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Report 36

DEVELOPMENT OF VISUAL PERFORMANCE BASED MESOPIC PHOTOMETRY

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Development of visual performance based mesopic photometry

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Abstract

This work started by investigating the applicability of the photopic V(λ) function to predict visual task performance at mesopic light levels. Visual acuity and pedestrian visibility experiments were carried out in varied lighting and viewing conditions. The results indicated the inadequacy of photopic photometry to characterise the response of peripheral vision at low mesopic light levels. They also indicated that mesopic spectral sensitivity is visual task dependent. Based on these findings, and on an extensive review of mesopic research work, it was evident that there was a demand for visual performance based mesopic photometry. In order to establish a basis for mesopic photometry, a European research consortium with multi-disciplinary expertise was formed. Following this, a framework for the development of performance based mesopic photometry was developed. With this framework the international lighting community and EC Fifth Framework Programme were convinced to identify the urgent need for mesopic photometry. The work continues by introducing a multi-technique approach developed and adopted in a European research work MOVE. In the work of MOVE, a large data-base of mesopic visual task performance was generated by investigating the visual performance of night-time driving using three visual sub-tasks. The data was used in modelling mesopic spectral sensitivity. The MOVE work resulted in two distinct mesopic models; a practical (i.e. linear) model and a more complex chromatic model. The practical model is applicable for the visual task of night-time driving in situations where the background and target both have fairly broad spectral power distributions. The chromatic model gives a better prediction of performance for tasks which colourfulness (chromatic saturation) is high. The MOVE practical model was applied in road lighting dimensioning via road luminance measurements. Road lighting installations using HPS and MH lamps were measured with a CCD luminance photometer. Analysis of the applicability of the MOVE model is conducted on the basis of luminance measurements, calculations and on comparison to a recently proposed X-model by Rea et al. The work concludes by describing how the new performance-based mesopic models of MOVE are integrated into the CIE (Commission Internationale de l'Eclairage) work in order to contribute to the establishment of a standard for mesopic photometry. Finally, the impacts of standardisation of mesopic photometry on lighting dimensioning and products are discussed.

Keywords mesopic, photometry, visual performance, luminance, spectral luminous efficiency

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Preface

The work presented in this thesis has been conducted at the Lighting Laboratory of Helsinki University of Technology during the period 1998-2005. Part of the work was carried out in national project funded by the National Technology Agency of Finland (Tekes), the Finnish Road Administration, Helsinki Energy, Idman Oy, Oy Philips Ab and Sito Oy. Another part of the work was carried out as part of the European project MOVE (Mesopic Optimisation of Visual Efficiency), funded by the EC in the Fifth Framework Programme (G6RD-CT-2001-00598). The Academy of Finland has also funded the work (210345). I am grateful for all those mentioned above for their support.

I am most grateful to my supervisor, Professor Liisa Halonen, for all her guidance through the years I have been working in the Lighting Laboratory. I want to thank her for her encouragement and support in preparing this thesis. I also want to express my warmest gratitude to her for the many conversations we have had about and aside science and for teaching me the joy of work.

I wish to acknowledge Professor Miyoshi Ayama and Professor John Barbur for the preliminary examination of this thesis and for their valuable comments.

I would like to thank the members of the Traffic Lighting and Vision Group of the Lighting Laboratory – Pasi Orreveteläinen, Lic.Sc., Jaakko Ketomäki, M.Sc., Meri Viikari, M.Sc., and Liping Guo M.Sc. – for all their help in preparing this thesis and for their excellent team work. My special thanks go to Jaakko Ketomäki for his great co-operation in conducting the pedestrian visibility experiments.

I would also like to thank my European co-workers in the MOVE consortium for the great work we did together and for the many fruitful conversations in our meetings. I wish to thank as well all my co-authors in Publications I-VI for their contribution.

Many thanks go to the personnel of the Lighting Laboratory for all their help during the years we have worked together and for the pleasant atmosphere in the lab. My special thanks go to our ‘Mesopic group’, Leena and Meri, for the joyful discussions and for cheering me up during the sometimes long hours of work.

To my dearest sons Ilkka and Lauri, I want to say that I shall always be grateful for all the joy and light you continually bring into my life.

Marjukka Eloholma

Contents

List of publications

I Eloholma M., Halonen L., Setälä K., ''The Effects of Light Spectrum on Visual Acuity in Mesopic Lighting Levels'', In *Proc EPRI/LRO Fourth International Lighting Research Symposium*, Orlando, USA, May 19-21, 1998, pp.149-161.

II Eloholma M., Ketomäki J., Orreveteläinen P., Halonen L., ''Pedestrian Visibility in Road Lighting Conditions'', In *Proc International Conference ILUMINAT 2003*, Cluj-Napoca, Romania, May 8-9, 2003, pp. (17)1-6.

III Eloholma M., Viikari M., Halonen L., Walkey H., Goodman T., Alferdinck J., Freiding A., Bodrogi P., Várady G., ''Mesopic models – from brightness matching to visual performance in night-time driving: a review'', *Lighting Research and Technology*, 2005, 37 (2): pp.155-175.

IV Eloholma M., Halonen L., ''Performance based model for mesopic photometry'', *Report 35*, HUT Lighting Laboratory, Otaniemi, 2005.

V Eloholma M., Ketomäki J., Orreveteläinen P., Halonen L., ''Visual performance in night-time driving conditions'', *Ophthalmic and Physiological Optics*, 2005, 25, In Press.

VI Eloholma M., Ketomäki J., Halonen L., ''New model for mesopic photometry applicable for night-time driving conditions'', In *Proc International Symposium of Automotive Lighting ISAL2005*, Darmstadt, Germany, September 27-28, 2005, pp.515-524.

The author has played a major role in all aspects of the work presented in the thesis. The author has been the responsible author in all the publications. The author was responsible for the experimental design and conducted the experimental work presented in publication [I]. The author was responsible for the work and contributed to the experimental design and conduction of experimental work presented in publication [II]. The author was responsible for the co-ordination and supervision of the design and execution of the vision experiments of the European research work MOVE presented in publications [III], [IV], [V] and [VI] and was responsible for these publications as the main author.

List of abbreviations

EC	European Commission
CCD	charge coupled device
CU	City University
CEN	Comité Européen de Normalisation, European Committee for Standardization
CIE	Commission Internationale de l'Eclairage, International Commission on Illumination
GROWTH	Competitive and Sustainable Growth Programme
CRT	cathode-ray tube
LED	light emitting diode
hbw	half bandwidth
HPS	high-pressure sodium
HUT	Helsinki University of Technology
IESNA	Illuminating Engineering Society of North America
ISO	International Organization of Standardization
MH	metal halide
MOVE	Mesopic Optimisation of Visual Efficiency
NPL	National Physical Laboratory
RLT	Relative Luminance Threshold
TC	Technical Committee
TNO	Toegepast Natuurwetenschappelijk Onderzoek, Netherlands Organisation for Applied Scientific Research
TUD	Technische Universität Darmstadt, Darmstadt University of Technology
UV	University of Veszprém

List of symbols

Δt	presentation time
ΔL	difference between mesopic and photopic luminance
λ	wavelength
a_1	coefficient in MOVE chromatic model
a_2	coefficient in MOVE chromatic model
a_3	coefficient in MOVE chromatic model
a_4	coefficient in MOVE chromatic model
a_5	coefficient in MOVE chromatic model
C	contrast
I_m	mesopic intensity value
k(x)	constant in MOVE linear model
L_{ave}	average road surface luminance
L_b	background luminance
L_m	mesopic luminance
L_{MOVE}	mesopic luminance calculated with the MOVE linear model
L_p	photopic luminance
L_{ped}	pedestrian luminance
L_t	target luminance
$L(\lambda)$	L-cone spectral sensitivity function
$M(\lambda)$	M-cone spectral sensitivity function
M(x)	normalising function
$S(\lambda)$	S-cone spectral sensitivity function
S/P-ratio	ratio of scotopic to photopic luminous output
$V(\lambda)$	photopic spectral luminous efficiency function, 2° field
$V'(\lambda)$	scotopic spectral luminous efficiency function
$V_{mes}(\lambda)$	mesopic spectral luminous efficiency function
$V_{MOVE}(\lambda)$	mesopic spectral luminous efficiency function, MOVE linear model
$V_{10}(\lambda)$	photopic spectral luminous efficiency function, 10° field
x	coefficient in the MOVE linear model
X	coefficient in the proposed unified X-model

1 Introduction

1.1 Background

Photometry, the measurement of visible light, forms the basis of lighting units and is consequently the basis of all lighting technology and practice. The general aim of photometry is to quantify light in various stimulus and observation conditions. In current photometric practice, the response of the visual system is approximated by the CIE (Commission Internationale de l'Eclairage) photopic spectral luminous efficiency function V(λ) established in 1924 [1]. The V(λ) function characterises the spectral sensitivity of foveal cones in photopic lighting conditions. In the mesopic luminance region, between the photopic and scotopic, both the rods and cones on the retina may be active. This results in changes of spectral sensitivity in the mesopic luminance region (between about 0.001 and 10 cd/m^2). Mesopic lighting applications include e.g. road and street lighting, outdoor lighting and other traffic lighting conditions [III].

The development of mesopic photometry has raised interest in the international lighting community for several decades [2, 3]. Still today, there are no internationally accepted mesopic models and consequently no accepted system of mesopic photometry. Thus suitable methods to evaluate the visual effectiveness of lighting products and installations in the mesopic region are not available.

Most of the mesopic research until the mid 1990's concentrated on using brightness matching as the visual criterion [2, 3]. These works are based on the assessment of lights in terms of their comparative brightness relationship. The existing brightness-based mesopic models provide much data on the spectral sensitivity changes of human vision with decreasing light levels. However, the steady visual assessment of brightness is not among the relevant visual tasks in e.g. night-time driving. The application of brightness-based mesopic models to characterise the visual response in traffic lighting can thus be questioned. Towards the end of 1990's, the interest in a visual task performance based approach in developing mesopic photometry had grown among the international research community [4, 5, 6].

1.2 Objectives of the work

The first objective of this work was to investigate the applicability of the photopic V(λ) function to describe foveal and peripheral visual performance in the mesopic region. Based on the experimental findings, and on extensive review of the research work conducted so far, it was evident that there was a need for visual performance based mesopic photometry. It was evident that an extensive amount of new data was needed. The next objective was to contribute to the development of an experimental method for establishing mesopic data using a task performance based approach. The efforts needed required the combination of resources from different scientific fields.

With this in mind, the next aim was to convince the lighting community and the Measurement and Testing activity of the EC Fifth Framework Programme of the urgent need for a new mesopic photometric system and to get the work started on scale never contemplated before.

The next objective was to contribute to the establishment of new mesopic spectral luminous efficiency functions. This was implemented in a European research consortium MOVE in which an extensive amount of mesopic visual performance data was generated in five countries. The outcomes of the MOVE work were a practical (i.e. linear) model for mesopic photometry and a more complex chromatic model. The further objectives were to apply the MOVE practical model in road lighting dimensioning, to analyse its applicability in practice and to compare it to the recently proposed X-model by Rea et al. [6]. The final objectives were to contribute to integrating the findings of MOVE into international standardisation through the CIE TC1-58 work.

2 Investigation of the validity of V(λ) in the mesopic region

2.1 The use of V(λ) as the basis of photometry

Photometry provides a method with which to assess light in terms of human visual spectral sensitivity. Spectral sensitivity functions are derived from psycho-physical experiments based on the use of certain visual criteria and a defined set of lighting and viewing conditions. Both the psychophysical criteria and the physical conditions of the experiments affect the derived functions [III]. In current photometric practice, spectral sensitivity is defined by the photopic V(λ) function. This function was derived from several experiments using flicker photometry and step-by-step brightness matching as visual criteria [7-14].

Photometry could be defined against various visual perception or performance measures, such as brightness matching, flicker resolution, visual acuity, detection threshold, minimally distinct border, reaction time, etc. The fact that the used visual criteria affect the shape of the derived functions was already recognised in the 1920's when the V(λ) was established by the CIE. The differences between flicker photometry and brightness matching were already recognized at that time [13]. Actually, a certain amount of smoothing of the data was carried out in combining data from several investigations in order to form the V(λ) in 1923 [11].

The use of brightness matching as the basic criterion in developing mesopic spectral luminous efficiency models has recently been questioned. For example, when driving a car, it is rarely that we need to visually assess adjacent surfaces in terms of their comparative brightness. In driving, the detection and recognition of visual objects at or near the visual threshold can be claimed to be more relevant than the visual assessment of brightness. In this work a decision was made to investigate the spectral response of mesopic vision on the basis of visual performance of night-time driving.

