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Photometry — The CIE system of physical photometry

Photométrie — Le système CIE de photométrie physique

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by the International Commission on Illumination (CIE) in cooperation with Technical Committee ISO/TC 274, *Light and lighting*.

This first edition of ISO/CIE 23539 cancels and replaces ISO 23539:2005/CIE S 010:2004, which has been technically revised.

The main changes are as follows:

— The scope of the document has changed to incorporate the spectral luminous efficiency functions published by the CIE for a) mesopic vision and b) 10° photopic vision, on the basis of CIE 018:2019.

— The International System of Units (SI) and its reformulation of the definition of the candela – effective on 20 May 2019 – has been incorporated (Resolution 1, 26th CGPM, 2018).

— A list of normative references has been added.

— Specific requirements have been added regarding the use of units, tabulated values and interpolation of intermediate values.

— The background of the CIE system of physical photometry, specifically the evolution of the photometric base unit, has been updated in Annex C.

— The CIE 2015 cone-fundamental-based spectral luminous efficiency functions for a) 2° field size and b) 10° field size have been added in Annex E based on CIE 170-2:2015.

Any feedback or questions on this document should be directed to the CIE Central Bureau or the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The purpose of photometry is to measure light as perceived by human eyes. The brightness of a luminous surface depends not only on the amount of radiation it emits, transmits or reflects, but also on its spectral composition and on the visual response function of the observer viewing it. Because human visual response varies at different light levels and from person to person, precise photometry requires the definition of representative standard observers. The CIE system of physical photometry specifies procedures for the quantitative evaluation of optical radiation in terms of internationally agreed spectral luminous efficiency functions for human vision. $V(\lambda)$ represents photopic vision, $V'(\lambda)$ represents scotopic vision and $V_{\mathrm{mes};m}(\lambda)$ represents mesopic vision, the latter being intermediate between photopic and scotopic vision. Furthermore, $V_{10}(\lambda)$ represents 10° photopic vision. These luminous efficiency functions adopted from CIE 018:2019[1] and BIPM-2019/05,[2] together with the SI base unit, the candela, constitute a system that enables the calculation of values of photometric quantities for optical radiation as well as light-emitting, light-transmitting or light-reflecting surfaces, to be precisely determined based on the International System of Units (SI), regardless of the spectral composition of the radiation emitted, transmitted or reflected.

The CIE system of physical photometry has some limitations in respect to the brightness of coloured surfaces: two light sources of different colour but with the same measured luminance value will not necessarily be perceived as equally bright. CIE has therefore published a more complex model (CIE 200:2011)[3] for specific situations. For eye-mediated non-image-forming effects of light induced partially or completely by the intrinsically photosensitive retinal ganglion cells (ipRGCs), CIE S 026/E:2018[4] is used.

Photometry — The CIE system of physical photometry

1 Scope

This document specifies the characteristics of the system of physical photometry established by the CIE and accepted as the basis for the measurement of light. It defines the photometric quantities, units and standards that make up the CIE system of physical photometry and that have been officially accepted by the Comité International des Poids et Mesures (CIPM). This comprises:

— the definition of photometric quantities, symbols and units;

— the definition of CIE spectral luminous efficiency functions for photopic vision, scotopic vision, mesopic vision and 10° photopic vision;

— the definition of CIE photometric observers that conforms to these functions;

— the definition of maximum luminous efficacy for photopic vision, mesopic vision, scotopic vision and 10° photopic vision.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

CIE S 017, *ILV: International Lighting Vocabulary*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in CIE S 017 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

CIE maintains a terminology database for use in standardization at the following address:

— CIE e-ILV: available at https://cie.co.at/e-ilv

3.1
CIE photometric observer
CIE observer
ideal observer having a relative spectral responsivity that conforms to a CIE-defined spectral luminous efficiency function for human vision and that complies with the summation law implied in the definition of luminous flux

Note 1 to entry: CIE has defined spectral luminous efficiency functions for photopic vision, $V(\lambda)$, and scotopic vision, $V'(\lambda)$, which are CIE standard photometric observer(s). Furthermore, CIE has defined CIE photometric observers for mesopic vision, $V_{\text{mes};m}(\lambda)$, and 10° photopic vision, $V_{10}(\lambda)$, as well as published definitions of cone-fundamental-based spectral luminous efficiency functions[5].

