Report on Quality Metrics related to Mesopic Measurements of SSL

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In the EMRP Joint Research Project (JRP) "Metrology for Solid State Lighting", the following partners cooperate to create a European infrastructure for the traceable measurement of solid state lighting: VSL (Coordinator), Aalto, CMI, CSIC, EJPD, INRIM, IPQ, LNE, MKEH, NPL, PTB, SMU, SP, Trescal, CCR, TU Ilmenau and Université Paul Sabatier. See http://www.m4ssl.npl.co.uk/ for more information.

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SUMMARY

The recent publication of the CIE system for mesopic photometry [1] has ended more than 70 years of debate regarding the weighting functions that should be used when making photometric measurements in the mesopic region. This development has major implications for products designed for applications that fall in the mesopic regime, arguably the most important of which is lighting for streets and roads at night. The publication of the CIE system allows optimisation of the spectral power distribution of lighting for such applications, in order to achieve a high mesopic luminous efficacy; SSL lighting products are particularly well-placed in this respect, due to the fact that many white LEDs have a strong blue feature, which gives them a higher S/P ratio, and the ability to 'tune' the spectral characteristics through, for example, combinations of differently-coloured LEDs. This report summarises the current recommendations regarding the CIE system for mesopic photometry and highlights the additional work that is being undertaken within the CIE to provide guidance on how the system should be implemented, how the performance of products for mesopic applications should be characterised, etc. This report also summarises the current situation regarding the quality metrics that should be used for characterising SSL products intended for mesopic applications (particularly road lighting); these recommendations are based on the outcomes from work carried out under the auspices of CIE TC4-48 and the Institution of Lighting Professionals (ILP) in the UK, which was aimed at introducing the CIE system for mesopic photometry into standards for lighting for residential roads.

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$V(\lambda)$	CIE photopic spectral luminous efficiency function
$V'(\lambda)$	CIE scotopic spectral luminous efficiency function
$V_{mes}(\lambda)$	CIE mesopic spectral luminous efficiency function
m	adaptation coefficient
$L_{v,adapt}$	photopic luminance of the adaptation field
R_{SP}	S/P ratio i.e. ratio of the luminous quantity evaluated according to the CIE scotopic spectral luminous efficiency function, $V'(\lambda)$, to the luminous quantity evaluated according to the CIE photopic spectral luminous efficiency function, $V(\lambda)$
I_v	(Photopic) luminous intensity
L_v	(Photopic) luminance
R_a	CIE general colour rendering index

LIST OF ABBREVIATIONS

CCPR	Consultative Committee on Photometry and Radiometry (part of the International Committee on Weights and Measures)
CIE	International Commission on Illumination (Commission International de l'Eclairage)
CRI	Colour Rendering Index
EMRP	European Metrology Research Programme
ILP	Institution of Lighting Professionals (UK)
JTC	Joint Technical Committee
JRP	Joint Research Project
NMI	National Measurement Institute
SSL	Solid State Lighting
TC	Technical Committee

1. Physical Photometry: Spectral Luminous Efficiency Functions

Physical photometry provides the framework under which the properties of light and lighting can be evaluated precisely, reproducibly and in a way that relates to the ability to stimulate a visual response and facilitate vision [2]. In contrast to the measurement of optical radiation in purely physical terms (i.e. in terms of the absolute radiant power or energy stimulating the visual system, which is termed radiometry), photometric measurements must take into account the spectral sensitivity of the human eye. This is done through the use of internationally-agreed spectral luminous efficiency functions that, whilst they do not describe the details of human visual performance, nevertheless provide a measurement framework for quantifying “light” in a way that correlates with human vision. These functions form the basis for all physical photometry. They are used as spectral weighting functions, enabling a conversion between measurements of the spectral radiant power stimulating the visual system and the analogous visual response. The conversion can be made either mathematically, by multiplying the spectral radiant power at each wavelength by the corresponding spectral luminous efficiency value and then summing across all wavelengths, or by the use of a measuring instrument whose spectral response has been modified to provide a close match to the required spectral luminous efficiency function.