In the following experiments, visual acuity (Chapter 2.2) [I] and pedestrian visibility (Chapter 2.3) [II] were used as the visual tasks in studying mesopic vision. The aim was to find out whether luminance levels defined in terms of the V(λ) result in equal visibility for foveal and peripheral visual tasks in the mesopic luminance region. The measurements were carried out in varied lighting and spectral conditions for a number of observers.

2.2 Visual acuity experiments

2.2.1 Measurement methods and set-ups

An experimental set-up was designed and constructed to measure visual acuity in the mesopic region [I]. Visual acuity was measured using Landolt-C test charts designed and developed for this work. The measurements were made with binocular viewing of two target contrasts (C=0.93 and 0.15) at 40 cm distance. In this work, contrast C is defined by

$$C = (L_b - L_t)/L_b \qquad (1)$$

where L_b is the luminance of the background and L_t is the luminance of the target.

Thirteen young subjects (22-26 years) participated in the experiments. They all had normal vision (colour vision, refraction, visual acuity, visual field, ocular fundi and ocular tension).

The experiments were carried out in two adjacent rooms. The subject was positioned at a chin rest while seated at a table, Figure 1. The luminance levels of the white background of the test charts were, in terms of photopic (V(λ)-weighted) luminances, 0.2, 1, and, 5 cd/m^2.

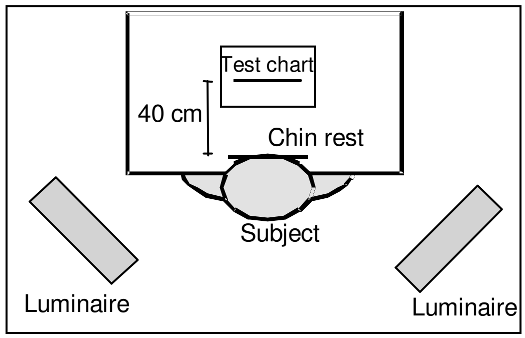

***Figure 1** Experimental set-up of the visual acuity measurements. The subject viewed the Landolt-C test chart at 40 cm viewing distance. Fluorescent lamps fixed in vertical position in two luminaries provided uniform luminance distribution to the test room.*

Visual acuity was measured under four different light spectra, Figure 2. Measurements were done under daylight fluorescent lamps with continuous spectrum (correlated colour temperature 5200 K). Additionally, three coloured lights were used. The spectral distributions of the coloured lights covered wavelength regions of 400-540 nm (peak at 457 nm), 510-630 nm (peak at 545 nm), and 600-700 nm (peak at 660 nm). In the following, the different light spectra are referred to as daylight, blue, green and red, respectively.

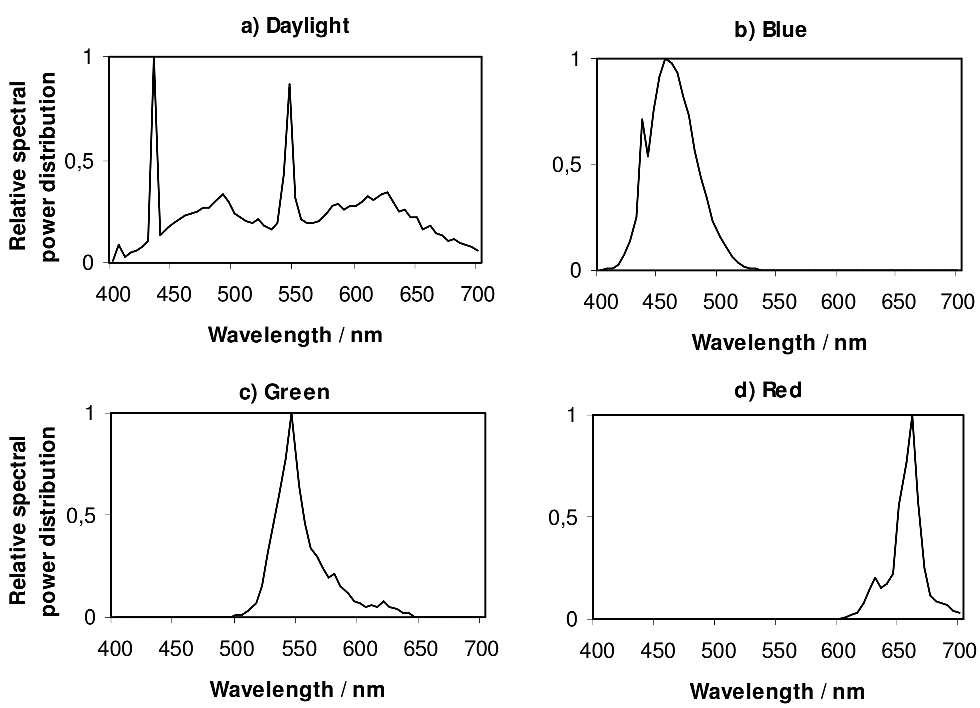

***Figure 2** The relative spectral power distributions of the a) daylight, b) blue, c) green and d) red lights of the visual acuity experiments.*

The measurement session of each subject started at the highest background luminance (5 cd/m^2) under the daylight spectrum. The subject adapted for 10 minutes to this lighting condition and for 5 minutes to each following lighting condition. The measurement session of each subject lasted for 1.5-2 hours.

2.2.2 Results

Figure 3 shows the mean visual acuity results of all the subjects as a function of luminance level at two target contrasts and for four different light spectra. Statistical analysis was carried out using the Friedman and Wilcoxon signed-rank tests ($p<0.05$).

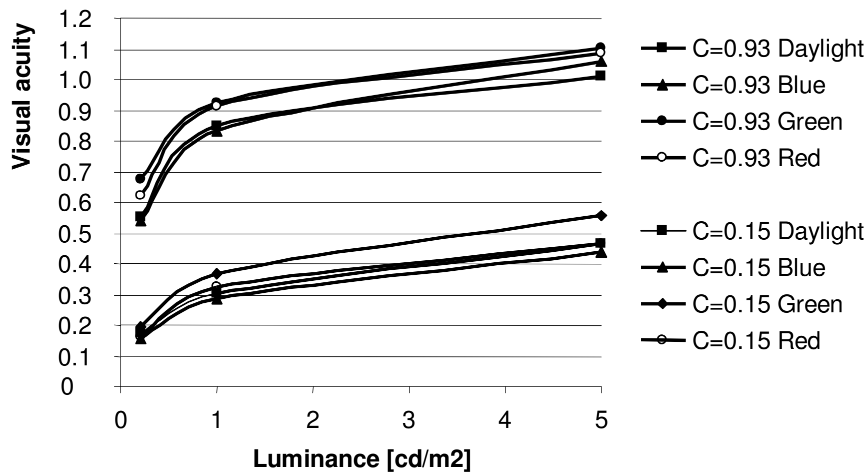

Figure 3 *Mean visual acuity of 13 subjects as a function of luminance at two target contrasts (C=0.15 and C=0.93) and under four light spectra (daylight, blue, green, red).*

The results clearly indicated the decrease in visual acuity with decreasing luminance level from 5 cd/m^2 to 0.2 cd/m^2. The lower the luminance level, the clearer were the changes in visual acuity as a function of luminance level. Also, the effects of target contrast on visual acuity were evident. Lower contrast resulted in lower visual acuity at all luminance levels and with all light spectra.

No significant differences in visual acuity were found between the different light spectra. Visual acuity remained the same under the blue light and red light (the most extreme spectral regions) at equal photopic luminance levels. The same was found for both the high- and low-contrast targets. In general, no spectral effects were found on visual acuity at equal photopic luminance levels and target contrasts.

Visual acuity in the measurements describes foveal vision. As visual acuity remained the same under different light spectra, both at the photopic/high-mesopic (5 cd/m^2) and mid-mesopic (0.20 and 1 cd/m^2) luminance levels, it is obvious that the spectral sensitivity of the foveal cones remains the same at photopic and mesopic levels. The results imply that the photopic $V(\lambda)$ is also valid for assessing the luminosity of centrally viewed small targets in the mesopic region. This holds true for at least the higher and middle part of the mesopic luminance region (>0.2 cd/m^2), which is of prime importance in road and street lighting conditions.

2.3 Pedestrian visibility experiments

2.3.1 Measurement methods and set-ups

An experimental set-up was designed and constructed to study visibility in road lighting conditions [II]. The test room was a 200 m long underground tunnel. The height of the tunnel was 3.5 m and the tunnel width was 5 m. Road lighting installations were built in the tunnel to simulate viewing conditions on roads at night-time when fixed road lighting is used.

Two similar installations were built in the tunnel, one with high-pressure sodium (HPS) lamps and the other with daylight metal halide (MH) lamps (correlated colour temperatures 2000 K and 5200 K, respectively). In both installations, the luminaires were positioned in five luminaire groups with 8 m spacing. The luminance distributions of the two installations were equal.

The visibility of a walking pedestrian was used as the basis of a visual task in three different test series. In each test series, the experimental setting and the visual task were slightly modified. In each setting, the task of the subject was to indicate the detection threshold of the pedestrian. The pedestrian was walking towards the dark end of the tunnel and thereafter approaching the illuminated area of the tunnel from the dark, Figure 4. The walking speed of the pedestrian was constant (0.2 m/s) and the length of one footstep was 40 cm. The pedestrian subtended a visual angle of 2° from 40 m viewing distance. Pedestrian visibility was measured in foveal and peripheral (at 15°/20° eccentricity) viewing. The viewing was binocular.

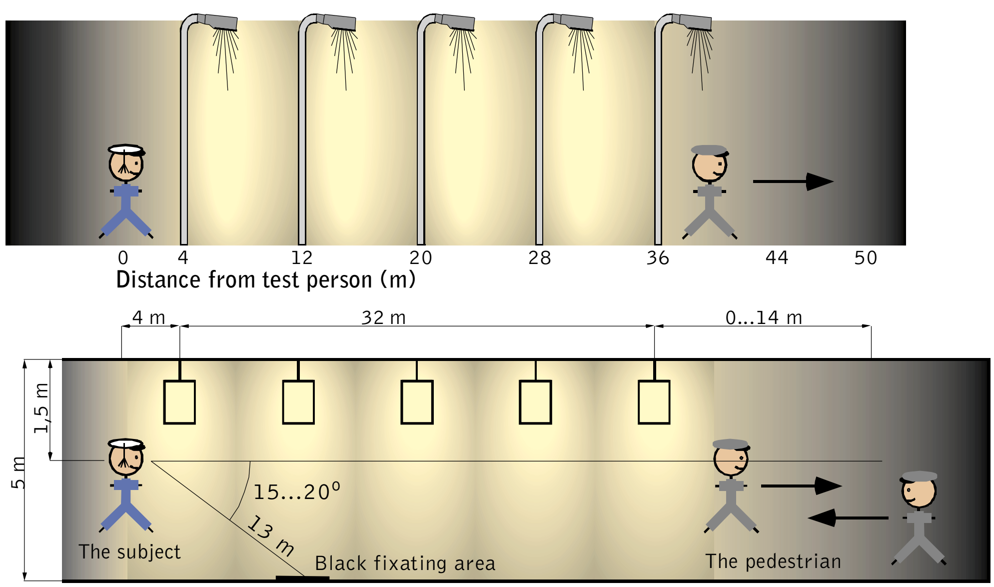

Figure 4 *Experimental set up of the pedestrian visibility experiments. In foveal viewing, the subject was fixating to the back of the walking pedestrian and in peripheral (15°/20°) viewing to the black fixating area on the tunnel wall.*

The pedestrian luminance (at 1.3 m height) at the detection distance corresponded to the lowest detectable target luminance in each lighting condition. The results are presented as a ratio of the pedestrian luminance at the detection distance and the average road surface luminance level (L_{ped}/L_{ave}). This is referred to as the Relative Luminance Threshold, RLT.

In the first test series, the pedestrian was dressed in grey clothing and wore a grey cap to cover his face. The tests were carried out for six subjects (22-25 years) in foveal and peripheral viewing at 15° eccentricity. The average road surface luminance levels were 0.1 and 1.5 cd/m^2. The measurement session of each subject consisted of four different lighting conditions (two light spectra, HPS/MH, and two luminance levels, 0.1 and 1.5 cd/m^2).

In the second test series, the visual test was modified. A new component, pedestrian arm movements, was included in the visual task. This was to emphasize the movement as a critical component of target detection. In the second test series, the pedestrian was constantly swinging his hands between the downwards and horizontal plane while walking. The second test series employed one trained subject (28 years). The tests were made in foveal and peripheral viewing at 20° eccentricity. Eight test sessions for the subject were carried out on subsequent days. One session consisted of four different lighting conditions (two light spectra, HPS/MH, and two luminance levels, 0.1/1.5 cd/m^2).

