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ANALYSIS OF THE EXISTING VISUAL PERFORMANCE BASED MESOPIC MODELS AND A PROPOSAL FOR A MODEL FOR THE BASIS OF MESOPIC PHOTOMETRY

Meri Viikari

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Helsinki University of Technology
Department of Electrical and Communications Engineering
Lighting Laboratory

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Abstract

The work started with outlining the current status of photometry. The origins of the photopic spectral luminous efficiency function $V(\lambda)$ were extensively investigated. The work continued to examine the ability of the existing photopic spectral luminous efficiency functions $V(\lambda)$, $V_M(\lambda)$, or $V_{10}(\lambda)$ to describe peripheral photopic vision. The conducted reaction time measurements indicated that none of the existing functions described the peripheral vision correctly. A new photopic spectral luminous efficiency function for peripheral vision $V_{per}(\lambda)$ is proposed for the photopic end with which the mesopic photometric model should merge at the upper luminance limit of the mesopic region.

The work continued to review the existing mesopic photometric systems. The previously proposed mesopic models are mainly based on brightness matching, which does not preserve additivity. The two recently proposed mesopic models, MOVE-model by the MOVE consortium (Eloholma 2005) and the X-model by Rea et al (2004), are based on visual task performance. Performance based mesopic models are claimed to preserve additivity within the given light level. The two performance based models are currently being analyzed by the CIE TC 1-58 in order to result in an internationally agreed system for performance based mesopic photometry.

The work continued to generate contrast threshold and reaction time data in order to compare the existing performance based mesopic models. The differences between the mesopic luminances predicted by the two models are evident. Also the upper transition points of the models between the mesopic and photopic regions are very different.

Finally, the work concluded by proposing a new performance based mesopic model. The new model is based on the same experimental data as the MOVE-model. Thus the newly proposed model is assigned as a modified MOVE-model. The modified MOVE-model was compared along with the other two performance based models using three independent experimental visual performance data sets. The comparison indicated that the modified MOVE-model described the experimental data best.

Keywords photometry, visual performance, mesopic model, spectral sensitivity

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Väitöskirjan nimi
Olemassa olevien näkösuorituspohjaisten mesooppisten mallien analysointi ja uuden mallin ehdotus näkösuorituspohjaisen mesooppisen fotometrian perustaksi

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Tiivistelmä

Tämä työ alkoi fotometrian nykytilan määrittämisellä. Fotooppisen spektriherkkyysfunktion $V(\lambda)$ historia ja alkuperä tutkittiin perusteellisesti. Työ jatkui tutkimalla nykyisten spektriherkkyysfunktioiden $V(\lambda)$, $V_M(\lambda)$ ja $V_{10}(\lambda)$ kykyä kuvata ääreisnäköä. Tehdyt reaktioaikamittaukset osoittivat, ettei yksikään olemassa olevista funktioista kuvaa ääreisnäköä oikein. Työssä ehdotetaan uutta fotooppista spektriherkkyysfunktiota ääreisnäölle $V_{per}(\lambda)$, johon mesooppisen fotometrisen mallin tulisi yhtyä mesoopisen alueen yläpäässä.

Työ jatkui olemassa olevien mesooppisten mallien tarkastelulla. Aikaisemmin ehdotetut mesooppiset mallit perustuvat kirkkauksien vertailu-menetelmään, joka ei noudata additiivisuutta. Kaksi viimeaikoina ehdotettua mesooppista mallia, MOVE-malli (Eloholma 2005) ja X-malli (Rea et al 2004), perustuvat tehtäväpohjaiseen näkösuoritukseen. Näkösuorituspohjaisten mesooppisten mallien on väitetty säilyttävän additiivisuuden annetulla valotasolla. Näitä kahta näkösuorituspohjaista mallia analysoidaan parhaillaan CIEn työryhmässä 1-58, jonka päämääränä on esittää kansainvälisesti hyväksytty malli näkösuorituspohjaisen mesooppinen fotometrian perustaksi.

Työ jatkui tekemällä kontrastikynnys ja reaktioaika mittauksia, jotta näkösuorituspohjaisia mesooppisia malleja pystyttiin vertailemaan. Erot näiden kahden mallin välillä ovat selviä. Myös mallien ylärajat mesooppisen ja fotooppisen alueen välissä ovat hyvin erilaiset.

Työ päätyi suosittelemaan uutta näkösuorituspohjaista mesooppista mallia. Uusi malli perustuu samaan mittausdataan kuin MOVE-malli, joten uusi malli nimettiin modifioiduksi MOVE-malliksi. Modifioitua MOVE-mallia verrattiin MOVE- ja X-malliin käyttäen kolmea itsenäistä näkösuoritukseen perustuvaa mittausdataa. Vertailu osoitti modifioidun MOVE-mallin kuvaavan parhaiten mitattua dataa.

Asiasanat fotometria, näkösuoritus, mesooppinen malli, spektriherkkyys

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Preface

This work was conducted at the Lighting Laboratory of the Department of Electrical and Communications Engineering at Helsinki University of Technology. The work was funded by the Academy of Finland and the Graduate School of Electrical and Communications Engineering. I acknowledge both institutions for their support. The thesis continues the research on mesopic photometry which has been considered in the dissertations of Eloholma (2005), Orreveteläinen (2005), and Ketomäki (2006) carried out in the TKK Lighting Laboratory.

I am grateful to my supervisor Professor Liisa Halonen for her support and encouragement through the work. Especially I am grateful for her understanding the challenge of combining the motherhood and work.

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Espoo, November 2007

Meri Viikari

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I Viikari M, Eloholma M, Halonen L. 2005. 80 years of V(λ) use: a review. *Light & Engineering*, 13(4):24-36.

II Orreveteläinen P, Viikari M, Halonen L. 2005. Make way for peripheral V(λ). *Light & Engineering*, 13(3):23-34.

III Eloholma M, Viikari M, Halonen L, Walkey H, Goodman T, Alfrendick J, Freiding A Bodrogi P, Várady G. 2005. Mesopic models – from brightness matching to visual performance in night-time driving: a review. *Lighting Research and Technology* 37(2):155-75.

IV Viikari M, Chen W, Eloholma M, Halonen L, Chen D. 2006. Comparative study of two visual performance based mesopic models based on reaction time and contrast threshold data. *Light & Engineering*, 14(4):21-32.

V Viikari M, Ekrias A, Eloholma M, Halonen L (*in press*). 2008. Modeling spectral sensitivity at low light levels based on mesopic visual performance. *Clinical Ophthalmology*, 2(1):1-13.

The author has played a major role in all aspects of the work presented in the thesis. The author was the responsible author and is responsible for the historical data collection and analysis in publication I. In publication II the author participated in the measurements and was responsible for the introduction part of the publication. In publication III the author was responsible for the data collection and analysis part of the existing mesopic models. The original idea for the measurements in the publication IV was authors and author designed and built the required measurement equipment. The author was the responsible author in publications IV and V. The data analysis and the comparison of mesopic models in publication V was done by the author. Author is responsible for the new mesopic model presented in the publication V.

List of abbreviations

CCT	Correlated Color Temperature
CEN	Comité Européen de Normalisation,
	European Committee for Standardization
CIE	Commission International de l'Éclairage,
	International Commission on Illumination
CT	Contrast Threshold
hbw	half bandwidth
HPS	High Pressure Sodium
TKK	Helsinki University of Technology
IES	Illuminating Engineering Society
IESNA	Illuminating Engineering Society of North America
LED	Light Emitting Diode
L-LAB	Lighting Laboratory of the University of Paderborn
MH	Metal Halide
MOVE	Mesopic Optimisation of Visual Efficiency
RT	Reaction Time
SPD	Spectral Power Distribution
TC	Technical Committee
UP	University of Pannonia

List of Symbols

a	coefficient in the MOVE- and modified MOVE-model
b	coefficient in the MOVE- and modified MOVE-model
C	contrast
C_{mes}	mesopic contrast
I_m	mesopic intensity value
L_{ave}	average road surface luminance [cd/m^2]
L_{bg}	background luminance [cd/m^2]
L_{mes}	mesopic luminance [cd/m^2]
L_p	photopic luminance [cd/m^2]
L_s	scotopic luminance [cd/m^2]
L_t	target luminance [cd/m^2]
m	parameter in the X-model
$M(x)$	normalizing function
S/P	ratio of scotopic to photopic luminous output
$V_{mes}(\lambda)$	mesopic spectral luminous efficiency function
$V(\lambda)$	photopic spectral luminous efficiency function
$V'(\lambda)$	scotopic spectral luminous efficiency function
$V_{10}(\lambda)$	photopic spectral luminous efficiency function for 10° field
$V_M(\lambda)$	modified photopic spectral luminous efficiency function
$V_{per}(\lambda)$	photopic spectral luminous efficiency function for peripheral vision
x	coefficient in the MOVE- and modified MOVE-model
X	coefficient in the X-model
β	parameter in the X-model
λ	wavelength [nm]

1. Introduction

1.1 Background

The photopic luminous efficiency function $V(\lambda)$, introduced by the CIE, has been the basis of photometry since its establishment in 1924 (CIE 1926, I). It forms the basis of all the lighting dimensioning and lighting practice we face today. The $V(\lambda)$ is based on photopic vision, thus it characterizes the spectral sensitivity of the foveal cones. However, in dim lighting conditions, namely in the mesopic region, both rods and cones are active and their contribution to visual perception changes with light level, which results in changes in spectral sensitivity. Peripheral vision becomes more important in mesopic conditions.

Major lighting applications, such as road and street lighting and other outdoor lighting, fall in the mesopic region. The use of the photopic $V(\lambda)$ as the basis of lighting dimensioning in these applications results in errors in the assessment of light. These errors may unnecessarily increase the energy consumption as well as lower the visibility and safety on the roads. Thus the development of mesopic photometry has raised interest in the international lighting community for decades (CIE 1989, 2001) and has culminated in the current urgent need for a practical system of mesopic photometry (Goodman et al 2007 discussion). The CIE has taken action towards the common goal of mesopic photometry by establishing a Technical Committee, CIE TC 1-58, whose terms of reference are: "*To define mesopic visual performance and related terms. To investigate performance based photometry in the luminance region below approximately 10 cd/m^2. To propose a model for the basis of performance based mesopic photometry.*"

Several models of mesopic photometry (CIE 1989, 2001; Rea et al 2004; Eloholma 2005) have been proposed for the international standardization work. The early works of mesopic photometry (CIE 1989, 2001) were based on brightness matching which is not among the relevant visual tasks in night-time driving. Moreover, the method of brightness matching is prone to additivity failures (III). The two recently proposed systems of mesopic photometry (Rea et al 2004; Eloholma 2005) are based on visual task performance. The performance based methods, e.g. reaction times and contrast threshold, are among the relevant visual tasks in night-time driving and they are claimed to preserve additivity within the given light level (III). Both of the proposed performance based models (Rea et al 2004; Eloholma 2005) have been proposed to the CIE TC 1-58. The TC 1-58 is currently analyzing the existing mesopic models and this work will result in an internationally agreed system for performance based mesopic photometry. The work of the TC 1-58 is to be completed by June 2008.