Over the years the CIE has defined several spectral luminous efficiency functions, each of which relates to specified conditions. The most widely used of these are [2]:

- the 2° photopic spectral luminous efficiency function, $V(\lambda)$, which applies at ‘high’ light levels (daylight, lit interiors etc.), where human vision is dominated by the activity of cones in the retina, the rods are relatively inactive, and colour discrimination and the ability to resolve detail in the visual field are both good, and
- the scotopic spectral luminous efficiency function, $V'(\lambda)$, which applies at ‘low’ levels (e.g. moonlight), where only the rods are active, visual acuity is poor, and it is not possible to distinguish colours.

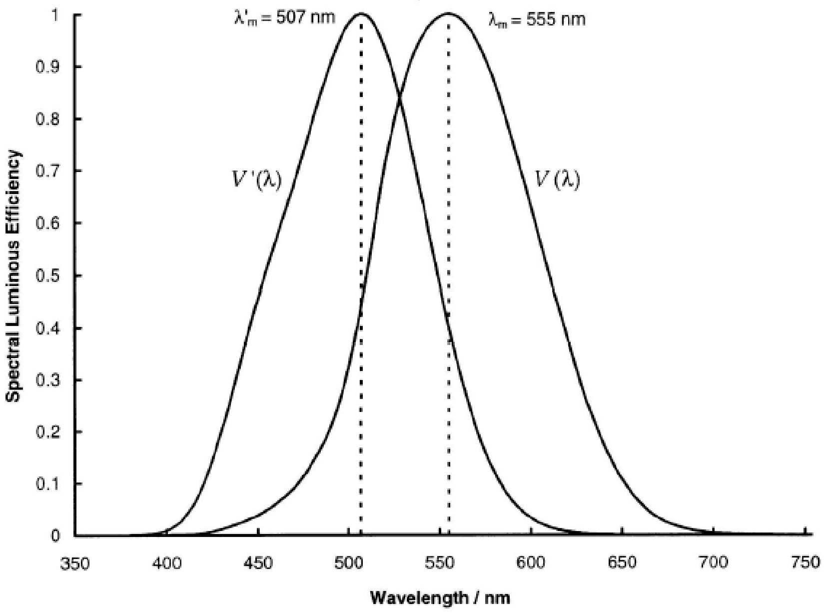

Figure 1. The CIE photopic and scotopic spectral luminous efficiency functions $V(\lambda)$ and $V'(\lambda)$.

1.1 CIE 191:2010 – The CIE System for Mesopic Photometry

Between the photopic and scotopic conditions, the eye's sensitivity changes rapidly depending on the characteristics (level and spectral distribution) of the lighting used, shifting towards the blue as the light level decreases. This is the mesopic region, which can be characterised using the CIE system for mesopic photometry[1]. Under this system, the relevant spectral luminous efficiency function, $V_{\text{mes}}(\lambda)$, is given by:

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

where the adaptation coefficient, m, is determined by the luminance and spectral characteristics of the visual adaptation field and $M(m)$ is a normalising function such that $V_{\text{mes}}(\lambda)$ has a maximum value of unity. For adaptation luminances of 5 cd m^{-2} or above, the value of m is one, whereas for adaptation luminances of 0.005 cd m^{-2} or below, m is zero. The spectral characteristics of the adaptation field are expressed in terms of the S/P ratio, which is the ratio of the luminous quantity evaluated according to the CIE scotopic spectral luminous efficiency function, $V'(\lambda)$, to the luminous quantity evaluated according to the CIE photopic spectral luminous efficiency function, $V(\lambda)$.

2. Photometric Quantities, Symbols and Units

CIE TC2-65, on photometric measurements in the mesopic range, and CIE JTC-2 (CIE-CCPR), on principles governing photometry, both include work related to the correct use of photometric quantities, symbols and units. Although these TCs have not yet published their recommendations, they have reached agreement on the basic principles; this section provides a synopsis of these principles. Further information on progress within these CIE TCs is available via the CIE website (www.cie.co.at).