In the third test series, a different approach was used to define the detection threshold. Arm movements of the pedestrian were again used to emphasize target movement. The pedestrian started to walk towards the dark end of the tunnel and after each footstep (40 cm apart) swung his arms once from downwards to the horizontal plane and back. The pedestrian gave two signals and the task of the subject was to indicate whether the arm movements occurred after the first or second signal. The detection distance was defined through several repetitions around the maximum detection distance. The pedestrian wore a grey shirt and white pants and a white cap. The tests were made in foveal and peripheral viewing at 20° eccentricity. Four subjects (22-30 years) participated in the tests and each test session was repeated four times for each subject. One session involved four different lighting conditions (two light spectra blue/yellow, and two luminance levels, 0.5/2.0 cd/m^2). The blue light was a little more bluish than the daylight MH light in the preceding tests and the yellow light was similar to the HPS lamp spectra, Figure 5.

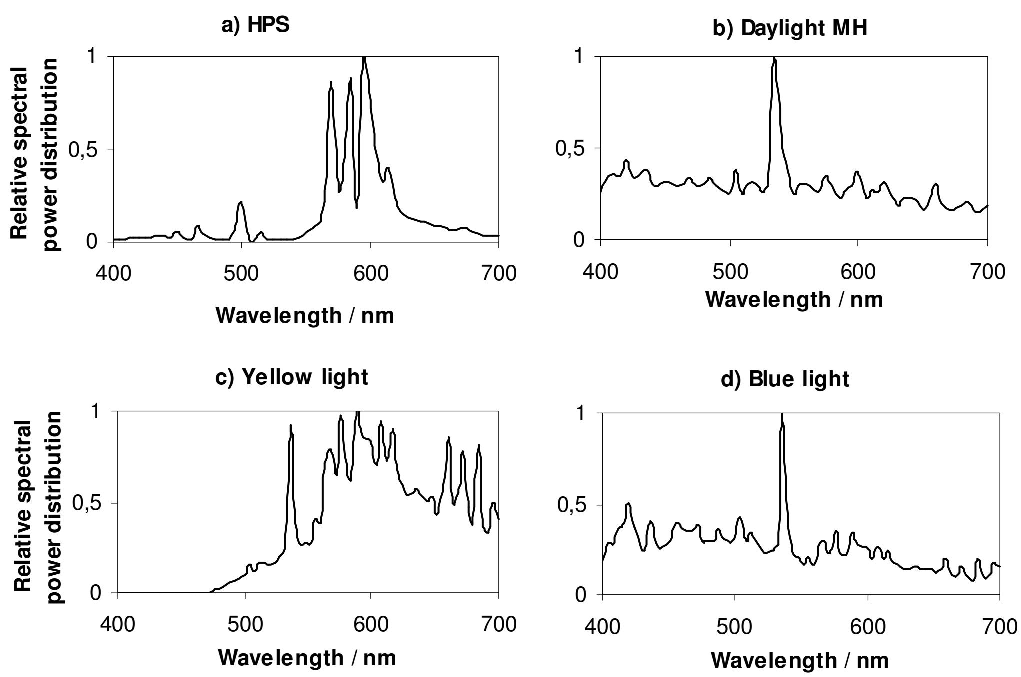

Figure 5 *The relative spectral power distributions of the a) HPS lamp, b) daylight MH lamp, c) yellow light and d) blue light used in the pedestrian visibility experiments.*

All the subjects in the experiments had normal vision (colour vision, refraction, visual acuity, visual field). Before starting the measurement session the subject had adapted for 30 minutes to the tunnel lighting. A 5-minute adaptation time preceded the tests in each of the following lighting conditions of the measurement session.

2.3.2 Results

The statistical analysis of the results was conducted using analysis of variance based on the Bonferroni and Friedmann tests ($p<0.05$).

The results of the first test series are shown in Figure 6, which shows the average relative luminance threshold of the six subjects in different lighting conditions. The results show that luminance level has a clear effect on visibility. This is seen as lower Relative Luminance Threshold at 1.5 cd/m^2 luminance level compared to 0.1 cd/m^2. At the higher luminance level (1.5 cd/m^2), visibility was relatively better for targets in foveal (0°) vision compared to peripheral (15°) vision. When luminance decreased to 0.1 cd/m^2 the differences between foveal and peripheral vision disappeared. Thus peripheral visibility was improved in relation to foveal visibility with a decreasing luminance level. In the first tests, no differences in visibility were found between the two light spectra (HPS/MH) at either luminance level.

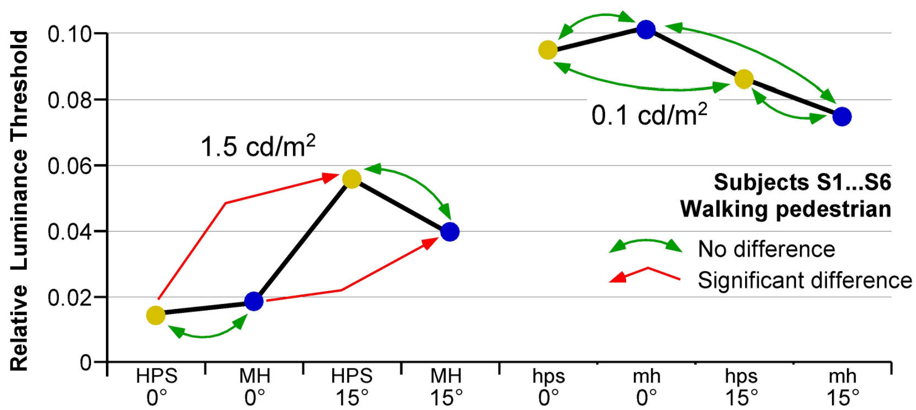

Figure 6 *Results of the first test series. Relative luminance threshold for detecting a pedestrian at two road surface luminance levels (1.5/0.1 cd/m^2), under two light spectra (HPS/ MH), and in foveal (0°) and peripheral (15°) viewing.*

The results of the second test series are shown in Figure 7, which shows the average relative luminance threshold of one subject in eight measurement sessions. Again the results indicate a clear effect of luminance level on visibility. Similarly to the first test series, visibility was better in foveal viewing compared to peripheral viewing at the higher luminance level (1.5 cd/m^2). At the lower luminance level (0.1 cd/m^2), visibility became better for peripheral viewing compared to foveal viewing. Differences between the two light spectra were found at the lower luminance level (0.1 cd/m^2) in peripheral (20°) viewing, where the relative luminance threshold was lower under MH lamps compared to HPS lamps. Again, no spectral effects were found in foveal vision at either of the luminance levels.

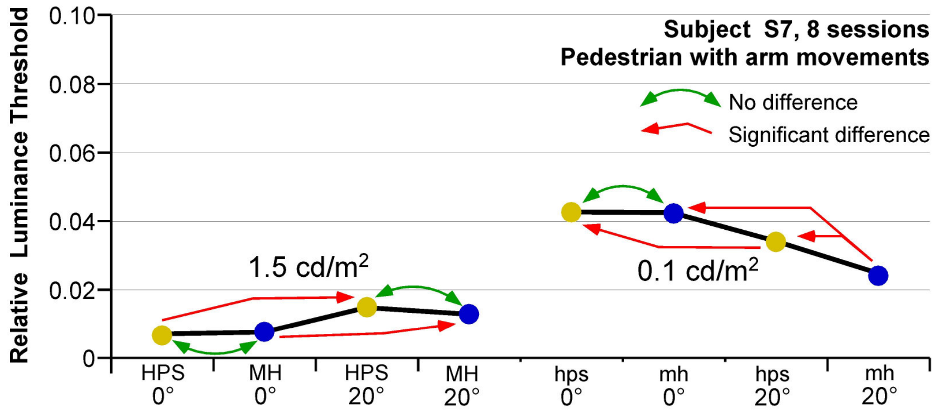

Figure 7 *Results of the second test series. Relative luminance threshold for detecting a pedestrian at two road surface luminance levels (1.5/0.1 cd/m²), under two light spectra (HPS/ MH), and in foveal (0°) and peripheral (20°) viewing.*

The results of the third test series are shown in Figure 8, which shows the average relative luminance threshold of the four subjects in four measurement sessions. Clear effects of luminance level on visibility were again found. At the higher luminance level (2.0 cd/m²), visibility was relatively better in foveal vision compared to peripheral vision. No differences between light spectra were found at the higher luminance level (2.0 cd/m²). At the lower luminance level (0.5 cd/m²), the differences between foveal and peripheral vision disappeared under the blue light but not under the yellow light. At the lower luminance level peripheral visibility was better under the blue light compared to the yellow light. Again, no spectral effects were found in foveal vision at either of the luminance levels.

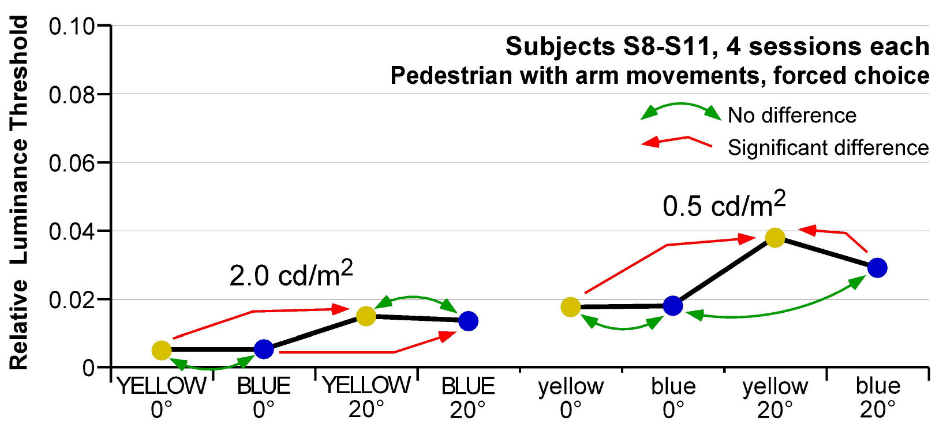

Figure 8 *Results of the third test series. Relative luminance threshold for detecting a pedestrian at two road surface luminance levels (2.0/0.5 cd/m²), under two light spectra (yellow/blue), and in foveal (0°) and peripheral (20°) viewing.*

The pedestrian visibility experiments showed that light spectrum does not affect foveal vision at equal photopic (V(λ)-weighted) luminances in the mesopic region. This is consistent with the findings of the visual acuity experiments. Effects of light spectrum were found on pedestrian visibility in peripheral viewing. These effects were, however, dependent on the luminance level and on the characteristics of the specific pedestrian visibility task.

2.4 Conclusions

The visual acuity and pedestrian visibility experiments showed that luminance level has a clear effect on target recognition and detection in the mesopic region. This was found for both foveal and peripheral vision. The effects of the light spectrum were not, however, consistent for foveal and peripheral visual tasks.

Foveal vision was investigated using two different visual tasks, visual acuity and pedestrian visibility. Both experiments resulted in similar findings in terms of the light spectrum. No effects of the light spectrum on foveal vision were found at constant photopic ($V(\lambda)$-weighted) luminance. The results imply that the photopic $V(\lambda)$ is valid for assessing the luminosity of centrally viewed small targets also in the mesopic luminance region.

The pedestrian visibility experiments showed that, at mesopic light levels, the spectral sensitivity of peripheral vision cannot be exclusively described by $V(\lambda)$. The results showed indications of the shift of spectral sensitivity towards shorter wavelengths in peripheral viewing. The spectral effects were found in the mid-mesopic luminance range (0.1….0.5 cd/m^2), but not at the higher mesopic luminance levels (1.5 ... 2.0 cd/m^2).

The pedestrian visibility task corresponds to a minimum target luminance contrast that is necessary for drivers to become aware of objects in their visual field. This task is related to *achromatic thresholds,* or the ability to simply perceive a visual stimulus (without necessarily being able to perceive colour or detail). The achromatic threshold is among the fundamental visual tasks in driving. The current road lighting design practice [15, 16] is broadly based on the concept of visibility, which is basically defined by threshold contrast, i.e. the minimum relative luminance difference between a target and its background [17].

Still, visibility of a pedestrian represents one visual performance measure and it is evident that the visual task of night-time driving cannot be comprehensively described with one visual task. The pedestrian visibility experiments revealed that even in using one visual task the effects of lighting on visual performance are dependent on the specific viewing conditions and target characteristics. The three different modifications of the pedestrian visibility task resulted in slightly different dependency of visual performance on lighting and viewing conditions. The spectral effects were more pronounced when the movement of the visual target was emphasized. Furthermore, the spectral effects were dependent on the luminance level and target eccentricity.

The visual acuity and pedestrian visibility experiments indicated task-dependency of mesopic spectral sensitivity. Based on the experimental results and an extensive review of existent mesopic research data, it was obvious that many test methods are needed to characterise mesopic spectral sensitivity. If mesopic spectral sensitivity was investigated using one visual criterion, the generated functions would be applicable for this visual performance measure only. It became obvious that several visual tasks and test methods were needed in order to comprehensively characterise mesopic spectral sensitivity.

