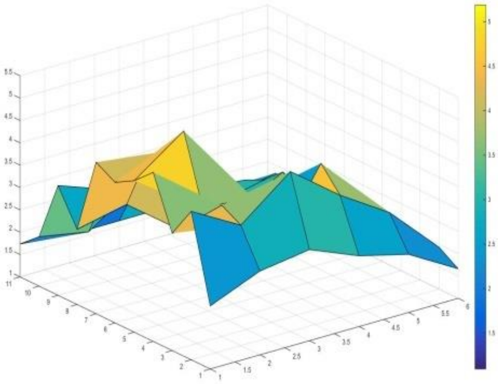
8.1.3 Adaptation Luminance

SET-1: For CWLED & CWSLE

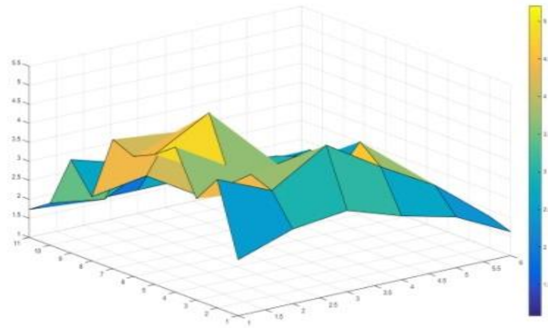
After measuring photopic luminance for the entire field of measurement corresponding adaptation luminance for the said area of measurement is calculated by three methods described in Chapter 4. Average values of adaptation luminance from three models (L_a), (L_{a1}) & (L_{a2}) are shown in table8.3. The Luminance distribution of Adaptation luminance (L_a), (L_{a1}) & (L_{a2}) is shown below



L_a



L_{a1}



L_{a2}

Fig 8.5 Distribution of Adaptation luminance

Table 8.3: Average adaptation luminance (in cd/m^2)

Only CWLED	**Average Luminance**		
	L_a	**L_{a1}**	**L_{a2}**
	2.783745	2.75141	2.779481

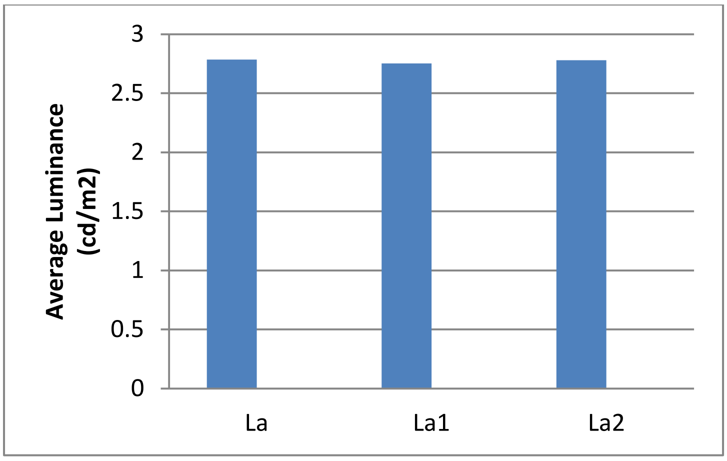


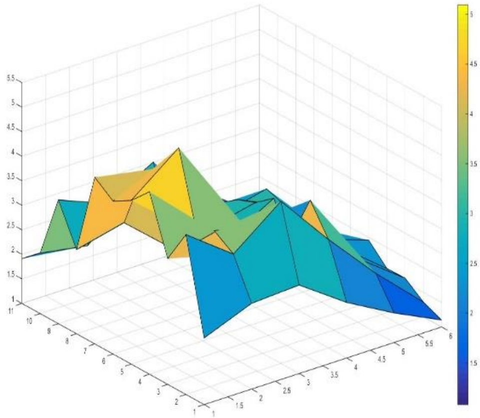
Fig 8.6 Comparison of adaptation luminance

The veiling luminance $L_{veiling}$ was added to the average photopic luminance L_p of the fields and this sum was considered to be the adaptation luminance.

