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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

TECHNICAL REPORT

RECOMMENDED SYSTEM FOR MESOPIC PHOTOMETRY BASED ON VISUAL PERFORMANCE

CIE 191:2010

UDC: 612.843.362.3
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Descriptor: Mesopic vision
Photometry
Night value curve

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3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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This Draft Technical Report has been prepared by CIE Technical Committee 1-58 of Division 1 „Vision and Colour“ and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

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RECOMMENDED SYSTEM FOR MESOPIC PHOTOMETRY BASED ON VISUAL PERFORMANCE

SUMMARY

This report deals with visual task performance based approaches to mesopic photometry, with a major aim to establish appropriate mesopic spectral sensitivity functions to serve as the foundation of a system of mesopic photometry. A review of the most important visual tasks and the range of visual conditions typically encountered in the context of night-time driving is given.

The existing visual performance based systems for mesopic photometry were reviewed and tested with new independent data sources. The outcome of the analysis and testing is a recommended system for mesopic photometry based on visual performance. The report summarises the justifications for the recommended system and gives general guidelines for its use and application.

SYSTEME DE PHOTOMETRIE MESOPIQUE RECOMMANDE FONDE SUR LA PERFORMANCE VISUELLE

RESUME

Ce rapport traite d'approches de la photométrie mésopique fondées sur la performance de tâches visuelles, avec l'objectif principal d'établir des fonctions de sensibilité spectrale mésopique convenables servant de base à un système de photométrie mésopique. Le rapport donne un inventaire des tâches visuelles les plus importantes, ainsi que l'éventail des conditions visuelles caractéristiques rencontrées dans le cadre de la conduite de nuit.

Les systèmes existants fondés sur la performance visuelle pour la photométrie mésopique sont passés en revue et testés avec de nouvelles sources indépendantes de données. Le résultat de cette analyse et de ces tests est un système de photométrie mésopique recommandé, fondé sur la performance visuelle. Le rapport récapitule les justifications du système recommandé et donne des orientations générales pour son usage et son application.

EMPFOHLENES SYSTEM FÜR MESOPISCHE PHOTOMETRIE BASIEREND AUF VISUELLER LEISTUNG

ZUSAMMENFASSUNG

Dieser Bericht behandelt Ansätze für mesopische Photometrie basierend auf visueller Leistung, mit dem wesentlichen Ziel, geeignete mesopische spektrale Empfindlichkeitsfunktionen festzulegen, die als Grundlage eines Systems der mesopischen Photometrie dienen sollen. Es wird ein Überblick über die wichtigsten visuellen Aufgaben und den Bereich visueller Bedingungen, die typischerweise im Zusammenhang mit nächtlichem Autofahren anzutreffen sind, gegeben.

Die bestehenden auf visueller Leistung basierenden Ansätze für mesopische Photometrie wurden überprüft und mit neuen unabhängigen Datenquellen getestet. Das Ergebnis der Analyse und der Tests ist ein empfohlenes System für mesopische Photometrie basierend auf visueller Leistung. Der Bericht fasst die Begründungen für das empfohlene System zusammen und vermittelt allgemeine Richtlinien für Gebrauch und Anwendung.

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TERMINOLOGY

mesopic visual performance

performance of the visual system for various visual tasks (e.g. contrast detection, speed of performance) when the eye is adapted to levels of luminance above the scotopic range and below the photopic range and where both the rods and cones contribute to vision

system of mesopic photometry

defined set of mesopic spectral sensitivity functions with a procedural model incorporating these functions to allow their use in a photometric measurement system between the scotopic and photopic luminance regions

visual performance based mesopic photometry

defined set of mesopic spectral sensitivity functions based on visual task performance criteria (i.e. recognition, detection, reaction time (RT) tasks) with a procedural model incorporating these functions to allow their use in a photometric measurement system between the scotopic and photopic luminance regions

S/P-ratio

ratio of the luminous output of a light source evaluated according to the CIE scotopic spectral luminous efficiency function, $V'(\lambda)$, to the luminous output evaluated according to the CIE photopic spectral luminous efficiency function, $V(\lambda)$:

$$\text{S/P-ratio} = \frac{K'_m \int_0^\infty S_\lambda(\lambda) V'(\lambda) d\lambda}{K_m \int_0^\infty S_\lambda(\lambda) V(\lambda) d\lambda} \quad (1)$$

where

$K'_m \approx 1\,700 \text{ lm} \cdot \text{W}^{-1}$ is the maximum value of the spectral luminous efficacy for scotopic vision, $K'(\lambda)$;

$K_m \approx 683 \text{ lm} \cdot \text{W}^{-1}$ is the maximum value of the spectral luminous efficacy for photopic vision, $K(\lambda)$;

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

λ is the wavelength.

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1 INTRODUCTION

This report summarises the work of CIE TC1-58, which was established with the terms of reference: "To define mesopic visual performance and related terms. To investigate performance based photometry in the luminance region below approximately $10 \text{ cd}\cdot\text{m}^{-2}$. To propose a model for the basis of performance based mesopic photometry."

1.1 Background

Current photometric practice is based primarily on the photopic spectral luminous efficiency function $V(\lambda)$, which characterises the spectral sensitivity of foveal cones under photopic lighting conditions. Although other spectral luminous efficiency functions have been defined by the CIE, most notably the $V'(\lambda)$ function for scotopic conditions (i.e. conditions under which the eye is fully dark adapted and visual response is dominated by the activity of the rods in the retina), in practice almost all photometric measurements, at all light levels, are made using $V(\lambda)$ as the spectral weighting function. This approach takes no account of the fact that in the mesopic luminance region, between the photopic and scotopic regions (i.e. between about $0,001 \text{ cd}\cdot\text{m}^{-2}$ and $10 \text{ cd}\cdot\text{m}^{-2}$), both the rods and cones in the retina may be active, leading to changes in spectral sensitivity with changing light level throughout this region. This compromises the effective use of light under these visual conditions where both rods and cones contribute to visual performance. Mesopic applications include road and street lighting, marine and air transport, emergency lighting, lighting for security and crime-prevention purposes etc.

The development of an effective system for mesopic photometry has been a topic of concern in the international lighting community for several decades (CIE, 1989, CIE, 2001). Until the mid 1990's most of the research in this area concentrated on using brightness matching as the visual criterion, i.e. the studies were based on the assessment of lights in terms of their comparative brightness relationships. The CIE Report 81-1989 "Mesopic Photometry: History, Special Problems and Practical Solutions" reviewed the current brightness based mesopic systems. This was updated by CIE Report 141-2001 "Testing of Supplementary Systems of Photometry", which concluded that it was not possible to identify one 'best' model and therefore made no recommendation for a CIE supplementary system of photometry for the mesopic region. Currently, TC1-37 is developing a supplementary system of photometry for evaluation of lighting at all levels in terms of brightness.