3 European collaboration work in the development of mesopic photometry

3.1 Establishment of the collaboration work

Due to the complex nature of mesopic vision, it was recognized that an extensive amount of data was needed to establish a solid basis for performance-based mesopic photometry. Although there had been a lot of work at national levels in the mesopic field, it was evident that the establishment of performance-based mesopic photometry required the collaboration of several countries. It was also evident that the complex interactions of vision and lighting necessitated interdisciplinary work and a combination of resources from different scientific fields.

It was recognised that co-operation at a European level would provide the means to take a step towards a future standard for mesopic photometry. The lack of mesopic photometry concerns the whole European Community, and also world-wide, since the adopted photometric practice is the same throughout the world. A standard of mesopic photometry would lead to international adoption of mesopic lighting dimensioning in the future.

The European research programmes provide possibilities for network research teams. The Competitive and Sustainable Growth Programme (GROWTH) was carried out during 1998-2002 in the EC Fifth Framework Programme. The objectives of the Measurements and Testing (M&T) activity in the GROWTH programme included the generation of scientific and technical data for the basis of European and international standardisation. For this M&T activity an expression of interest titled 'Spectral luminous efficiency functions for the intermediate luminance levels' was prepared where the urgent need for a standard on mesopic photometry was indicated. This expression of interest was accompanied by thirty-eight endorsement letters collected from CIE, CEN (Comité Européen de Normalisation) and the international lighting community, where the development of such a standard was encouraged. The suggested topic was published in the Official Journal of the European Communities in December 2000 [18]. The author was responsible for formulating this topic and for collecting the endorsement for the outlined work from the standardization bodies and lighting community.

A European research consortium, MOVE (Mesopic Optimisation of Visual Efficiency), was built to meet the challenge of establishing a basis for performance based mesopic photometry. The consortium brought together expertise in the fields of lighting engineering, vision science, metrology, human behaviour and image processing. The HUT Lighting Laboratory of Finland led the consortium: the other members were the City University and NPL UK, TNO Human Factors the Netherlands, Darmstadt University of Technology Germany and the University of Veszprém Hungary [III].

A detailed plan for the accomplishment of the MOVE work was prepared by the consortium with HUT Lighting Laboratory as the coordinator. This plan was submitted to the EC GROWTH programme dedicated call in March 2001. The suggested research work was accepted to be included in M&T activities of the GROWTH programme. Following this the EC project MOVE started in January 2002 and was carried out during 2002-2004. The objective of MOVE was to define relevant spectral sensitivity functions for the mesopic range of 0.01 – 10 cd/m^2 and to document the results as the basis of an international standard. The objective was to provide performance-based data and a scientific basis for the future development of an international standard on mesopic photometry. No work on this scale had been accomplished before.

3.2 Performance-based multi-technique method of MOVE

3.2.1 Three sub-tasks in characterizing visual performance of night-time driving

In the approach adopted in MOVE, emphasis was placed on visual performance of night-time driving and the attempt to describe mesopic spectral sensitivity in a realistic way. The approach started by identifying the relevant visual tasks of night-time driving [IV, V]. The task of night-time driving was divided into three visual sub-tasks, which are characterised by the questions for which they provide visual information:

Can an object be seen? - how quickly? - what is it?

These visual tasks are related to the detection of a visual target, the speed of detection and the identification of the details of that target.

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 [19]. In order to detect a target, a certain luminance difference is needed between the target and its background. The first visual task, characterised by the question ''*Can an object be seen?''*, is related to *achromatic thresholds.* This is the ability to perceive a visual stimulus without necessarily being able to perceive colour or detail. The pedestrian visibility task in the experiments of Chapter 2.3 is related to the first sub-task of MOVE.

The second visual task characterised by the question *"How quickly?"* is related to the *speed of detection*. Reaction times, i.e. the time between the onset of a visual stimulus and the detection response of that stimulus, were used to describe this task. Reaction times were measured under conditions where the observer was instructed to respond manually by pressing a button as quickly as possible after detecting the target. In night-time driving reaction times are claimed to play an important role in safe driving [20]. It has been stated that reaction times, from a practical perspective, are a good performance measure for realistic situations, such as driver hazard detection responses [21].

The next step in the visual process is recognition, when, according to its visual details, the target is being recognized and a more conscious and wilful action can be initiated. This third visual sub-task is characterised by the question *"What is it?"*. Visual recognition indicates whether the details of the target can be identified and is thus related to the ability to comprehend more of the target, than just where it is seen [19]. Recognition is related to, for example the legibility of traffic signs, dashboard displays, markings on the roadway, etc. One of the critical tasks in driving is the ability to read warning signs quickly [22]. The visual acuity experiments of Chapter 2.2 are related to the third sub-task of MOVE.

3.2.2 Parallel visual experiments in generating new visibility data

The key idea of the MOVE work was to generate data on mesopic spectral sensitivity using several visual criteria. No investigation at this depth had been undertaken previously. The MOVE work steered away from conventional techniques, where only one aspect of visual performance had been considered at a time, and developed a multi-technique method [III, IV]. The author was responsible for the co-ordination and supervision of the design and execution of the vision experiments in the MOVE work.

It was realised that the only way to provide enough data for building a comprehensive mesopic model was to generate data with various vision experiments using different experimental techniques. In MOVE this was implemented by dividing the experimental work between several test locations in different countries. The objective was to ensure that the experiments covered a number of visual criteria under various lighting and viewing conditions. After careful consideration of the required visibility data, the MOVE consortium developed experimental techniques to quantify the visibility of targets when performing each of the three visual tasks. For each visual sub-task, data was simultaneously generated in two to four laboratories using different experimental methods in each location. Vision experiments were conducted simultaneously in five partner countries of the MOVE consortium.

In MOVE, data for the first visual sub-task was generated with the method of ***achromatic detection threshold***, i.e. the increment and/or decrement of the visual target's intensity around the threshold, to detect the target. Achromatic threshold data was generated using three different experimental settings: modified Goldman perimeter (carried out by HUT in Finland), large homogeneous screen (TUD, Germany) and screen with computer-controlled projector (UV, Hungary). Data for the second visual sub-task was generated by measuring ***reaction times*** for a number of coloured targets with different spectral characteristics. Reaction time data were generated using four different experimental settings: large uniform hemisphere (HUT, Finland), computer controlled CRT display (CU, UK), driving simulator (TNO, Netherlands) and large homogeneous screen (TUD, Germany). Data for the third visual sub-task was generated by measuring ***achromatic recognition threshold*** using a screen with a computer-controlled projector (UV, Hungary). Each test location was responsible for the design of their experimental setting and for conducting the experiments in order to support the common criteria and goals adopted in MOVE.

The work between the parallel experiments was distributed in a way that allowed the exchange of data between test locations and input of data from one test to another. Thus joint decisions on further work and on parameter adjustments could be made during the course of the work.

The comparison of different mesopic models generated so far has been difficult because of the use of different experimental parameters. The merit of the approach adopted in MOVE was the use of a common set of parameter values as the basis of each particular data set generated in different test locations. The joint parameters were: background photopic luminance 0.01 cd/m^2, 0.1 cd/m^2, 1 cd/m^2, 10 cd/m^2, stimulus eccentricity 0° and 10°, stimulus size 2° (and 0.29°), and nearly steady presentation with $\Delta t \geq 3$ s (or $\Delta t \leq 500$ ms for part of reaction time experiments). The highest luminance level (10 cd/m^2) was foreseen to provide a connection of the mesopic spectral response to the present photopic $V(\lambda)$ function. The use of common parameter values was to ensure comparison of the data from different test locations and to assist in modelling of the data. In addition to the luminance levels given above, experiments were also conducted at intermediate levels 0.03, 0.3 and 3 cd/m^2 in order to provide data for validating the generated new model. The high number of observers (123) compared to earlier studies was to ensure that the empirically-modelled spectral sensitivity curves would be more representative of an average observer.

The optical radiation measurement equipment used in MOVE were calibrated by NPL against the UK photometric and spectroradiometric scales. This was to ensure that the results from the different laboratories were compatible and could be combined in the modelling process. The linking of the measurements to a common scale was also foreseen to aid in gaining international acceptance for the developed models.

The vision experiment work of MOVE was divided into four phases. After each phase a combined analysis of all test data was made by each partner. The author provided the criteria and common guidelines for the analysis and co-ordinated the planning of the experimental work of each phase. The key elements in co-ordinating the experimental work were to ensure that the data describes the relevant components of visual tasks in driving and that sufficient data was generated for each of the visual subtasks. Furthermore, it was ensured that the core parameters (joint parameter values) were covered in the experimental conditions. It was also emphasized that the spectral characteristics of the lighting conditions should sufficiently cover the visible spectrum and that the data were generated using both (quasi-)monochromatic and broadband sources. The experimental design was adjusted and modified when necessary during the course of the work. This was to make sure that the experimental work conducted in the five countries was constantly in accordance with the MOVE objectives.

3.3 MOVE data-base on mesopic visual performance

An extensive amount of mesopic visual performance data describing the interactions of lighting and viewing conditions was generated in MOVE. The data characterized the dependencies between light spectra and visual performance as a function of visual task and experimental setting, luminance level, target eccentricity and target size [IV, V].

Achromatic detection thresholds were measured in three laboratories using quasi-monochromatic (hbw= 10 nm) and broadband stimuli. Modified absolute thresholds and increment thresholds were measured with quasi-monochromatic stimuli to directly determine relative spectral sensitivity curves. These measurements yielded to relative spectral sensitivity curves with three-peak behaviour. This peaked behaviour in spectral sensitivity curves has also been observed by other researchers and is believed to be caused by the colour-opponent mechanisms in the visual system. The chromatic effect seemed to be less significant at the lower luminance levels (0.01 cd/m^2) but more pronounced for peripheral observation.

The achromatic detection threshold results obtained with broadband stimuli were in accordance with the expected shift of spectral sensitivity to shorter wavelengths with decreasing luminance. The results showed that, at low mesopic luminances (0.01 and 0.1 cd/m^2), the photopic V(λ) underestimates sensitivity to short wavelengths and overestimates sensitivity to long wavelengths.

Reaction times were measured in four laboratories to investigate the spectral dependence of the reaction time response in mesopic conditions. Reaction time data was generated for stimuli with quasi-monochromatic (hbw=10 nm), narrowband (hbw=16-37 nm) and broadband spectral distributions in three laboratory experiments and for broadband stimuli in a driving simulator. Reaction times were generally found to decrease non-linearly with increasing light level and approach an asymptote that corresponds to a minimum reaction time. The recorded absolute reaction times varied with the experimental setting. Longest reaction times were recorded in the driving simulator where the subjects had to do a more complicated task. The reaction time results showed that for foveal viewing the spectral dependence of the reaction time task can be described adequately by the photopic V(λ). For peripheral viewing spectral sensitivity changes as a function of light level were found and these were in accordance with the Purkinje shift. At low mesopic luminance levels (0.01 cd/m^2) the spectral response approached the scotopic V'(λ) function.

Achromatic recognition thresholds were measured in one laboratory setting using quasi-monochromatic (hbw=10 nm) stimuli. The directly-derived relative spectral sensitivity curves showed two-peak behaviour. Similarly to the quasi-monochromatic detection threshold experiments this was assumed to be caused by the chromatic channel contribution. The spectral sensitivity functions based on recognition contrast thresholds were different from the $V(\lambda)$ function both for foveal and peripheral observation. The peaked behaviour of the derived curves seemed less significant for lower mesopic light levels but somewhat more pronounced for peripheral observation.

The vision experiment data generated in MOVE were combined to form an extensive data-base on mesopic visual performance under varied spectral and lighting conditions. This data represents a significant resource to be used in modelling mesopic spectral luminous efficiency based on visual performance measures.

3.4 Conclusions

A European research consortium was formed to take up the challenge of establishing a scientific and technical basis for performance based mesopic photometry. It was realized that the work needed could not be carried out by one laboratory, or even in one single country. The MOVE consortium brought together multi-disciplinary expertise from six research institutes in five countries.

The Measurement & Testing activity of the EC GROWTH programme was convinced of the urgent need for mesopic photometry. This was achieved by collecting endorsement from the international standardization bodies and lighting community. The establishment of mesopic photometry was foreseen as benefiting the international lighting community and lighting industry. Following an expression of interest and a dedicated call of the European research programme, GROWTH, the MOVE consortium started the work on developing performance-based mesopic photometry as a basis of an international standard on mesopic photometry.

The objective of the MOVE work was to define relevant spectral sensitivity functions for the luminance range of 0.01 – 10 cd/m^2, where standardisation is most urgently needed. Much of the earlier research work in the mesopic field has used brightness matching as the visual criterion in developing mesopic spectral sensitivity models. The MOVE work adopted a different approach. In MOVE, the emphasis was placed on visual performance of night-time driving and the attempt to describe luminous efficiency in a realistic way.