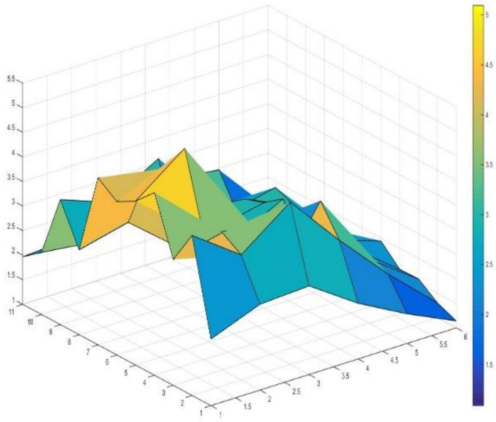
The increments to adaptation luminance caused by adding veiling luminance for three models were 5.92%, 4.69% and 5.75% respectively. Therefore from this plot it is very clear that calculated adaptation luminance is almost same for all the three models.

SET-2: For CWLED & WWSLE

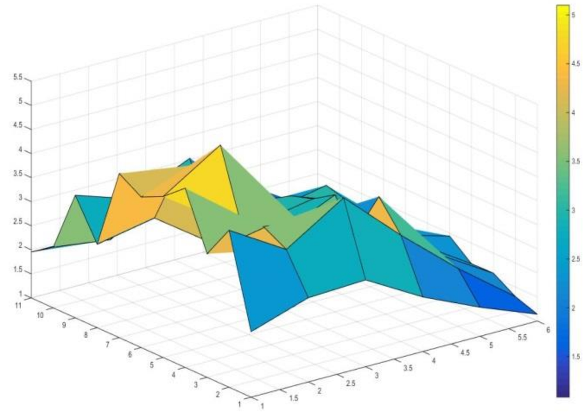
After measuring photopic luminance for the entire field of measurement corresponding adaptation luminance for the said area of measurement is calculated by three methods described in Chapter 4. Average values of adaptation luminance from three models (La), (La1) & (La2) are shown in table8.4. The Luminance distribution of Adaptation luminance (L_a), (L_{a1}) & (L_{a2}) is shown below:



L_a



L_{a1}



L_{a2}

Fig 8.7 Distribution of Adaptation luminance

Table 8.4: Average adaptation luminance (in cd/m^2)

Only CWLED	**Average Luminance**		
	L_a	**L_{a1}**	**L_{a2}**
	2.737141	2.6964404	2.706025

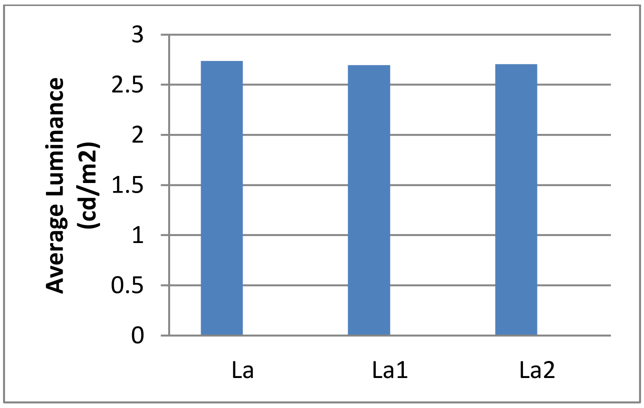


Fig 8.8 Comparison of adaptation luminance

The veiling luminance $L_{veiling}$ was added to the average photopic luminance L_p of the fields and this sum was considered to be the adaptation luminance.

The increments to adaptation luminance caused by adding veiling luminance for three models were 4.14%, 2.59% and 2.96% respectively. Therefore from this plot it is very clear that calculated adaptation luminance is almost same for all the three models.