Note 2 to entry: CIE photometric observers are distinct from CIE standard photometric observers, which only include spectral luminous efficiency functions for photopic vision, $V(\lambda)$, and scotopic vision, $V'(\lambda)$.

Note 3 to entry: Other spectral luminous efficiency functions defined in this document are also intended to define CIE photometric observers.

Note 4 to entry: Other spectral luminous efficiency functions will possibly be included as CIE photometric observers. However, only the functions tabled in Clause 8 relate the given spectral radiometric quantity to the International System of Units (SI).

3.2
10° photopic vision
10° vision
photopic vision based on the CIE 10° photopic photometric observer

Note 1 to entry: 10° photopic vision corresponds to vision by the normal eye in situations where the visual target has an angular subtense larger than 4° or is seen off-axis.

4 Photometric quantities and units

4.1 Photometric quantities

The most commonly used photometric quantities are:

— luminous flux;

— luminous intensity;

— luminance;

— illuminance.

These quantities are defined in CIE S 017 and their definitions, adopted by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM), are referred to in this clause. After the redefinition of the SI units in 2019,[6] the definition of the unit of candela is tied to the definitions of the SI units kilogram, second and metre. It is important to note that the 2019 reformulation of the definition of the candela does not make a numerical difference in the calculations of the photometric quantities.

To avoid confusion, photometric quantities are distinguished symbolically from their radiometric equivalents by the subscript “v”, whereas radiometric quantities receive the subscript “e”. The same subscripts are also applicable to photometric and radiometric quantities other than those listed (e.g. luminous exposure, radiant exposure). For photometric quantities using spectral luminous efficiency functions other than that for 2° photopic vision, $V(\lambda)$, the quantity names and symbols described in Clause 6 are used.

For many practical purposes the simplest physical quantity used in optical radiometry is the radiant flux or radiant power, Φ_e, measured in watts (W), which is emitted by a source of radiation, transmitted by a medium of propagation or received at a surface. The corresponding photometric quantity is the luminous flux, Φ_v, measured in lumen (lm), derived from radiant flux, Φ_e, by evaluating the radiation according to its action upon a CIE standard photometric observer or CIE photometric observer. In this document the relation between radiometric quantities and photometric quantities is shown by example using the relation between the radiant flux and the (photopic) luminous flux using the CIE standard photometric observer for photopic vision, as well as other CIE photometric observers. The general relation between a given luminous flux, $\Phi_{v,X}$, for a specific photometric condition, X, and the spectral radiant flux $\Phi_{e,\lambda}(\lambda)$ is given in 7.3, with specific observers shown in 7.5 to 7.8.

The most commonly used photometric quantities given in this subclause, as well as others such as luminous exitance and luminous exposure, are defined in CIE S 017. All photometric quantities can be formulated in terms of luminous flux and appropriate geometric factors. The defining relationships for other photopic, scotopic and mesopic photometric quantities are formed from the formulae in 7.5 to 7.8 by replacing the symbols for radiant flux and luminous flux with the appropriate radiometric and photometric symbols.

Where a particular spectral luminous efficiency function is not specified, the photopic condition is implied.

4.2 Photometric units

The General Conference on Weights and Measures (CGPM) has fundamentally revised the SI to be based on seven defining constants.[6] In particular, the luminous efficacy of a monochromatic radiation of frequency 540 × 10^{12} Hz, K_{cd}, is introduced and its value is set to 683 lm·W^{-1}. This constant relates the photometric units (lm, cd and lx) directly to the corresponding radiometric units (W, W·sr^{-1} and W·m^{-2}).

