International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

TECHNICAL NOTE

The Use of Terms and Units in Photometry – Implementation of the CIE System for Mesopic Photometry

CIE TN 004:2016

CIE Technical Notes (TN) are short technical papers summarizing information of fundamental importance to CIE Members and other stakeholders, which either have been prepared by a TC, in which case they will usually form only a part of the outputs from that TC, or through the auspices of a Reportership established for the purpose in response to a need identified by a Division or Divisions.

This Technical Note has been prepared by CIE Technical Committee 2-65 of Division 2 “Physical Measurement of Light and Radiation" and has been approved by the Board of Administration as well as by Division 2 of the Commission Internationale de l'Eclairage. 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.

Any mention of organizations or products does not imply endorsement by the CIE. Whilst every care has been taken in the compilation of any lists, up to the time of going to press, these may not be comprehensive.

The following members of TC 2-65 “Photometric measurements in the mesopic range“ took part in the preparation of this Technical Note. The committee comes under Division 2 “Physical measurement of light and radiation”.

Authors:

Goodman, T.M. (Chair)	**United Kingdom**
Bergen, T.	Australia
Blattner, P.	Switzerland
Ohno, Y.	USA
Schanda, J. †	Hungary
Uchida, T.	Japan

Advisors:

Dam-Hansen, C.	Denmark
Schakel, M.	Netherlands
Shpak, M.	Finland

CONTENTS

Summary

This Technical Note gives guidance on the use of terms and units in photometry, particularly in relation to terms and units applicable for mesopic photometry. It can be used in conjunction with CIE 191:2010 (CIE, 2010), which gives details of the method that should be used to calculate mesopic quantities and is fully compliant with the requirements of the SI system (Organisation Intergouvernementale de la Convention du Mètre, 2006) and the principles governing photometry (BIPM, 1983).

1 Introduction

The complexity of the human visual system means that the response of the eye varies depending on many factors, such as the lighting level and its spectral qualities, the position of an observed target in the visual field and the size of that target, and the age of the observer. As a result, it is not possible to define a single spectral luminous efficiency function that applies for all visual situations, or to devise a measurement system that will provide a complete prediction of visual performance for all tasks or environmental conditions. Instead, lighting standards, specifications, product descriptions etc. are based on a small number 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 and provide a direct link between a given radiometric quantity, $X_{\mathrm{e},\lambda}(\lambda)$, (e.g. spectral radiant intensity) and the corresponding photometric quantity, $X_{\mathrm{v,x}}$, (e.g. luminous intensity) using:

$$X_{\mathrm{v,x}} = \frac{K_{\mathrm{cd}}}{V_{\mathrm{x}}(\lambda_{\mathrm{a}})} \int_{\lambda} X_{\mathrm{e},\lambda}(\lambda)\, V_{\mathrm{x}}(\lambda)\, \mathrm{d}\lambda \qquad (1)$$

where $V_{\mathrm{x}}(\lambda)$ is the relevant spectral luminous efficiency function; $V_{\mathrm{x}}(\lambda_{\mathrm{a}})$ is the value of this function at the wavelength λ_{a} in standard air corresponding to a frequency of 540×10^{12} Hz (i.e. a wavelength of 555,016 nm); and K_{cd} is the spectral luminous efficacy for monochromatic radiation of frequency 540×10^{12} Hz and has the value 683 $\mathrm{lm \cdot W^{-1}}$ according to the SI definition of the photometric base unit, the candela (Organisation Intergouvernementale de la Convention du Mètre, 2006).

Until recently, only two spectral luminous efficiency functions had been internationally agreed (CIE, 1983):

- The 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.
- 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.

Over recent years, a number of other spectral luminous efficiency functions have additionally been defined, each of which applies for a different, specific condition, such as $V_{10}(\lambda)$ which applies for a 10° field under photopic adaptation conditions (CIE, 2005). However, even with the definition of these additional functions, a significant shortcoming remained in the system for photometric measurements: namely the absence of an agreed method for defining appropriate luminous efficiency functions for use in the mesopic region, where 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 deficiency has been addressed with the publication of the CIE system for mesopic photometry in CIE 191:2010 (CIE, 2010). CIE 191:2010 establishes a comprehensive procedure for measurement of photometric quantities at all light levels, by providing a smooth transition between the photopic and scotopic conditions (i.e. between the $V(\lambda)$ and $V'(\lambda)$ functions respectively). Under this system, called MES2 in CIE 191:2010, the relevant spectral luminous efficiency function, $V_{\mathrm{mes};m}(\lambda)$, is given by:

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

where the adaptation coefficient, m, can be determined from the photopic adaptation luminance and spectral characteristics of the visual adaptation field and $M(m)$ is a normalizing factor such that $V_{\mathrm{mes};m}(\lambda)$ attains a maximum value of one. If the mesopic luminance of the adaptation field is 5 cd·m^{-2} or above, the value of m is unity, whereas if the mesopic adaptation luminance is 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, i.e. 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, $V(\lambda)$.

