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Day to Day Life Performance in Mescopic Photometry (Mescopic Vision and Photometry)

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Abstract—*Mesopic photometry has a long history, but most mesopic photometric models have concentrated on brightness evaluation. Recently for traffic lighting applications the attention illuminating engineering has turned towards the question of most efficient lighting for early recognition of obstacles and dangerous situations. From other investigations it is well known that photopic visibility of details is not a brightness contrast recognition task but can be better described by a luminance contrast. At present there are no internationally recognized luminous efficiency functions for the mesopic region. Resulting from this, there are no products, policies, standards dealing with the mesopic light levels. New luminosity functions are needed to describe correctly mesopic visibility, the key item for e.g. traffic lighting. The project consortium brought together multi-disciplinary expertise in the areas of lighting engineering, vision science, metrology, human behaviour and image processing. The outcome of the project is a mesopic model based on visual task performance.*

1. INTRODUCTION

The objective of the project was to define relevant spectral sensitivity functions for the luminance range of 0.01 – 10 cd/m2, where standardisation is most urgently needed. To find out how the eye's spectral sensitivity, lighting conditions and visual stimuli interact, a large number of experiments were needed with the human eye as a detector. Earlier research has shown that for different visual tasks different spectral responsivity functions can be measured. Therefore the MOVE consortium decided to first consider the different measuring methods that could lead to the determination of the visibility function. It was decided that at the different laboratories different techniques should be used. The vision experiments of the project generated data for mesopic visibility functions using several visual criteria. The majority of spectral luminous efficiency curves obtained to date in the mesopic range have been acquired using heterochromatic brightness matching. In MOVE, the emphasis was placed on night-time driving performance and the attempt to describe luminous efficiency in a realistic way. Emphasis was placed on methods like contrast threshold, reaction time, recognition, which are highly linked to driving performance. A common set of parameters was used in the experiments to ensure that although all the partners were using different equipment and techniques there was a degree of compatibility between them. This assisted with the comparison of results and their use in the development of a model for mesopic photometry.

The vision experiments carried out in the project split the task of night-time driving into three sub-tasks, each of which was investigated separately. These subtasks can be characterized by the questions 'Can it be seen?' (contrast threshold), 'How quickly? (reaction time) and 'What is it?' (recognition threshold). Based on the experimental data a practical model for mesopic photometry for night-time driving was developed. The practical model is applicable for all three sub-tasks studied within this project, and for the general task of night-time driving, in situations where the background and target both have fairly broad spectral power distributions. This encompasses most situations that will be encountered in practice, including situations involving LED sources. It should therefore be considered for implementation by highways agencies, road lighting designers, lighting manufacturers, regulatory authorities and all other organisations and users who may be working in the mesopic domain.

The practical model is proposed to the CIE (Commission Internationale de l'Éclairage) for consideration as the basis for a task-based system of mesopic photometry. The results of the project are integrated in the CIE TC1-58 work to form the basis of a new standard on performance based mesopic photometry.

2. MESCOPIC VISION & PHOTOMETRY

2.1 Mescopic Vision

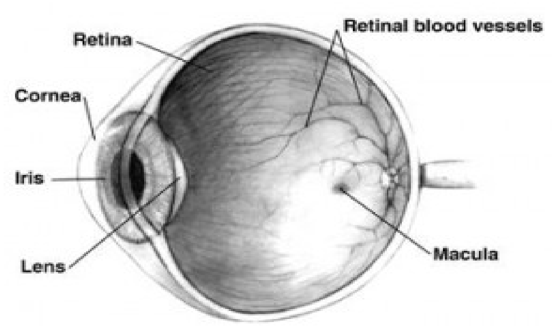
Mesopic vision is a combination of photopic vision and scotopic visionin low but not quite dark lighting situations. Mesopic light levels range from luminances of approximately 0.001 to 3 cd m^{-2}. Most night-time outdoor and traffic lighting scenarios are in the mesopic range. Humans see differently at different light levels. This is because under high light levels typical during the day (photopic vision), the eye uses cones to process light. Under very low light levels, corresponding to moonless nights without electric lighting (scotopic vision), the eye uses rods to process light. At many night-time levels, a combination of both cones and rods supports vision. Photopic vision has excellent color discrimination ability, whereas colors are indiscriminable under scotopic vision. Mesopic vision falls between these two extremes. In most night-time environments, there is enough ambient light at night to prevent true scotopic vision.