As a consequence, the SI unit of luminous intensity of a source in a given direction, the candela, symbol cd, is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz, K_{cd}, to be 683 when expressed in the unit lm·W^{-1}, which is equal to cd·sr·W^{-1}, or cd·sr·kg^{-1}·m^{-2}·s^3, where the kilogram, metre and second are defined in terms of h, c and $\Delta\nu_{Cs}$.

This definition of the candela applies equally to any photometric condition (photopic vision, scotopic vision, mesopic vision and 10° photopic vision). The evolution of the photometric units is found in Annex C.

5 CIE standard spectral luminous efficiency functions

5.1 General

Photometric quantities are related to radiometric quantities through internationally agreed spectral weighting functions defined by the CIE as “spectral luminous efficiency functions”. These spectral luminous efficiency functions provide representations of the relative spectral sensitivity of the human visual system under defined conditions and are normalized to unity at the wavelength of peak sensitivity. The relevant spectral luminous efficiency function is applied as a spectral weighting to the spectral distribution of the corresponding radiometric quantity in order to calculate the corresponding photometric quantity (see Clause 7 for further details).

The most common spectral luminous efficiency functions are:

— $V(\lambda)$: photopic luminous efficiency function;

— $V'(\lambda)$: scotopic luminous efficiency function;

— $V_{mes;m}(\lambda)$: mesopic luminous efficiency function;

— $V_{10}(\lambda)$: 10° photopic efficiency function.

These are described in 5.2 to 5.5 and given as tabled values in Clause 9.

This document defines the spectral luminous efficiency functions for photopic, scotopic, mesopic and 10° photopic photometric conditions. These functions shall be used in the determination of photometric quantities when the corresponding condition is met.

Outside the specified spectral range, all values of the luminous efficiency functions shall be set to zero. See also 8.3.2.

5.2 Photopic vision

The spectral luminous efficiency function $V(\lambda)$ applies to photopic vision and shall be used for determination of photometric quantities at luminance levels above 5 cd·m^{-2}. It is important to note that the $V(\lambda)$ function applies at all luminance levels for foveal vision or for all on-axis visual tasks (objects seen by the eye are in a narrow field of view in central vision i.e. ≤4°). It is defined by the numerical values given in Table 6, the wavelength being measured in standard air.[7] For numerical computations, the peak value of the $V(\lambda)$ function shall be evaluated at 555 nm exactly. For calculation purposes, linear interpolation shall be used exclusively to evaluate $V(\lambda)$ at wavelengths intermediate to those given in Table 6.

5.3 Scotopic vision

The spectral luminous efficiency function $V'(\lambda)$ applies to scotopic vision and shall be used for determination of photometric quantities in situations where the eye is adapted to average luminance levels less than 0,005 cd·m^{-2}. This function is defined by the numerical values given in Table 7, the wavelength λ being measured in standard air. For numerical computations, the peak value of the $V'(\lambda)$ function shall be evaluated at 507 nm exactly. For calculation purposes, linear interpolation shall be used exclusively to evaluate $V'(\lambda)$ at wavelengths intermediate to those given in Table 7.

5.4 Mesopic vision

The spectral luminous efficiency function $V_{\text{mes};m}(\lambda)$ applies to mesopic vision under given adaptation conditions and shall be used for determination of photometric quantities at luminance levels in the intermediate range between photopic and scotopic vision. The procedure to calculate $V_{\text{mes};m}(\lambda)$ for a given adaptation coefficient, m, is given in this subclause and the calculation of the mesopic luminous flux is given in 7.7 as an example.