Towards the end of 1990s, interest in a visual task performance based approach for the development of a system for mesopic photometry had grown among the international research community (Goodman, 1997, McGowan and Rea, 1994). This approach is based on the use of visual performance measures relevant to 'real-life' situations in defining spectral sensitivity functions. For example, when driving a car, we rarely need to make visual assessments of adjacent surfaces in terms of their comparative brightness; instead the detection and recognition of visual objects at or near the visual threshold is more relevant than the visual assessment of brightness for this and many other real-life situations.

One major consideration in the development of a system for mesopic photometry is that it should be additive, since the CIE definition of photometry carries an inherent assumption of additivity (CIE, 1978). The rules of additivity state that a given spectral radiant quantity (e.g. flux, intensity, radiance etc.) can be weighted with an appropriate spectral luminous efficiency function and then summed linearly across the spectrum in order to quantify the corresponding luminous quantity. This requires that the description of mesopic spectral luminous efficiency is linear in form throughout the mesopic region. (It should be noted that additivity does not imply proportionality. Indeed Abney's law of proportionality (Wyszecki and Stiles, 1982) must, by definition, be violated in the mesopic region: since the relative contributions from rods and cones not only change with radiance at any given wavelength, but also with wavelength at a given radiance, equivalence of luminance for two differently coloured sources cannot, by definition, be preserved as the luminance is changed in the mesopic region.) It is known that there are a number of visual tasks for which additivity does not hold. The visual system can be described as comprising of two key channels. One, the luminance channel, is achromatic and additive; the other, the chromatic channel, provides colour information and is non-additive. A number of studies indicate that the use of brightness matching techniques involves non-linear

interactions between the achromatic and chromatic channels and therefore results in non-linear spectral sensitivity descriptions. In other words, a photometric system based on brightness matching cannot obey Abney's law of additivity. This report deals with visual task performance based approaches to mesopic photometry, with a major aim being to establish a system for mesopic photometry based on spectral sensitivity functions that do obey the laws of additivity.

1.2 Objectives

The goal of TC1-58 was "to propose a model for the basis of performance based mesopic photometry" i.e. to establish appropriate mesopic spectral sensitivity functions to serve as the foundation of a system of mesopic photometry based on visual performance. The spectral sensitivity of the human visual system changes with light level throughout the mesopic region, due to the varying contribution of rods and cones with changing light level. Thus, instead of one spectral sensitivity function, several functions are needed, together with defined procedure for using these functions in a photometric measurement system. The spectral sensitivity functions to be used in this system were to be based on criteria of visual task performance, i.e. on recognition, detection, reaction time tasks, rather than on brightness matching (the approach used in most previous studies). This is the distinction between *visual performance based mesopic photometry* and *brightness matching based mesopic photometry*. It should be noted, however, that no single system could ever hope to provide a complete prediction of visual performance for all tasks and lighting conditions. Vision is a hugely complicated process and the spectral luminous efficiency of the eye is influenced by a large number of factors, including size and location of the stimulus in the visual field, ambient light level and spectrum, stimulus contrast and spectrum, and speed of response required by the task being conducted. Changing any of these parameters will change the efficiency of the visual system and the ability to perform the requisite task. Thus it is important to recognise that the system of mesopic photometry proposed within TC1-58 is distinct from a model of visual performance.

In proposing a recommended system for the basis of performance based mesopic photometry it was acknowledged that the practical utility of the system to be recommended was an important issue and that this would place certain constraints on the system. In particular, in order to be implemented alongside the current system of photometry, the mesopic spectral sensitivity functions should tend to the photopic spectral luminous efficiency function, $V(\lambda)$, at the upper end of the mesopic region, and to the scotopic spectral luminous efficiency function, $V'(\lambda)$, at the lower end. It was also necessary that the system should preserve the fundamental requirement of photometry - additivity - to allow integration of weighted spectral values. Whilst recognising these constraints, it was likewise appreciated that a practical system of photometry must be grounded on human vision and allow predictions of visual task performance to be made which are in reasonable agreement with the actual ability to perform these tasks. Thus in proposing a system of mesopic photometry it was also required that it should (within limits) provide a result that is meaningful in relation to visual performance and provide a correlation with visual performance under a range of different conditions. After all, the whole justification for research in the mesopic region is that the visual response functions, and consequently the ability to perform visual tasks, are different from those in the photopic or scotopic regions. Thus a further task of TC1-58 was to investigate visual performance based mesopic photometry, which included testing of the systems for mesopic photometry already proposed in the literature to see how well they predict the luminous stimulus (mesopic luminance) under various task and lighting conditions. The existing systems were reviewed and tested with new independent data sources, using both the spread in mesopic contrast for constant visual performance and trend analysis as the evaluation criterion.

The outcome of this analysis and testing carried out within the TC is a proposal for a recommended system for mesopic photometry based on visual performance. Section 2 of this report summarizes the system for performance based mesopic photometry that is recommended by the CIE for use in practical photometry. The recommendation is based on the work carried out in the TC, which included:

- a) A review of the most important visual tasks and the range of visual conditions typically encountered when these tasks are considered in the context of night-time driving, which

is considered as a key representative example of a mesopic lighting application (Section 3).

- b) A review of systems for visual performance based mesopic photometry already proposed in the literature, namely the Unified System of Photometry or USP-system (Rea et al., 2004) and the MOVE-system (Goodman et al., 2007), as well as an Intermediate system developed during the course of the TC's work (Section 4).
- c) Testing and analysis of these systems using new independent visual performance data sets (Sections 5, 6). Two different evaluation criteria were used, depending on the type of data:
 1. Spread in mesopic contrasts (i.e. contrast calculated using $V_{\text{mes}}(\lambda)$ instead of $V(\lambda)$) for studies involving determination of the target spectral radiance necessary for constant visual performance using different target colours against a constant background. The smaller the spread in mesopic contrasts for a given set of background and target eccentricity conditions, the better the selected $V_{\text{mes}}(\lambda)$ function represents the measured visual performance.
 2. Trend analysis for studies in which the target and background have the same spectral characteristics. Here the criterion is that the measured visual performance data should be transitive with the system predictions of background (mesopic) luminance.

The report concludes, in Section 7, by summarizing the justifications for the proposed system for mesopic photometry and giving general guidelines for its use and application.