1.2 Objectives of the work

The first objective was to review the origins of the current photometry. An extensive review of the history of the $V(\lambda)$ function revealed several misunderstandings of the development process of the $V(\lambda)$ function and the experimental conditions under which it was defined. The second objective was to generate new reaction time data in order to validate whether the existing photopic spectral luminous efficiency functions $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ described the peripheral vision correctly.

A further objective was to generate new visual performance based data and to analyze and compare the existing performance based mesopic models using this data. The final objective was to propose a new performance based mesopic model and to compare it with the previously proposed models using extensive and independent data sets of mesopic visual performance provided by different European universities.

2. Current status of photometry

2.1 Photopic and scotopic photometry

2.1.1 Photopic spectral luminous efficiency function $V(\lambda)$

The photopic spectral luminous efficiency function $V(\lambda)$ has been the basis of all photometry and lighting dimensioning since its establishment in 1924 (I). The values of the $V(\lambda)$ were proposed by Gibson and Tyndall in 1923 as a result of a comparison of their own work with that of their predecessors (Gibson and Tyndall 1923). The president of the U.S. National Committee of the International Commission on Illumination (CIE) had requested the U.S. National Bureau of Standards to make measurements of visibility using the step-by-step equality of brightness method. The task of accomplishing this was assigned to Gibson and Tyndall by a committee appointed by the Bureau of Standards (Gibson and Tyndall 1923).

Gibson and Tyndall undertook the challenge and made measurements of visibility using the step-by-step equality of brightness method. Gibson and Tyndall compared their own data with the carefully reviewed experimental data of Coblentz and Emerson (1918), Hyde, Forsythe, and Cady (1918), Ives (1912), Nutting (1914), Reeves (1918), So (1920) and the average data recommended or adopted by Ives (1919), Priest (1920; 1922a,b), and I.E.S. (Illuminating Engineering Society). Unfortunately, the details of how the original I.E.S. curve was determined have apparently not been preserved (CIE 1990). The experimental data of Gibson and Tyndall (1923) and Hyde et al (1918) is based on the method of step-by-step equality of brightness matching and the data of Coblentz and Emerson (1918), Ives (1912), Nutting (1914), Reeves (1918) and So (1920) is based on the method of flicker photometry. The experimental data were conducted using photometric field sizes varying from 1.5° to 7°. As far as is known from the information given, the photometric field was viewed through an ocular slit or an artificial pupil, which decreased the amount of light entering the eye. The resulting retinal illuminance values can be approximated to have varied in between 6 and 168 Td (I). These troland values correspond to natural pupil luminances of 0.14 and 3.6 cd/m^2 for corresponding field sizes calculated using the equation given by Trezona (1983). The calculated natural pupil luminance values lay in the mesopic region (I).

Gibson and Tyndall decided to consider the I.E.S. data as the basis for the new visibility curve, i.e. the new spectral luminous efficiency function. However, the I.E.S. data was not a good representative of the accumulated data of the several studies reviewed by Gibson and Tyndall (1923) in the wavelength region from 510 to 550 nm. Thus Gibson and Tyndall chose the values of Coblentz and Emerson (1918) in this region and combined them with the I.E.S. curve. Additionally, some changes were made to the I.E.S. data in the wavelength region from 620 to 690 nm, at 560 and at 720 nm to produce a smooth curve. As a major part of the present spectral luminous efficiency function $V(\lambda)$ is based on the I.E.S. curve, whose origins are not known, it seems impossible to say exactly on which methods it is based. Attention in the compilation process of the $V(\lambda)$ function should be drawn especially to the short wavelength region, where the I.E.S. data were accepted by Gibson and Tyndall (1923) "*for lack of any good reason for changing them, but the relative as well as the absolute values are very uncertain and must be considered as tentative only*" (I).

The revised I.E.S. visibility curve as given by Gibson and Tyndall (1923) was presented to the CIE, which introduced the values of the spectral luminous efficiency function $V(\lambda)$ in its 6th session in

1924 (CIE 1926). The values of the $V(\lambda)$ function were recommended by CIE for general use as provisional ones, since it was obvious that the values might be incorrect in the extreme regions of the visible spectrum or in special viewing conditions (CIE 1926). Despite the given notice considering particularly the short wavelengths, $V(\lambda)$ established itself in practical use (I).

In 1951, Judd pointed out the low sensitivity of the $V(\lambda)$ curve below 460 nm and proposed a modification to the 1924 $V(\lambda)$ function (Judd 1951). However, Judd's modification was slightly too sensitive below 410 nm and in 1978 Vos (Vos 1978) presented a second-order correction to this. This *modified 2° spectral luminous efficiency function for photopic vision,* i.e. the $V_M(\lambda)$ function, was approved as a supplement to, not a replacement of, the $V(\lambda)$ function by the CIE in 1988 (CIE 1990).

Eighty years after the $V(\lambda)$ function was introduced, CIE standardized the values of $V(\lambda)$ function as they defined *the CIE standard spectral luminous efficiency function for photopic vision* in 2004 (CIE 2004).

2.1.2 Scotopic spectral luminous efficiency function $V'(\lambda)$

Rods are used exclusively for vision at very low, scotopic, light levels. The scotopic vision is represented by the scotopic spectral luminous efficiency function $V'(\lambda)$ established by the CIE in 1951 (CIE 1951). The $V'(\lambda)$ function was determined for a large central field of 20° under conditions of dark adaptation. It is based on the detection threshold data of Wald (1945) and on the direct brightness matching data of Crawford (1949). Altogether 70 subjects under age of 30 participated in the experiments (CIE 1978).

2.1.3 Photopic spectral luminous efficiency function for peripheral vision $V_{per}(\lambda)$

In modeling mesopic spectral sensitivity, the photopic and scotopic spectral luminous efficiency functions are used to describe the upper and lower limits of the mesopic region. The photopic end is commonly described by either the $V(\lambda)$ (Rea et al 2004; Eloholma 2005) or the $V_{10}(\lambda)$ (He et al 1997,1998) function and the scotopic end by the $V'(\lambda)$ function. The photopic ten degree spectral luminous efficiency function $V_{10}(\lambda)$ was determined for the central 10° visual field by the CIE in 1963 (CIE 1963). The $V_{10}(\lambda)$ function is more sensitive to radiation in the short wavelength region than the $V(\lambda)$ function. This is due to the fact that the short wavelength sensitive cones are absent from the central fovea (Curcio et al 1991) but contribute to the visual spectral sensitivity of peripheral parts of the retina.

The significance of the peripheral vision is emphasized in the mesopic lighting conditions and especially in night-time driving, where a lot of essential visual information is received from the periphery. The retinal distribution of rods and cones is not uniform. Cones are concentrated in the fovea while rods occupy mainly the peripheral areas. The maximum density of rods is at 20° eccentricity from the fovea (Palmer 1999). In the mesopic region, the contribution of rods on to vision increases with decreasing light levels, which underlines the importance of the peripheral vision in mesopic lighting applications.

The foveal vision is described adequately well by the photopic $V(\lambda)$ function at mesopic light levels above 0.01 cd/m^2 (Eloholma 2005) while the peripheral vision requires a model or a wide range of functions to be described properly because the spectral sensitivity changes with changing light levels in the mesopic region. The proposed mesopic models (Rea et al 2004; Eloholma 2005) are based on peripheral visual performance data. In this work, new reaction time data was generated in order to see whether the $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ functions are proper descriptions of the peripheral spectral sensitivity at low photopic light levels (II).

2.1.3.1 Experimental setup

The reaction times of five normal subjects were measured using a large hemispherical surface as a background (II, Orreveteläinen 2005). The background was illuminated uniformly by fluorescent lamps with correlated color temperature (CCT) of 4930 K. In the first phase of the experiments, the luminance of the background was adjusted to 10 cd/m^2. Five visual targets of different SPDs were presented both foveally and peripherally at an eccentricity of 10°. The target SPDs are referred to as blue, cyan, green amber, and red, according to their peak wavelengths, which were at 467, 503, 525, 593, and 638 nm, respectively. The hbws of the LEDs varied between 16 and 36 nm. The visual size of the circular targets was 0.29°. The targets were viewed binocularly (II).

Reaction times were measured for three different target contrasts. Contrast C is defined as follows

$$C = \frac{L_t - L_{bg}}{L_{bg}}, \tag{1}$$

where L_t is the photopic luminance of the target and L_{bg} is the photopic luminance of the background. The contrasts of each target SPD were adjusted to attain a common reaction time for all five target SPDs. The common reaction time was required in order to validate whether the same contrast produced the same RT (II).

2.1.3.2 Results

The mean reaction times of the five subjects as a function of photopic contrast are presented in Figure 1 for the eccentricity of 10°. Figure 1 shows that in order to reach a common RT, the contrasts for the five target SPDs were not equal. The spectral sensitivity of the eye is underestimated with respect to the blue and cyan targets. This implies that the $V(\lambda)$ function does not describe peripheral vision correctly at 10 cd/m^2, which is commonly considered to be a photopic light level.

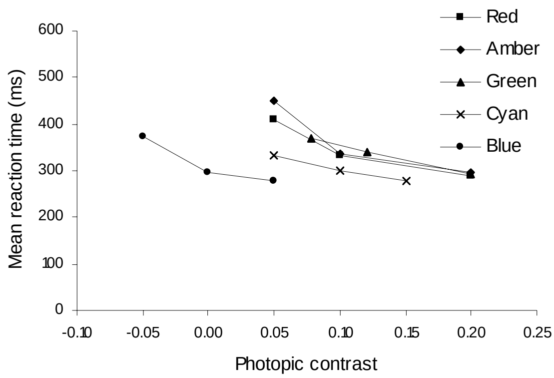


Figure 1. RT as a function of photopic contrast in peripheral vision at 10 cd/m² for five target SPDs. The measurement points are the average RTs of five subjects (II).

In addition to the $V(\lambda)$ function, the ability of the $V_M(\lambda)$ and $V_{10}(\lambda)$ functions to describe the RT data were investigated. The contrasts of the five colored targets that produced the common reaction time were calculated using the $V_M(\lambda)$ and $V_{10}(\lambda)$ functions. The standard deviations of the contrasts between the five colored targets were calculated as well. The smaller the standard deviation, the better the spectral luminous efficiency function describes the data. It turned out that none of the photopic spectral luminous efficiency functions $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ described the photopic peripheral visual performance correctly. The standard deviations of contrasts were 0.067, 0.066, 0.032 for $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$, respectively. The $V_{10}(\lambda)$ function performed best, as could be assumed, as its sensitivity to the short wavelengths is greater than that of the other two functions.