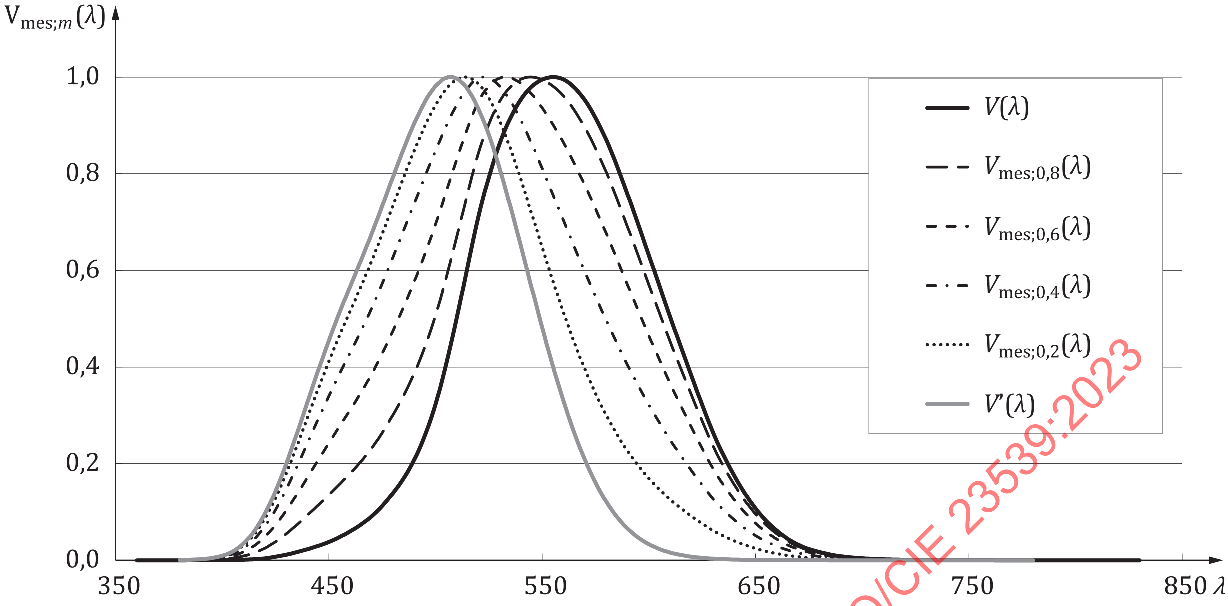
The spectral luminous efficiency function for mesopic vision is denoted by $V_{\text{mes};m}(\lambda)$ and is defined according to Formula (1):

$$V_{\text{mes};m}(\lambda) = \frac{1}{M(m)}\{mV(\lambda) + (1-m)V'(\lambda)\} \quad \text{for } 0 \le m \le 1 \tag{1}$$

where

- m is the adaptation coefficient, the value of which depends on the visual adaptation conditions (see 7.7);
- $M(m)$ is a normalizing function such that $V_{\text{mes};m}(\lambda)$ attains a maximum value of 1.

Figure 1 shows the curves of the mesopic spectral luminous efficiency function $V_{\text{mes};m}(\lambda)$ for m = 0,2; 0,4; 0,6; 0,8 as examples, plotted with $V(\lambda)$ and $V'(\lambda)$. Table A.1 in Annex A shows the values of $V_{\text{mes};m}(\lambda)$ for m = 0,8 as an example, which corresponds to the visual adaptation condition for a typical road lighting luminance level (≈ 1 cd·m^{-2}), considering Formulae (12) and (13).



Key

λ wavelength in nm

$V_{mes;m}(\lambda)$ spectral luminous efficiency for mesopic vision

Figure 1 — The spectral luminous efficiency for mesopic vision, $V_{mes;m}(\lambda)$, at m = 0,2; 0,4; 0,6; 0,8 as examples, plotted with $V(\lambda)$ and $V'(\lambda)$

5.5 10° photopic vision

The spectral luminous efficiency function $V_{10}(\lambda)$ applies for 10° photopic vision and shall be used for measurements in situations where the visual target has an angular subtense larger than 4° or is seen off-axis. The values of $V_{10}(\lambda)$ are given in Table 8.

6 Names, symbols and units for photometric quantities

6.1 General

This clause describes the relations between the names, symbols and units for photometric quantities used in the CIE system of physical photometry.