A multi-technique method was developed for MOVE in which the experimental work was divided between several test locations using different visual criteria and experimental settings. The vision experiments split the task of night-time driving into three visual sub-tasks, each of which was investigated separately. All experiments were based on a common set of parameter values and altogether 123 observers participated in the experiments. The data generated in the vision experiments provided a significant database on mesopic visual performance for establishing new mesopic luminous efficiency functions.

4 Performance-based models for mesopic photometry as an outcome of MOVE

4.1 Starting point for modelling

An important consideration in the MOVE work was to provide a model for mesopic photometry that is applicable to the task of night-time driving and, importantly, suited to practical implementation. The model should be based on mesopic visual performance behaviour and on the other hand it should be simple enough to be applied and used by lighting practitioners. The CIE definition of photometry assumes additivity. It was thus recognised, that to have practical validity, a mesopic photometric system should obey the Abney's law of additivity. Still, it is recognised that, in the mesopic region, additivity can be claimed to hold only within a given adaptation level, due to the spectral sensitivity changes with the adaptation level. The rules of additivity state that radiant flux in the mesopic region can be weighted with a mesopic spectral luminous efficiency function and then added linearly to quantify the corresponding amount of light. This requires that the description of mesopic spectral luminous efficiency is linear in form throughout the mesopic region. The linearity requirement guided much of the modelling process.

The vision experiment data based on relatively broadband targets presented against a white or coloured (broadband) background could be fitted to various potential forms of linear models. However, the data based on quasi-monochromatic (hbw = 10 nm) visual targets resulted in spectral sensitivity curves showing distinctive 'three-peak' behaviour. This behaviour was assumed to be related to the non-opponent chromatic channels of the visual system and could not be described by a linear model. Thus, two distinct approaches were used in the modelling, resulting in a linear model of mesopic spectral luminous efficiency and in a more complex non-linear 'chromatic model' [IV].

In the MOVE work, NPL (UK) was responsible for the mathematical modelling process. The main directions of the modelling process and agreements on the final outcomes of the modelling work were jointly agreed by the consortium.

The vision experiment data used in the modelling was based on investigations in five countries with 109 observers. In addition, supportive experiments to characterise mesopic vision where conducted for 14 observers, but this data was not included in the modelling process [IV].

4.2 Linear i.e. practical model

In developing a practical system of mesopic photometry, certain constraints had to be placed on the model developed. A distinction was made between a model applicable in practice and a model of the eye response in the mesopic region. In order to be implemented alongside the current photopic photometry, the mesopic spectral sensitivity functions should tend to the photopic $V(\lambda)$ at the upper end, and to the scotopic $V'(\lambda)$ at the lower end of the mesopic region. Still, the model should predict visual task performance reasonably well. These constraints were considered in establishing a linear model based on the data generated in MOVE.

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. In modelling the MOVE data each type of the three visual sub-task measurements was modelled separately, with each background light level taken in turn. It was, however, found that an acceptably good fit to all the data sets was obtained with a single model. It was found that for peripheral observation a linear model of mesopic spectral luminous efficiency describes adequately all the three visual subtasks investigated. This model defines mesopic spectral luminous efficiency as a combination of the photopic V(λ) and the scotopic V'(λ). The model is of the form

$$M(x)V_{MOVE}(\lambda) = x\,V(\lambda) + (1\text{-}x)\,V'(\lambda), \qquad (2)$$

where $V_{MOVE}(\lambda)$ represents the relative spectral luminous efficiency function and $M(x)$ is a normalising function such that $V_{MOVE}(\lambda)$ attains a maximum value of 1. The proportions of the photopic and scotopic functions are determined by parameter x. The parameter x itself is determined by an iterative approach for a given background light level and background light spectrum.

Once x has been calculated, the corresponding mesopic background luminance, L_{MOVE}, is given by

$$L_{MOVE} = k(x) \int E(\lambda)\; V_{MOVE}(\lambda)\, d\lambda \qquad (3)$$

where $k(x)$ is a constant (this is derived from $M(x)$ above) and $E(\lambda)$ is the spectral distribution of the background.

Figure 9 shows a combined analysis of the experimental data of the linear model. The values of parameter x_i are plotted against $\log_{10} I_{\mathrm{m}}(x_i)$ (mesopic intensity value) for each of the data sets analysed (contrast threshold, reaction time, recognition threshold). The best-fit line to the $(x_i, \log_{10} I_m(x_i))$ data is also plotted in Figure 9.

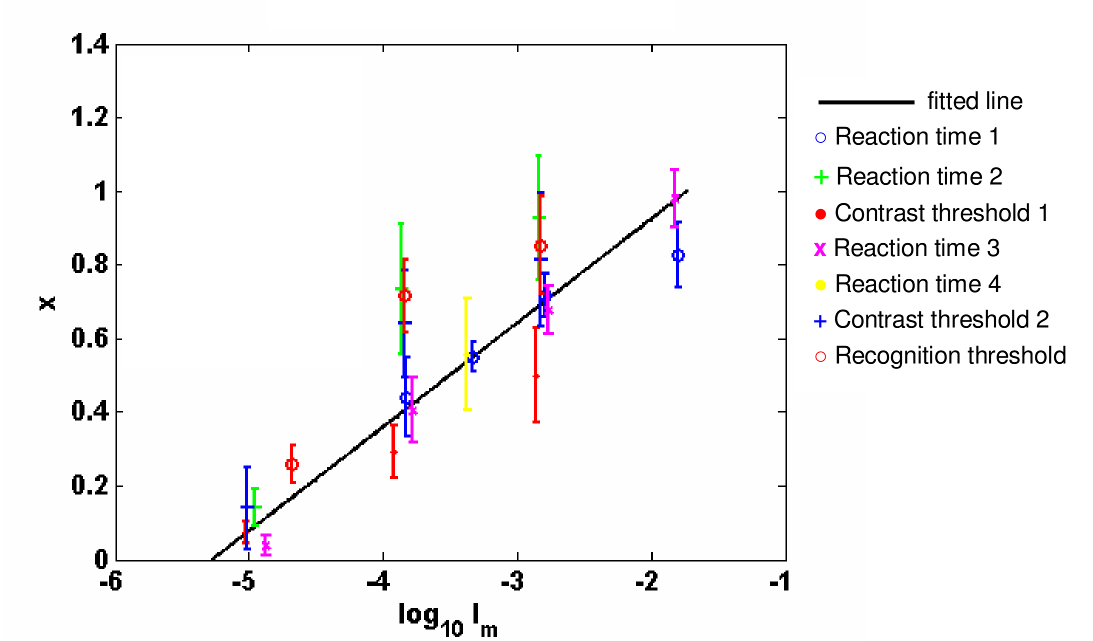

Figure 9 *Fitted values of MOVE linear model parameter x as a function of* $\log_{10} I_{\mathrm{m}}$ *for all results at 10° target eccentricity. The bars represent the interval [x-2u(x), x+2u(x)] where u(x) is the standard uncertainty associated with the value of the x determined from the fit of* $V_{MOVE}(\lambda, x)$ *to experimental data.*

In calculating mesopic luminances with the MOVE linear model the photopic luminance and light source spectral data are needed. The model is available in the form of MATLAB files. The linear model of MOVE is also referred to as ‘practical model’ in the following.

Figure 10 shows the parameter x of the MOVE linear model as a function of S/P-ratio (scotopic to photopic luminous output) of the background light source. The x-values are presented for different photopic luminance levels between 0.01 – 10 cd/m^2. The lower the background luminance, the lower is the value of x, and, consequently, the higher the scotopic weighting in calculating the corresponding mesopic luminance. When photopic luminance approaches the upper luminance limit of the MOVE model (10 cd/m^2), the x-value approaches its maximum value of x=1. Figure 10 also shows x-values and corresponding mesopic luminances L_{MOVE} for three light sources with S/P-ratios 0.55, 1.55 and 2.55 at equal photopic luminance L_p=0.03 cd/m^2. Light sources with high output in the short wavelength region (high S/P-ratio) get higher values of x at the same photopic luminance level. This results in higher mesopic luminances. In the MOVE linear model equal values of x relate to equal adaptation levels and consequently result in equal description of mesopic luminous efficiency.

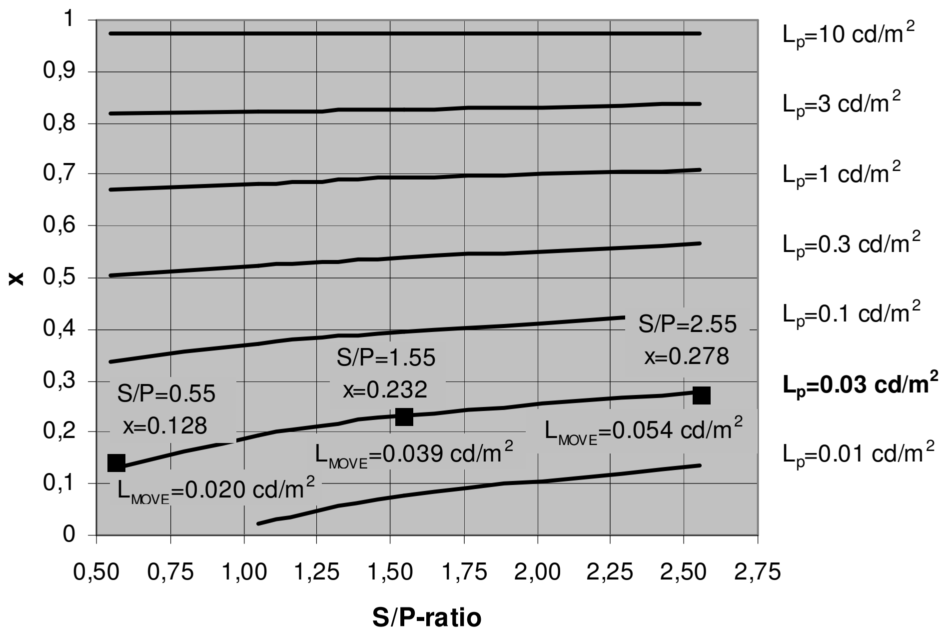

Figure 10 *Parameter x as a function of light source S/P-ratio for different photopic luminances in the MOVE linear model. Mesopic luminances L_{MOVE} are shown for S/P-ratios 0.55, 1.55 and 2.55 at photopic luminance L_p=0.03 cd/m^2.*

For a target eccentricity of 0° (i.e. foveal vision), the MOVE broadband data showed that the photopic luminous efficiency function V(λ) gives an acceptably good fit to the data at all levels, except at the lowest luminance level 0.01 cd/m^2. The findings of the MOVE work are thus consistent with the findings of the author (Chapter 2) in confirming that foveal spectral sensitivity can be adequately described by the photopic V(λ) also in the mesopic luminance region.

4.3 Chromatic model

In the work of MOVE, part of the vision experiments were carried out using quasi-monochromatic (hbw = 10 nm) visual targets presented against a background with broadband spectral distribution. These experiments allowed relative spectral sensitivity curves to be derived directly. These experiments were conducted using four different methods: achromatic contrast threshold (carried out by TUD in Germany), achromatic increment threshold (UV, Hungary), reaction time (TUD, Germany) and achromatic recognition threshold (UV, Hungary).

The data from the quasi-monochromatic measurements yielded to similar, but not identical, spectral sensitivity curves with three peaks. The observed three peaks were least apparent at low background luminances (0.01 cd/m^2) but were strongly evident at the investigated intermediate and high levels (0.1-10 cd/m^2) in the mesopic region. The distinctive three-peak behaviour has also been observed by other researchers and is believed to be associated with the influence of colour channels in the visual system. It is assumed that the observed three-peak behaviour reflects the combined response of the achromatic and chromatic channels of the visual system [23, 24, 25, 26]. The chromatic channels include non-linear processes in combining signals from the different receptors. These subtractive interactions can not be described by a linear model.

A different approach was therefore taken for the analysis of the results based on quasi-monochromatic visual targets. These data were modelled using the $L(\lambda)$, $M(\lambda)$ and $S(\lambda)$ cone spectral sensitivity functions as well as the photopic $V(\lambda)$ function and the scotopic $V'(\lambda)$ function, but only at the specific background luminances for which they had been measured. In modelling the directly measured spectral sensitivity curves using the $L(\lambda)$, $M(\lambda)$, $S(\lambda)$,$V(\lambda)$ and $V'(\lambda)$ functions, the model took the form:

$$V_{mes}(\lambda) = a_1 V(\lambda) + a_2 V'(\lambda) + a_3 | L(\lambda) - a_4 M(\lambda)| + a_5 S(\lambda) \quad (4)$$

This chromatic model aims to account for contributions from a cone-based achromatic mechanism (with $V(\lambda)$), the rods (with $V'(\lambda)$), the L-M opponent colour channel and a chromatic contribution from the S-cones. The chromatic model applies to peripheral observation for visual targets of which the colourfulness (chromatic saturation) is high, but not to spectrally broadband visual targets [IV].