The effect of switching from cones to rods in processing light is called the "Purkinje shift". During photopic vision, people are most sensitive to light that is greenish-yellow. In scotopic vision, people are more sensitive to light which would appear greenish-blue.

The traditional method of measuring light assumes photopic vision and is often a poor predictor of how a person sees at night. Typically research in this area has focused on improving street and outdoor lighting as well as aviation lighting.

2.2 Mescopic photometry

If you are involved with outdoor area or roadway lighting design, you will undoubtedly encounter such terms as *mesopic multipliers*, *scotopic lumens*, and *S/P ratios*, and you will sooner or later need to consider mesopic photometry in your design efforts. For example, you may encounter a government specification that states, “Luminaires must have a minimum S/P ratio of *x*.” It begins with the human eye:



where light entering the eye through the cornea is focused on the retina. The retina consists of approximately six million cones located mostly at the center of the retina, surrounded by some 120 million rods. The cones, which are responsible for our color vision, function best in bright light, while the color-blind rods are responsible for our night vision.

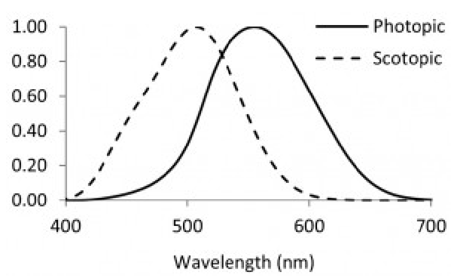


Fig. 2: Luminous efficiency functions

For scenes with an average luminance above approximately 5.0 cd/m^2, *photopic* vision dominates. The cones have an average spectral response that is described by the*photopic luminous efficiency function* V(λ) with peak responsivity at 555 nm (Fig. 2). Below approximately 0.005 cd/m^2, *scotopic* vision dominates, with the rods having a spectral response that is described by the *scotopic luminous efficiency function* V'(λ) with peak responsivity at 507 nm

Mesopic vision occurs when the average scene luminance is between approximately 0.005 and 5.0 cd/m^2, as both the rods and cones contribute to what we perceive.

We can directly perceive this blending of photopic and scotopic vision due to the *Purkinje effect*. Cones are more sensitive to red light than are rods. As the light levels dim, red colors appear to darken more quickly than other colors:

This is due to the gradual shift from the photopic to the scotopic luminous efficiency function as the rods begin to predominate.

A light source will have a characteristic *spectral power distribution* (SPD), such as this one for a typical cool white fluorescent lamp:

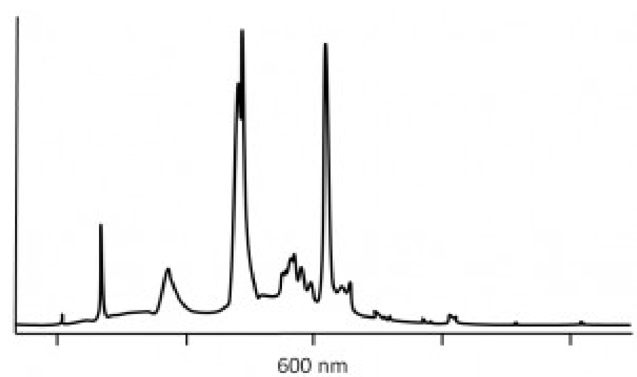


Fig. 4: Cool white fluorescent lamp spectral power distribution

Calculating the photopic lumens generated by a light source is easy: multiply the SPD by the photopic luminous efficiency function on a per-wavelength basis (typically at 5 nm intervals) sum the results, and scale as required. Calculating the scotopic lumens is the same, only using the scotopic luminous efficiency function.

2.3 S/P Ratios

Herein lies the crucial point: because the photopic and scotopic luminous efficiency functions are different, they will yield different values for the scotopic and photopic lumens. The ratio of these two values is the *scotopic-to-photopic (*S/P*) ratio*. In general, light sources with more blue light will have higher S/P ratios. For example:

Table 1: Typical S/P ratios

Lamp Type	Typical S/P Ratio
Low-pressure sodium	0.2
High-pressure sodium	0.4 to 0.6
Halogen headlamp	1.4
Linear fluorescent	1.3 to 2.3
Metal halide	1.2 to 2.1
Warm white LED	1.2
Cool white LED	2.0

Some publications on mesopic lighting have indicated that the S/P ratio of a lamp can be estimated from its *correlated color temperature* (CCT), but this is incorrect except for incandescent lamps (which have little practical application to mesopic lighting). Here for example are two LED modules with the same CCT of 3500 K but very different spectral power distributions and different S/P ratios.