The spectral luminous efficiency functions for various values of the adaptation coefficient m are shown in Figure 1.

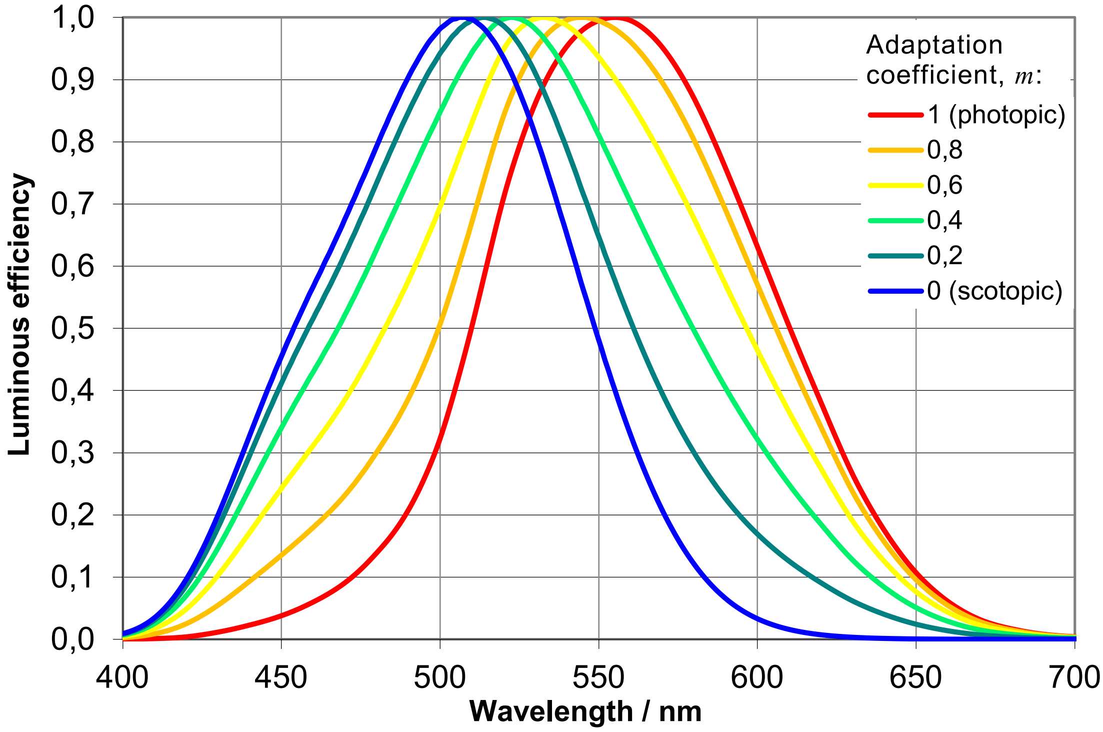

Figure 1 – Spectral luminous efficiency functions $V_{\mathrm{mes};m}(\lambda)$ for various values of the adaptation coefficient, m

As noted previously, the spectral luminous efficacy for monochromatic radiation of frequency 540 × 10^{12} Hz (i.e. wavelength of approximately 555 nm) always has the value 683 lm·W^{-1} according to the SI definition of the candela. For any given adaptation coefficient, m, the spectral luminous efficacy at the wavelength for which $V_{\mathrm{mes};m}(\lambda)$ is a maximum (i.e. the maximum luminous efficacy for mesopic vision under that adaptation condition) is given by Equation (3) below. This is the multiplier in front of the integral in Equation (1) and is shown graphically in Figure 2. It varies from 683 lm·W^{-1} for m = 1 (photopic) to 1 700 lm·W^{-1} for m = 0 (scotopic).

$$K_{\mathrm{mes};m} = \frac{K_{\mathrm{cd}}}{V_{\mathrm{mes};m}(\lambda_{\mathrm{a}})} \tag{3}$$