Figure 11 shows, as an example, the spectral sensitivity function generated by the chromatic model at 0.1 cd/m^2 luminance level and the directly measured spectral sensitivity data by the achromatic contrast threshold technique at the same luminance level (10° eccentricity).

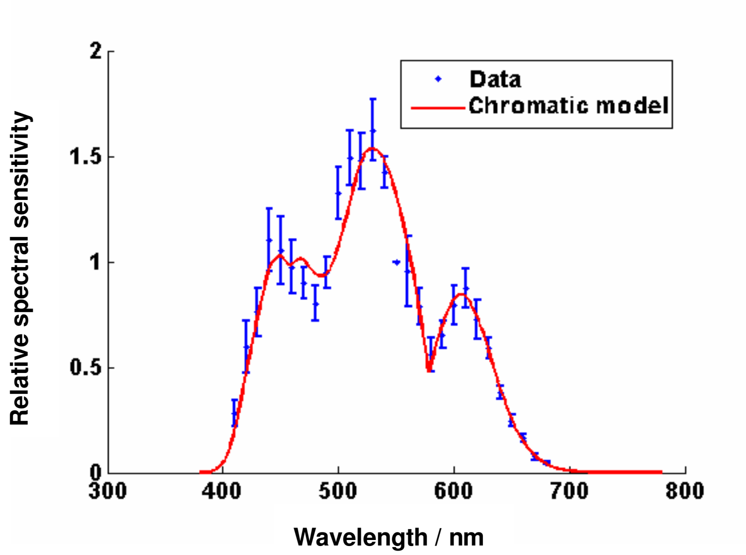

Figure 11 *Spectral sensitivity function generated using the chromatic model at 0.1 cd/m^2 compared with that measured directly using contrast threshold technique (eccentricity 10^0).*

The directly measured spectral sensitivity curves for foveal vision showed differences from those based on peripheral vision (10° eccentricity), but still exhibited some three-peak behaviour. This indicated that a new spectral luminous efficiency model for foveal tasks involving monochromatic stimuli is required and that this model is different from both the developed linear model and the chromatic model.

4.4 Conclusions

The modelling of the vision experiment data of the MOVE work resulted in two distinct models characterising the mesopic spectral sensitivity of peripheral vision.

The linear, i.e. practical, model describes mesopic spectral luminous efficiency as a transition between the photopic V(λ) function at the upper end, and the scotopic V'(λ) function at the lower end, of the mesopic luminance region. This linear model is applicable for peripheral viewing for all three visual sub-tasks investigated (detection threshold, speed of performance and recognition threshold) in situations where the background and target both have fairly broad spectral power distributions. For broadband visual targets in foveal vision, it was found that the V(λ) function provides an acceptably good prediction of task performance regardless of the background level, except at 0.01 cd/m^2.

The linear model uses a parameter x for determining the scotopic and photopic weighting in calculating mesopic values. The model requires the background photopic luminance and spectral data as input values and calculates the corresponding mesopic luminance.

The linear model is not suited to situations where it is critical that the activity of the chromatic mechanisms is taken into account. This concerns situations where the colourfulness (chromatic saturation) of the visual target is especially high, or when the target has a very narrow spectral power distribution. In this case, the more complex chromatic model based on the quasi-monochromatic methods gives a better description of spectral sensitivity. The chromatic model shows three-peak behaviour of spectral sensitivity, which is assumed to be associated with the colour-opponent channels in the visual system. For foveal quasi-monochromatic targets, a different type of chromatic model incorporating the three-peak behaviour is required.

An important consideration within the work of MOVE was to draw a distinction between a practical system of mesopic photometry and a model describing in detail the visual response in the mesopic region. No model can comprehensively describe visual performance in driving. It is also acknowledged that the different visual tasks investigated in MOVE are not independent from each other. The use of three visual tasks to describe visual performance in night-time driving is therefore a simplified approach. The MOVE practical model allows predictions of task performance to be made that are in reasonable agreement with the actual ability to perform these tasks in varied lighting conditions.

The linear model as outcome of the MOVE work is recommended for practical mesopic photometry in, for example, road lighting applications. It is expected that the adoption of a new practical system for mesopic photometry in road lighting dimensioning would be of benefit in optimising the visual conditions of night-time driving.

5 Applicability of the MOVE practical model to road lighting

5.1 Luminance measurements on roads using a CCD photometer

Luminance measurements in road lighting installations were conducted in order to apply the linear, i.e. practical, model of MOVE into practice. The objective was to test the practical model for predicting luminances in road lighting conditions and compare the model predictions to luminances based on photopic photometry.

Road lighting luminance distributions were measured using a ProMetric1400 CCD luminance photometer [VI]. The measured luminance values are based on photopic photometry, as the photometer camera was supplied with a V(λ)-filter.

The lighting of the measured scenes were provided by fixed road lighting using 150 W high-pressure sodium (HPS) and 150 W metal halide (MH) lamps. The colour temperatures of the HPS lamp and MH lamp were 2000 K and 4200 K, respectively. The S/P-ratios of the HPS lamp and MH lamp were S/P=0.61 and S/P=1.66, respectively. The lamp spectra are shown in Figure 12.

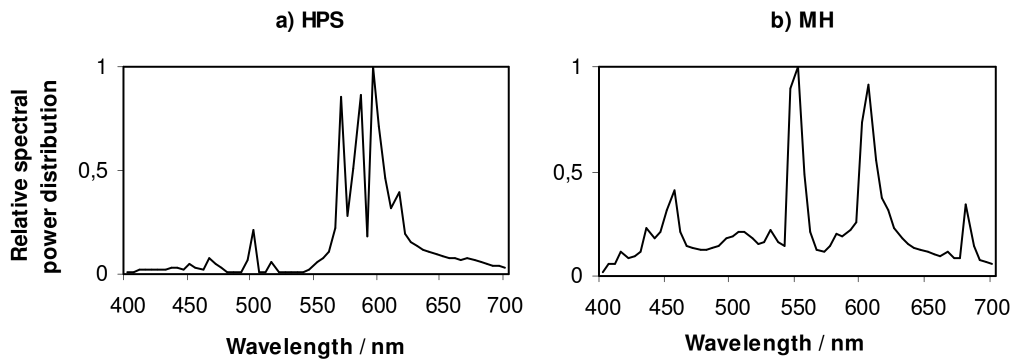

Figure 12 *Relative spectral power distributions of a) HPS (S/P=0.61) and b) MH (S/P=1.66) lamp of the road lighting installations.*

The measurements were made by positioning the photometer camera on the right side of the road at the outermost lane marking at 1.5 m height. The captured luminance scenes include simultaneous luminance data from the road surface as well as areas adjacent to the road.

The measured luminance distributions of the HPS and MH lamp installations are shown in Figure 13. The measured average road surface luminance in the HPS lamp installation was L_{ave}= 2.1 cd/m^2 and in the MH lamp installation L_{ave} =1.1 cd/m^2.

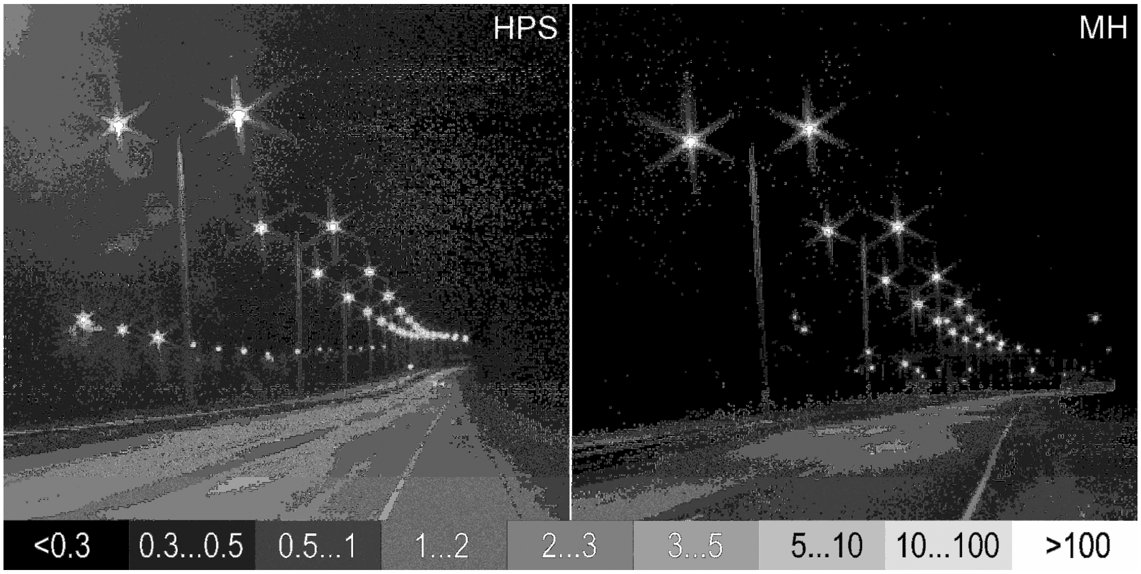

***Figure 13** Luminance distributions of HPS (left) and MH lamp (right) road lighting installations measured with a CCD photometer. Isoluminance values [cd/m^2] presented on greyscale.*

The measured scenes represent driving conditions where the influence of external sources on fixed road lighting is low and the luminance distribution of the visual field is relatively uniform. In more complex viewing conditions luminances of visual objects surrounding the road (traffic signs, guiding systems, buildings, commercial lighting etc.) may significantly affect the luminance distribution of the visual field [27]. Car headlights in their turn change the luminance conditions in driving. Still, the measured luminance distributions illustrate that luminance of the visual field while driving is not solely determined by the road surface luminance. The measured scenes include luminances in the photopic (luminaries), mesopic (road surface, areas adjacent the road) and even in the scotopic (areas further away from the road, sky) range, Figure 13.

Night-time driving is a very complex situation for the adaptation of the eye. The luminances in the driver's visual field change constantly while the car is moving and the direction of view is changing. In calculating mesopic luminances with the MOVE model the background photopic luminance is required as input value. This raises the question as what should be used as the background luminance in, for example, driving conditions. In addition to the road surface ahead, the visual field in driving consists of a combination of other surfaces and objects with varying luminance values. In the following calculations (Chapter 5.2) luminances measured from different areas of the visual field were used as background values in calculating the corresponding mesopic luminances with the MOVE practical i.e. linear model.

5.2 Calculation of mesopic luminances with the practical model of MOVE

The measured photopic luminances were used to calculate the corresponding mesopic luminances using the MOVE practical, i.e. linear, model (Chapter 4.2). Figure 14 shows the two road scenes with measured photopic ($V(\lambda)$-weighted) and calculated mesopic luminances of the corresponding areas. The luminance values are average luminances of the circled areas. Figure 14 shows also the MOVE model x-values and percentual differences between the mesopic and photopic luminances.

Figure 14 *Measured photopic luminances (L_p, $V(\lambda)$-weighted), the MOVE model x-values and calculated mesopic luminances (L_{MOVE}) of the circled areas in the a) HPS lamp and b) MH lamp road lighting installations. ΔL is the percentual difference between mesopic and photopic luminances.*

The MOVE model x-value indicates the weighting of the photopic and scotopic contents of the light source in calculating mesopic values at a certain photopic level. The x-value is determined by the spectral distribution and photopic luminance of the background.

The measured photopic road surface luminance level in the HPS installation is higher compared to the MH lamp installation. In the HPS lamp installation the mesopic luminances are slightly lower (2-7%) compared to the photopic values. This is due to the HPS lamp spectral distribution which has a relatively high output in the long wavelength region (S/P=0.61). In the MH lamp installation the opposite occurs and the mesopic luminances are 12-18% higher compared to the photopic values. The MH lamp favours mesopic weighting due to its relatively high output in the short wavelength region (S/P=1.66).

The design criteria for average road surface luminances in the European and US road lighting recommendations fall in the range of 0.3 - 2 cd/m^2 [28, 29]. The European Standard on road lighting classifies recommended average road luminances between 0.3 – 2 cd/m^2 [28]. In the US, the IESNA recommended average roadway luminances are between 0.3 – 1.2 cd/m^2 [29]. The measured road lighting installations represent cases where the road surface luminance levels are in the middle or at the upper end of these regions (relatively heavily trafficked road, high lighting performance criteria). In the following calculations, the MOVE practical model was applied to road lighting installations with average road surface luminances 0.3 and 0.5 cd/m^2 (e.g. local or collector roads, lower lighting performance criteria). The luminance calculations were made for road lighting installations using HPS lamps (S/P=0.61) and daylight MH lamps (S/P=2.32). The daylight metal halide lamp has considerably high content in the short wavelength region and is thus an example of a mesopically optimized light source. Table 1 shows the MOVE model x-values and mesopic luminances for the photopic luminances 0.3 cd/m^2 and 0.5 cd/m^2 for these two lamps.