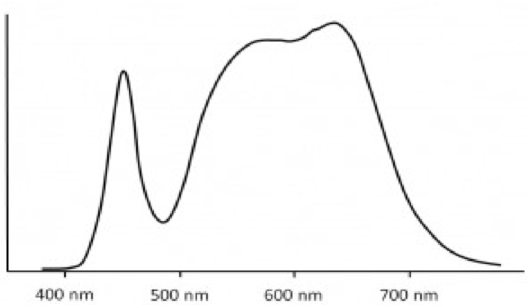


Fig. 5A: Phosphor-coated 3500 K LED (SP = 1.41)

Simply put, the only way to accurately determine the S/P ratio of a light source is through calculation using its spectral power distribution.

Scotopic lumens are important because they better represent how bright objects appear under low light level conditions than do photopic lumens. This leads to the concept of*effective luminance factors* (ELF). These factors are defined simply as:

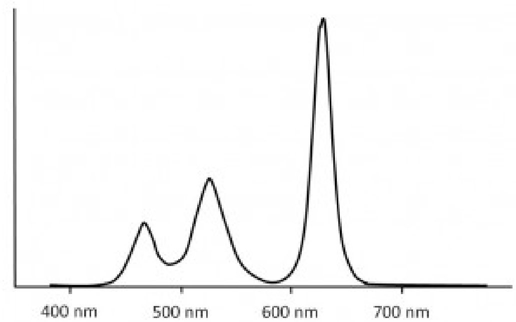


Fig. 5B: Red-green-blue 3500 K LED module (S/P = 2.02)

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Comprehensive ELF tables are presented in IES TM-12-12 and CIE 191:2010, but they can be summarized as:

Some caution is needed here in that a government or industry specification may have already taken mesopic lighting into account, in which case the specified minimum luminance has already had a mesopic multiplier applied. This will undoubtedly be the case if the specification also includes a minimum S/P ratio for the light sources. When in doubt, ask.

But now the fun begins – a specification is much more likely to specify a minimum photopic illuminance value, expressed in lumens per square meter (or foot). Now what?

To begin with, mesopic photometry (for lighting applications) assumes that all surfaces being illuminated are: a) grey or pastel-colored; and b) diffuse reflectors. In this case, the luminance L of the illuminated object is given by:

$$L = \rho * E / \pi$$

where ρ is the reflectance of the surface and E is the illuminance. (As a reminder, π is approximately 3.14.)

If the surface is strongly colored, then the spectral power distribution of the reflected light will be very different from the SPD of the light source, and so the S/P ratio will not apply in terms of the surface luminance.

This assumes of course that the surface reflectance is known or can be estimated. For example, the diffuse reflectance of roadway surfaces ranges from approximately 8 percent for bituminous asphalt to 17 percent for concrete (Gillet 2001). Ideally, the target reflectance will be included in the specification.

We must now ask, "What is the meaning of average scene luminance?" The point here is that mesopic photometry depends on the visual adaptation of the viewer to the average scene luminance. Unlike other photometric quantities such as lumens, luminance, luminous intensity, luminous exitance, and illuminance, mesopic quantities are meaningless without a viewer whose state of visual adaptation is known.

As it turns out, the majority of the cones in the retina occupy only the central 2 degrees or so of our visual field of view (called the *fovea*). It may seem nonsensical, but we perceive color only within a region about the diameter of two thumbnails held at arm's length. We may think we perceive color within our entire field of view, but this is only because our brains are filling in the details as we visually scan a scene.

What this means is that our *mesopic adaptation* is mostly determined by the luminance of the surface we happen to be looking at (Moon 1943). The *background surround* has very little influence on this adaptation (less than 10 percent). As we shift our gaze towards different objects, our visual adaptation state changes accordingly.

Visual adaptation is not, of course, instantaneous. It is a complex mechanism involving mechanical changes in pupil size, photochemical changes (pigment bleaching in the retina), and neural changes (synaptic interactions). This is likely why the IES Lighting Handbook (Section 4.12.3, "Spectral Effects") recommends that mesopic photometry not be applied to roadway lighting where the speed limit is greater than 40 kph (25 mph). (This limit may be increased in the future, subject to ongoing roadway vision research.)