2.1.3.3 New model for peripheral photopic vision

The results of the RT measurements indicate that the human spectral sensitivity in the short wavelength region is underestimated by the present $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ functions. A first estimate for a new luminous efficiency function for peripheral vision is proposed. The sensitivity of the new function, $V_{per}(\lambda)$, is increased in relation to the $V_{10}(\lambda)$ function in the short wavelength region of the visible spectrum. The weighted difference between the $V_{10}(\lambda)$ and $V(\lambda)$ is added to the $V_{10}(\lambda)$ at wavelengths shorter than 557 nm in order to enhance the short wavelength part of the function. The sensitivity of the $V_{per}(\lambda)$ function in the wavelength region above 557 nm is similar to that of the $V_{10}(\lambda)$ function. This form of luminous efficiency function is easy to reproduce and the transition from the new part to the $V_{10}(\lambda)$ function is smooth. The new $V_{per}(\lambda)$ function is of the form

$$\begin{aligned} V_{per}(\lambda) &= V_{10}(\lambda) + k(V_{10}(\lambda) - V(\lambda)) \qquad \text{for } \lambda = 380...556\,\text{nm} \\ V_{per}(\lambda) &= V_{10}(\lambda) \qquad \text{for } \lambda = 557...800\,\text{nm} \end{aligned} \tag{2}$$

where k is a weighting coefficient, $V_{10}(\lambda)$ is the photopic spectral luminous efficiency function for 10° field and $V(\lambda)$ is the photopic spectral luminous efficiency function (II, Orreveteläinen 2005). Wavelength 557 nm was selected as the transition point as it is the peak wavelength of the $V_{10}(\lambda)$ function. The weighting coefficient k was optimized to minimize the standard deviation of the contrasts calculated using $V_{per}(\lambda)$. The best possible standard deviation (0.014) for the RT data of this experiment was given by the k value of 0.8215.

In order to validate and to improve the reliability of the $V_{per}(\lambda)$ function, further RT measurements were made at background luminance level of 20 cd/m^2 in the second phase of the experiments. A new estimate for the coefficient *k* was optimized for both background luminance levels simultaneously. The new value for *k* was 0.7684 resulting in standard deviations of the calculated contrasts of 0.014 and 0.023 for 10 and 20 cd/m^2 background luminance levels, respectively. For the 20 cd/m^2 data, the $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ functions gave standard deviations of the calculated contrasts of 0.054, 0.53, and 0.30, respectively (II).

The presented $V_{per}(\lambda)$ function was further validated by Orreveteläinen (2005) using two visual performance tasks (RT and CT), a wider range of eccentricities (0°, 10°, 30° and 60°) and a larger number of subjects. For the RT data, the estimate for the coefficient *k* was the same as previously presented *k*=0.7684. The CT experiments resulted in a new estimate for the coefficient *k* with a value of *k*=1.7322 (Orreveteläinen 2005).

2.2 Mesopic photometry

2.2.1 Brightness based models

Most of the mesopic research until the mid 1990's concentrated on using brightness matching as the visual criterion (Walters and Wright 1942; Kinney 1964; Palmer 1967, 1968; Kokoschka and Bodmann 1975; Ikeda and Shimozono 1981; Sagawa and Takeichi 1986, 1992; Trezona 1987; CIE 1989; Ikeda and Ashizawa 1991; Viénot and Chiron 1992; CIE 2001). In using brightness matching as the visual criterion, two adjacent illuminated fields are assessed in terms of their comparative brightness relationship. The use of brightness matching as the basic task in developing a mesopic photometric system has recently been questioned (III). When driving a car, we rarely see adjacent surfaces that need to be visually assessed in terms of their comparative brightness.

Another known difficulty in using brightness matching is additivity. The property of additivity in photometry allows luminances of multiple lights to be summed to predict their combined luminance (III). However, the mesopic models based on heterochromatic brightness matching do not preserve additivity. The additivity failures become apparent when predictions of the brightness of non-monochromatic lights are made (III). Thus, the methods based on brightness matching (CIE 1989, 2001) failed to provide a system for mesopic photometry that could be applied in practice.

2.2.2 Performance based models

Towards the end of the 1990's, an alternative approach for mesopic photometry based on visual task performance raised interest among the international research community. Two performance based models of mesopic photometry were introduced to the lighting community by the mid 2000's, the X-model by Rea et al (2004) and the MOVE-model by the MOVE consortium (Eloholma 2005). These two models share the same form of linear combination of the photopic $V(\lambda)$ and the scotopic $V'(\lambda)$

$$M(x)V_{mes}(\lambda) = xV(\lambda) + (1-x)V'(\lambda) \qquad \text{for } 0 \le x \le 1 \qquad (3)$$

Where $V_{mes}(\lambda)$ is the mesopic luminous efficiency function under the given conditions, $M(x)$ is a normalizing function such that $V_{mes}(\lambda)$ attains a maximum value of 1 and *x* is a coefficient dependent on the adaptation luminance and spectrum (Rea et al 2004; Eloholma 2005).

Despite the similar form, the definitions of the weighting factor *x* for the MOVE-model and *X* for the X-model as well as the experimental basis of the models are very different. Thus the two models yield different values of mesopic luminance.

2.2.2.1 X-model

Two investigations by He et al (1997,1998) form the experimental basis of the X-model. In the first work of He et al (1997), reaction times for three subjects were measured monocularly under two light sources (HPS and MH). A target contrast of 2.3 was used in the experiment. The contrast is defined in Equation 1. The resulting model was a linear combination of the scotopic $V'(\lambda)$ and the ten degree $V_{10}(\lambda)$ functions. The transition point between the photopic and mesopic occurs in the model at a luminance level of 0.6 cd/m^2. He et al (1997) concluded that the derived simple, preliminary model for mesopic luminous efficiency could be further modified as more complete data were obtained.

In the second work by He et al (1998), mesopic luminous efficiency functions of one subject were measured using a method of reaction time differences between the two eyes. The transition point between the mesopic and photopic was not reached within the retinal illuminance range investigated. However, the transition point was estimated from the data to occur at 21 Td, which corresponds to a luminance level of about 1.7 cd/m^2. 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). Thus, the predicted transition point of both He et al (1997,1998) studies occurs at or above 1.7 cd/m^2.

The visual performance based mesopic model proposed by Rea et al (2004), namely the X-model, is based on the data of He et al (1997,1998) studies. In proposing a model, several simplifications were proposed to the approach of He and others. Firstly, the transition point between the mesopic and photopic was assumed to occur at 21 Td as estimated by He et al (1998). However, in the paper of Rea et al (2004), the luminance value corresponding to 21 Td was not that of 1.7 cd/m^2 given by He et al (1998), but 0.6 cd/m^2. The choice of the 0.6 cd/m^2 level was based on an assumption that pupil diameter below 1 cd/m^2 is a constant 0.7 mm when transferring troland values into luminance values (Rea et al 2004).

Further simplifications were that the relationship between the coefficient *X* and mesopic luminance was assumed to be linear in order to develop a closed-form solution for *X* and that $V_{10}(\lambda)$ was substituted with $V(\lambda)$. The formulation of the X-model uses luminous efficiency functions derived from combinations of $V(\lambda)$ and $V'(\lambda)$, as presented in Equation 3 (Rea et al 2004).

Equations 4 and 5 give the simple, closed-form expression for calculating the mesopic luminance L_{mes} and corresponding coefficient *X*.

$$L_{mes} = 0.834L_p - 0.335L_s - 0.2 + \sqrt{0.696L_p^{\,2} - 0.333L_p - 0.56L_pL_s + 0.113L_s^{\,2} + 0.537L_s + 0.04}\,, \quad \text{for } 0.001 \le L_{mes} \le 0.6 \qquad (4)$$

$$X = mL_{mes} + \beta \qquad \text{for } 0 \le X \le 1, \qquad (5)$$

where, L_{mes} is the mesopic luminance, L_p is the photopic luminance, L_s is the scotopic luminance, X is the coefficient, m and β are parameters equal to the quantities (m = 1/0.599) and (β = -0.001/0.599) (Rea et al 2004).

2.2.2.2 MOVE-model

The MOVE-model proposed by the MOVE consortium (Eloholma 2005) is based on a multi-technique approach where the task of night-time driving was divided into three visual subtasks. These visual tasks were 1) the detection of a visual target, which is related to the achromatic threshold (Freiding et al 2007), 2) the speed of detection, which is related to reaction times (Walkey et al 2007), and 3) the identification of the details of the target, which is related to the achromatic recognition threshold (Várady et al 2007) (Eloholma 2005).

A common set of parameter values were used as the basis of each particular data set generated in different test locations (Eloholma 2005). The joint parameters were: background photopic luminances 0.01, 0.1, 1 and 10 cd/m^2, target eccentricities 0° and 10°, target size 2° (and 0.29°), and nearly steady presentation $\Delta t \geq 3$s (or $\Delta t \leq 500$ms for part of the reaction time experiments). The contrasts were at or near threshold and both quasi-monochromatic (hbw = 10 nm) and broadband light sources were used. Altogether 109 subjects participated in the experiments.

The vision experiment data of the MOVE work resulted in a linear model of mesopic photometry characterizing the mesopic spectral sensitivity of peripheral vision. This linear, i.e. practical model, of the form presented by Equation 3 is recommended for practical photometry (Eloholma 2005).

Based on the vision experiments, the MOVE linear model predicts the transition between mesopic and photopic regions will occur at about 10 cd/m^2. The MOVE experiments at the higher mesopic levels were conducted at 1 and 10 cd/m^2, but not in the region between. Thus it remains unknown whether there had already been saturation in visual performance at luminance levels lower than the 10 cd/m^2. In Eloholma (2005), the fitted values of model parameter x are presented as a function of $\log_{10}(I_m)$ (mesopic intensity value) which can be converted to mesopic luminance L_{mes} values. More datapoints (14) lay above the fitted curve than below it (7). This implies that the MOVE-model underestimates the value of x when compared to the measured data. Perhaps more luminance levels should have been measured in the region from 1 to 10 cd/m^2 to confirm the upper transition point between mesopic and photopic. In the MOVE-model, the transition between mesopic and scotopic is around 0.01 cd/m^2, though both the upper and lower limit is dependent on the S/P ratio as well.

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

$$x_{n+1} = a + b\log_{10}\left[\frac{1}{M(x_n)}\left(x_n\frac{L_p}{K_p} + (1-x_n)\frac{L_s}{K_s}\right)\right] \qquad \text{for } 0 \leq x_{n+1} \leq 1, \tag{6}$$

$$L_{mes} = \frac{xL_p + (1-x)L_s V'(\lambda_0)}{x + (1-x)V'(\lambda_0)}, \tag{7}$$

where, a and b are parameters that 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, K_s is the scotopic maximum luminous efficacy K_s = 1699 lm/W, L_{mes} is the mesopic luminance, $V'(\lambda_0)$ = 683/1699 is the value of scotopic spectral sensitivity function $V'(\lambda)$ at λ_0=555 nm, which is the wavelength where photopic spectral sensitivity function attains its maximum $V(\lambda_0)$=1, and $M(x)$ is a normalizing function such that the mesopic spectral sensitivity function attains a maximum value of 1 as follows

$$M(x) = \max\left[x(V(\lambda) + (1-x)V'(\lambda)\right] \approx 1 - 0.65x + 0.65x^2 \tag{8}$$

where $V(\lambda)$ is the photopic spectral luminous efficiency function and $V'(\lambda)$ is the scotopic spectral luminous efficiency function (Ketomäki 2006).

3. Visual experiments

The first objective of the visual experiments conducted in this work was to study the relationship between visual performance and different visual parameters at mesopic luminance levels. The aim was to study the effect of SPD on visual performance at different luminance levels and target contrasts, and further to compare the reaction time and contrast threshold behavior in relation to lighting conditions in the mesopic region (IV).