The SI defines the photometric units through the introduction of the constant K_{cd} = 683 lm·W^{-1}, i.e. the luminous efficacy for monochromatic radiation of frequency 540 × 10^{12} Hz. Thus, by construction the unit of the photometric quantity “luminous flux” is lumen and therefore independent of the photometric condition (i.e. photopic, scotopic, mesopic, 10° photopic), see also Formula (2). The independence of the unit from the observer holds also for the other photometric units, i.e. for all photometric quantities listed in 4.1 the same SI units – cd, lm, lx, cd·m^{-2} – apply, and these shall not be modified.

Also, when a photometric quantity is expressed with photometric units, additivity shall hold (at least within the stated visual adaptation conditions).

Photometric units are not used for non-visual effects.[4] For non-visual effects, radiometric units are used.

NOTE See Annex D for guidance on the valid description of photometric values.

6.2 Photopic vision

Table 1 shows the quantity names, symbols and units that apply for photopic vision [using the spectral luminous efficiency function for photopic vision, $V(\lambda)$] and derivations of the units.

Table 1 — Photometric quantities for photopic vision with their associated symbol, SI unit and unit expressed in terms of other SI units

Quantity	Symbol	SI unit	Unit expressed in terms of other SI units
(Photopic) luminous flux	Φ_v	lm	cd·sr
(Photopic) luminous intensity	I_v	cd	lm·sr^{-1}
(Photopic) luminance	L_v	cd·m^{-2}	lm·sr^{-1}·m^{-2}
(Photopic) illuminance	E_v	lx	lm·m^{-2}, cd·sr·m^{-2}
NOTE 1 The descriptor “photopic” is used only when quantities other than photopic are reported or discussed in the same document and there is a possibility of confusion.			
NOTE 2 The steradian (symbol sr) is the unit for solid angle. 1 sr is the solid angle subtended at the centre of a sphere by an area of the surface that is equal to the squared radius. The steradian can be expressed in terms of the metre as sr = m^2/m^2.			

6.3 Scotopic vision

Table 2 shows the quantity names and symbols that apply for scotopic vision [using the spectral luminous efficiency function for scotopic vision, $V'(\lambda)$].

Table 2 — Photometric quantities for scotopic vision with their associated symbol and SI unit

Quantity	Symbol	SI unit
Scotopic luminous flux	Φ'_v	lm
Scotopic luminous intensity	I'_v	cd
Scotopic luminance	L'_v	cd·m^{-2}
Scotopic illuminance	E'_v	lx

6.4 Mesopic vision

Table 3 shows the quantity names and symbols that apply for mesopic vision[8] [using the spectral luminous efficiency function for mesopic vision, $V_{\mathrm{mes};m}(\lambda)$].

Table 3 — Photometric quantities for mesopic vision with their associated symbol and SI unit

Quantity	Symbol	SI unit
Mesopic luminous flux	$\Phi_{\mathrm{mes};\,m}$	lm
Mesopic luminous intensity	$I_{\mathrm{mes};\,m}$	cd
Mesopic luminance	$L_{\mathrm{mes};\,m}$	cd·m^{-2}
Mesopic illuminance	$E_{\mathrm{mes};\,m}$	lx

m is a coefficient ($0 \leq m \leq 1$) determined by the visual adaptation level. The value of m shall be specified as appendage to the quantity name, for example “mesopic luminous flux (m = 0,5)”, as well as subscript to the symbol, for example “$\Phi_{\mathrm{mes};\,0,5}$”. Further guidance is available in Reference [8].

NOTE Mesopic photometric quantities follow the law of additivity only within a scene at a certain adaptation luminance level. For m = 1 and m = 0, the mesopic photometric quantities are identical to the photopic and scotopic quantities, respectively (see 7.7).

6.5 10° Photopic vision

Table 4 shows the quantity names and symbols that apply for 10° photopic vision [using the spectral luminous efficiency function for 10° photopic vision, $V_{10}(\lambda)$].