2.4 Calculation Procedure

1. Obtain the lamp S/P ratio.
2. Determine the target design illuminance E_{design}.
3. Determine the target reflectance ρ.
4. Determine the required design luminance $L_{design} = E_{design} * \rho / \pi$
5. Calculate the photopic illuminance $E_{photopic}$ of the target.
6. Determine the target photopic luminance $L_{photopic} = E_{photopic} * \rho / \pi$
7. Determine the effective luminance multiplier ELF based on S/P and $L_{photopic}$.
8. Convert the photopic luminance to the effective (mesopic) luminance $L_{effective} = L_{photopic} * \text{ELF}$
9. Reiterate steps 5 to 8 while modifying the design until $L_{effective}$ equals or exceeds L_{design}.
10. If necessary, calculate the effective target illuminance $E_{effective} = L_{effective} * \pi / \rho$.

2.5 Some Possible Reasons

Given this, you would expect that roadway and outdoor area luminaire manufacturers would provide S/P ratios for their products, but to date this has not been the case. Information on lamp S/P ratios can be exceedingly difficult to find. Possible reasons include:

1. The S/P ratio is a function of the lamp or lamp module rather than the luminaire. For fluorescent and high-pressure discharge (HID) lamps, the luminaire manufacturer typically has no control over what lamps the contractor or owner may install in the luminaires.
2. Most lamp manufacturers do not provide SPDs or S/P ratios for their products. This is difficult to explain, as they can be easily measured by a spectroradiometer by an independent photometric laboratory.
3. The SPDs of fluorescent and HID lamps is a function of their proprietary gas fill mixtures and phosphors. If lamp manufacturers were to provide S/P ratios for their products, they might have to change their product numbers if these proprietary formulations were to change.
4. The SPDs of white light LEDs are dependent on the dominant wavelength of the blue pump LEDs and the proprietary phosphors and phosphor mixtures used to down-convert the blue light to longer wavelengths. Again, if LED manufacturers were to provide S/P ratios for their products, they might have to change their product numbers if these proprietary designs were to change. (For whatever reason, phosphor manufacturers are equally protective of the detailed SPDs for their products.)
5. Many LED lamp module manufacturers purchase their LEDs from third parties, and so have no control over changes to the LEDs apart from specifying minimum luminous flux output and CCT binning.
6. Many luminaire manufacturers purchase their LED modules from third parties, which makes it even more difficult for them to guarantee the S/P ratios of their products.

In an ideal world, lighting designers would have unfettered access to the S/P ratios of the luminaires they specify in order to perform mesopic lighting calculations. Unfortunately, this will require changes to the entire supply chain of phosphors, fluorescent and HID lamps, LEDs and LED modules, and luminaires. These changes are possible, but it may take some time for the lighting industry to adapt to the brave new world of mesopic photometry.

3. NEW APPROACH FOR DEVELOPING MESOPIC PHOTOMETRY

3.1 Night Time Driving

The measurement of mesopic spectral luminous efficiency is dependent on the experimental method used. In the earlier works on mesopic photometry the experimental techniques used have only considered one aspect of visual performance such as recognition of brightness differences or measurement of thresholds. In general, the process of seeing consists of an initial searching, seeing, perceiving and recognition process. Flicker photometry and direct brightness matching are not representative of tasks undertaken whilst driving at night-time, rather, visual performance during driving consists of the steps mentioned above. Therefore, these aspects should be considered in the new approach of developing a model for mesopic vision. In MOVE the emphasis was placed on night-time driving and the attempt to describe luminous efficiency in a realistic way.

The visual performance of night-time driving was divided into three visual subtasks characterised by the questions:

Can it be seen? 2. How quickly? 3. What is it?

The first subtask – Can it be seen? - is related to detection threshold i.e. the minimum luminance contrast of a target against its surroundings that is necessary for the observers to become aware of objects in their visual field.

The second subtask – How quickly? - is related to reaction times i.e. the time between the onset of a visual stimulus and the detection response of that stimulus under conditions where the observer is instructed to respond manually by pressing a button as quickly as possible. In night-time driving conditions reaction times play an important role for safe driving.

The third subtask – What is it? - is related to recognition and identification of the target i.e. the perception of fine details. This visual subtask describes how the target, after being detected, is being recognized according to its visual details and a more conscious and wilful action can be initiated.

3.2 Multi-Technique Experimental Methords

The idea of MOVE was to generate data for mesopic visibility functions using several visual criteria. No investigation at this depth has been undertaken previously. The project steered away from conventional techniques, where only one aspect of visual performance has been considered at time, and developed a multi-technique system.