2 RECOMMENDED SYSTEM FOR PERFORMANCE BASED MESOPIC PHOTOMETRY

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

$$M(m) V_{\text{mes}}(\lambda) = m V(\lambda) + (1 - m) V'(\lambda) \quad \text{for } 0 \leq m \leq 1 \quad (2)$$

and

$$L_{\text{mes}} = \frac{683}{V_{\text{mes}}(\lambda_0)} \int V_{\text{mes}}(\lambda) L_e(\lambda) d\lambda \quad (3)$$

where:

m is a coefficient the value of which depends on the visual adaptation conditions;

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

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

L_{mes} is the mesopic luminance;

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

if $L_{\text{mes}} \geq 5,0 \text{ cd} \cdot \text{m}^{-2}$, then $m = 1$;

if $L_{\text{mes}} \leq 0,005 \text{ cd} \cdot \text{m}^{-2}$, then $m = 0$.

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

$$m_0 = 0,5,$$

$$L_{\text{mes},n} = \frac{m_{(n-1)} L_p + (1 - m_{(n-1)}) L_s V'(\lambda_0)}{m_{(n-1)} + (1 - m_{(n-1)}) V'(\lambda_0)}, \quad (4)$$

$$m_n = a + b \log_{10}(L_{\text{mes},n}) \quad \text{for } 0 \leq m_n \leq 1, \quad (5)$$

where L_p is the photopic luminance of the visual adaptation field, L_s is the scotopic luminance of the visual adaptation field, and $V'(\lambda_0) = 683 / 1\,699$ is the value of scotopic spectral luminous efficiency function at $\lambda_0 = 555$ nm, a and b are parameters which have the values $a = 0,767\,0$ and $b = 0,333\,4$, and n is the iteration step. The value of L_{mes} obtained by the equations above is the mesopic luminance of the visual adaptation field. The mesopic luminance of objects in the visual adaptation field is obtained according to equations (2) and (3) using the value of m determined for the adaptation field

The values of m and L_{mes} for this system as a function of photopic luminance and light source S/P-ratio (ratio of scotopic-to-photopic luminous output) are given in Appendix 1.

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

Several factors need to be considered when deciding how to implement this new system of photometry into lighting practice; these are discussed in Section 7 of this report.

3 MESOPIC VISUAL PERFORMANCE AND MESOPIC CONDITIONS

3.1 Most Relevant Mesopic Applications

Mesopic vision is defined as vision intermediate between photopic and scotopic vision (CIE, 1987). In mesopic vision, both the cones and rods are active; photopic vision, on the other hand, is dominated by cone activity and in scotopic vision only the rods are active. Scotopic vision is generally believed to extend from the minimum visible stimulus up to about $0,001 \text{ cd} \cdot \text{m}^{-2}$ (CIE, 1978), which can consequently be considered as the lower limit of the mesopic region. The upper luminance limit of mesopic vision cannot be precisely defined, as it is dependent on several factors, including the size and position of the visual object in the field of view. Mesopic light levels cover a range of several log units, which are neither completely photopic (for which $V(\lambda)$ is applicable) nor scotopic ($V'(\lambda)$ applicable) (Rea et al., 2004, Eiloholma et al., 2005).

Mesopic lighting applications are those for which our visual system is operating in a mesopic state, i.e. where both rods and cones contribute to visual functions. However it is not straightforward to determine whether and how this condition is satisfied in any given practical

situation. One important issue is that the range of light levels encountered in the visual environment can vary significantly, frequently extending from low mesopic to high photopic values, with the result that the adaptation condition is difficult to assess. A further complication is that the concentration of rods and cones varies throughout the retina, and most lighting applications involve a range of visual tasks which require both foveal and peripheral vision. In pure foveal vision only the cones are active and $V(\lambda)$ characterises spectral sensitivity at all light levels (Goodman, 1997, He et al., 1997, Eloholma et al., 1998). However, the involvement of foveal vision in a given application does not mean that only cone activity needs to be considered, as in most applications the surrounding periphery needs to be taken into account as well; in other words mesopic spectral luminous efficiency functions are frequently needed. The question, then, is: what are the lighting applications where the luminances are predominantly in the mesopic region and where peripheral vision is relevant?

One particularly important application is road lighting, since the visual environment in night-time driving conditions falls largely in the mesopic luminance region. The design criteria for average road surface luminances given by current road lighting recommendations for various classes of roads are between $0.3 \text{ cd}\cdot\text{m}^{-2}$ and $2 \text{ cd}\cdot\text{m}^{-2}$ (Raynham, 2004). However the road surface provides only part of the adaptation luminance for night-time driving and luminances in various other parts of the visual scene will also influence the adaptation state of different parts of the retina (Akashi et al., 2007). In night-time driving the driver must be able to perform various visual tasks at different light levels and the luminous scene may include luminances in the photopic range (car headlights, luminaires), mesopic range (road surface, areas adjacent the road) and even in the scotopic range (areas further away from the road, sky). Visual objects and luminous surfaces surrounding the road (traffic signs, guiding systems, buildings, commercial lighting etc.) also have their effect on the luminance distribution within the visual field. However, although the adaptation level of the eye in night-time driving is not constantly in the mesopic region, the road lighting conditions are such that the luminances fall largely in the mesopic region, and the visual tasks involved mean that both foveal and peripheral vision are needed. Road, street and similar outdoor lighting conditions can thus be claimed to be relevant applications where mesopic vision plays an important role and where mesopic optimization of the lit environment is of relevance.

There are also many other important lighting applications where the luminances are in the mesopic region, such as marine and air transport, emergency lighting, lighting for security and crime-prevention purposes etc.

3.2 Critical Visual Tasks

3.2.1 Characteristics of the Visual Tasks

As mentioned in Section 3.1, there are a number of important lighting applications where the prevailing light levels fall in the mesopic region. Each of these applications involves a range of visual tasks, such as the ability to discriminate a target against the background or the ability to recognise a potential hazard. Possibly the most demanding of these lighting applications in terms of visual performance is night-time driving, and driving on a road at night involves all of the tasks that are encountered in other applications. Thus the remainder of Section 3 of this report concentrates on night-time driving as an example of the need for a system of photometry for the mesopic region and of the range of tasks that must be considered. This should not be taken to suggest, however, that the recommendations are limited to this application area; on the contrary, the recommended system is proposed for use in all applications requiring the performance of visual tasks in the mesopic region, where both the rods and cones in the retina are active.