8.1.4 Comparison of Photopic, Mesopic & Adaptation Luminance

SET-1: For CWLED & CWSLE

Average Luminance ($L_{average}$) values of theoretical photopic luminance ($L_{p,t}$), photopic luminance (L_P), mesopic luminance (L_M) and adaptation luminances (L_a,L_{a1},L_{a2}) of COOL WHITE LED are shown in the table

Table 8.5: Average luminance (in cd/m^2)

	$L_{p,t}$	L_P	L_M	L_a	L_{a1}	L_{a2}
CWLED & CWSLE	2.05562	2.628136	2.719066	2.783745	2.75141	2.779481

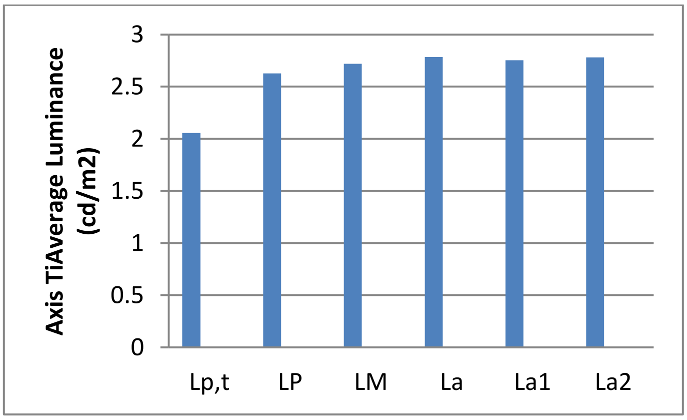


Fig 8.9 Comparison of Average luminance

The value of Average theoretical ($L_{p,t}$) photopic luminance is 2.05562 in cd/m^2 and measured Average photopic luminance (L_P) is 2.628136 in cd/m^2 .There is a difference between these two value of Average theoretical ($L_{p,t}$) & measured Average photopic luminance(L_P) . Here the measured photopic luminance (L_P) value is higher than the theoretical ($L_{p,t}$) photopic luminance because the luminance coefficient value (q) of the grid surface is very poor .

Average Mesopic luminance (L_M) value is higher than both Average theoretical ($L_{p,t}$) photopic luminance and measured Average photopic luminance (L_P) because the S/P ratio of the light source (CWLED) is higher than one.

The veiling luminance $L_{veiling}$ was added to the average photopic luminance L_p of the fields and this sum was considered to be the adaptation luminance. The increments to adaptation luminance caused by adding veiling luminance for three models were 5.92%, 4.69% and 5.75% respectively.

SET-2: For CWLED & WWSLE

Average Luminance ($L_{average}$) values of theoretical photopic luminance ($L_{p,t}$) , photopic luminance(L_P) , mesopic luminance(L_M) and adaptation luminances (L_a,L_{a1},L_{a2}) of COOL WHITE LED are shown in the table

Table 8.6: Average luminance (in cd/m^2)

	$L_{p,t}$	L_P	L_M	L_a	L_{a1}	L_{a2}
CWLED & WWSLE	2.05562	2.628136	2.719066	2.737141	2.6964404	2.706025