2.1 Photometric Quantities and Symbols

Photometric and radiometric quantities are generally distinguished from one another by the use of the words "luminous" and "radiant" respectively (e.g. luminous intensity and radiant intensity, or luminous flux and radiant flux); the exceptions to this rule are the quantities illuminance (the photometric equivalent of the radiometric quantity irradiance) and luminance (the photometric equivalent of radiance). However for photometric quantities it is not sufficient just to use the adjective "luminous"; it is essential also to specify the spectral luminous efficiency function used. If no spectral luminous efficiency function is specified, it is assumed, by convention, that the $V(\lambda)$ function applies; more strictly, however, the qualifying descriptor "photopic"' should be used. For quantities evaluated using the $V'(\lambda)$ function, the qualifying descriptor "scotopic" must be used. In the case of quantities evaluated using the CIE system for mesopic photometry, the spectral luminous efficiency function can be specified as follows (the first approach is the simplest):

- By specifying the value of the adaptation coefficient, m, e.g. "mesopic luminous intensity for an adaptation coefficient of 0.2" or "mesopic luminous intensity (m=0.2)".
- By specifying the photopic adaptation luminance, $L_{\mathrm{v,adapt}}$ and the S/P ratio of the adaptation field, R_{SP}, e.g. "mesopic luminous intensity for an adaptation field with a photopic luminance of 0.2 cd m^{-2} and an S/P ratio of 2.2" or "mesopic luminous intensity ($L_{\mathrm{v,adapt}}$ =0.2, R_{SP}=2.2)".

The symbols used for the various photometric quantities must likewise clearly distinguish the weighting function used. Conventionally, the symbols for radiometric quantities are differentiated from those for photometric quantities through the use of the subscript e. In the case of symbols for photometric quantities, however, the use of a single subscript is not sufficient since this leads to ambiguity; instead the weighting function used must be clearly identified using the following conventions:

- For photopic quantities, the subscript v alone is used to designate evaluation using the $V(\lambda)$ function e.g. I_{v}
- For scotopic quantities, the $'$ symbol is used together with subscript v to designate evaluation using the $V'(\lambda)$ function e.g. I'_{v}
- For quantities evaluated using the CIE system for mesopic photometry, the subscript mes is used and the adaptation coefficient, *m,* is given in brackets after the symbol e.g. $I_{\mathrm{mes}}(0.2)$ indicates

luminous intensity evaluated using the CIE system for mesopic photometry with an adaptation coefficient m=0.2.

- For quantities evaluated using the CIE system for mesopic photometry, the adaptation conditions may alternatively be given in the form ($L_{v,adapt}$, R_{SP}), where $L_{v,adapt}$ is the photopic luminance of the adaptation field and R_{SP} is its S/P ratio e.g. $I_{mes}(0.3,2.0)$ indicates luminous intensity evaluated using the CIE system for mesopic photometry with an adaptation field that has a photopic luminance of 0.3 cd m^{-2} and an S/P ratio of 2.0.
- For quantities evaluated using other standardised spectral luminous efficiency functions, $V_s(\lambda)$, where s is an agreed subscript designating the specific function involved, the subscript s is used. This means, for example, that luminous intensity evaluated using the CIE 10° standard observer function, $V_{10}(\lambda)$, is designated I_{10}.

2.2 Photometric Units

The SI base unit for photometry, the candela, is defined as follows [3]:

> "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency of 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian."

It is important to note that although the frequency of 540 $\times$ 10^{12} Hz in this definition corresponds to a wavelength of 555.016 nm in standard air, which is approximately the peak of the $V(\lambda)$ function, the definition does not make reference to any particular spectral luminous efficiency function. In other words, although in practice a spectral luminous efficiency function must be applied in order to determine the luminous intensity of radiation at other wavelengths, the definition of the candela is the same regardless of the function that is used. The CIPM (International Committee of Weights and Measures) has published additional guidance to clarify this point [4], which includes the following key statements:

- The definition of the candela applies equally for photopic, scotopic and mesopic vision.
- The SI units of the other photometric quantities can be derived from the SI base unit, the candela, and the units of the geometric quantities, area and solid angle.