Driving is a complex dynamic task in which visual perception plays an extremely important role. Vision, in turn, is supported by many different visual processes. In a review of vision and driving (Charman, 1997), several factors were listed as having an influence on a driver's visual performance, including static and dynamic visual acuity, contrast sensitivity, stereopsis, colour vision, motion perception, and visual field size. Visual tasks in driving include detection, discrimination, perception of movement, perception of objects by, for example, their form and colour, and the perception of interactions between steady and/or moving objects (Akashi et al., 2007, Bullough and Rea, 2000, CIE, 1992, Eloholma et al., 2005, IESNA, 2006). These visual tasks are involved, for example, in the need to:

- detect other drivers ahead and the signals they give;
- detect obstacles, holes and bumps on the road surface;
- see the lane boundaries and the curvature of the road and its exits;
- read road and exit signs and possible warnings in order to respond safely;
- detect pedestrians nearby and any animals on the roadsides.

Similarly pedestrians using roads and streets at night need to carry out various visual tasks e.g. to detect other people approaching and get an overview of the surrounding scene.

The basic visual task in night-time driving (or indeed, driving during the day) is to obtain sufficient information from the visual field to be able to function effectively in the environment. However it is widely acknowledged that there is no single task or target that can be taken to characterise the full complexity of the tasks involved (CIE, 1992). One approach, yet simplified, is the visual performance-based approach adopted by the MOVE consortium (Freiding et al., 2007, Walkey et al., 2007, Várady et al., 2007, Goodman et al., 2007). In this approach the task of night-time driving is split into three visual tasks (both foveal and peripheral), which are characterised by three questions for which visual information is required: *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 use of these three visual tasks to describe visual performance in night-time driving is a simplified approach and cannot, by any means, describe the details of the performance of the human visual system. It provides, however, a means by which to describe visual performance for practical and relevant tasks and allows a system of mesopic photometry to be developed that has its roots in, and provides reasonable correlation with, visual task performance data, whilst also recognising that it is not necessary or possible to have a single system which can completely predict visual performance for all tasks and lighting conditions. (A recent study by Rea et al. (2009) demonstrates how different task requirements require different luminous efficiency functions in the mesopic region to describe the visual stimulus even though the physical characteristics of the visual field remain unchanged.) Furthermore, although these tasks have been selected on the basis of their importance for night-time driving, it should be remembered that visual detection, speed of detection and recognition are also critical in most other mesopic applications such as marine, aviation and security lighting.

Detection is related to the observation that something is changed in a particular area of the visual field. In order to trigger visual perception and to detect a target a certain luminance and/or chromatic difference between the target and its background is needed. In the approach described above the first visual task (characterised by the question "*Can it be seen?*") is related to *achromatic detection thresholds*, or the ability to simply perceive a visual stimulus (without necessarily being able to perceive colour or detail) (Freiding et al., 2007). This is one of the most fundamental visual tasks in driving. Current road lighting design practice (Adrian, 2004, Raynham, 2004) 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 that is needed for a driver to be able to perceive the target (Adrian, 1989). Visibility levels, in turn, are defined by multiplying the laboratory luminance threshold values by certain factors to indicate how much the luminance difference must be above its threshold value in order to take into account the practical viewing conditions.

The second visual task is related to the *speed of detection* and is characterised by the question "*How quickly?*" (Walkey et al., 2007). Reaction times are used to describe this task. Reaction time is the time between the onset of a visual stimulus and the response to the detection of that stimulus. For example, the observer is often instructed to respond manually by pressing a button as quickly as possible after 'seeing' the target. McGowan and Rea (1994) have proposed using reaction times as a useful way to characterize spectral luminous efficiency. In night-time driving conditions reaction times play an important part in safe driving (Bullough and Rea, 2000) and are a good performance measure for realistic situations, such as driver hazard detection responses (He et al., 1998). A link between reaction times and driving performance in terms of road accident rates has also been reported: road accidents increase at low light levels where visibility is reduced and reaction times are longer (Plainis

and Murray, 2002) Reaction times were used as performance criteria in the development of the USP-system proposed by Rea et al. (2004), and in the MOVE-system (Goodman et al., 2007).

The next step in the visual process is recognition, when the target is recognized according to its visual details and a more conscious and wilful action can be initiated. This third visual sub-task is characterised by the question “*What is it?*” (Váradý et al., 2007). 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, not just where it is seen. 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 (Richards, 1977).

3.2.2 Parameters for Defining Visual Performance

In mesopic vision both the rod and cone photoreceptors are active. The relative contribution of rods and cones to the visual tasks depends on the adaptation level, as towards the upper regions of the mesopic range cone vision dominates and at the lower end of the mesopic region rod vision dominates. In between, mesopic vision is characterized by rod-cone interactions determined by the light level and the retinal location of the task. Thus, several parameters are needed to characterize the performance of the visual system in the mesopic region. These include the background luminance, contrast, target size and location in the visual field and spectral characteristics of the target and background. The viewing conditions can be further described by presentation time, speed and shape of the target and whether the viewing is monocular or binocular.

Luminance

Luminance level is one of the most critical parameters for defining visual performance. It is known that visual performance is degraded in night-time driving conditions, where luminances are significantly lower compared to daytime. This has been shown to be true for different aspects of vision, such as contrast threshold (Blackwell, 1946), visual acuity (Richards, 1977, Adrian, 1989), reaction time (Pollack, 1968, Lit et al., 1971, He et al., 1997) and colour vision (Smith et al., 1994). In understanding mesopic visual performance it is important to consider the large range of luminance levels encompassed within the mesopic region and that the degree of rod and cone interaction occurring throughout this range is subject to change. It is thus expected that any model of the eye's response function in the mesopic region will vary significantly as the luminance level changes. Under typical night-time driving conditions the driver's adaptation levels tend to be at mid- to high mesopic values, rather than near the lower limits of the mesopic region (Plainis et al., 1997).