Many test methods are needed to generate the required visibility data. All test parameters and test methods cannot be covered with one experimental technique and one test apparatus. The only way to have enough data for building a comprehensive mesopic model is to generate visibility data with various experiments using different experimental techniques. This was implemented by dividing the work between the partner laboratories so that the tests cover all the required methods and parameters. After careful consideration of the required visibility data, the consortium developed experimental techniques to quantify the visibility of targets when performing each of the three visual tasks. Work between the parallel experiments was distributed and linked in a way that allowed the exchange of data between test locations and input of data from one test to another.

For each visual subtask, data was simultaneously generated in two to four laboratories using different experimental methods in each location. This approach differs from earlier techniques. The consortium has developed an alternate multi-technique system where the visual performance of driving is described with three different subtasks.

The parallel tests complemented each other in two ways. Firstly, the tests were carried out using different experimental techniques based on different visual criteria. Secondly, the information was exchanged between the different test locations; the same test parameters and parameter combinations could be examined in different locations. During the project a combined analysis of all the test data were made by all partners. Thus information between test locations was constantly exchanged and joint decisions on further work and parameter adjustments could be made during the project course.

3.3 (1) Large homogeneous screen

In the large homogenous screen at TUD a slide projector was used to provide an adapting background with a colour temperature of approximately 2856 K. The slide projector illuminated a screen that was painted matt white. To avoid the de-saturation of the stimuli the target was not superimposed on the background but presented through a hole in the screen. The aperture of the hole defined the size of the target, which was a 2o-diameter circle.

The light of a metal halide lamp passed through several different lenses and a pockels cell to produce pulses of light that formed the target (rectangular pulse of 3 sec duration). The luminance of the target could be adjusted by changing the output level of the pockels cell using a 12-bit digital input controlled by a computer. Ahead of and behind the pockels cell there was a polarizer and an analyser. After passing through the pockels cell the light-beam was widened and focused to the observer's eye.

Monochromatic filters were used to modify the spectral power distribution of the target. The half-bandwidth (HBW) of the filters was HBW ≤ 10 nm. The target was presented on- axis or at 10° eccentricity. The photopic luminance of the stimulus was manually increased until the observer just perceived the pulse to determine the achromatic threshold for the coloured stimulus. Each trial started with a three times presentation of the λ = 550 nm stimulus. Afterwards the wavelength is decreased from λ = 700 nm to λ = 380 nm in 10 nm steps. Observations were made monocularly with the right eye.

3.3 (2) Screen with controlled computer projector

The experimental set-up for the increment threshold measurements at UV consisted of two projectors; a slide projector which provided the adapting background and a data projector (video projector) to superimpose the target stimulus on the background. For the background the projector was set to a correlated colour temperature of approximately 2856 K, and by use of neutral filters in front of the projector different background luminance levels were achieved.

Metal interference filters were placed in front of the data projector to produce the target spectra. The wavelength of the nominal maximum transmittance of the interference filters varied between λ = 420 nm and λ = 700 nm in 10 nm steps. The half-bandwidth (HBW) of the filters was equal to 10 nm. The data projector was computer-controlled, enabling the luminance of the target to be adjusted by the operator and also controlling the position at which the target was displayed (either centrally or at 10° eccentricity). The target was a 2° diameter disk which was presented for 3 seconds (quasi-static observation). The observer hadto respond for every presentation whether he/she could see the target or not. The luminance of the target was adjusted at each wavelength by the operator. The viewing was binocular.

3.3 (3) Computer controlled display(CRT)

Reaction time measurements were performed at CU using CRT display-based system on which a custom-designed computer-controlled program was run. The subject was positioned at a viewing distance of 70 cm with the aid of a chin rest and forehead support. At this distance the background field subtended 23o x 36o visual angle. The background was uniform and of fixed chromaticity (x = 0.305, y = 0.323).

Neutral density filters were used to reduce the luminance of the target and background, with fine adjustments made by modifying the voltage across the red, green and blue electron guns. The filters were mounted between the display and the subject, and a hood prevented any light from the display reaching the subject without first passing through the filter.

A target based on a Landolt ring was presented at one of six different positions on a circle with a radius of 10o visual angle centred on the fixation marker. The target ring had an outer diameter of 2o visual angle and an inner diameter of 1.2o (thickness 0.4o), but a 45o sector removed to provide a gap. An example of the stimulus is shown in Figure 7. The target ring was presented for 500 ms. The subject was required to press a button as soon as he/she detected the target. Reaction times were recorded with a temporal resolution of 1 ms. Reaction times were measured for achromatic targets, i.e., targets with the same relative spectral power distribution (SPD) as the background, and for coloured targets, i.e. targets with different relative SPDs than the background. The stimulus was viewed binocularly.