The second objective was to compare the two recently introduced visual performance based mesopic models, the MOVE-model (Eloholma 2005) and the X-model (Rea et al 2004). The two models were compared in terms of their prediction of reaction time and contrast threshold behavior as a function of light level (IV).

3.1 Experimental set-up

In the visual experiments, reaction time (RT) and contrast threshold (CT) were selected as the criteria of visual performance: these were measured at two light levels (0.1 and 1 cd/m^2) using 10° target eccentricity. Four colored lights (blue, green, amber, red LEDs) were used to illuminate the background and the visual target. The half-bandwidths of the LEDs were between 16-37 nm. The target was superimposed on the background, thus, in each spectral condition, the target and the background spectra were the same. Five subjects, one female and four male aged 24-33 years (mean 29) participated in the experiments (IV).

Reaction time and contrast threshold were measured using a modified Goldman perimeter, which is a white painted hemisphere with a diameter of 600 mm. A visual target of size 2° was projected by a LED on the surface of the hemisphere at an eccentricity of 10°. A number of LEDs were positioned around the edge of the hemisphere to distribute the light to the background uniformly. The hemisphere surface luminance and the visual target luminance could be independently controlled by a computer (IV).

In the CT experiments, the subject was asked to increase the luminance of the target until the target became just visible. This threshold luminance value was recorded and used in calculating the target contrast against the background. The contrast definition is given by Equation 1.

In the RT experiments, the task of the subject was to indicate the detection of the flash-like target of 1000 ms as quickly as possible. A maximum of 1 second following the onset of the target was allowed for response. The time between target display and response was recorded as the reaction time. Reaction times were recorded for two different contrasts for each background luminance (C=0.1 and 0.15 for L_{bg}=0.1 cd/m^2, C=0.05 and 0.1 for L_{bg}=1 cd/m^2) (IV).

3.2 Results

Figure 2 shows the results of the contrast threshold measurements as a function of the light spectrum at background luminance levels L_{bg}=0.1 cd/m^2 and L_{bg}=1 cd/m^2. As expected, contrast threshold decreased with increasing background luminance (IV).

The light spectra significantly affected the contrast threshold at the lower background luminance level, where shorter wavelengths (blue) gave smaller values of CT than longer wavelengths (red). At the higher background luminance level, these differences were less pronounced, though blue spectrum produced significantly smaller CT values than the other light spectra.

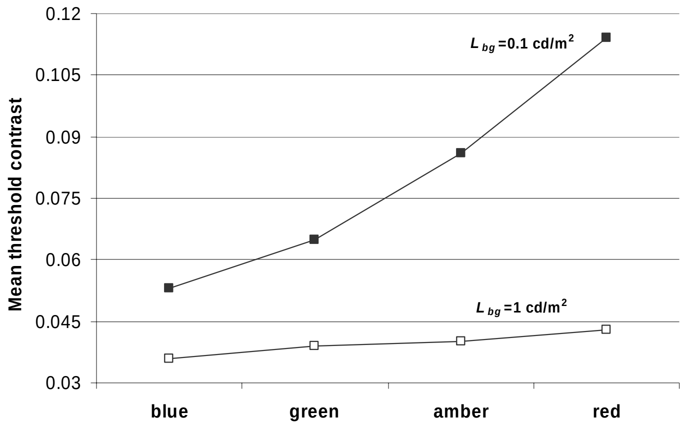
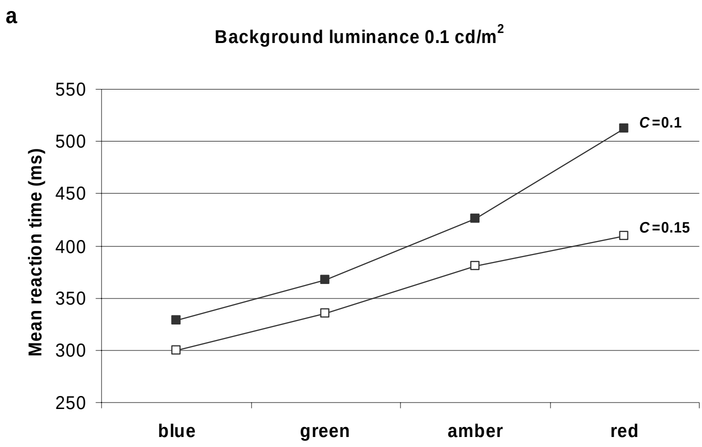


Figure 2. Mean threshold contrast plotted against light spectrum at the two background luminance levels of L_{bg}=0.1 cd/m^2 and L_{bg}=1 cd/m^2 (IV).

Figure 3 shows the results of the reaction time experiments as a function of the light spectrum for different target contrasts and luminance levels (IV). As expected, the higher background luminance level as well as higher target contrasts produced shorter reaction times, while the lower luminance level and smaller contrast prolonged the reaction times.

Light at short wavelengths (blue) yielded significantly shorter reaction times than light at longer wavelengths (red) at the lower background luminance level. This is in accordance with the results of the CT experiment. The higher luminance level resulted in differences between light spectra only for the lower target contrast, where red light produced significantly longer reaction times than the other colors. Higher contrast at the higher background luminance level resulted in no significant differences between the light spectra.



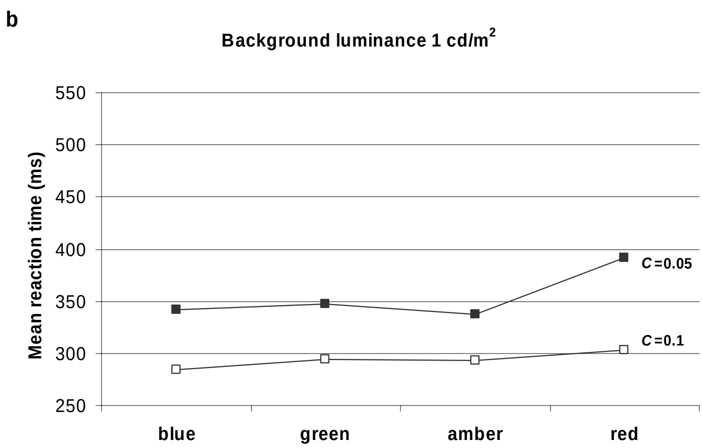
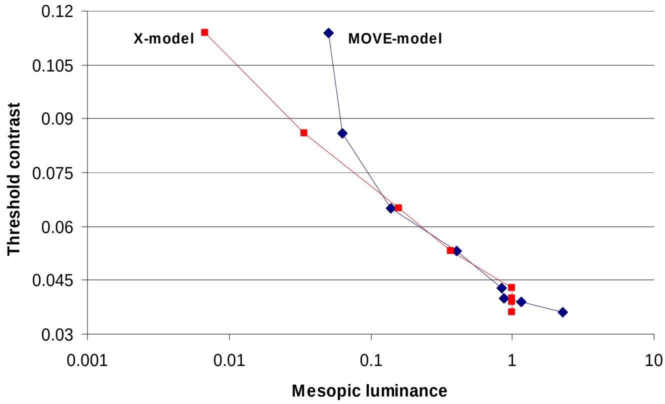


Figure 3. Mean reaction time (RT) plotted against light spectrum a) at background luminance L_p=0.1 cd/m^2 and target contrasts C=0.10 and C=0.15, b) at background luminance L_p=1 cd/m^2 and target contrasts C=0.05 and C=0.10 (IV).

3.3 Fitting the results to the MOVE- and X-models

The contrast threshold data for the both background luminances is presented as a function of mesopic luminance in Figure 4 (IV). Mesopic luminances were calculated using both the MOVE- and X-models. The models indicate a similar trend in predicting visual performance as a function of mesopic luminance: visual performance in terms of contrast threshold increases with increasing light level. However, the different behavior of the two models is evident, especially for the longer wavelength lights (red and amber) at the lower 0.1 cd/m^2 background luminance level. The X-model gives almost one log unit smaller values of mesopic luminance for the red light than the MOVE-model. Also at the higher background luminance level the two models differ in their predictions of mesopic luminance. This is due to the fact that the upper luminance limit of the X-model is 0.6 cd/m^2, while the MOVE-model calculates mesopic luminances up to about 10 cd/m^2.

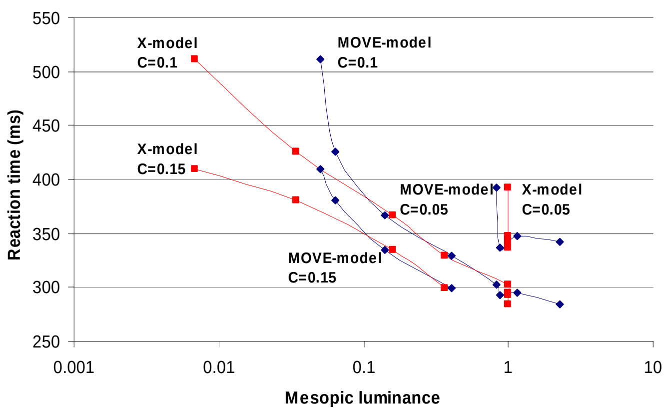


	L_p (cd/m^2)	CT
red	0.1	0.114
amber	0.1	0.086
green	0.1	0.065
blue	0.1	0.053
red	1	0.043
amber	1	0.040
green	1	0.039
blue	1	0.036

Figure 4. Contrast threshold data as a function of mesopic luminance calculated using the MOVE- and X-models (IV).

Figure 5 illustrates the reaction time data for both background luminances plotted as a function of mesopic luminance calculated using the MOVE- and X-model (IV). Both models indicate the increase in visual performance with increasing light level.

The two models differ considerably in their predictions of mesopic luminance at the lowest luminance level for red and amber lights, while green and blue lights produce quite similar mesopic luminances. This is valid for both contrasts. At the highest luminance level, mesopic luminances of the two models differ again for both contrasts. This is due to the fact that the upper luminance limit of the X-model is 0.6 cd/m^2, while the MOVE-model calculates mesopic luminances up to about 10 cd/m^2.



	L_p (cd/m^2)	RT (ms)		
		C=0.15	C=0.1	C=0.05
red	0.1	409	512	
amber	0.1	380	426	
green	0.1	335	367	
blue	0.1	300	329	
red	1		303	392
amber	1		293	337
green	1		295	347
blue	1		285	342

Figure 5. Reaction time data as a function of mesopic luminance calculated using the MOVE- and X-model (IV).

3.4 Conclusions

The contrast threshold and reaction time data showed a clear effect of background luminance on visual performance under mesopic conditions. There was a clear increase in visual performance when luminance was increased from 0.1 cd/m^2 to 1 cd/m^2. Both CT and RT data showed a clear dependence of visual performance on the light spectrum and that the spectral effects were more pronounced when the visual task became more and more difficult (lower luminance, lower contrast for RT). The results indicated the change in spectral sensitivity towards short wavelengths with decreasing luminance level. The results confirmed the inaccuracy of the photopic $V(\lambda)$ to predict spectral sensitivity of peripheral mesopic visual performance (IV).