The upper luminance limit of mesopic vision cannot be precisely defined, as it is dependent on several factors, including the chromaticity, size and position of the visual object in the field of view. According to a review by LeGrand (1972) the upper luminance limit of mesopic vision is about $5 \text{ cd}\cdot\text{m}^{-2}$ with a 3° central field and at least $15 \text{ cd}\cdot\text{m}^{-2}$ for a 25° field. According to Kokoschka (1997), the upper luminance limit of the mesopic region extends to about $10 \text{ cd}\cdot\text{m}^{-2}$. The CIE definition for the border between mesopic and photopic luminance regions is “at least several $\text{cd}\cdot\text{m}^{-2}$ ” (CIE, 1978). Bullough and Rea (2001) report that rods can participate in visual function up to $65 \text{ cd}\cdot\text{m}^{-2}$. In their review of mesopic research Rea et al. (2004) found that brightness based mesopic models predict that rod participation under mesopic conditions disappears roughly one log unit lower than it does for models based upon reaction times. In IESNA (2000) the mesopic luminance region is defined to extend to approximately $3 \text{ cd}\cdot\text{m}^{-2}$, whereas a lower limit of approximately $0,01 \text{ cd}\cdot\text{m}^{-2}$ is given which is tenfold higher than the CIE (1978) definition. In its review on mesopic visual performance data the IESNA report (2006) acknowledges the upper level of the mesopic region to be task and geometry dependent, with reported upper values ranging from lower than $1 \text{ cd}\cdot\text{m}^{-2}$ to higher than $10 \text{ cd}\cdot\text{m}^{-2}$. The terms of reference of TC1-58 include the investigation of performance based photometry in the luminance region below approximately $10 \text{ cd}\cdot\text{m}^{-2}$. The adaptation luminance levels in the experiments underlying the existing visual performance based systems, namely the USP-system (Rea et al., 2004) and the MOVE-system (Goodman et al., 2007), range from $0,003 \text{ cd}\cdot\text{m}^{-2}$ to $10 \text{ cd}\cdot\text{m}^{-2}$.

In night-time driving conditions the luminances in the visual field change constantly while the car is moving and the direction of view is changing. Especially in urban areas the luminances in the visual field of the driver may vary significantly. In addition to the road surface the surrounding areas (traffic signs, guiding systems, buildings, commercial lighting, etc.) also affect the adaptation conditions of the road-users. Luminance measurements with an imaging luminance photometer are a useful tool to analyze the luminance conditions in road lighting, as also pointed out by the expert survey carried out during the course of the work of TC1-58. Figure 1 shows an example of measured luminance distributions of visual scenes encountered during night-time driving conditions in urban areas in Finland. The measurements were made with an imaging luminance photometer whose system accuracy for luminance measurements was evaluated as $\pm 8.2\%$. (In imaging luminance photometer measurements scattered light may have a significant influence on the measured values under conditions where bright lights (e.g. luminaries) are found in conjunction with relatively dark surrounds (TechnoTeam, 2007)). In street lighting conditions the adaptation luminance is affected not only by the road surface, but to large extent by surrounding lighting from adjacent buildings, illuminated signs etc. Figure 1 indicates that luminances up to about $5 \text{ cd}\cdot\text{m}^{-2}$ may be encountered in the visual scene (road with its immediate surroundings) when driving in urban areas. It should be noted that it is not possible to describe completely the luminance conditions in night-time driving as they may significantly vary on different roads, depending on several factors. The luminances in Figure 1 are only indicative of those that may be encountered in real conditions. They do serve, however, to suggest that the luminance range in the visual field while driving is not limited to the recommended values for road surface luminances ($0,3 \text{ cd}\cdot\text{m}^{-2}$ to $2 \text{ cd}\cdot\text{m}^{-2}$) (Raynham, 2004), especially in urban areas.

Figure 1: Measured luminance distributions of visual scenes encountered during night-time driving conditions in urban areas in Finland.

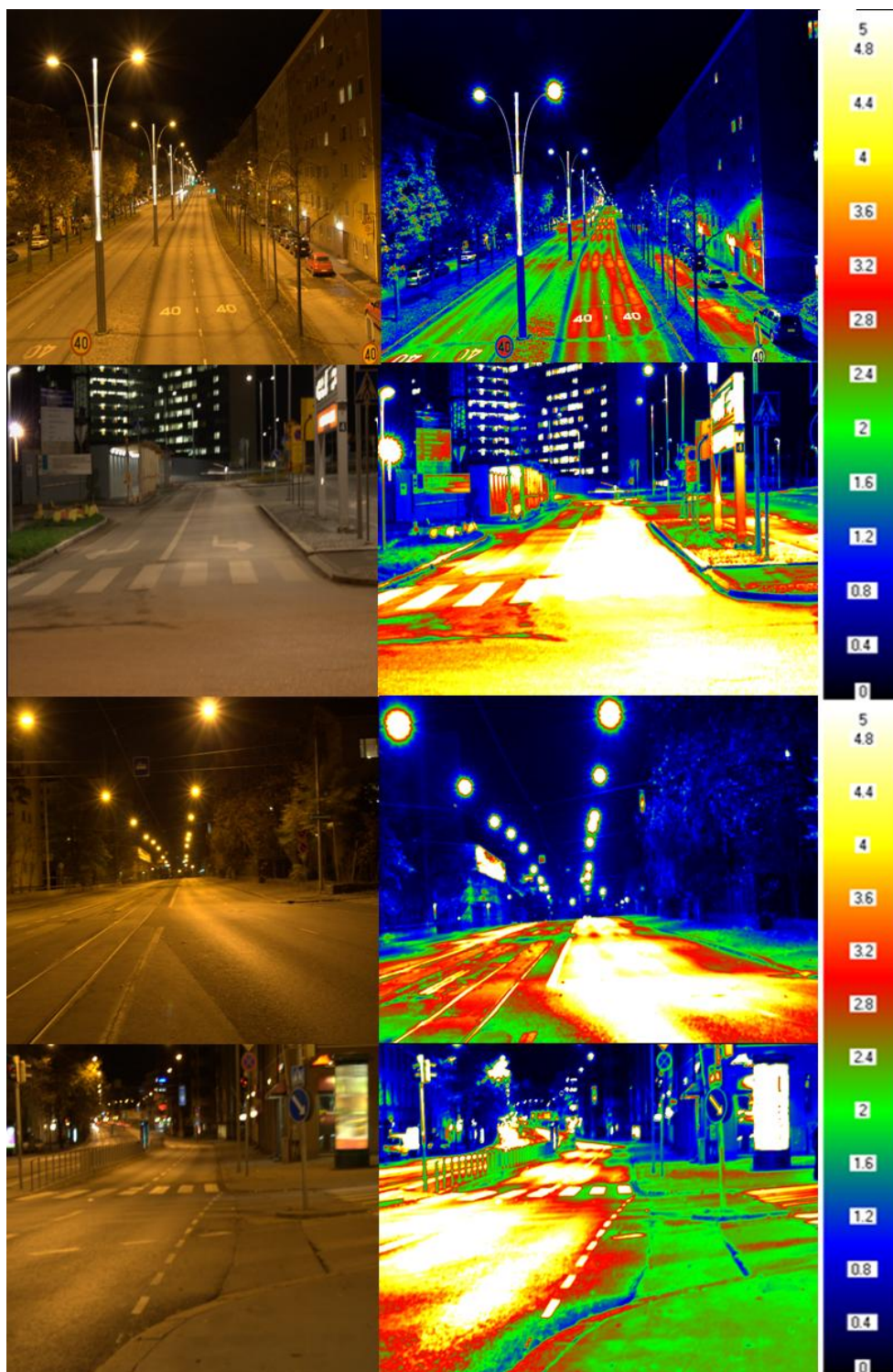


Figure 1. Luminance distributions of driving scenes in urban lighting measured with an imaging luminance photometer. Photographs on the left and measured isoluminance scenes of the corresponding areas on the right.