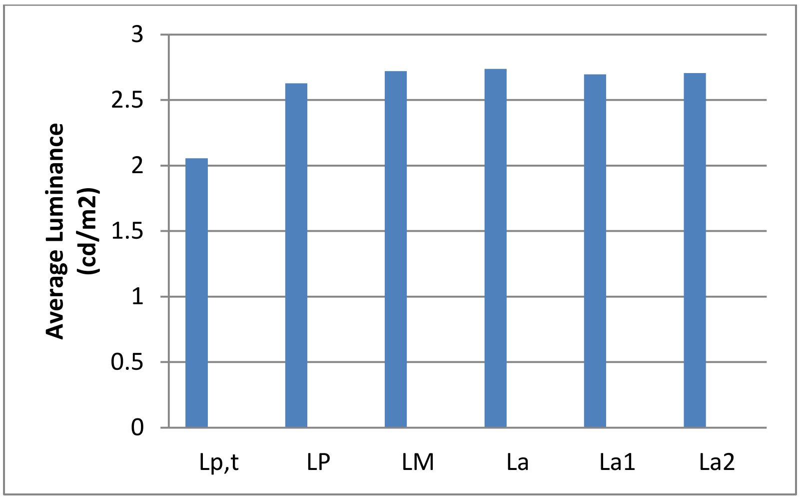


Fig 8.10 Comparison of Average luminance

The value of Average theoretical ($L_{p,t}$) photopic luminance is 2.05562 in cd/m^2 and measured Average photopic luminance (L_P) is 2.628136 in cd/m^2 .There is a slight difference between these two value of Average theoretical ($L_{p,t}$) & measured Average photopic luminance (L_P). Here the measured photopic luminance (L_P) value is higher than the theoretical ($L_{p,t}$) photopic luminance because the luminance coefficient value (q) of the grid surface is very poor.

Average Mesopic luminance (L_M) value is higher than both Average theoretical ($L_{p,t}$) photopic luminance and measured Average photopic luminance (L_P) because the S/P ratio of the light source (CWLED) is higher than one.

The veiling luminance $L_{veiling}$ was added to the average photopic luminance L_p of the fields and this sum was considered to be the adaptation luminance.

The increments to adaptation luminance caused by adding veiling luminance for three models were 4.14%, 2.59% and 2.96% respectively.

8.2 Surrounding Luminance effect (SLE) in mesopic luminance

To understand the effect of presence of other surrounding sources with the main light source in any application area under mesopic system, two different sets of measurement and calculation have been done.

- At first, mesopic luminance of the main light source CWLED (L_{M1}) and mesopic luminance of surrounding light source FTL (L_{M2}) from measured photopic luminance value have been calculated separately. These two individual mesopic luminance ($L_{M1}+L_{M2}$) value have been added to get the combined mesopic effect.

- Then for the second set, photopic luminance have been measured when the main light source CWLED and surrounding light source FTL both are lit together. After that mesopic luminance (L_M) value were calculated directly using CIE Table.

These two sets of data have been listed below and their difference is also discussed.

8.2.1 SET-1

In this case the main light source is Cool White LED and the surrounding light source is Cool White FTL.

Table11: Average Luminance (in cd/m^2)

Only CWLED		**Only CWFTL**		**Both CWLED & CWFTL**	
Photopic (L_p)	2.628136	Photopic (L_p)	0.724258	Photopic (L_p)	2.96803
Mesopic(L_{M1})	2.719066	Mesopic(L_{M2})	0.764526	Mesopic(L_M)	3.049995
$L_{M1}+L_{M2}$ = 3.483592				**L_M = 3.049995**	

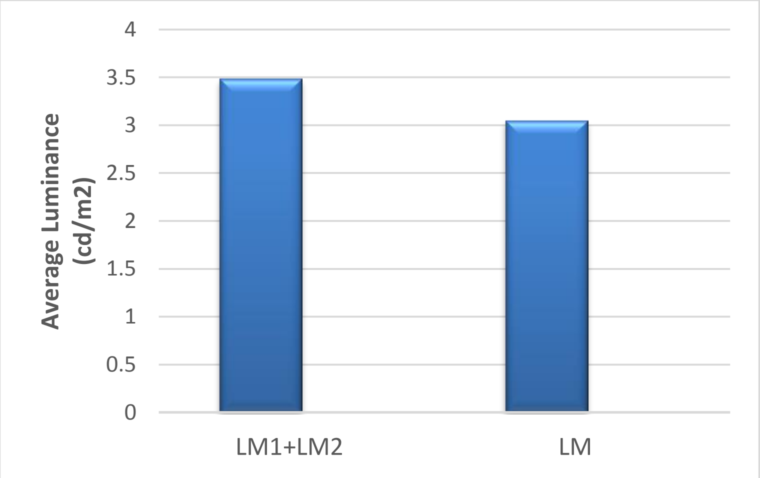


Fig 8.11 Mesopic Luminance for SET 1

The result in Fig 8.11 shows that the combine mesopic luminance value (L_{M1}+L_{M2}) is higher than the mesopic luminance value (L_M) when both light source were lit together. This combine mesopic luminance value is higher because, the main light source and the surrounding light source both were cool white light source. So it can be concluded that when both the main light source of any application area and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly.