Two recently introduced performance based mesopic models, the MOVE-model and the X-model, were compared using the measured CT and RT data. The ability of the models to indicate the same mesopic luminance at the same visual performance levels was compared. Both models indicated the increase in visual performance with increasing mesopic luminance. The two models were not, however, consistent in predicting mesopic luminance and mesopic visual performance. This was seen as diverging RT and CT data curves when mesopic luminances were calculated with the two models. Further on the shapes of the visual performance data curves were not consistent between the two models. The differences between the models became clearer with decreasing visibility conditions, i.e. lower luminance, lower contrast. The reasons for the differences between the models may be the different parameter conditions under which the models' data were generated. The X-model is based on reaction time experiments at high target contrast (C=2.3) (He et al 1997,1998). The MOVE-model experiments covered a range of target contrasts with particular attention paid to the low-contrast range (Eloholma 2005). The target contrasts in the experiments of this work were relatively low (C=0.05, 0.10, 0.15 in RT, at threshold in CT). The inconsistency of the X-model to predict low-contrast RT data (three various shapes of curves) may be caused by the X-models inaccuracy to assess spectral sensitivity for low contrast targets (IV).

4. New model for performance based mesopic photometry

There is a definite need for a practical system of mesopic photometry to be used in assessing light at low light levels, especially in road and other outdoor lighting applications. The CIE TC 1-58 is currently analyzing the two models proposed for performance based mesopic photometry, namely the MOVE-model (Eloholma 2005) and the X-model (Rea et al 2004). The lighting community has had discussions on the subject of the upper luminance limit of the mesopic region, which is regarded to be too high for the MOVE-model (Rea and Bullough 2007) and too low for the X-model (Eloholma and Halonen 2006). And indeed, the upper limits predicted by the two models (10 cd/m^2 for MOVE- and 0.6 cd/m^2 for X-model) are far apart from each other. This large difference suggests that either one or both of the models are inaccurate in defining the upper luminance limit. A new modified MOVE-model, whose upper luminance limit is adjusted to meet the actual road and street lighting luminance values measured in different weather conditions, is proposed (V).

4.1 Starting point for modeling

In road and street lighting, luminances fall in the mesopic region. In Europe, the recommended average road surface luminances are between 0.3 – 2 cd/m^2 (CEN 2003) and in the US between 0.3 – 1.2 cd/m^2 (IESNA 2000). The luminance levels of road surfaces are usually very dynamic and depend to large extent on weather conditions.

In a recent study by Ekrias et al (2007) and Castillo (2007), road surface luminances were measured in different installations under varying weather conditions. The installations covered local streets with minor lighting requirements as well as heavily trafficked roads. In wet conditions, the luminance distributions of road surfaces change significantly compared to dry conditions. Average luminances of wet road surfaces are usually higher compared to dry conditions (Ekrias et al 2007).

Luminances of snowy road surfaces can be multiple times higher than in dry and so-called “normal” conditions. And even if there is a minor amount of snow and snow clearance is completed, luminance levels are still 40…100 % higher compared to conditions without any snow. By taking into account the luminances of the road surfaces and their surrounding areas and considering the effects of different weather conditions on luminances, it can be concluded that the average visual field luminances in night-time driving conditions fall below 5 cd/m^2 (Ekrias et al 2007, Castillo et al 2007). Figure 6 shows an example of road luminances of a local street and a highway when the road surface is dry, snowy and wet (Ekrias et al 2007).

Figure 6. Luminance measurement results from a local street in Espoo, Finland, illuminated by HPS lamps under a) dry, b) very snowy, and c) wet weather conditions. Luminance measurement results from Highway 3 in Helsinki, Finland, illuminated by HPS lamps under d) dry, e) slightly snowy, and f) wet weather conditions (Ekrias et al 2007).

Driving is a complex task. The visual environment consists of several visual elements such as other vehicles, lane markings, signs, pedestrians, cyclists, and any unexpected objects appearing in the visual field. Much of the visual information in driving is peripheral. The basic visual task in driving a car is to obtain sufficient information from the visual field to be able to get by in the environment (CIE 1992). In order to trigger visual perception and to detect a target a certain luminance difference between the target and its background is needed. In night-time driving conditions the contrasts of visual targets depend on the target reflectance properties, vehicle headlights, the geometry of the lighting installation as well as on the location of the target in relation to the luminaries (V).

In Lighting Laboratory of Helsinki University of Technology TKK the variation of target contrast was studied in different lighting levels and weather conditions on a recently built extension section of the highway Ring Road III. In this pilot location road lighting installation is new and consists of HPS lamps (250 W) with luminaire spacing of 55 m. The visual targets used in the measurements were a pedestrian with grey clothing (reflectance 16 %) and 20 cm x 20 cm flat square targets with different reflection factors. Figure 7 shows an example of the variation of target contrast for two different targets. Measurements were made in different target locations (10 m, 20 m, 30 m, 40 m, and 50 m from the first luminaire) between the luminaire spacing. The square target was placed in the middle of the carriageway. The pedestrian was positioned on the side of the road to create a realistic and common night-time driving scene with the pedestrian walking on the roadside or aiming to cross the road. Figure 7 represents measurement results from two different lighting scenes: one with an old pavement and full road lighting and the other one with a new pavement and dimmed road lighting (power 50 %). The average road surface luminances (L_{ave}) were 1.7 cd/m^2 (power 100 %, old pavement) and 0.8 cd/m^2 (power 50 %, new pavement) (V). The target contrasts C are defined by Equation 1.

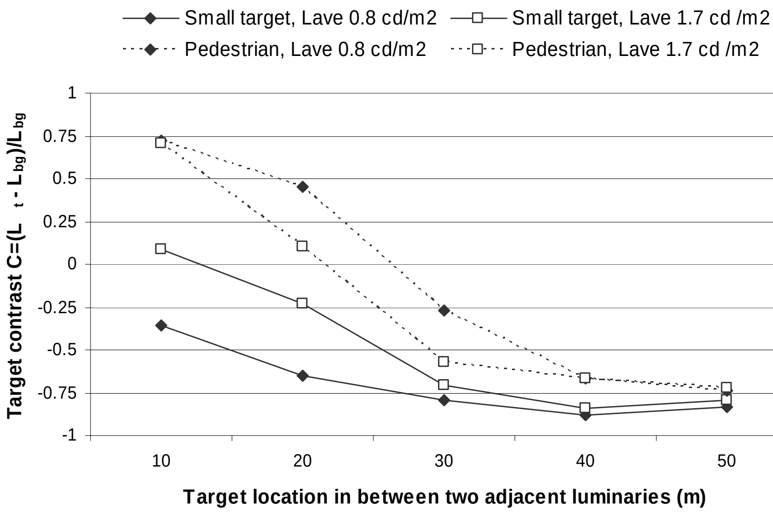


Figure 7. Contrasts of a small flat target (20cmx20cm, ρ=0.2) and a pedestrian (ρ=0.16) when located at varying positions on the road and the roadside. The results represent two different road lighting conditions measured in dry weather conditions at Ring Road III Vantaa, Finland. The road surface was illuminated by 250 W high pressure sodium lamps with a pole spacing of 55 m. The target contrasts vary between C = -0.88…0.72 (V)

According to the results of the example (Figure 7) and many other measurements conducted at TKK, the variation of target contrasts can be said to be within C = -0.9…1. The luminance contrast of the target depends on the target reflectance and the target location in relation to the luminaries (V).

The investigations underlying the X-model were based on visual targets of high-contrast (C=2.3), which can argued not to be representative of those encountered in night-time driving, whereas the MOVE experiments covered a range of contrasts with particular attention paid to the low contrast range. It has been indicated that the spectral sensitivity changes are more pronounced at low visibility conditions (low luminance, low contrast) (IV). The high contrast value of the X-model experiments can be suspected to result in inaccuracy of the X-model to assess spectral sensitivity for low contrast visual tasks encountered in night-time driving (V).

It can be argued that the X-model upper luminance limit 0.6 cd/m^2 is too low to cover the mesopic luminances in road and street lighting. Moreover, mesopic spectral sensitivity changes were found in the He et al (1997,1998) experiments up to above 1.7 cd/m^2 and in the MOVE-experiments up to about 10 cd/m^2, indicating that the mesopic region extends above 0.6 cd/m^2. However, the differences between mesopic and photopic luminances given by the MOVE-model become small, less than 5 %, when photopic luminance increases above 5 cd/m^2 for most common light sources with S/P-ratios 0.5…2.5. The road lighting measurements indicate that, in road and street lighting, luminances rarely exceed 5 cd/m^2, but can reach up to this value due to changing weather conditions (Ekrias et al 2007, Castillo 2007). This limit is sufficiently high to cover all practical road and street lighting levels in varying weather conditions, without impinging unnecessarily on higher luminance levels and applications where peripheral vision is less important. It is thus chosen as the upper luminance limit of the mesopic region in the mesopic modeling to be presented in this paper (V).

4.2 Modified MOVE- model

The new modified MOVE-model is based on the same experimental data as the original MOVE-model (Freiding et al 2007; Walkey et al 2007; Várady et al 2007). The upper luminance level of the modified MOVE-model is at approximately 5 cd/m^2, which is lower than the 10 cd/m^2 of the original MOVE-model. The lower luminance limit of the modified MOVE-model is approximately 0.005 cd/m^2, but it should be noted that both the upper and lower limits of the model are dependent on the light source S/P-ratio (V).

The modified MOVE-model is similar in form to the original MOVE-model and the X-model, although the parameter values and the luminance regions over which they apply are all different. The modified MOVE-model transition from the photopic $V(\lambda)$ to the scotopic $V'(\lambda)$ is presented in Equation 3 (V). As all practical photometry, lighting dimensioning, and light measurement equipment are based on photopic $V(\lambda)$, for practical reasons rather $V(\lambda)$, than the proposed more precise $V_{per}(\lambda)$ function, was used as the photopic end of the modified MOVE-model.

The coefficient x and the mesopic luminance of the proposed modified MOVE-model can be iteratively calculated as follows:

$$x_0 = 0.5\,,$$

$$L_{mes,n} = \frac{x_{n-1}L_p + (1-x_{n-1})L_s V'(\lambda_0)}{x_{n-1} + (1-x_{n-1})V'(\lambda_0)}\,, \tag{9}$$

$$x_n = a + b\log_{10}(L_{mes,n}) \qquad \text{for } 0 \le x_n \le 1\,, \tag{10}$$

where L_{mes} is the mesopic luminance, 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 $V'(\lambda)$ at λ_0=555 nm, which is the wavelength where photopic spectral sensitivity function attains its maximum $V(\lambda_0)$=1, a and b are parameters that have the values a=0.7670 and b=0.3334, and n is an iteration step (V). A similar type of formulation of x-calculation has been discussed in CIE TC 1-58 Beijing 2007 meeting.

The values of x and L_{mes} given by the modified MOVE-model as a function of photopic luminance and light source S/P-ratio are presented in Table 1 (V).