Table 1 *Photopic luminances (L_p) [cd/m²] and corresponding MOVE model x-values and mesopic luminances (L_{MOVE}) [cd/m²] for HPS and daylight MH lamp road lighting installations. ΔL is the percentual difference between mesopic and photopic luminances.*

L_p	HPS (S/P=0.61)			MH (S/P=2.32)		
	x	L_{MOVE}	ΔL %	x	L_{MOVE}	ΔL %
0.30	0.506	0.273	-9	0.559	0.405	35
0.50	0.578	0.466	-7	0.622	0.644	29

The examples of Table 1 indicate increasing differences between photopic and mesopic dimensioning when light level decreases in the mesopic region. For the HPS lamps the mesopic luminances are 7-9% lower compared to the photopic values. For the daylight MH lamp the mesopic luminances are 29-35% higher compared to the photopic values.

The calculations using the MOVE model show that there may be noticeable differences in dimensioning the low luminance levels of road lighting depending on whether photopic or mesopic photometry is applied. The differences become significant for light sources with high luminous output in the short wavelength region. HPS lamps have traditionally been considered as having high luminous efficacy as their output is high around the peak wavelength of the photopic V(λ) function. HPS lamps have consequently been the major lamp of choice for many road lighting applications. The above calculations show, however, that in using mesopic photometry in dimensioning road lighting the considered superiority of HPS lamp is lower. At equal photopic luminance L_p=0.5 cd/m², the use of daylight MH lamps results in as much as 38% higher mesopically weighted luminance compared to the conventional HPS lamps. This should have major impacts on, for example, the energy-efficiency aspects of road lighting.

For calculating mesopic luminances using the MOVE model the light source spectral data is needed as input value. This complicates the application of the model in practice. A more simplified, although not as accurate, means of applying the MOVE model is to use tabulated values given for x and mesopic luminance as a function of photopic luminance and light source S/P-ratio [IV].

5.3 Comparison of the practical model of MOVE and the proposed X-model

A photometric X-model has recently been introduced by Rea et al. [30, 6] as a unified system for photometry. As in the case of the MOVE practical model, the X-model is a linear combination of the scotopic V'(λ) and the photopic V(λ) functions in the mesopic region.

Two investigations by He et al. [21, 31] form the experimental basis of the X-model. In the first work of He et al. [31], reaction times were measured for three subjects under two light sources (HPS and MH) at eight luminance levels between 0.003 – 10 cd/m². The result was a linear model of mesopic luminous efficiency based on reaction time observations. This model is based on reaction time data of two subjects, as one subject's data was excluded from the modelling because of great variability. The model is a linear combination of the scotopic V'(λ) function and the photopic $V_{10}(\lambda)$ function. According to He et al. [31], the visual inspection of the two subjects' off-axis reaction time data showed a separation between the two light sources below 0.3 cd/m², but no clear separation was observed above 1 cd/m². As the midpoint between these luminances in log units is 0.6 cd/m², and as the literature referred to described 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. Furthermore, He et al. assumed that there is no rod contribution above 0.6 cd/m^2 to the reaction time task investigated. He et al. concluded that, as more complete data would be obtained, the derived simple, preliminary model for mesopic luminous efficiency could be further modified [31].

The work of He et al. [31] was continued by investigations in which mesopic luminous efficiency functions were measured using a method of reaction time differences between the two eyes [21]. In this binocular simultaneity method, luminous efficiency for five quasi-monochromatic stimuli (hbw=10 nm, peaks at 436, 470, 510, 546, and 630 nm) were measured. The measurements were conducted for one subject at retinal illuminances 0.3, 3 and 10 Td. The derived mesopic luminous efficiency functions were fitted with the linear model developed in the earlier work of He et al. [31]. Most of the data points were described well by the linear model. However, the data of 436 nm at 0.3 and 3 Td deviated significantly from the model predictions. This was assumed to indicate that the variability of people's spectral sensitivities is great at wavelengths shorter than 450 nm. Consequently, the data at 436 nm was excluded from the modelling. The transition point between mesopic and photopic regions was not reached within the retinal illuminance range studied (0.3, 3, 10 Td). Using a relationship between adaptation coefficient x 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 1.7 cd/m^2. The latter study of He et al. [21] resulted in a computational iterative procedure for calculating mesopic light levels. In this procedure, the transition point between mesopic and photopic regions occurs at 21 Td. He et al [21] strongly suggested repetition of their experiment with particular attention being paid to wavelengths shorter than 480 nm. It was also concluded that more subjects were needed to make the luminous efficiencies in the short wavelength region more representative of an average observer [21].

In proposing the X-model as a unified system of photometry, Rea et al. [30, 6] made several simplifications to the approaches of the earlier works of He et al. [21, 31]. The X-model describes mesopic luminous efficiency $V_{mes}(\lambda)$ as a linear transition between the scotopic $V'(\lambda)$ and the photopic $V(\lambda)$ functions in the mesopic region and is of the form

$$V_{mes}(\lambda) = X\, V(\lambda) + (1\text{-}X)\, V'(\lambda) \quad (5)$$

where the uppercase X is a parameter characterising the proportion of the photopic luminous efficiency at any luminance level. The X-model is introduced by Rea et al. in two papers [30, 6] where the values for the uppercase X and for the transition point between mesopic and photopic regions are not consistent. The experimental basis for both proposed models are taken from the two works of He et al. [21, 31]. According to the latter paper by Rea et al. [6], the coefficient X is based on the retinal illuminances from the second study of He et al [21]. Rea et al. [6] claimed that the results of the two studies of He et al. are in substantial agreement by assuming a constant pupil diameter of 7 mm. This led to the choice of 0.6 cd/m^2 as the transition point between mesopic and photopic regions. Furthermore, Rea et al. assumed that the relationship between X and unified luminance is linear between 0.001 and 0.6 cd/m^2 [6]. In the former paper by Rea et al. [30], the transition point luminance between mesopic and photopic regions occurred above 1 cd/m^2. The X-models use the $V(\lambda)$ instead of the $V_{10}(\lambda)$ to represent photopic luminous efficiency. Tables for the X-models give the X values and corresponding unified luminances as a function of photopic luminance and light source S/P-ratio [30, 6].

The practical (i.e. linear) model of MOVE [IV] was compared to the latter X-model of Rea et al [6]. The comparison was made for two broadband light sources similar to HPS (S/P=0.65) and daylight MH (S/P=2.35) lamps. Figure 15a shows the adaptation coefficients x and X for the MOVE and X-model, respectively, as a function of photopic luminance. Figure 15b shows the corresponding ratio of mesopic (calculated alternatively using MOVE and X-model) to photopic luminance as a function of photopic luminance. The luminance region 0.3 - 2 cd/m^2 is highlighted in Figure 15b in order to point out the region of average road surface luminances given in the CEN and IESNA road lighting recommendations [28, 29].

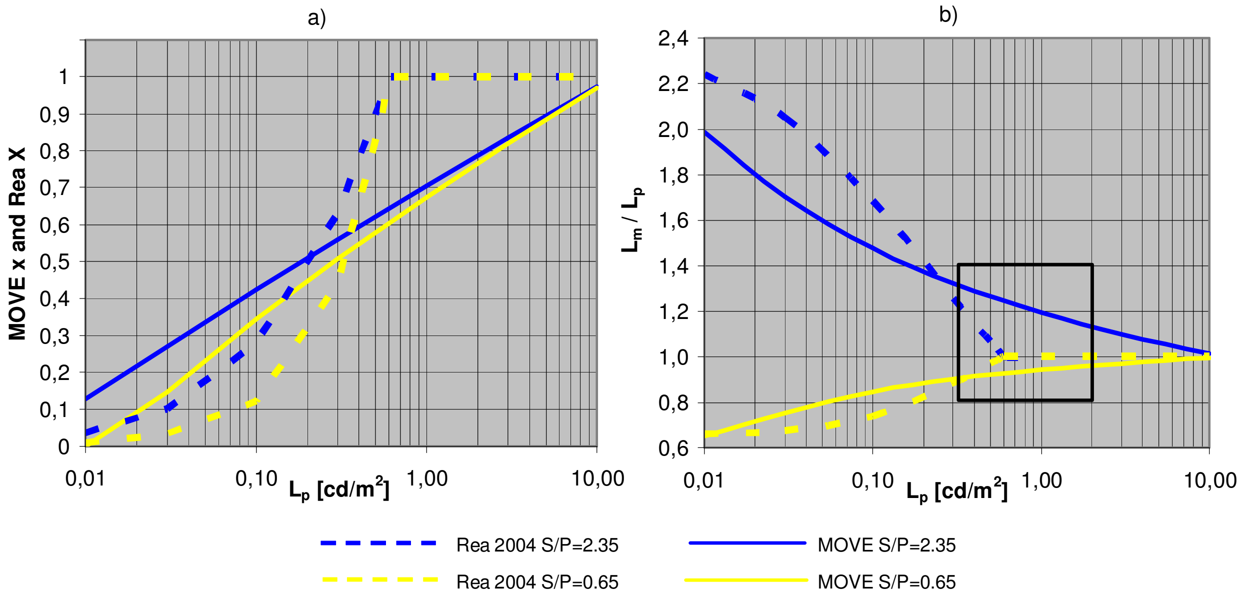

Figure 15 *a) Adaptation coefficients x and X of the MOVE [IV] and X-models [6], respectively, and b) corresponding ratios of calculated mesopic to photopic luminances (L_m/L_p) as a function of photopic luminance L_p [cd/m^2] for two light sources similar to HPS (S/P=0.65) and daylight MH (S/P=2.35) lamps.*

In the MOVE model the adaptation coefficient x is a linear function of log photopic luminance, Figure 15a. The uppercase X of the X-model shows a different behaviour as a function of photopic luminance. The X-values as a function of log photopic luminance increase gradually below 0.10 cd/m^2 after which there is a steep increase in X between 0.1-0.6 cd/m^2. Another notable difference between the models is the transition point between mesopic and photopic regions. This is the photopic luminance at which x and X become unity. In the X-model, this point is at 0.6 cd/m^2. The MOVE model calculates mesopic values for photopic luminances up to about 10 cd/m^2, where x becomes unity.

Due to the different approach in defining the adaptation coefficients as a function of photopic luminance and lamp spectra (S/P-ratio), the MOVE and X-models result in different corresponding mesopic luminances. The models are similar in giving relatively higher mesopic luminances for lamps with high S/P-ratio (e.g. MH lamp with S/P=2.35) and relatively lower mesopic luminaces for lamps with low S/P-ratio (e.g. HPS lamp with S/P=0.65), Figure 15b. The lower the photopic luminance the more significant are the differences between mesopic and photopic weighting in both models. The absolute luminance values calculated using the two models are, however, not similar.

Both models indicate substantial differences between photopic and mesopic luminances for a daylight MH lamp. This is due to the lamp high output in the short wavelength region. At photopic luminance L_p=0.01 cd/m^2 the mesopic luminances for this lamp are 100% (MOVE model) and 124% (X-model) higher compared to the photopic value. The X-model assimilates to photopic dimensioning at L_p = 0.6 cd/m². At this level the MOVE model gives 27% higher mesopic luminance for the daylight MH lamp. For the HPS lamp the differences in mesopic and photopic weighting are smaller. At photopic luminance L_p=0.01 cd/m^2 for the HPS lamp, both models give 35% lower mesopic luminances. At L_p=0.6 cd/m^2, the MOVE model gives 6% lower mesopic luminance for the HPS lamp. At photopic luminance L_p=2 cd/m^2, which is the upper value in the European recommendations for road luminances, the mesopic luminance using the MOVE model for the MH lamp is 16% higher compared to the photopic value. In the luminance region covered by the present road lighting recommendations, the differences between the MOVE model and X-model are obvious. The X-model assimilates to photopic dimensioning already at L_p=0.6 cd/m^2, while the MOVE model results in differences between photopic and mesopic photometry over the entire luminance region covered by the recommendations (L_p= 0.3 - 2 cd/m^2).