The luminance levels of road surfaces can be dynamic and depend to a large extent on weather conditions. In recent studies by Ekrias et al. (2007) and Castillo (2007) road surface luminances were measured in different installations under varying weather conditions. The installations covered local streets with minor lighting requirements as well as heavily trafficked roads. In wet conditions the luminance distributions of road surfaces are significantly different from those with dry conditions. Road surface areas with specular reflection towards the observation point become very bright. On the other hand, the luminances of the darker areas

of the road surface decrease. This results in lower luminance uniformities and worsened driver visibility conditions. However, average luminances of wet road surfaces are usually higher compared with dry conditions. In foggy conditions, on the other hand, despite the increased average luminance and luminance uniformities, the fog may result in substantially decreased driver visibility. Luminances of snowy road surfaces can be many times higher than in dry conditions. In cases where there is a minor amount of snow and snow clearance is carried out, luminance levels can still be about 50 % higher compared with conditions without any snow. Figure 2 shows examples of road luminances of a local street and a highway in Finland when the road surface is dry, snowy or wet. Compared with the design values for road surface luminances ($0,3 \text{ cd}\cdot\text{m}^{-2}$ to $2 \text{ cd}\cdot\text{m}^{-2}$), the changing weather conditions can result in increased road surface luminances.



Figure 2. Luminance measurement results from a local street illuminated by HPS lamps under a) dry, b) very snowy, and c) wet weather conditions and from a highway illuminated by HPS lamps under d) dry, e) slightly snowy, and f) wet weather conditions (Ekrias et al., 2007).

Contrast

Target contrast is defined by the relative luminance difference between the target and its background. Both laboratory and field experiments indicate that target contrast affects visual performance in the mesopic region (IESNA, 2006). It has been further indicated that the spectral sensitivity changes become more pronounced when luminance and contrast are decreased (Viikari et al., 2006).

In night-time driving conditions the contrasts of visual targets depend on the target reflectance properties and the geometry of the lighting installation, as well as on the location of the target in relation to the luminaires. As an example, Figure 3 shows the results of a study carried out on a main ring road in Helsinki Finland, in which the variation in target contrast was measured for two different targets positioned in various locations on the road between two adjacent luminaires at two road surface luminance levels ($0,8 \text{ cd}\cdot\text{m}^{-2}$ and $1,7 \text{ cd}\cdot\text{m}^{-2}$). The targets were a pedestrian with grey clothing (reflectance 16 %) and a $20 \text{ cm} \times 20 \text{ cm}$ flat surface (reflectance 20 %), which is also known as a Small Target Visibility (STV) target (De Boer, 1967). The target contrasts, C , are defined as

$$C = \frac{L_t - L_b}{L_b} \quad (6),$$

where L_t is the luminance of the target and L_b that of the background. The target contrasts in this case were found to vary between $C = -0,88$ and $C = 0,72$.

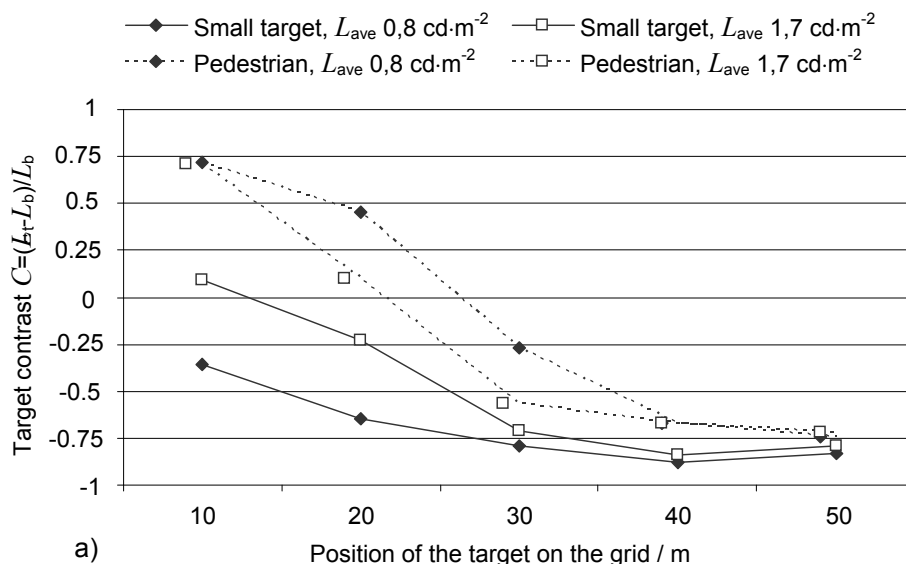


Figure 3. a) Contrasts of a small flat target (20 cm × 20 cm, reflectance $\rho = 0,2$) and a pedestrian ($\rho = 0,16$) when located at varying positions on the road between one luminaire spacing measured on a main ring road in Vantaa, Finland. The road surface was illuminated by 250 W high pressure sodium lamps with a luminaire spacing of 55 m (b).

b) Scene of the road with the small targets and the pedestrian (left), luminance distribution of the road (right).

For targets with the same spectral characteristics as the background the contrast is defined by luminance difference alone and the contrast is achromatic. However the target and background may have different spectral characteristics, in which case the contrast is chromatic. In road lighting conditions the spectral characteristics of the background and visual targets are defined by the illuminating light sources and the reflectance properties of the background and targets. A pedestrian wearing grey clothing seen against the road surface (black/grey) has achromatic contrast whereas a pedestrian with coloured clothing has chromatic contrast. Also, coloured traffic signs have chromatic contrast against the surrounding scene due to the selective reflectance of the coloured markings at different wavelengths.

The visual target contrasts in the experiments underlying the existing visual performance based mesopic systems, namely the USP-system and the MOVE-system, represent two extremes of the contrast range that might be encountered in night-time driving conditions. The USP-system is based on high contrast achromatic tasks ($C = 2,3$) while the MOVE-system is based on contrasts at or near the threshold contrast values, with both chromatic and achromatic targets.

Target Size and Eccentricity

In driving, both central and peripheral vision are needed. The weighting of on-axis and peripheral visual information may be different for different types of roads and driving situations. In night-time driving the balance between on-axis and off-axis visual tasks should be considered in defining the relevant spectral sensitivity function to be applied (Boyce, 2003).