Table 1 a) The values of x given by the modified MOVE-model as a function of photopic luminance and S/P-ratio. b) The values of L_{mes} given by the modified MOVE-model as a function of photopic luminance and S/P-ratio (V).

a

x	Photopic luminance cd/m²					
S/P	**0.01**	**0.03**	**0.1**	**0.3**	**1**	**3**
0.25		0.1542	0.3830	0.5644	0.7538	0.9225
0.35		0.1804	0.3920	0.5688	0.7558	0.9230
0.45	0.0000	0.1992	0.4000	0.5730	0.7576	0.9235
0.55	0.0190	0.2140	0.4073	0.5770	0.7594	0.9240
0.65	0.0459	0.2265	0.4139	0.5808	0.7612	0.9245
0.75	0.0655	0.2373	0.4201	0.5844	0.7629	0.9249
0.85	0.0812	0.2468	0.4258	0.5878	0.7646	0.9254
0.95	0.0943	0.2553	0.4311	0.5911	0.7662	0.9258
1.05	0.1057	0.2631	0.4361	0.5942	0.7678	0.9263
1.15	0.1157	0.2702	0.4408	0.5972	0.7693	0.9267
1.25	0.1247	0.2767	0.4452	0.6001	0.7708	0.9272
1.35	0.1329	0.2828	0.4494	0.6029	0.7723	0.9276
1.45	0.1404	0.2885	0.4534	0.6056	0.7737	0.9280
1.55	0.1473	0.2939	0.4573	0.6082	0.7751	0.9284
1.65	0.1538	0.2990	0.4609	0.6107	0.7764	0.9289
1.75	0.1598	0.3038	0.4645	0.6131	0.7778	0.9293
1.85	0.1654	0.3083	0.4678	0.6155	0.7791	0.9297
1.95	0.1708	0.3126	0.4711	0.6178	0.7803	0.9301
2.05	0.1758	0.3168	0.4742	0.6200	0.7816	0.9304
2.15	0.1806	0.3207	0.4772	0.6221	0.7828	0.9308
2.25	0.1852	0.3245	0.4801	0.6242	0.7840	0.9312
2.35	0.1895	0.3282	0.4830	0.6263	0.7852	0.9316
2.45	0.1937	0.3317	0.4857	0.6283	0.7863	0.9319
2.55	0.1977	0.3351	0.4883	0.6302	0.7875	0.9323
2.65	0.2015	0.3383	0.4909	0.6321	0.7886	0.9327
2.75	0.2052	0.3415	0.4934	0.6339	0.7896	0.9330

b

L_{mes}	Photopic luminance cd/m²					
S/P	**0.01**	**0.03**	**0.1**	**0.3**	**1**	**3**
0.25	0.0025	0.0145	0.0705	0.2467	0.9130	2.9265
0.35	0.0035	0.0174	0.0750	0.2545	0.9253	2.9367
0.45	0.0045	0.0198	0.0793	0.2620	0.9373	2.9468
0.55	0.0057	0.0220	0.0834	0.2693	0.9492	2.9568
0.65	0.0069	0.0239	0.0873	0.2764	0.9608	2.9666
0.75	0.0079	0.0258	0.0911	0.2833	0.9722	2.9763
0.85	0.0088	0.0275	0.0947	0.2901	0.9835	2.9859
0.95	0.0096	0.0292	0.0983	0.2967	0.9945	2.9953
1.05	0.0104	0.0308	0.1017	0.3032	1.0054	3.0046
1.15	0.0111	0.0323	0.1051	0.3096	1.0161	3.0139
1.25	0.0118	0.0338	0.1083	0.3158	1.0267	3.0230
1.35	0.0125	0.0353	0.1115	0.3220	1.0371	3.0319
1.45	0.0132	0.0367	0.1147	0.3280	1.0473	3.0408
1.55	0.0138	0.0381	0.1178	0.3339	1.0575	3.0496
1.65	0.0145	0.0395	0.1208	0.3398	1.0674	3.0582
1.75	0.0151	0.0408	0.1238	0.3455	1.0773	3.0668
1.85	0.0157	0.0421	0.1267	0.3512	1.0870	3.0753
1.95	0.0163	0.0434	0.1295	0.3568	1.0966	3.0836
2.05	0.0169	0.0446	0.1324	0.3623	1.1060	3.0919
2.15	0.0174	0.0459	0.1352	0.3677	1.1154	3.1001
2.25	0.0180	0.0471	0.1379	0.3731	1.1246	3.1082
2.35	0.0185	0.0483	0.1406	0.3784	1.1338	3.1162
2.45	0.0191	0.0495	0.1433	0.3836	1.1428	3.1241
2.55	0.0196	0.0506	0.1459	0.3888	1.1517	3.1319
2.65	0.0201	0.0518	0.1485	0.3939	1.1605	3.1396
2.75	0.0207	0.0529	0.1511	0.3989	1.1693	3.1473

4.3 Conclusions

A new performance based mesopic model for peripheral vision is proposed. The new modified MOVE-model is based on the same experimental data as the original MOVE-model. The luminance limits of the mesopic region of the modified MOVE-model have been adjusted to meet the actual road and street lighting levels in varying weather conditions. The proposed upper luminance limit is 5 cd/m^2 and the lower limit 0.005 cd/m^2 in terms of photopic luminance. It should be noted that the luminance limits, especially the lower one, are dependent on the S/P-ratio of the light source.

The new modified MOVE-model has the same form as the previously proposed MOVE- and X-models, although the definition of coefficient *x* is different. This results in different predictions of mesopic luminances between the three models. The coefficient *x* of the modified MOVE-model is defined through an iterative process.

5. Comparison of the previously proposed and new performance based mesopic models

5.1 General comparison

The MOVE-, modified MOVE-, and X-models were compared using two broadband light sources similar to high pressure sodium (S/P = 0.65) and daylight metal halide (S/P = 2.35) lamps. Figure 8a presents the coefficients *x* of the MOVE– and modified MOVE–models and coefficient *X* of the X-model as a function of photopic luminance. Figure 8b shows the corresponding ratio of mesopic luminance (calculated using the MOVE-, modified MOVE-, and X-models) to photopic luminance as a function of photopic luminance (V).

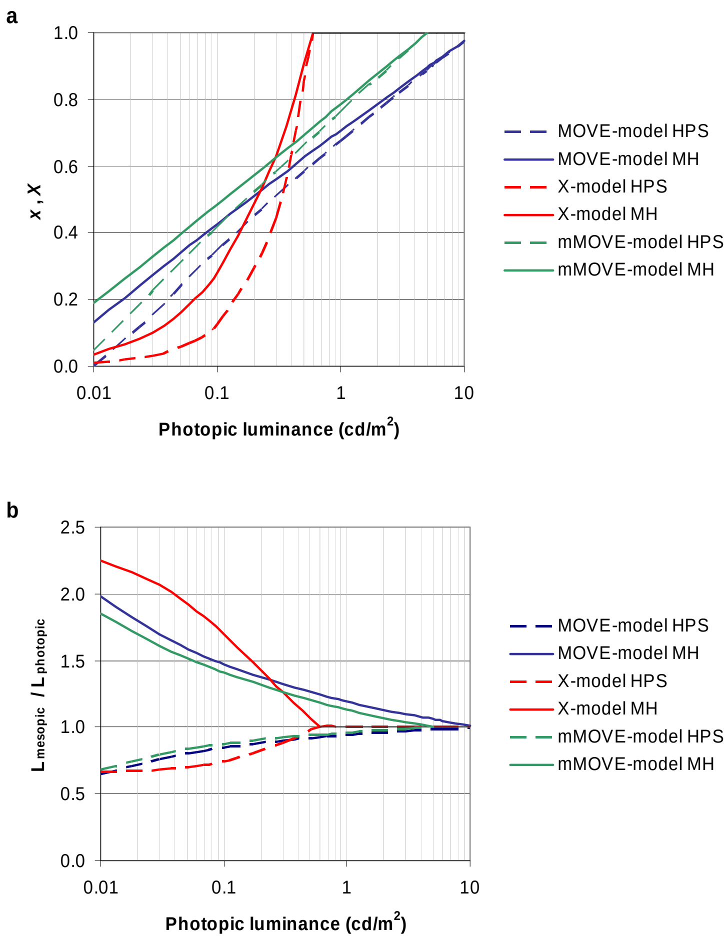


Figure 8 a) Coefficients *x* of the MOVE- and modified MOVE-model, and coefficient *X* of the X-model as a function of photopic luminance for HPS (S/P = 0.65) and MH (S/P = 2.35) lamps. b) The ratio of mesopic luminance (calculated using the MOVE-, modified MOVE-, and X-models) to photopic luminance as a function of photopic luminance for HPS (S/P = 0.65) and MH (S/P = 2.35) lamps (V).

Both in the MOVE- and modified MOVE-model, the coefficient *x* is a linear function of log photopic luminance, while the uppercase *X* of the X-model shows a different behavior. The values of *X* increase gradually from 0.01 cd/m^2 to 0.1 cd/m^2, after which there is a steep increase in between 0.1-0.6 cd/m^2. The three models differ also in the transition point between mesopic and photopic regions, which is the point where *x* and *X* become unity. In the X-model this point is 0.6 cd/m^2. The modified MOVE-model and the MOVE-model give mesopic values for photopic luminances up to about 5 and 10 cd/m^2, respectively (V).

Due to the different approach in defining the coefficients *x* and *X* as a function of photopic luminance and lamp spectra (S/P-ratio), the three models result in different corresponding mesopic luminances. The differences between the MOVE- and the modified MOVE-models are small compared to the differences between the X-model and the two other models (V).

5.2 Comparison with three independent experimental data sets

The MOVE-, modified MOVE-, and X-models were compared using three independent visual performance data sets. The data sets were the detection threshold data of L-LAB, University of Paderborn, Germany (Raphael and Leibenger 2007), detection threshold data of Virtual Environments and Imaging Technologies Laboratory, University of Pannonia UP, Hungary (Vas and Bodrogi 2007), and the reaction time data of Lighting Laboratory, Helsinki University of Technology TKK, Finland (Orreveteläinen 2005). The experimental setups and measurement parameters of the three data sets are presented in Table 2 (V).

Table 2. The experimental setups and measurement parameters of the three independent visual performance datasets (Raphael and Leibenger 2007; Vas and Bodrogi 2007; Orreveteläinen 2005) (V).

	L-LAB	UP	TKK
Method	Detection threshold	Detection threshold	Reaction time
Background luminance	0.01, 0.07, 0.7 cd/m^2	0.5 cd/m^2	0.1, 0.3, 1, 3 cd/m^2
Background spectra	Uniform grey, S/P ≈ 2.8	White, S/P ≈ 2.05	White, S/P ≈ 1.86
Target eccentricity	2°, 6°, 10°, 14°	20°	10°
Target spectra	blue, green, grey, red	from 410 to 680 nm, 10 nm steps	blue, cyan, green, amber, red
Target size	0.7°	2°	0.29°
Subjects	40	1 (4 repetitions)	5

Mesopic visual conditions are well represented by the experimental parameters used in the visual performance datasets under comparison. A wide range of luminance levels from 0.01 to 3 cd/m^2 as well as several peripheral eccentricities varying from 2° to 20° were investigated. Both quasimonochromatic and broadband target spectra were used against the white or grey backgrounds of different S/P-ratios. Two visual tasks were employed, both of which are considered relevant in night-time driving (III). A large number of subjects, altogether 46, participated in the experiments.