8.2.2 SET-2

In this case the main light source is Cool White LED and the surrounding light source is Warm White FTL.

Table12: Average Luminance (in cd/m^2)

Only CWLED		**Only WWFTL**		**Both CWLED & WWFTL**	
Photopic (L_p)	2.628136	Photopic (L_p)	0.930439	Photopic (L_p)	3.259106
Mesopic(L_{M1})	2.719066	Mesopic(L_{M2})	0.695973	Mesopic(L_M)	3.336158
L_{M1}+L_{M2} = 3.415039				**L_M = 3.336158**	

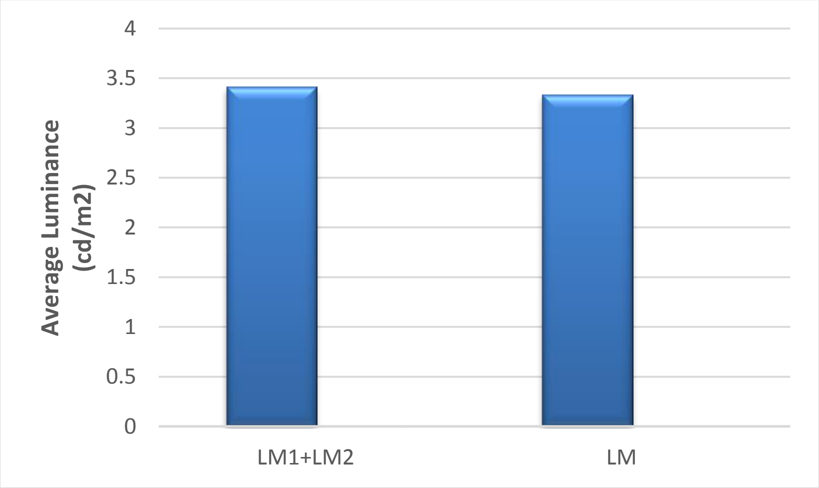


Fig 8.12

The result shows that the combine mesopic luminance value (L_{M1}+L_{M2}) is almost same with the mesopic luminance value (L_M) when both light source were lit together. There is slight difference between these two mesopic luminance values because, the main light source and surrounding light source were cool white and warm white respectively. . So it can be concluded that when the main light source of any application area and surrounding sources are of opposite types of S/P ratio (i.e. more or less than 1), then their effect will cancel each other. Therefore effective luminance in both cases will remain same.

8.3 Effect of different types of Surrounding Source:

Comparison of Average photopic Luminance (L_P) of the adaptation field and the adaptation state, $L_a = L_p + L_{veiling}$ as the sum of the average photopic Luminance of the adaptation field and the veiling luminance are shown below in Table 8.7.

Table 8.7 Effect of different surrounding source type

	SET-1 For CWLED & CWSLE	**SET-2 For CWLED & WWSLE**
L_P	2.628136	2.628136
L_a, using Uchida and Ohno equation	2.783745	2.737141
L_{a1} , using Fry equation	2.75141	2.696404
L_{a2} , using CIE general disability glare equation	2.779481	2.706025
Average increase by $L_{veiling}$ to adaptation state	5.456%	3.236%