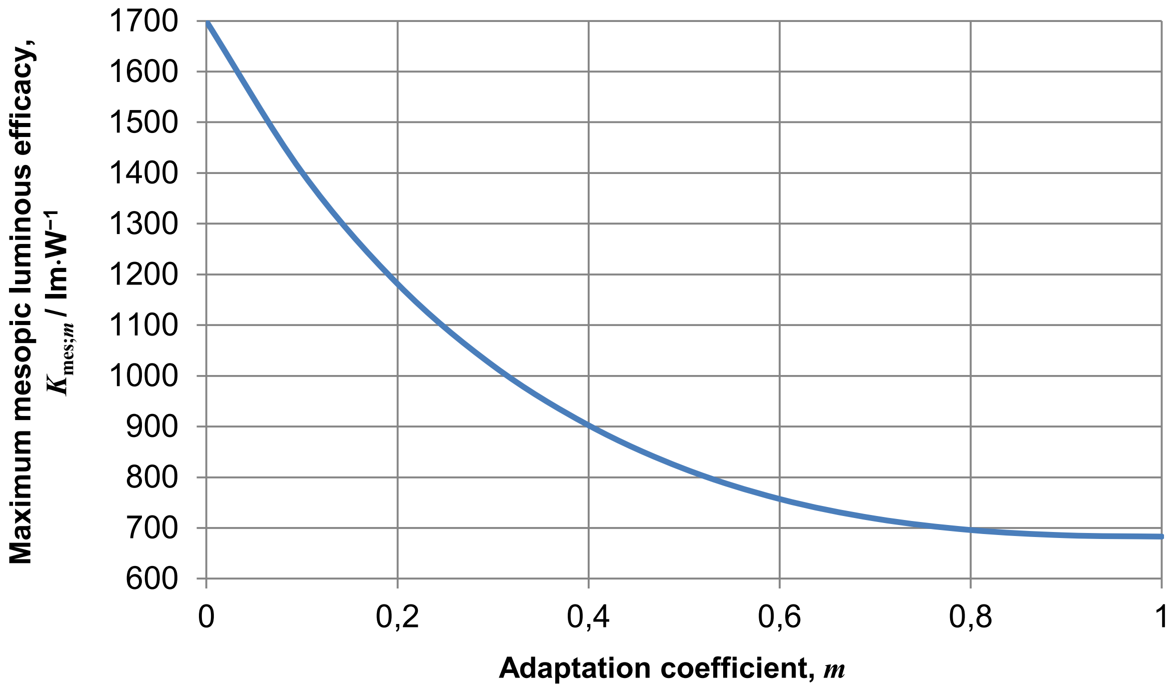

Figure 2 – Maximum mesopic luminous efficacy $K_{\mathrm{mes};m}$ as a function of the adaptation coefficient, m

2 Photometric quantities and symbols

The International Lighting Vocabulary (CIE, 2011) defines radiometry as the "measurement of the quantities associated with optical radiation", while photometry is defined as the "measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency function". In all cases, it is the measurement geometry being used that determines the quantity being measured, or conversely, it is the required quantity to be measured that determines the measurement geometry to be used. For example, the quantity total (radiant) flux refers to the total optical radiant power emitted from a source, while the quantity (radiant) intensity refers to the optical radiant power emitted by a source into an infinitesimal solid angle in a given direction. Photometric quantities are generally distinguished from the geometrically-equivalent radiometric quantities by the use of the word "luminous" (e.g. total luminous flux, luminous intensity); 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, the simple addition of the word "luminous" to the quantity is not sufficient: it is essential also to specify the spectral luminous efficiency function used. This necessity has often been ignored in the past; the fact that only two functions ($V(\lambda)$ and $V'(\lambda)$) had been internationally recognized, and that $V(\lambda)$ was used for almost all practical applications, meant there was little possibility of confusion. Where further clarification was necessary, the relevant spectral luminous efficiency function was made more explicit through the addition of the qualifying adjectives "photopic" and "scotopic" to the description of the quantity, indicating the use of the $V(\lambda)$ or $V'(\lambda)$ function respectively. For example, the quantity photopic luminous flux refers to optical radiant power evaluated using the photopic spectral luminous efficiency function, $V(\lambda)$, whereas scotopic luminous flux refers to optical radiant power evaluated using the scotopic spectral luminous efficiency function, $V'(\lambda)$. With the introduction of new internationally recognized luminous efficiency functions, however, this relatively simple situation has now changed.