Spectral sensitivity is usually investigated by determining the target radiance required to achieve a specific level of performance (eg detection threshold or fixed reaction time) in any specific background conditions. In the detection threshold experiment, the intensity of the target is increased or decreased until the target becomes visible or invisible. At the threshold, the photopic luminance or radiance of the target is recorded (Freiding et al 2007). In a fixed reaction time experiment, the intensity of the target is adjusted to elicit a fixed reaction time (Walkey et al 2007). The intensity of the target, both in the detection threshold and reaction time experiments, can be described by the contrast against its background. In the mesopic region, the mesopic contrast can be calculated with any given candidate mesopic model. The mesopic contrast C_{mes} is defined as

$$C_{mes} = \frac{L_{mes,t} - L_{mes,bg}}{L_{mes,bg}}, \tag{11}$$

where $L_{mes,t}$ is the mesopic luminance of the target and $L_{mes,bg}$ is the mesopic luminance of the background (V).

Assuming that, for specific background conditions and target eccentricity, the mesopic contrast required to reach the detection threshold or fixed reaction time is the same for all target colors, then the spectral sensitivity function (ie mesopic model) describes the visual performance correctly. An optimal model is such that the variation in the mesopic contrasts is minimal (Goodman et al 2007). Thus, the spread of mesopic contrasts gives a measure of how closely a spectral sensitivity function (ie mesopic model) describes the measured data. The smaller the spread, the better the model predicts the data. In this work, the standard deviation of the mesopic contrasts is used as a measure of spread. The testing procedure does not provide an answer to the question “Which of the mesopic models produces the most correct values of mesopic luminance for the testing data?”. Rather, the testing procedure addresses “Which of the mesopic models comes closest to predicting the equivalence of the target and background mesopic luminances that produce equal visual performance?”.

Figure 9 shows the mesopic contrast thresholds (calculated using the MOVE-, modified MOVE-, and X-models) of L-LAB detection threshold data as a function of target color at three target eccentricities.

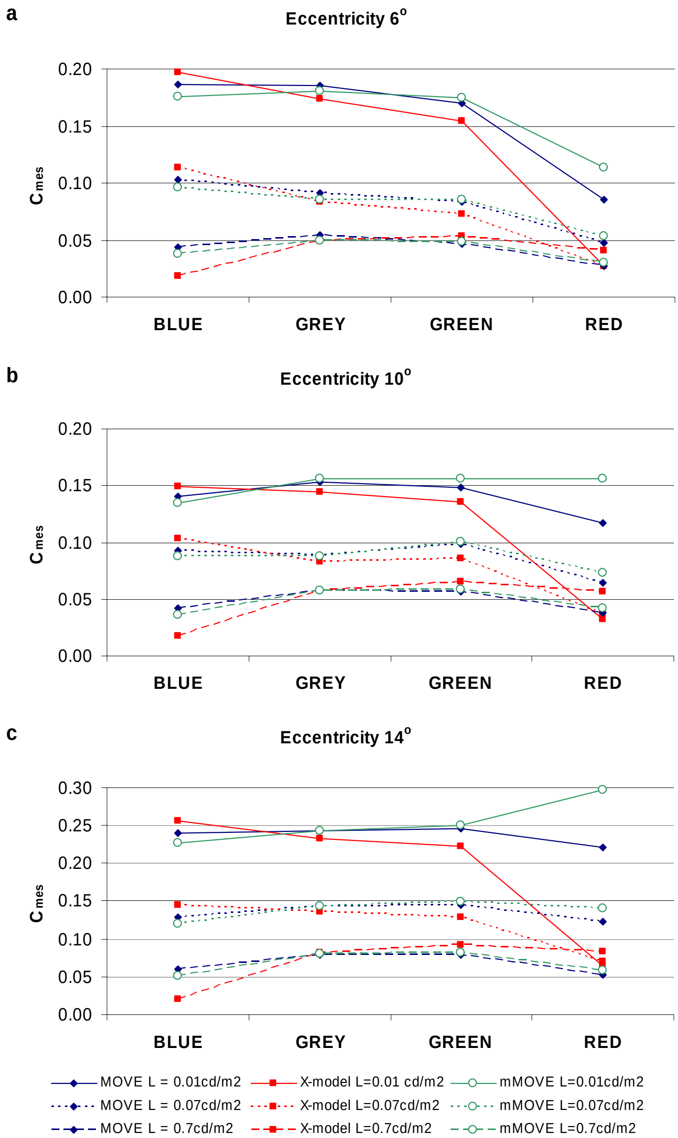


Figure 9. Mesopic contrast thresholds of L-LAB detection threshold data (Raphael and Leibenger 2007) as a function of target color at an eccentricity of a) 6°, b) 10°, c) 14°.

Figure 10 shows the mesopic contrast threshold of UP detection threshold data as a function of target peak wavelength.

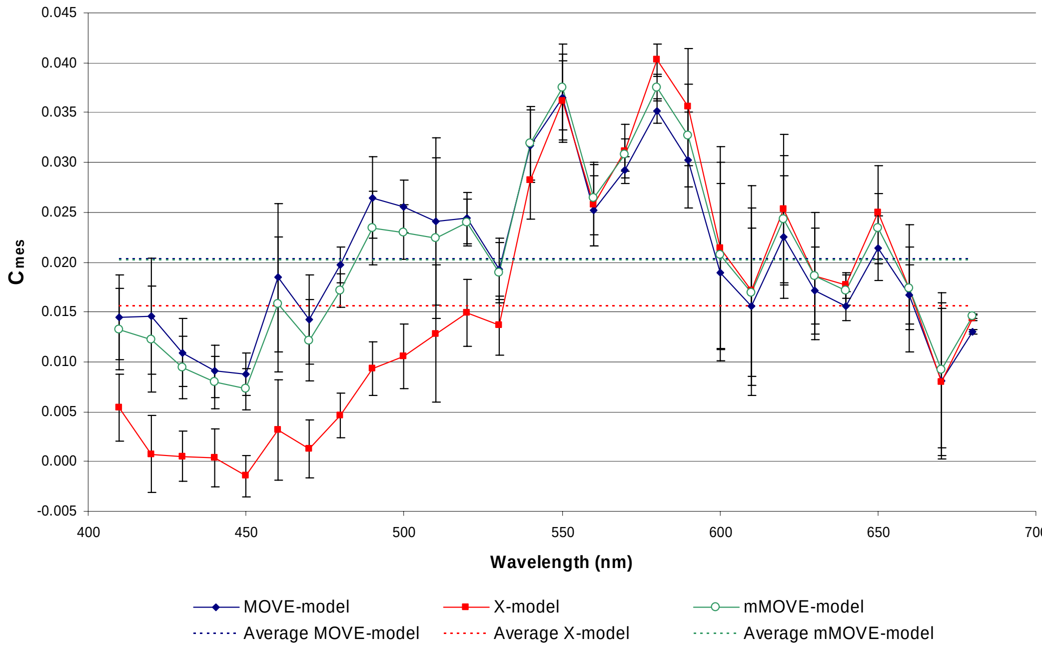
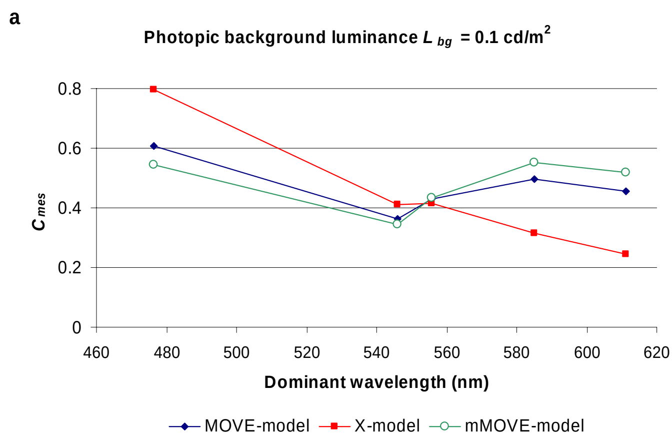


Figure 10. The mesopic contrast threshold of UP detection threshold data (Vas and Bodrogi 2007) as a function of target peak wavelength.

Figure 11 shows the mesopic contrasts of TKK reaction time data that produce fixed reaction times as a function of dominant wavelength of target spectra.



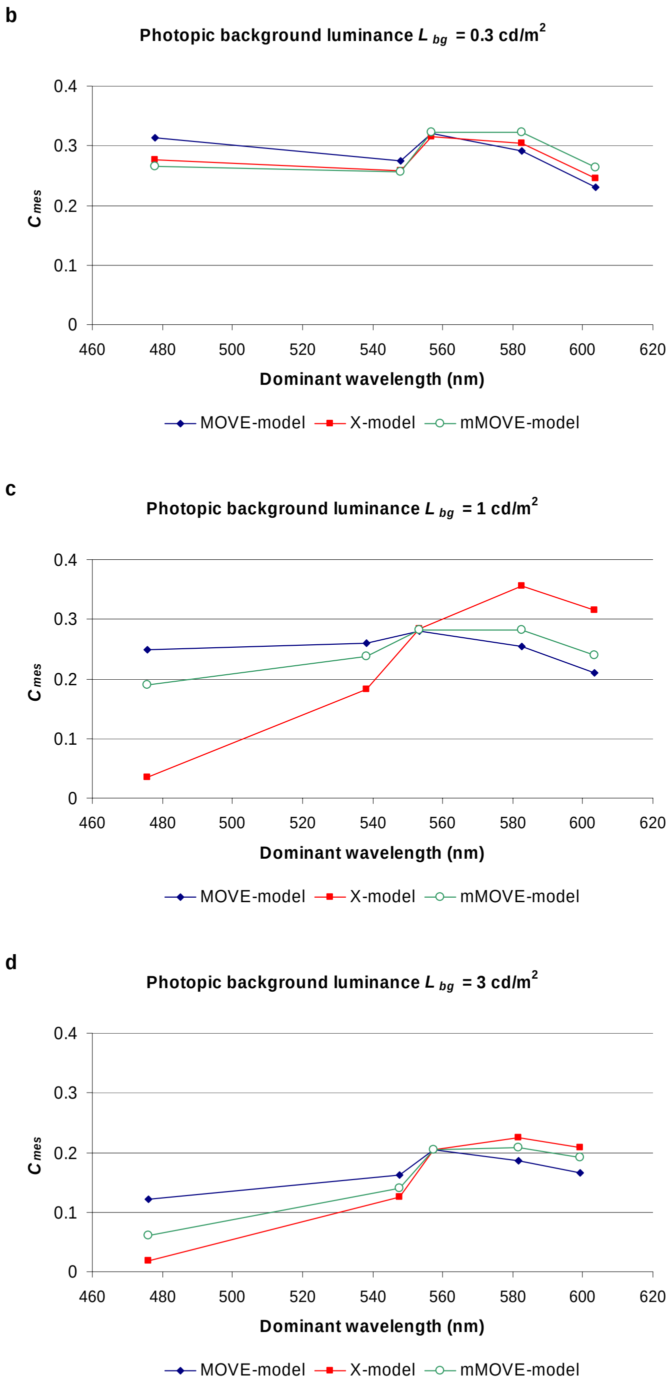


Figure 11. The mesopic contrasts of TKK reaction time data (Orreveteläinen 2005) that produce fixed reaction times as a function of dominant wavelength of target spectra at background luminance level of a) 0.1 cd/m^2, b) 0.3 cd/m^2, c) 1 cd/m^2, d) 3 cd/m^2.