Thus the photometric unit to be used for any given measurement depends only the measurement geometry and is completely independent of the spectral luminous efficiency function used. Luminous intensity, for example, is always measured in candela, and illuminance is always measured in lux, whether measurements are made in the photopic, mesopic or scotopic regime. Descriptions such as "mesopic candela" or "mesopic lumen" are not allowed within the SI system and must never be used; descriptor terms such as "scotopic" and "mesopic" must be specified in the quantity name, and must not be associated with the unit.

3. Mesopic Photometry in Practice

In principle, the system for mesopic photometry should be simple to put into practice. It is only necessary to know, or measure, the photopic luminance and scotopic luminance of the adaptation field; this then allows the value of the coefficient, m, and the appropriate spectral luminous efficiency function, $V_{\mathrm{mes}}(\lambda)$, to be determined. The apparent simplicity of this approach, however, masks what is potentially the most challenging aspect of using the system in practice, namely: what is meant by the "adaptation field"? Consider a typical night-time driving environment, as shown in Figure 2. The luminance in this situation is far from uniform, meaning that it is necessary to consider many different issues, such as:

- the size and shape of the region of the entire visual scene that is most important in terms of the visual adaptation conditions
- where in the visual scene this critical region is centred (which in turn will depend on where the driver's attention is focussed, for example)
- whether bright sources of light outside of the critical region have a significant influence on the visual adaptation
- whether variations in luminance within the critical area affect adaptation, or is the average luminance all that matters
- what is the impact of temporal changes in luminance, e.g. due to headlights of oncoming vehicles (i.e. how quickly does the eye adapt to changes in luminance).

Figure 2. An example of a night-time driving scene.

These issues are being considered in CIE JTC-1, "Implementation of CIE 191 mesopic photometry in outdoor lighting", and until this work is completed it is unlikely that large-scale changes in standards for lighting applications at mesopic levels, such as road lighting, will be introduced. In parallel, CIE TC2-65, "Photometric measurements in the mesopic range", is considering related measurement instrumentation, procedures, calculation methods and measurement uncertainties, although recommendations from this TC cannot be finalised until JTC-1 has defined the relevant adaptation field. Nevertheless, although many questions are still to be answered, some progress has already been made relating to the introduction of the mesopic system into residential street lighting. This has been carried out under the auspices of CIE TC4-48 (looking at the effect of spectral power distribution on lighting for urban and pedestrian areas), and the mesopic lighting panel of the Institution of Lighting Professionals (ILP) in the UK. The outcomes from this work are summarised in Section 3.1.

3.1 Residential Street Lighting

Much research has been conducted in recent years into the impact of spectral power distribution on lighting for urban and pedestrian areas [5]. This indicates that lighting in residential roads needs to serve two main purposes:

- to provide an environment which is safe for pedestrians as well as drivers to use, which means, for example, that drivers need to be able to see pedestrians walking by the side of the road, and that pedestrians need to be able to see obstacles such as raised paving stones that may otherwise be a trip hazard.
- to ensure that the environment is perceived to be safe; this is influenced by factors such as a general feeling of safety, which may result from a “brightly lit” street, and an ability to recognise the faces and expressions of other road users at a distance sufficient to take avoiding action if necessary.

This research has also shown that although values of mesopic luminance and/or illuminance correlate well with the general ability of the street lighting to meet both these needs, and mesopic photometry is therefore a good metric to use when designing and installing residential street lighting, it is not, by itself, sufficient to ensure all aspects are fully met. In particular, mesopic photometry alone does not adequately predict the ability to recognise facial expressions and so does not ensure that a lit area is perceived to be safe. These aspects additionally require that the lighting provides good colour discrimination i.e. that it has good colour rendering properties. The mesopic lighting panel of the ILP therefore decided to recommend [6] that lighting for residential streets in the UK should be based on the use of the CIE system for mesopic photometry, coupled with a requirement for a CIE general colour rendering index of at least 60. The approach is as follows:

1. Choose the appropriate photopic illuminance to suit the road and traffic conditions and assume this applies for a specified baseline lamp (in the UK this has been chosen to be low pressure sodium).
2. Convert the specified photopic illuminance to a photopic luminance value using a standard luminance factor for the road surface of 0.07.
3. Using the CIE system for mesopic photometry and the S/P ratio of the baseline lamp, calculate the corresponding mesopic luminance.