Table 4 — Photometric quantities for 10° photopic vision with their associated symbol and SI unit

Quantity	Symbol	SI unit
10° luminous flux	Φ_{10}	lm
10° luminous intensity	I_{10}	cd
10° luminance	L_{10}	cd·m^{-2}
10° illuminance	E_{10}	lx

6.6 Photometric quantities for other observers

For research purposes, photometric quantities for observers other than those introduced in 6.2 to 6.5 may be used, for example observers adapted from the cone-fundamental-based spectral luminous efficiency functions defined in CIE 170-2:2015[5] and the CIE 1988 modified 2° observer.[9] When one of these CIE observers is used, the respective spectral luminous efficiency function shall be specified to avoid any confusion with other CIE-defined photometric quantities. Additionally, an appropriate quantity name (e.g. CIE 2015 luminous flux or CIE 1988 luminous flux) and an appropriate symbol for the quantity (e.g. Φ_F or Φ_M) shall be used. The same SI units – cd, lm, lx, cd·m^{-2} – are used and these shall not be modified.

7 Basic formulae relating photometric quantities to radiometric quantities

7.1 General

The spectral luminous efficiency functions and the basic formulae relating radiometric and photometric quantities defined in this document supplement the reformulation of the definition of the candela approved in the 28th CGPM.[6] These definitions in conjunction constitute a rational system of physical photometry, which:

— correlates the radiant power of broadband radiation acting upon the human visual system with the physiological characteristics of the latter;

— is consistent with visual experience;

— establishes precisely defined numerical relationships between radiometric and photometric quantities.

In 7.2 the general formula linking radiometric and photometric quantities is presented; in 7.3 this relation is specified for luminous flux as an example; in 7.4 the formulae for the maximum luminous efficacies are given; and in 7.5 to 7.8 examples of relations between radiant flux and luminous flux are provided for each photometric condition.

7.2 General formula

Formula (2) forms the basis of the CIE system of physical photometry and provides a direct link between a given spectral radiometric quantity, $X_{e,\lambda}(\lambda)$, (e.g. spectral radiant intensity) and the corresponding photometric quantity, $X_{v,X}$, (e.g. luminous intensity) using:

$$X_{v,X} = \frac{K_{cd}}{V_X(\lambda_{cd})} \int_{\lambda} X_{e,\lambda}(\lambda) V_X(\lambda)\, d\lambda \tag{2}$$

where

K_{cd} is the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz (683 lm·W^{-1});

$V_X(\lambda)$ is the relevant spectral luminous efficiency function;

λ_{cd} is the wavelength at 540 × 10^{12} Hz according to the definition of the unit candela (555,017 nm in standard air);

$V_X(\lambda_{cd})$ is the value of the relevant spectral luminous efficiency function at the wavelength λ_{cd} in standard air.

7.3 General formula for luminous flux

For a specific spectral luminous efficiency function, $V_X(\lambda)$, the relationship between the photometric quantity luminous flux, $\Phi_{v,X}$, and its corresponding spectral radiant flux, $\Phi_{e,\lambda}(\lambda)$, is given according to Formula (3):

$$\Phi_{v,X} = \frac{K_{cd}}{V_X(\lambda_{cd})} \int_{\lambda} \Phi_{e,\lambda}(\lambda) V_X(\lambda) \, d\lambda \tag{3}$$

where

K_{cd} is the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz (683 lm·W^{-1});

$V_X(\lambda)$ is the relevant spectral luminous efficiency function;

$\Phi_{v,X}$ is the luminous flux evaluated using a defined spectral luminous efficiency function $V_X(\lambda)$;

$\Phi_{e,\lambda}(\lambda) = \frac{d\Phi_e}{d\lambda}$ is spectral radiant flux, i.e. the spectral distribution of radiant flux, Φ_e;

λ_{cd} is the wavelength at 540 × 10^{12} Hz according to the definition of the unit candela (555,017 nm in standard air);

$V_X(\lambda_{cd})$ is the value of the relevant spectral luminous efficiency function at the wavelength λ_{cd} in standard air.

Formula (3) requires that the spectral luminous efficiency function has a non-zero value at wavelength λ_{cd}. The wavelengths for the spectral luminous efficiency functions are typically wavelengths in air.