For on-axis viewing of relatively small targets ($< 2^\circ$) it has been shown that the $V(\lambda)$ function provides an acceptably good prediction of task performance in the mesopic region as well, since foveal vision is dominated by cones (He et al., 1997, Goodman et al., 2007). In peripheral vision the rods also contribute to vision and this results in changes in the spectral sensitivity that depend on both the eccentricity of the target from the line of sight and the target size. Thus a comprehensive characterisation of mesopic spectral sensitivity would require a number of spectral weighting functions in order to take these effects into account. In the experiments underlying the existing visual performance based mesopic systems, fixed target eccentricities (e.g. 10°) and target sizes (2°) were used to represent the visual task conditions in driving (Rea et al., 2004, Goodman et al., 2007). The use of the 10° target eccentricity in the experiments for the MOVE system was based on findings of eye-fixation behaviour in night-time driving. The use of 10° target eccentricity is also consistent with the scotopic spectral luminous efficiency function, $V'(\lambda)$, which is partly based on brightness matching data for a centrally viewed 20° field (Crawford, 1949).

Spectral Characteristics of Light

One parameter which can be used to characterize the spectral characteristics of a light source, and which is particularly useful as a metric in relation to its effect on mesopic spectral sensitivity, is the 'S/P-ratio' (Rea et al., 2004). This is defined as the ratio of the luminous output of the light source evaluated according to the CIE scotopic spectral luminous efficiency function, $V'(\lambda)$, to the luminous output evaluated according to the CIE photopic spectral luminous efficiency function, $V(\lambda)$.

There are commercially available sources with a wide range of S/P-ratios, such as low pressure sodium lamps with an S/P-ratio of $\sim 0,23$, warm white metal halide lamps (MH) with an S/P-ratio of $\sim 1,2$ and daylight metal halide lamps (with high content in the short wavelength region) with an S/P-ratio of $\sim 2,40$. High pressure sodium lamps (HPS) are a commonly used light source in many outdoor applications. Because of the relatively high content of emission at long wavelengths, these lamps have a low S/P-ratio of the order of 0,60. This suggests that the high pressure sodium lamp is not necessarily the optimum light source for the low luminance levels encountered in street and road lighting. White light sources with higher content in the blue wavelength region, such as metal halide lamps, may be more effective for good visual performance in road lighting.

The visual experiments underlying the USP-system and the MOVE-system used a variety of targets and backgrounds, with a range of spectral characteristics. Both quasi-monochromatic and broadband lights were used for both target and background, and both achromatic (target and background of same spectra) and chromatic (target spectra different from the background) viewing conditions were used.

3.3 Definition of Mesopic Visual Performance

Mesopic visual performance can be defined as:

performance of the visual system for various visual tasks (e.g. contrast detection, speed of performance) when the eye is adapted to levels of luminance above the scotopic and below approximately $10 \text{ cd}\cdot\text{m}^{-2}$ and where both the rods and cones contribute to vision.

4 SYSTEMS FOR MESOPIC PHOTOMETRY BASED ON VISUAL TASK PERFORMANCE

4.1 Introduction

The foundations for any system of photometry must lie in empirical visual performance data using human subjects. Photometry has always had its roots in human visual psychophysics. Significantly, however, the current system of photometry is truly representative of the spectral sensitivity of human vision for only a very limited number of visual tasks (e.g., reading achromatic alphanumeric text). The spectral sensitivity of the visual system for tasks such as brightness perception is not well represented by either of the spectral luminous efficiency functions, $V(\lambda)$ and $V'(\lambda)$, that currently underlie photometry.

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

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

- it must be additive;
- it must tend to $V(\lambda)$ at the upper end of the mesopic region and to $V'(\lambda)$ at the lower end.

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

$$V_{\text{mes}}(\lambda) = y V(\lambda) + (1 - y) V'(\lambda), \quad (7)$$

with y being a function of the adaptation luminance.

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

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

4.2 USP-System

Two investigations by He et al. (1997, 1998) form the experimental basis of the USP-system. In the first work of He et al. (1997) reaction times were measured monocularly under two light sources (HPS and MH) at eight luminance levels between 0,003 cd·m⁻² and 10 cd·m⁻². A target

contrast of $C = 2,3$, as defined by Equation 6, was used in the experiments. The spectral power distributions of the test target and the adaptation backgrounds were the same i.e. the only information available to the visual system was the achromatic content of the stimulus. (More specifically, the tasks involved luminance contrast with no colour contrast.) The resultant system was a linear combination of the scotopic $V(\lambda)$ and the 10^0 photopic $V_{10}(\lambda)$ functions. The system is based on reaction time data for two subjects. According to He et al. (1997) visual inspection of the two subjects' off-axis reaction time data showed a separation between the two light sources below $0,3 \text{ cd}\cdot\text{m}^{-2}$, but no clear separation was observed above $1 \text{ cd}\cdot\text{m}^{-2}$. As the midpoint between these luminances in log units is $0,6 \text{ cd}\cdot\text{m}^{-2}$, and as the literature referred to in the paper described the rod-cone discontinuity at about this luminance, the $0,6 \text{ cd}\cdot\text{m}^{-2}$ luminance value was chosen by He et al. as a convenient point of bifurcation on fitting the data curves. Based on the reaction time data, He et al. concluded that there is no rod contribution above $0,6 \text{ cd}\cdot\text{m}^{-2}$ to the reaction time task investigated. An independent study of Bierman et al. (1998) confirmed the reaction time data of He et al. (1997) by using reaction time differences of the two eyes as the criterion.

In the second work by He et al. (1998) mesopic spectral luminous efficiency functions of one subject were measured using a method of reaction time differences between the two eyes. In this binocular simultaneity method, luminous efficiencies for five quasi-monochromatic stimuli (half bandwidth of 10 nm, peaks at 436 nm, 470 nm, 510 nm, and 630 nm) were measured against a yellow reference field (monochromatic 589 nm) at three light levels (0,3 Td, 3 Td, 10 Td). Thus in this experimental study the spectral power distribution of the reference field was different from that of the test field and each eye was adapted to a different condition (i.e. light level and wavelength). The derived mesopic spectral luminous efficiency functions were fitted with the linear model developed in the earlier work of He et al. (1997). The transition point between mesopic and photopic regions was not reached within the retinal illuminance range studied (0,3 Td, 3 Td, 10 Td). Using a relationship between adaptation coefficient and retinal illuminance, the transition point for the data of the one subject in question was estimated to occur at 21 Td, corresponding to a luminance level of $1,7 \text{ cd}\cdot\text{m}^{-2}$. The latter study of He et al. (1998) resulted in an iterative computational procedure for calculating mesopic light levels. In this procedure, the transition point between mesopic and photopic regions occurs at 21 Td. When the monocular viewing used in the previous study by He et al. (1997) is transferred to correspond to binocular viewing conditions, the transition point of $0,6 \text{ cd}\cdot\text{m}^{-2}$ corresponds to a retinal illuminance value of 25 Td as remarked by He et al. (1998).