The multiplicity of spectral luminous efficiency functions now available means that in order to express a measured quantity in an unambiguous form, the description of the quantity **must** include a description of the weighting function used. If no spectral luminous efficiency function is specified (or if the simple qualifying descriptor "photopic" is used), it is assumed, by convention, that the $V(\lambda)$ function applies. For quantities evaluated using the $V'(\lambda)$ function, the qualifying descriptor "scotopic" is sufficient, but must always be used. In the case of mesopic quantities, the spectral luminous efficiency function can be described either by specifying the value of the adaptation coefficient, m, or by specifying both the photopic adaptation luminance, $L_{\mathrm{v,adapt}}$, and the S/P ratio of the adaptation field, R_{SP}; the former approach is the simplest and is therefore strongly recommended.

The symbols used for the various photometric quantities must likewise clearly distinguish the weighting function used. Conventionally, the symbols for radiometric and photometric quantities are differentiated through the use of the subscripts e and v respectively. To avoid any ambiguity for photometric symbols, however, the weighting function used must additionally be clearly identified using the following conventions:

1. For photopic quantities, the subscript v alone is used to designate quantities evaluated using the $V(\lambda)$ function, e.g. I_{v}
2. For scotopic quantities, the symbol ' is used together with subscript v to designate quantities evaluated using the $V'(\lambda)$ function, e.g. I'_{v}
3. For quantities evaluated using other standardized spectral luminous efficiency functions, $V_{\mathrm{s}}(\lambda)$, where s is an agreed subscript designating the specific function involved, the subscript s is used with the appropriate quantity symbol, e.g. I_{s}. This means, for example, that luminous intensity evaluated using the CIE 10° standard observer function, $V_{10}(\lambda)$, is designated I_{10}.
4. For quantities evaluated using the CIE system for mesopic photometry, the subscript mes must be used followed by a semicolon and the value of the adaptation coefficient, m, 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.

Table 1 gives some examples of acceptable photometric quantities, the symbol used to describe those quantities, and the associated spectral luminous efficiency functions for which they apply.

Table 1 – Some photometric quantities with their associated symbols and spectral luminous efficiency functions

Photometric quantity	Quantity symbol	Spectral luminous efficiency function
(Photopic) illuminance	E_{v}	$V(\lambda)$
(Photopic) luminous intensity	I_{v}	$V(\lambda)$
Photopic luminous flux for the CIE 10° photopic photometric observer function	Φ_{10}	$V_{10}(\lambda)$
(Photopic) luminance	L_{v}	$V(\lambda)$
Scotopic luminance	L'_{v}	$V'(\lambda)$
Mesopic luminance using an adaptation coefficient m = 0,4	$L_{\mathrm{mes;0,4}}$	$V_{\mathrm{mes;0,4}}(\lambda)$ *

* The spectral luminous efficiency function for $V_{\mathrm{mes;0,4}}$ is calculated from 0,4 $V(\lambda)$ + 0,6 $V'(\lambda)$ with a normalization factor $M(m)$ = 0,8472.

3 Photometric units

The SI base unit for photometry, the candela, is defined as follows (Organisation Intergouvernementale de la Convention du Mètre, 2006):

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

This definition, which was adopted by the CGPM (General Conference of Weights and Measures) in 1979, is independent of the spectral luminous efficiency function that is used to weight radiation at other wavelengths (frequencies); in other words, it applies for all spectral luminous efficiency functions. This approach was taken in recognition of the fact that, although only two spectral luminous efficiency functions had been defined at the time the definition was being prepared – the $V(\lambda)$ and $V'(\lambda)$ functions – it was likely that additional functions would be defined by the CIE in the future. By setting the absolute level of the candela through a radiant intensity value at just one wavelength (frequency), it was possible to ensure the definition did not need to be updated each time a new spectral luminous efficiency function was introduced. For practical use of photometric units, however, the spectral luminous efficiency function used must be defined and the CIPM (International Committee of Weights and Measures) has therefore published additional guidance to clarify this point (BIPM, 1983). This guidance 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.

These statements make clear that (a) the SI system can be used with any defined spectral luminous efficiency function for human vision and (b) the SI units are the same, whichever spectral weighting function is used. (Additionally it is implicit that the spectral luminous efficiency function must obey the law of additivity under the defined conditions for which it applies, and must have a non-zero value at a wavelength of 555 nm. These conditions are satisfied for all spectral luminous efficiency functions published by the CIE.)

Thus the photometric unit to be used for any given measurement depends only on the measurement geometry: it 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" should be specified in the quantity name, not with the unit (so, for example, "mesopic illuminance" is acceptable but "mesopic lux" is not).