The experimental data of MOVE indicated rod contribution well above 0.6 cd/m^2, which is the transition point between mesopic and photopic vision adopted in the latter X-model [6]. The definition of the transition point between mesopic and photopic regions in the X-models is not unequivocal. In the first work of He et al. [31], the choice of the transition point luminance 0.6 cd/m^2 was made by assuming that there was no rod contribution above this level. This luminance corresponded to monocular viewing conditions [31]. In the second work of He et al. [21], the corresponding retinal illuminance for binocular viewing was estimated to be 25 Td. The value 25 Td was defined after adjustments were made for the pupil size, which is larger for monocular viewing compared to binocular viewing [21]. Thus, for binocular viewing conditions, the 25 Td corresponds to luminances well above 0.6 cd/m^2. In the second study by He et al. [21], the transition point between mesopic and photopic vision was not reached within the investigations, but was estimated to be at 21 Td corresponding to a luminance level 1.7 cd/m^2. Rea et al. [6] based the X-values on the retinal illuminances of the second study of He et al. [21] and assumptions were made that pupil size is constant over the mesopic region. According to Rea et al. [6], this led to the choice of 0.6 cd/m^2 as the transition point. In the former paper by Rea et al., the mesopic luminance region of the proposed X-model extended above 1 cd/m^2. He et al. [21] strongly suggested repetition of their experimental data especially in the short wavelength region. In view of this, there is the possibility that generation of more data for the basis of the X-model might result in different definitions of the mesopic region and predictions of the mesopic behaviour. It is indeed the short wavelength region where the rod contribution in mesopic conditions plays a relevant role.

In MOVE, three aspects of visual performance were investigated (contrast threshold, reaction time and recognition threshold), whereas the X-model is based on studies of monocular and binocular reaction time behaviour. The database for the MOVE model represents the visual task performance of 109 observers, while the X-model is based on data of 3 observers (reaction time data of two observers, binocular simultaneity data of one observer). The investigations underlying the X-model were based on high-contrast (C=0.70) stimuli. The MOVE experiments covered a range of contrasts with particular attention paid to the low contrast range, which is believed to be of importance in night-time driving conditions. Compared to the X-model the MOVE model covers a wider range of experimental conditions, and is thus claimed to be more representative of viewing and lighting conditions in, for example, night-time driving.

The author agrees with Rea et al. [6] in claiming that a system of photometry should be grounded on human vision but, on the other hand, it can never be a complete representation of the visual response to a specific stimulus. It is fair to admit that no one photometric system can ever characterise the complex behaviour of mesopic vision. This was, in fact, foreseen in conducting the work of MOVE and the two distinct models as outcomes of MOVE are in agreement with the above claims. The complex chromatic model of MOVE accounts for the non-additive chromatic channel responses of the visual system. The practical model of MOVE is linear in form and is suitable for practical mesopic photometry. Although both the practical model of MOVE and the X-model are linear descriptions of mesopic luminous efficiency between the V(λ) and V'(λ) functions, the predictions of the two models are not consistent. Compared to the X-model, the MOVE model is claimed to be more representative of mesopic spectral luminous efficiency of an average observer in visual conditions encountered in night-time driving.

5.4 Conclusions

Road lighting luminance measurements were conducted in order to apply the practical (i.e. linear) model of MOVE into road lighting dimensioning. Luminance distributions of two road lighting installations using HPS and MH lamps were measured using a CCD-photometer with V(λ)-filter. The measured photopic luminances and the lamp spectral data were used to calculate the corresponding mesopic luminances using the MOVE linear i.e. practical model.

The application of the MOVE linear model in road lighting indicated that the current photometry based on the photopic V(λ) misestimates light sources at low mesopic levels. For a light source with high output in the short wavelength region, the differences between photopic and mesopic dimensioning are significant and increase with decreasing light level. The current road lighting practice favours HPS lamps because of their high output around the peak wavelength of the photopic V(λ). The adoption of mesopic photometry could result in a different classification of light sources in terms of their luminous output. The visual effectiveness, as well as energy-efficiency, of road lighting might be improved by using new mesopically optimised light sources.

Both the practical model of MOVE and the recently proposed X-model by Rea et al. [6] are linear descriptions of mesopic luminous efficiency between the scotopic V'(λ) and the photopic V(λ) functions. The two models are not, however, similar in their prediction of mesopic luminances. If the upper luminance limit for the mesopic region proposed by the recent X-model (L_p=0.6 cd/m^2) was used, the adoption of mesopic dimensioning in road lighting would concern only the roads in the lower lighting classes (lower lighting performance criteria). However, the calculations using the MOVE model show that the adoption of mesopic dimensioning would affect road lighting practice over the whole luminance region of the present recommendations. Being based on a substantially more comprehensive visual performance database and on a wider set of visual conditions the MOVE model is claimed to be more representative of mesopic luminous efficiency than the X-model.

6 Integration of MOVE models into CIE standardisation work

6.1 Work of CIE TC1-58

The International Commission on Illumination, CIE (Commission Internationale de l'Eclairage), is an organization devoted to international co-operation and exchange of information on all matters relating to the science and art of lighting. As a global professional organization, the CIE is internationally renowned as the leading authority on the subject. Through formal agreements with CEN (Comité Européen de Normalisation) and ISO (International Organization of Standardization), CIE is recognised as the principal organisation for standardisation in the lighting field. The objectives of CIE include the development and publishing of basic standards in the fields of light and lighting.

The technical activities of CIE are carried out in Technical Committees (TC's). Through the establishment of the technical committee TC1-58 'Visual Performance in the Mesopic Range' the CIE has recognised the merit of the performance based approach for developing mesopic photometry. The objective of the TC1-58 is to propose a model for the basis of performance based mesopic photometry to be adopted worldwide. The author is the secretary of TC1-58 and is contributing the work of this thesis to the TC1-58 work. No other works of the scale of MOVE have been performed so far. Thus it is foreseen that the MOVE work will provide a major contribution to the TC1-58 work and consequently to the establishment of a new standard for performance based mesopic photometry.

The MOVE work has been introduced to the CIE at CIE Expert Symposia held along with the CIE Divisional meetings and in the TC1-58 meetings during 2002-2005 [32, 33]. It has recently been recognised within the CIE that the work on performance-based mesopic photometry is now sufficiently advanced to form a basis for a practical system of mesopic photometry [34]. It is also acknowledged that the new practical mesopic model will be a linear transition between the $V'(\lambda)$ and $V(\lambda)$ functions. This is consistent with the approach of the MOVE practical model. It is found encouraging within the CIE that, after more than 70 years of research, the time is now close to establishing a practical system of mesopic photometry, as this will be a major breakthrough for the CIE also. The CIE awaits this work to be carried out under the TC1-58.

6.2 Impacts of standardisation of mesopic photometry

Mesopic lighting applications are of substantial practical interest as they include road lighting, outdoor lighting and other night-time traffic environments. It is especially the higher part of the mesopic luminance region that is of importance for practical applications (e.g. traffic lighting) and for which a practical system of mesopic photometry is very much needed. The CIE photopic $V(\lambda)$ has been the basis of all photometry since its establishment in 1924. The objective of a future standard on performance based mesopic photometry is to provide a consistent and internationally accepted basis for assessing and dimensioning lighting in the mesopic region.

A standard on mesopic photometry will promote the development of mesopically optimised lighting products. It will give the lamp manufacturers foundations on which to develop light sources that are optimised for low light level applications. This will result in better energy-efficiency and visual effectiveness in, for example, night-time driving conditions. The accuracy of photometric instrumentation used in mesopic applications can be increased by taking into account the actual spectral sensitivity at these levels. Industry and users should be strongly motivated to use a photometric method that is valid and functionally relevant.

Meanwhile, it is expected that LEDs (Light Emitting Diodes) will become a major contributor to lighting technology in the near future. LEDs may offer new solutions also to various mesopic applications, not least because of the possibilities of producing LEDs with varying spectral properties. Depending on the LED spectra, their ranking on a luminous efficiency scale may be subject to significant changes if mesopic luminous efficiency functions are used instead of the photopic. Consequently, a future standard of mesopic photometry may have a major impact on the evolution and adoption of LEDs as the future light sources.

An internationally accepted system of mesopic photometry would enhance the quality and performance of mesopic lighting installations. This all relates to better energy-efficiency, visual effectiveness and safety in mesopic lighting applications.

7 Conclusions

The work started with visual performance experiments to find out the applicability of the photopic V(λ) function to predict visual response in the mesopic region. Foveal visual acuity and foveal and peripheral pedestrian visibility were used as the visual tasks in the experiments. The results of foveal vision implied, that the photopic V(λ) is valid for assessing the luminosity of centrally viewed small targets also in the mesopic luminance region. The results of peripheral viewing indicated that at mesopic light levels the spectral sensitivity cannot be exclusively described by V(λ). In the mesopic region, the spectral sensitivity is shifted towards shorter wavelengths in peripheral viewing where both rods and cones are active. However, the spectral effects are dependent on the light level and also on the characteristics of the visual task.

The work was continued by the development of an experimental framework to develop performance based mesopic photometry. The Measurement and Testing activity of the EC Fifth Framework Programme was convinced of the urgent need for mesopic photometry. Following this, the work to establish a basis for a new mesopic photometric system could start on a scale never done before. Compared to the earlier works in the mesopic field, the European research consortium MOVE adopted a different approach. A multi-technique approach was developed for the MOVE work to investigate visual performance of night-time driving in varied lighting and viewing conditions. The aim was to describe mesopic spectral sensitivity in a realistic way. The vision experiments of MOVE split the task of night-time driving into three visual sub-tasks and visibility data was generated simultaneously in five countries. The vision experiment data of MOVE provided a comprehensive data base of mesopic visual performance as a function of lighting and task parameters.

The work of MOVE resulted in two distinct models characterising mesopic spectral sensitivity of peripheral vision. The linear, i.e. practical, model is a linear description of mesopic spectral luminous efficiency between the photopic V(λ) at the upper end, and the scotopic V'(λ) at the lower end, of the mesopic luminance region. The linear model is applicable in situations where the background and target both have fairly broad spectral power distributions. In situations where the colourfulness (chromatic saturation) of a peripheral visual target is especially high, or when the target has a very narrow spectral power distribution, a more complex chromatic model gives a better description of spectral sensitivity. The chromatic model shows a three-peak behaviour of spectral sensitivity which is assumed to be associated with the colour-opponent channels in the visual system. For broadband visual targets in foveal vision the V(λ) function provides an acceptably good prediction of task performance. For foveal quasi-monochromatic targets a different type of chromatic model incorporating the 'three-peak' behaviour is required.

It has recently been acknowledged within the CIE that, in developing mesopic photometry, two distinct approaches shall be adopted [34]. The other approach should account for the achromatic, i.e. luminance, channel and result in an additive mesopic model. The other approach should account for the responses of the non-additive chromatic channel. This is consistent with the MOVE findings. The two distinct models of MOVE provide data for both approaches.

The practical i.e. linear mesopic model of MOVE was applied to road lighting. Luminance measurements in road lighting installations using HPS and MH lamps were conducted and the measured data was used in calculating mesopic luminances with the MOVE linear model. The calculations showed that there may be substantial differences in dimensioning low luminance levels of road lighting depending on whether photopic or mesopic photometry is used. HPS lamps are the major lamp of choice for many road lighting applications because of their high output around the peak wavelength of the photopic V(λ). The application of the MOVE model show, however, that in using mesopic photometry the considered superiority of HPS lamp is lower. It is evident that the adoption of mesopic photometry could result in different classification of light sources in terms of their luminous output.

The practical, i.e. linear, model of MOVE was compared to a recently introduced X-model by Rea et al [6]. Both models are descriptions of mesopic luminous efficiency based on linear combinations of the scotopic V'(λ) and the photopic V(λ). The models are not, however, similar in predicting mesopic luminances. A major difference between the MOVE model and the X-model is the transition point between mesopic and photopic vision. The X-model assimilates to V(λ) at photopic luminance 0.6 cd/m^2, whereas the MOVE model calculates mesopic values up to about 10 cd/m^2. The calculations using the MOVE model show that the adoption of mesopic dimensioning and mesopicially optimised light sources would have an impact on road lighting practice over the whole luminance region of the present recommendations (L_p=0.3 – 2 cd/m^2). Being based on a substantially more comprehensive database and a wider set of visual conditions, the MOVE model is claimed to be more representative of mesopic luminous efficiency than the X-model.

Mesopic photometry will provide the means to compare light sources at low light levels using a common criterion. To be internationally accepted and used, a new mesopic photometric system has to be adopted and recommended by the CIE (Commission Internationale de l'Eclairage). The MOVE findings are integrated into the CIE TC1-58 work in order to contribute to the establishment of a future standard on performance based mesopic photometry. Recently, it has been acknowledged within the CIE that the work performed so far is sufficiently advanced to form a basis for practical mesopic phometry, and that this work is carried out within the TC1-58 work [34]. The CIE awaits a trial system for field-testing by the road lighting and road safety industries.

A future standard on mesopic photometry – *mesometry* - will promote the development of mesopically optimised lighting products. It is foreseen that there will be strong motivation within the lighting community to adopt and use a photometric method that is valid and justified in the mesopic applications.

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