7.4 Maximum luminous efficacy

7.4.1 General

The maximum luminous efficacy for a specified photometric condition, K_X, constitutes the link from the defining constant in the SI, K_{cd}, to the CIE standard observers and CIE observers according to Formula (4):

$$K_X = K_{cd} \frac{V_X(\lambda_X)}{V_X(\lambda_{cd})} \tag{4}$$

where

K_{cd} is the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz (683 lm·W^{-1});

$V_X(\lambda)$ is the relevant spectral luminous efficiency function;

λ_{cd} is the wavelength at 540 × 10^{12} Hz according to the definition of the unit candela (555,017 nm in standard air);

λ_X is the wavelength of the maximum of $V_X(\lambda)$;

$V_X(\lambda_{cd})$ is the value of the relevant spectral luminous efficiency function at the wavelength λ_{cd} in standard air.

For the CIE standard observers and CIE observers the maximum luminous efficacies shown in 7.4.2 to 7.4.5 are defined (see also Table 5).

7.4.2 Photopic vision

The maximum luminous efficacy for photopic vision, K_m, i.e. the luminous efficacy at the peak of the $V(\lambda)$ function, which is at a wavelength of λ_m = 555 nm (exactly), is given by Formula (5):

$$K_m = K_{cd} \frac{V(\lambda_m)}{V(\lambda_{cd})} \tag{5}$$

(= 683,002 ... lm·W^{-1} ≈ 683 lm·W^{-1} in standard air).

7.4.3 Scotopic vision

The maximum luminous efficacy for scotopic vision, K'_m, i.e. the luminous efficacy at the peak of the $V'(\lambda)$ function, which is at a wavelength of λ'_m = 507 nm (exactly), is given by Formula (6):

$$K'_m = K_{cd} \frac{V'(\lambda_m)}{V'(\lambda_{cd})} \tag{6}$$

(= 1 700,13 ... lm·W^{-1} ≈ 1 700 lm·W^{-1} in standard air).

7.4.4 Mesopic vision

The maximum luminous efficacy for mesopic vision, $K_{m,mes;m}$, varies as a function of m and is given by Formula (7):

$$K_{m,mes;m} = \frac{K_{cd}}{V_{mes;m}(\lambda_{cd})} \tag{7}$$

The value of $K_{m,mes;m}$ varies from 683 lm·W^{-1} at m = 1 (photopic) to 1 700 lm·W^{-1} at m = 0 (scotopic)[1]. Figure 2 shows this relationship. Annex B provides the values of the maximum luminous efficacy for mesopic vision for specific values of m.

7.4.5 10° photopic vision

The maximum luminous efficacy for 10° photopic vision, $K_{m,10}$, i.e. the luminous efficacy at the peak of the $V_{10}(\lambda)$ function, which is at a wavelength of $\lambda_{m,10}$ = 557 nm (exactly), is given by Formula (8):

$$K_{m,10} = K_{cd} \frac{V_{10}(\lambda_{m,10})}{V_{10}(\lambda_{cd})} \tag{8}$$

(= 683,601... lm·W^{-1} ≈ 684 lm·W^{-1} in standard air).

1) The subscript m, in roman, in $K_{m,mes;m}$ refers to “maximum”, whereas the subscript m, in italic, represents a variable, referring to the adaptation coefficient.

7.4.6 Summary of maximum luminous efficacies

Table 5 gives a summary of maximum luminous efficacies for the different photometric conditions (observers).

Table 5 — Summary of maximum luminous efficacies

Observer	Symbol	Wavelength in standard air, λ, frequency, V	Relevant formula	Value ($lm \cdot W^{-1}$)
	K_{cd}	λ_{cd} = 555,017 nm V_{cd} = 540 THz		683 (exactly)
Photopic vision	K_m	λ_m = 555 nm (exactly)	(5)	683,002 ≈ 683
Scotopic vision	K'_m	λ'_m = 507 nm (exactly)	(6)	1 700,13 ≈ 1 700
Mesopic vision	$K_{m,mes;\, m}$	Depends on adaptation	(7)	Depends on adaptation[a]
10° photopic vision	$K_{m,10}$	$\lambda_{m,10}$ = 557 nm (exactly)	(8)	683,601 ≈ 684

Key

m adaptation coefficient

$K_{m,mes;m}$ maximum luminous efficacy for mesopic vision

[a] The maximum luminous efficacy in mesopic vision as a function of the adaptation coefficient, m, is shown in Figure 2.