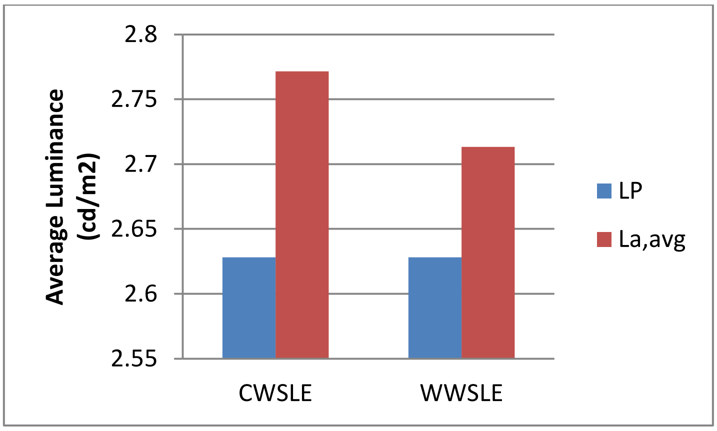


Fig 8.13 Comparison of Average luminance

Fig 8.14 Percentage change in adaptation luminance

The veiling luminance $L_{veiling}$ was added to the average photopic luminance (L_p), and this sum was considered to be adaptation states. The results shows that the increment in adaptation state for set 1 when the main light source was cool white LED and surrounding light source was cool FTL is 5.456% and for set 2 when the main light source was cool white

LED and surrounding light source was warm FTL is 3.236%. This is happened because in set 1 both the source were cool white and for set 2 main light source was cool white LED and surrounding light source warm white.

Therefore from the above result it can be concluded that

- Cool White LEDs provides better performance in mesopic region.
- The surrounding light source have a significant role on adaptation luminance.
- The nature of surrounding light source plays an important role on effective adaptation luminance to observer's eyes.
- When both the main light source of any application area and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly.
- When the main light source of any application area and surrounding sources are of opposite types of S/P ratio (i.e. more or less than 1), then their effect will cancel each other. Therefore effective luminance in both cases will remain same.
- When spectral characteristics of both main and surrounding light sources are same then the effective luminance to observer's eyes increases.
- Lamp performance under the above condition will be better in mesopic region.
- Therefore it is more accurate to consider adaptation luminance instead of photopic & mesopic luminance in case of outdoor lighting under mesopic region.

CHAPTER :9

CONCLUSION AND FUTURE SCOPE

Mesopic photometry aims to measure light in a way which correlates with the mesopic vision. In mesopic photometry, adaptation luminance is needed to derive the Mesopic luminance for the measurement field. Adaptation luminance is the average luminance (or brightness) of those objects and surfaces in the immediate vicinity of an observer estimating the visual range. Outdoor lighting installations incorporate different types of white Light Emitting Diode (WLED) lamps. The luminance level generally lies in Mesopic zone for different types of outdoor lighting. Adaptation luminance is also a factor for outdoor lighting. The objectives of the thesis work was to study the behaviour of cool white LED lamps under mesopic conditions & to compare adaptation luminance & mesopic luminance of cool white LED lamp under different surrounding luminance conditions.

From the thesis work & experimental results it can be concluded that cool white LEDs provides better performance in mesopic region. The surrounding light source have a significant role on adaptation luminance. The nature of surrounding light source plays an important role on effective adaptation luminance to observer's eyes. When both the main light source of any application area and surrounding sources are of same S/P ratio, then the effective luminance will increase significantly. When the main light source of any application area and surrounding sources are of opposite types of S/P ratio (i.e. more or less than 1), then their effect will cancel each other. Therefore effective luminance in both cases will remain same. When spectral characteristics of both main and surrounding light sources are same then the effective luminance to observer's eyes increases. Therefore lamp performance under the above condition will be better in mesopic region.

In this thesis work cool white LEDs were used as main light source so in future this study can also be performed for more than one light source like High pressure Sodium Vapour Lamp, Metal Halide, Warm White LED and their performance & adaptation luminance in mesopic photometry system can also be studied, .Measurement of luminous intensity in C-plane will give more accurate data. The experiment was conducted inside the laboratory room so there is a scope to carry the experiment outside the laboratory, in real outdoor (road lighting) condition considering other real environmental factors. Inside the laboratory room there were lots of obstruction and reflected light which slightly effect the measured data .So, in future these kinds of errors can be removed to get more accurate results.

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