4. VISUAL PERFORMANCE MODEL

A model for mesopic photometry was developed on the basis of the results from the vision experiments carried out in the project. An important consideration within the MOVE project was to draw a distinction between a practical system of mesopic photometry and a model of the eye response in the mesopic. A practical system of photometry must be grounded on human vision and allow predictions of task performance to be made which are in reasonable agreement with the actual ability to perform these tasks. It will not necessarily describe the details of the performance of the human visual system, however, nor will it predict the actual spectral sensitivity of the eye under any given conditions. In this way mesopic photometry is no different from the system of photometry that has been developed for photopic vision and which is based on the use of the internationally agreed photopic luminous efficiency function, V(λ).

The majority of the experiments in MOVE used relatively broadband targets presented against a white or coloured (broadband) background of specified photopic luminance; these results could be fitted to various potential forms of model to determine the relevant model parameters and to test the validity of the candidate models. For some of the experiments, however, narrow-band (quasi-monochromatic) targets were used, which enabled the appropriate spectral sensitivity functions to be determined more directly.

The key aim of the MOVE project was to develop a practical system of photometry that is based on the ability of the eye to perform the task of night-time driving (or to sub-tasks of this key task), that obeys Abney's laws of additivity, and, critically, that will be suited to practical implementation by road lighting engineers, specifiers, instrument manufacturers etc. It was recognised that this need for practical implementation would place some constraints on the system developed within the project, namely that the spectral sensitivity curve should tend to the universally adopted photopic luminous efficiency function, V(λ), at the upper end of the mesopic range and to the scotopic luminous efficiency function, V′(λ), at the lower end of the mesopic range. Thus these constraints were applied during much of the modelling process. However it was also appreciated (based on the results of work by other researchers and by the results of the experiments to measure spectral sensitivity during this project) that the spectral sensitivity curves predicted by such a system would be unlikely to agree with those determined by direct measurement. These curves typically show a distinctive 'three peak' behaviour, which is believed to be associated with the influence of colour channels in the eye response mechanism and which cannot be modelled using combinations of V(λ) and V′(λ). More complex models utilising such response curves were therefore also examined to see how well they fitted the results of the experiments to investigate task performance, but it was agreed that such a system would only be recommended if it provided a significant improvement in the fit of the model to the data. In this context, it is important to appreciate

that a significant advantage of using combinations of V(λ) and V′(λ) is that the effective mesopic luminance can be determined directly from the photopic and scotopic luminances(measured using broadband photometers), without requiring knowledge of the relative spectral power distribution of the source being measured.

5. MODEL OF MESCOPIC PHOTOMETRY

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6. APPLICABILITY OF MODEL

The practical (i.e. recommended) MOVE model is applicable for all three sub-tasks studied within this project, and for the general task of night-time driving, in situations where the background and target both have fairly broad spectral power distributions. This encompasses most situations that will be encountered in practice, including situations involving LED sources. It should therefore be considered for implementation by highways agencies, road lighting designers, lighting manufacturers, regulatory authorities and all other organizations nand users who may be working in the mesopic domain.

For situations where on-axis viewing of relatively small targets (<2o) is critical, it has been shown in the project 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 or for quasi- monochromatic stimuli (neither of which condition is likely to be encountered in a practical night-time driving situation). This difference in visual performance as a function of target eccentricity may have significant implications for road lighting design in the future. For example, different specification and measurement criteria may be necessary in situations where there is a different weighting of on-axis and peripheral visual information to process. These points will require careful consideration within the various specification organizations (highways agencies etc.)

The practical model is not suited to situations where it is critical that the activity of the chromatic mechanisms is taken into account e.g. when the colourfulness (chromatic saturation) of the target is especially high, or when the target has a very narrow spectral power distribution. In this case the chromatic model based on the quasi-monochromatic methods may be more appropriate. For such situations, however, it must be recognised that V(λ) is similarly a poor predictor of performance in the photopic and a completely new system of photometry may be necessary. This is beyond the scope of this project, but is being investigated within the CIE.

The data gathered in the MOVE project represents a significant resource. The modeling undertaken as part of the project has attempted to characterise its main features, particularly those relevant to providing guidance to lighting engineers with applications to night-time driving. However, it is recommended that further analysis of the data by researchers is undertaken to extend and/or qualify the results presented here so that the full benefit of measurement data may be realised.

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