The standard deviations between the mesopic contrasts calculated using each model are presented in Table 3.

Table 3 The standard deviations between the mesopic contrasts calculated using the MOVE-, modified MOVE-, and X-models (V).

			MOVE-model	X-model	modified MOVE-model
L-LAB Detection threshold	**0.01 cd/m^2**	2°	0.1738	0.2076	**0.1557**
		6°	0.0482	0.0758	**0.0317**
		10°	0.0159	0.0553	**0.0108**
		14°	**0.0115**	0.0877	0.0299
	0.07 cd/m^2	2°	0.0509	0.0669	**0.0445**
		6°	0.0238	0.0361	**0.0186**
		10°	0.0148	0.0282	**0.0110**
		14°	**0.0110**	0.0338	0.0124
	0.7 cd/m^2	2°	0.0117	0.0105	**0.0090**
		6°	0.0114	0.0154	**0.0090**
		10°	**0.0101**	0.0217	0.0112
		14°	**0.0140**	0.0330	0.0156
UP Detection threshold	**0.5 cd/m^2**	20°	**0.0078**	0.0120	0.0085
TKK Reaction time	**0.1 cd/m^2**	10°	0.0910	0.2127	**0.0885**
	0.3 cd/m^2	10°	0.0360	**0.0301**	0.0335
	1 cd/m^2	10°	**0.0261**	0.1286	0.0386
	3 cd/m^2	10°	**0.0314**	0.0861	0.0626

Figure 9 and Table 3 suggest that the modified MOVE-model describes the L-LAB detection threshold data best, giving the smallest value of standard deviation in eight situations out of 12. The original MOVE-model performs best at an eccentricity of 14° at every background luminance level and at an eccentricity of 10° at the highest 0.7 cd/m^2 luminance level. Figure 9 shows that the differences between the three models are largest for the blue and red target colors and smallest for the grey and green. The differences between the MOVE- and the modified MOVE-model are considerably smaller than the differences between the MOVE- and X-model and the modified MOVE- and X-model (V).

The UP detection threshold data presented in Figure 10 is described best by the MOVE-model. The standard deviation given by the MOVE-model is slightly smaller than that given by the modified-MOVE model and evidently smaller than that given by the X-model, as can be seen in Table 3. The differences between the three models are largest at the blue end of the spectrum at wavelengths approximately below 540 nm, while at the red end of the spectrum all the three models perform quite similarly. Again, the X-model differs from the MOVE- and modified MOVE-models, especially at the blue end of the spectrum (V).

Table 3 suggests that the TKK reaction time data is described best by the MOVE-model at the two highest luminance levels. The modified MOVE-model gives the smallest value of standard deviation at 0.1 cd/m^2, and the X-model at 0.3 cd/m^2 background luminance level. The modified MOVE-model, however, performs better than the MOVE-model at 0.3 cd/m^2. Figure 11 shows that the differences between the three models are largest for the blue, amber, and red target colors, while the green target color provides very marginal differences (V).

5.3 Conclusions

The new modified MOVE-model was compared with the two previously proposed MOVE- and X-models. The models' predictions of the coefficient *x* (or *X*) and L_{mes} at different light levels were compared in general using two S/P-ratios similar to HPS and daylight MH light sources. The comparison indicated differences between the models. The differences in the predicted mesopic luminances were more pronounced at low light levels and with higher S/P-ratio. The differences between the MOVE- and modified MOVE-models were smaller than the differences between the X-model and the other two models.

The proposed modified MOVE-model was examined along with the MOVE- and X-models using three independent experimental visual performance data sets. The mesopic contrasts that yielded equal visual performance (CT or RT) were calculated using each model. The standard deviations of the calculated mesopic contrasts were used as a measure of goodness of the model to describe the data. The modified MOVE-model described the data best in nine situations out of 17. The MOVE-model was best in seven situations and X-model in one. The modified MOVE-model described the independent datasets best at low luminance level and at small eccentricities, while the MOVE-model described the datasets best at higher luminance levels and at lager eccentricities. The differences between the MOVE- and modified MOVE-model were considerably smaller than the differences between X-model and the other two models. The X-model provided the largest standard deviations in all but two situations.

6. Conclusions

The photopic spectral luminous efficiency function $V(\lambda)$ has been the basis of all photometry since its establishment in 1924 (CIE 1926, I). In order to understand the basics of the photometric measurements, it was relevant to investigate the foundations on which the current photometry is built. The work gives an extensive overview of the establishment procedure of the $V(\lambda)$ and highlights the differences in the experimental settings and data of several researchers whose works contributed to the establishment of $V(\lambda)$ (I).

The work continued to generate new RT data in order to validate whether the existing photopic spectral luminous efficiency functions $V(\lambda)$, $V_M(\lambda)$ or $V_{10}(\lambda)$ described the peripheral vision correctly, as the proposed performance based mesopic models are combined functions of the photopic and scotopic spectral luminous efficiency functions. The current photopic functions were discovered to underestimate the peripheral spectral sensitivity at the short wavelengths at low photopic luminance levels. A first estimate for a new photopic luminous efficiency function for peripheral vision is presented. The new $V_{per}(\lambda)$ function is a linear combination of the $V(\lambda)$ and $V_{10}(\lambda)$ functions. The $V_{per}(\lambda)$ function described the measured RT data best at both background luminance levels investigated (II).

The work continued to review the current status of the mesopic photometry and the research work conducted so far. Two approaches to establish mesopic models have been introduced, namely the brightness matching and visual performance based approach. Brightness matching is questioned with respect to its ability to characterize the visual response in road lighting because the steady assessment of brightness is not among the relevant visual tasks in night-time driving (III). Thus the two recently proposed models of mesopic photometry, the MOVE-model by the MOVE consortium (Eloholma 2005) and the X-model by Rea and others (Rea et al 2004), are based on visual task performance. The MOVE-model is based on the experimental data of 109 subjects measured using three different visual tasks, while only three subjects were used in the RT experiments underlying the X-model. A wider range of experimental conditions, as well as a greater number of subjects, lay behind the MOVE-model. Thus the visual experiments, on which the MOVE-model was based, can be considered as more representative of visual tasks and lighting conditions in the mesopic region and especially in road and street lighting (Eloholma 2005). Comprehensive analysis of the existing mesopic models was essential in order to move further in developing a new mesopic model.

The work continued by generating new mesopic visual performance data for the comparison of the existing performance based mesopic models. Two relevant visual tasks were used: contrast threshold and reaction time. Both experiments showed a clear effect of adaptation luminance and SPD on visual performance under mesopic conditions. The results showed that the magnitude of the effect of the SPD on visual performance was more pronounced when the visual task became more difficult (IV).

The new data sets were applied to the MOVE- and X-models, and the models' predictions of mesopic luminances were evaluated. The two models were not consistent in predicting mesopic visual performance. The shapes of the CT and RT curves were not consistent between the two models. The reasons for the divergences in the models may be the different parameter conditions under which the models were established (IV).

Another major difference between the X- and MOVE-models is the transition point between mesopic and photopic regions. In the X-model, this point is at 0.6 cd/m^2, while the MOVE-model calculates mesopic values for photopic luminances up to about 10 cd/m^2. The different transition points will result in differences when calculating mesopic luminances with the two models in the photopic luminance region 0.3 - 2 cd/m^2, which is the region of average road surface luminances given in the CEN and IESNA road lighting recommendations (IESNA 2000; CEN 2003).

The upper luminance limit of the mesopic region predicted by the previously proposed MOVE-model and the X-model have given rise to much discussion in the lighting community (Eloholma 2005; Eloholma and Halonen 2006; Rea and Bullough 2007). The upper luminance limit of the MOVE-model (10 cd/m^2) is claimed to unnecessarily complicate practical photometry and lighting specifications for “high” light levels (Rea and Bullough 2007), whereas the upper luminance limit proposed by the X-model (0.6 cd/m^2) would make the mesopic dimensioning concern only the roads in the lower lighting classes (Eloholma and Halonen 2006), which, at least in the European countries, are very few. The work continued to propose a new mesopic model for peripheral vision, namely the modified MOVE-model, whose upper luminance limit is in between the limits of the previously proposed models (V). The modified MOVE-model is based on the same experimental data as the MOVE-model. The selection of the upper luminance limit of the modified MOVE-model is based on Ekrias (2007) and Castillo (2007) road lighting measurements in different weather conditions. The proposed limit of 5 cd/m^2 covers luminances encountered in road and street lighting conditions without unnecessarily impinging on higher luminance levels where peripheral vision is less important (V).

The proposed modified MOVE-model was examined along with the MOVE- and X-models using three (Orreveteläinen 2005; Raphael and Leibenger 2007; Vas and Bodrogi 2007) independent experimental visual performance data sets (V). The experimental data consisted of detection threshold and reaction time measurements. A wide range of experimental parameters and a large number of subjects (46) were covered by the experiments. The experiments can be considered as closely representative of the mesopic visual conditions throughout the mesopic region as well as in night-time driving.

The ability of the three models to describe mesopic visual performance was compared (V). The mesopic contrasts that yielded equal visual performance were calculated using each model. The standard deviations of the calculated mesopic contrasts were used as a measure of goodness of the model to describe the data. The modified MOVE-model was found to describe the data best in nine situations out of seventeen. The MOVE-model was best in seven situations and X-model in one. The modified MOVE-model described the independent datasets best at low luminance level and at small eccentricities, while the MOVE-model described the datasets best at higher luminance levels and at lager eccentricities. The differences between the MOVE- and modified MOVE-model were small compared to the differences between the X-model and the other two models. The modified MOVE-model can be considered as a good estimate of the spectral sensitivity in the mesopic region.

The urgent need for a practical system of mesopic photometry has recently been acknowledged by the head organizations in the lighting field. Both CIE (Eloholma 2005) and the Illuminating Engineering Society of North America (IESNA 2006) have taken actions to reach the common objective of establishing a mesopic photometric system within the near future. Also, the lighting industry has encouraged the researchers in the lighting field to take prompt actions towards a new international standard on mesopic photometry (Goodman et al 2007, discussion). And, indeed, the adoption of mesopic photometry could result in a different classification of light sources in terms of their luminous output (Eloholma and Halonen 2006). Light sources with high output in the short wavelength region have frequently been acknowledged to be visually more effective at the mesopic light levels (Eloholma et al 2005; Ketomäki 2006; Akashi et al 2007), whereas the usage of photopic photometry at the low light levels of road and street lighting favors HPS lamps because of their high output around the peak wavelength of the photopic $V(\lambda)$.

Based on the comparison of the visual performance based mesopic models and on the fact that 5 cd/m^2 is practical upper limit for the mesopic region, the work concludes by proposing that the new modified MOVE-model would be further evaluated along with the MOVE- and X-models.

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