4. Using the CIE system for mesopic photometry and the S/P ratio of the type of lamp that is to be installed, calculate the photopic luminance for this new lamp type that has the same mesopic luminance as the baseline lamp.
5. Convert this new photopic luminance for the selected lamp to a photopic illuminance value using a standard luminance factor for the road surface of 0.07.
6. Design the road lighting to meet the new photopic illuminance: this will provide the same visual performance (according to the CIE system of mesopic photometry) as the original baseline lamp.

The ILP recommendation has now been proposed for the latest revision of BS5489 and is included in the technical report from CIE TC4-48[7], which is due to be published shortly.

3.2 Other Issues

Although the CIE system for mesopic photometry, coupled with high colour rendering as indicated in Section 3.1, is a good metric for overall “visibility”, other factors (and therefore other quality metrics) may also need to be considered depending on the specific application. In particular:

- It is likely that the benefits of mesopically-enhanced lighting (i.e. lighting with a higher proportion of lower wavelength radiation) will be reduced for older road users, who generally have lower blue sensitivity (due to yellowing of the lens) and suffer from increased glare under blue light (due to increased scattering in the eye). Further discussion is needed to determine when, where and how to account for observer age in street lighting design.

- It is also important to appreciate that the light reaching an observer’s eyes does not usually come directly from the installed street lighting, but is reflected from the street surface, walls etc. within the visual field. If these are strongly coloured, then the effective spectral power distribution of the lit environment will be different from that of the installed lighting i.e. in such cases the spectral reflectance properties, as well as the average luminance coefficient, may need to be considered when determining the adaptation conditions.

- It is not just the spectral properties of the lamp and the luminance or illuminance at the road surface that is important; the type of luminaire and the spatial distribution of light from the chosen luminaire must also be considered in order to avoid glare effects and to minimise energy wastage / light pollution effects.

4. Quality Metrics Related to Mesopic Measurements of SSL

The publication of an internationally-agreed system for mesopic photometry paves the way for the new lighting solutions aimed specifically at applications in the mesopic regime, particularly lighting for residential areas and roads at night. The system will support the design and installation of lighting that is more visually-effective at mesopic lighting levels, and therefore offers opportunities for energy savings and/or improved lighting. SSL products are particularly well-placed to exploit these opportunities, since they offer the potential for tailoring the spectral power distribution in order to maximise performance for any given state of visual adaptation. However it is important to appreciate that the mesopic efficiency of a lighting product depends on the visual adaptation, and is not an intrinsic property of the lamp or luminaire. The same lamp may lead to many different states of visual adaptation depending on how it is used. Traditionally the output of a lamp has been quoted in terms of the (photopic) luminous flux, and luminance and illuminance values when using the lamp in any given luminaire or any specified lighting installation have been simple to calculate using parameters such as the light output ratio and the lighting column height and spacing. For mesopic applications, however, the resultant mesopic luminance and illuminance values depend on the visual adaptation, and will change if, for example, the lighting column height or spacing is altered. It is therefore no longer such a straightforward matter to calculate the optimum configuration of lamp and luminaire, column height and spacing etc. needed to achieve a specified lighting performance. Full implementation of mesopic photometry requires not only that revisions are made to the relevant lighting standards, but also that lighting design software for mesopic applications is modified in order to allow mesopic values to be calculated. Despite this complication, the metrics for characterising the performance of lighting products (including SSL) for mesopic applications are very straightforward: all the information required can be provided simply by stating the photopic luminous flux and the S/P ratio.

In addition, as indicated in section 3, it must be remembered that characterisation according to the system for mesopic photometry is not sufficient to ensure that the resultant lighting is of high quality i.e. meets all the relevant needs of the end users. Other aspects, such as good colour rendering and minimisation of glare, are also critical.

Based on these considerations, the following metrics should be regarded as the minimum needed in order to adequately characterise lighting products (including SSL) for mesopic applications:

- The relevant photopic quantity, typically photopic luminous flux
- The S/P ratio
- The colour rendering index
- The angular light distribution (including the angular distribution expressed in terms of S/P ratio and colour rendering if the spectral power distribution varies with angle)

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