Photometric values should be expressed in the form of an unambiguous description of the photometric quantity (including declaration of the spectral luminous efficiency function), a numerical value, and the appropriate photometric unit. As a general rule, the number of significant figures given for the adaptation coefficient (if needed) should be the same as the number of significant figures for the associated photometric value e.g. if the mesopic luminance is 5,00 $cd \cdot m^{-2}$ (3 significant figures) the adaptation coefficient should also be expressed to 3 significant figures. If the S/P ratio is given, this should also be expressed to the same number of significant figures as the associated photometric value. The examples given in Table 2 are all acceptable descriptions of photometric quantities and values.

Table 2 – Examples of valid verbal and symbolic descriptions of photometric values

Verbal description	Symbolic description
Photopic luminous intensity of 35,0 cd	I_v = 35,0 cd
Luminous flux of 230 lm *	Φ_v = 230 lm
Scotopic luminous flux of 6,5 lm	Φ'_v = 6,5 lm
Mesopic luminance using an adaptation coefficient of 0,60 is 2,6·cd m^{-2}	$L_{mes;0,60}$ = 2,6 cd·m^{-2}
Mesopic luminance is 5,05 cd·m^{-2}, evaluated for an adaptation field with a photopic luminance of 0,300 cd·m^{-2} and an S/P ratio of 1,80 #	$L_{mes;0,614}$ = 5,05 cd·m^{-2}
Mesopic luminous flux is 30,0 lm, evaluated for visual adaption at a photopic luminance of 0,100 cd·m^{-2} using a source with an S/P ratio of 2,20 §	$\Phi_{mes;0,479}$ = 30,0 lm
Photopic luminous flux using the CIE 10° photopic photometric observer function is 5 000 lm	Φ_{10} = 5 000 lm

* Note: where no qualifying descriptor is given, as in this case, it is assumed that the quantity is a photopic quantity.

\# See Appendix 1a of (CIE, 2010) for determination of m = 0,61 for these adaptation conditions.

§ See Appendix 1a of (CIE, 2010) for determination of m = 0,479 for these adaptation conditions.

4 Open issues

It should be noted that further guidance is still needed for the practical use of mesopic photometric quantities, e.g. how to determine the adaptation field, for what applications mesopic quantities are relevant, and what values should be specified in the associated application standards. Work is in progress under the auspices of CIE JTC 1 (D1/D2/D4/D5) to develop further recommendations. In addition, CIE JTC 2 (CIE/CCPR) is working to prepare a comprehensive joint CIPM/CIE publication on “Principles Governing Photometry” that will explicitly formalize the above recommendations under the SI system of units.

5 Conclusions

Photometry is used to quantify the visual effect produced by optical radiation as it is perceived by the human eye. The response of the eye is not constant, but varies depending on many factors such as the lighting level and its spectral qualities, the position of an observed target in the visual field and the size of that target, and the age of the observer. Consistent and reproducible photometric measurement therefore relies on the use of standardized spectral luminous efficiency functions, which are used to define the visual effectiveness of light under specified visual adaptation conditions. When making measurements and reporting the results, it is essential to state which of these standardized spectral luminous efficiency functions has been used, following the recommendations given in this Technical Note.

The units associated with photometric measurements do not depend on the spectral luminous efficiency function used, but only on the measurement geometry. Qualifying descriptors, such as “photopic”, “scotopic” or “mesopic”, must never be used in association with a photometric unit. However, these qualifying descriptors must be used when describing or specifying photometric quantities; if no qualifying descriptor is given, the quantity is assumed to be a photopic quantity (i.e. calculated using the photopic spectral luminous efficiency function, $V(\lambda)$).

References

ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU MÈTRE, 2006*. The International System of Units (SI) 8th Edition*. ISBN 92-822-2213-6. Available from www.bipm.org.

CIE, 1983. CIE 18.2-1983: *The Basis of Physical Photometry, 2nd edition*. Vienna: CIE.

CIE, 1965. CIE 165:2005*: CIE 10 Degree Photopic Photometric Observer*. Vienna: CIE.

CIE, 2010. CIE 191:2010. *Recommended System for Mesopic Photometry Based on Visual Performance*. Vienna: CIE.

CIE, 2011. CIE S 017/E:2011: *ILV: International Lighting Vocabulary*. Vienna: CIE.

BIPM, 1983. Bureau International des Poids et Mesures. *Principles Governing Photometry*. Available from www.bipm.org.