Table 1. The experimental conditions underlying the USP-system (He et al., 1997, He et al., 1998). ($\Delta\lambda_{1/2}$ = half bandwidth)

Method	Stimuli	Contrast	Luminance	Subjects	
RT	MH and HPS	2,3	$0,003 \text{ cd}\cdot\text{m}^{-2} - 10 \text{ cd}\cdot\text{m}^{-2}$	2	3
RT	470 nm, 510 nm, 546 nm, 630 nm*	2,3	0,3 Td; 3 Td; 10 Td	1	

$$*\Delta\lambda_{1/2} = 10 \text{ nm}$$

$$C = (L_t - L_b) / L_b$$

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

$$V_{\text{mes}}(\lambda) = X V(\lambda) + (1 - X) V'(\lambda) \quad \text{for } 0 \leq X \leq 1 \quad (8)$$

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

In proposing the USP-system Rea et al. (2004) made several simplifications to the approaches of the works of He et al. Firstly, since the pupil size is large and essentially constant below $1 \text{ cd}\cdot\text{m}^{-2}$, it was assumed that a constant pupil diameter of 7 mm could be taken to apply, so that the transition point between the mesopic and photopic regions determined from each of the two studies (He et al., 1997, He et al., 1998) are in substantial agreement. This led to the choice of $0,6 \text{ cd}\cdot\text{m}^{-2}$ as the transition point between the mesopic and photopic regions. Secondly, the relationship between the coefficient X and mesopic luminance was assumed to be linear between $0,001 \text{ cd}\cdot\text{m}^{-2}$ and $0,6 \text{ cd}\cdot\text{m}^{-2}$ in order to develop a closed-form solution for X . And thirdly, in the final form of the USP-system, $V_{10}(\lambda)$ was substituted by $V(\lambda)$, based on the observation that for most practical conditions photometric quantities based on $V(\lambda)$ and $V_{10}(\lambda)$ do not differ substantially.

Equations 9 and 10 give the closed-form expression for calculating the mesopic luminance L_{mes} and the corresponding coefficient X :

$$L_{\text{mes}} = 0,834 L_p - 0,335 L_s - 0,2 + \sqrt{0,696 L_p^2 - 0,333 L_p - 0,56 L_p L_s + 0,113 L_s^2 + 0,537 L_s + 0,04} \quad (9)$$

for $0,001 < L_{\text{mes}} < 0,6$

$$X = m L_{\text{mes}} + \beta \quad \text{for } 0 \leq X \leq 1, \quad (10)$$

where L_p is the photopic luminance, L_s is the scotopic luminance, and m and β are coefficients given by $m = 1/0,599$ and $\beta = -0,001/0,599$ (Rea et al., 2004).

The values of X and L_{mes} given by the USP-system as a function of photopic luminance and light source S/P-ratio are presented in Tables 2a and 2b. The lamp notations LPS (low pressure sodium), HPS (high pressure sodium) and MH (metal halide) on the left side of the table refer to the typical regions of S/P-ratios of these lamp types.

Table 2a. Values of X given by the USP-system as a function of photopic luminance and S/P-ratio (Rea et al., 2004).

		Photopic luminance / cd·m ⁻²						
	S/P	0,001	0,003	0,01	0,03	0,1	0,3	0,55
LPS ~	0,25		0,000 0	0,002 6	0,011 9	0,056 2	0,330 6	0,881 1
	0,35		0,000 1	0,004 3	0,017 2	0,074 9	0,365 2	0,887 6
	0,45		0,000 6	0,006 0	0,022 3	0,091 9	0,393 8	0,893 4
HPS ~	0,55		0,001 1	0,007 6	0,027 3	0,107 4	0,418 3	0,898 6
	0,65		0,001 6	0,009 3	0,032 2	0,121 8	0,439 7	0,903 2
	0,75		0,002 1	0,011 0	0,037 0	0,135 2	0,458 8	0,907 5
	0,85		0,002 6	0,012 6	0,041 6	0,147 7	0,476 1	0,911 3
	0,95		0,003 1	0,014 2	0,046 2	0,159 5	0,491 7	0,914 9
MH warm white ~	1,05	0,000 1	0,003 6	0,015 8	0,050 6	0,170 7	0,506 1	0,918 1
	1,15	0,000 2	0,004 1	0,017 4	0,054 9	0,181 4	0,519 4	0,921 1
	1,25	0,000 4	0,004 6	0,019 0	0,059 2	0,191 5	0,531 8	0,923 9
	1,35	0,000 6	0,005 1	0,020 6	0,063 4	0,201 1	0,543 3	0,926 4
	1,45	0,000 7	0,005 6	0,022 1	0,067 5	0,210 4	0,554 1	0,928 8
	1,55	0,000 9	0,006 0	0,023 7	0,071 5	0,219 2	0,564 3	0,931 1
	1,65	0,001 1	0,006 5	0,025 2	0,075 4	0,227 8	0,573 9	0,933 2
	1,75	0,001 2	0,007 0	0,026 7	0,079 3	0,236 0	0,583 0	0,935 2
	1,85	0,001 4	0,007 5	0,028 2	0,083 1	0,243 9	0,591 5	0,937 0
	1,95	0,001 6	0,008 0	0,029 7	0,086 8	0,251 6	0,599 7	0,938 8
MH day-light ~	2,05	0,001 7	0,008 5	0,031 2	0,090 5	0,259 0	0,607 5	0,940 4
	2,15	0,001 9	0,009 0	0,032 7	0,094 1	0,266 1	0,614 9	0,942 0
	2,25	0,002 1	0,009 4	0,034 2	0,097 7	0,273 0	0,622 0	0,943 5
	2,35	0,002 2	0,009 9	0,035 6	0,101 2	0,279 8	0,628 7	0,944 9
	2,45	0,002 4	0,104 0	0,037 1	0,104 6	0,286 3	0,635 2	0,946 2
	2,55	0,002 6	0,010 9	0,038 5	0,108 0	0,292 9	0,641 5	0,947 5
	2,65	0,002 7	0,011 4	0,040 0	0,114 0	0,298 9	0,647 4	0,948 7
	2,75	0,002 9	0,011 8	0,041 4	0,114 7	0,304 9	0,653 2	0,949 9