7.5 (Photopic) luminous flux

The (photopic) luminous flux, Φ_v, is related to spectral radiant flux, $\Phi_{e,\lambda}(\lambda)$, according to Formula (9):

$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda}(\lambda) V(\lambda) d\lambda \tag{9}$$

where

K_m is the maximum luminous efficacy for photopic vision;

$V(\lambda)$ is the spectral luminous efficiency function for photopic vision (see Table 7).

Other photopic photometric quantities [e.g. (photopic) luminous intensity, (photopic) luminance, (photopic) illuminance] are calculated similarly.

7.6 Scotopic luminous flux

The scotopic luminous flux, Φ', is related to spectral radiant flux, $\Phi_{e,\lambda}(\lambda)$, according to Formula (10):

$$\Phi' = K'_m \int_\lambda \Phi_{e,\lambda}(\lambda) V'(\lambda) d\lambda \tag{10}$$

where

K'_m is the maximum luminous efficacy for scotopic vision;

$V'(\lambda)$ is the spectral luminous efficiency function for scotopic vision (see Table 7).

Other scotopic photometric quantities (e.g. scotopic luminous intensity, scotopic luminance, scotopic illuminance) are calculated similarly.

7.7 Mesopic luminous flux

The mesopic luminous flux, $\Phi_{\text{mes};\,m}$, is related to spectral radiant flux, $\Phi_{\text{e},\lambda}(\lambda)$, according to Formula (11):

$$\Phi_{\text{mes};m} = K_{\text{m,mes};m} \int_{\lambda} \Phi_{\text{e},\lambda}(\lambda) V_{\text{mes};m}(\lambda)\, \text{d}\lambda \tag{11}$$

where

$K_{\text{m,mes};m}$ is the maximum luminous efficacy for mesopic vision;

$V_{\text{mes};m}(\lambda)$ is the spectral luminous efficiency function for mesopic vision (see 5.4).

The value of $K_{\text{m,mes};m}$ varies from 683 lm·W^{-1} for $m = 1$ (photopic) to 1 700 lm·W^{-1} for $m = 0$ (scotopic).[2)] Figure 2 shows this relationship.

The values of $K_{\text{m,mes};m}$ are given in Table B.1 for representative values of m.

The value of m is determined from the photopic luminance, $L_{\text{v,adapt}}$, and the scotopic luminance, $L'_{\text{v,adapt}}$, of the visual adaptation field[3)]. It is obtained to a given precision by iteratively solving Formulae (12) and (13)[10] with m_0 (the starting value for the iterative calculation of m) usually set to 0,5:

$$L_{\text{mes},n} = \frac{m_{(n-1)} L_{\text{v,adapt}} + (1 - m_{(n-1)}) L'_{\text{v,adapt}} V'(\lambda_{\text{m}})}{m_{(n-1)} + (1 - m_{(n-1)}) V'(\lambda_{\text{m}})} \tag{12}$$

and

$$m_n = a + b \log_{10}(L_{\text{mes},n}) \quad \text{for } 0 \le m_n \le 1 , \tag{13}$$

where

n is the iteration step number (1, 2, 3, ...);

$L_{\text{mes},n}$ is the mesopic luminance at iteration step n (in cd·m^{-2});

a and b are parameters which have the values a = 0,7670 and b = 0,3334;

$V'(\lambda_{\text{m}})$ is the value of the spectral luminous efficiency function for scotopic vision at λ_{m} = 555 nm.

At the end of the iteration using the final value of n, the mesopic luminance is given by Formula (14):

$$L_{\text{mes};m} = L_{\text{mes},n} \tag{14}$$

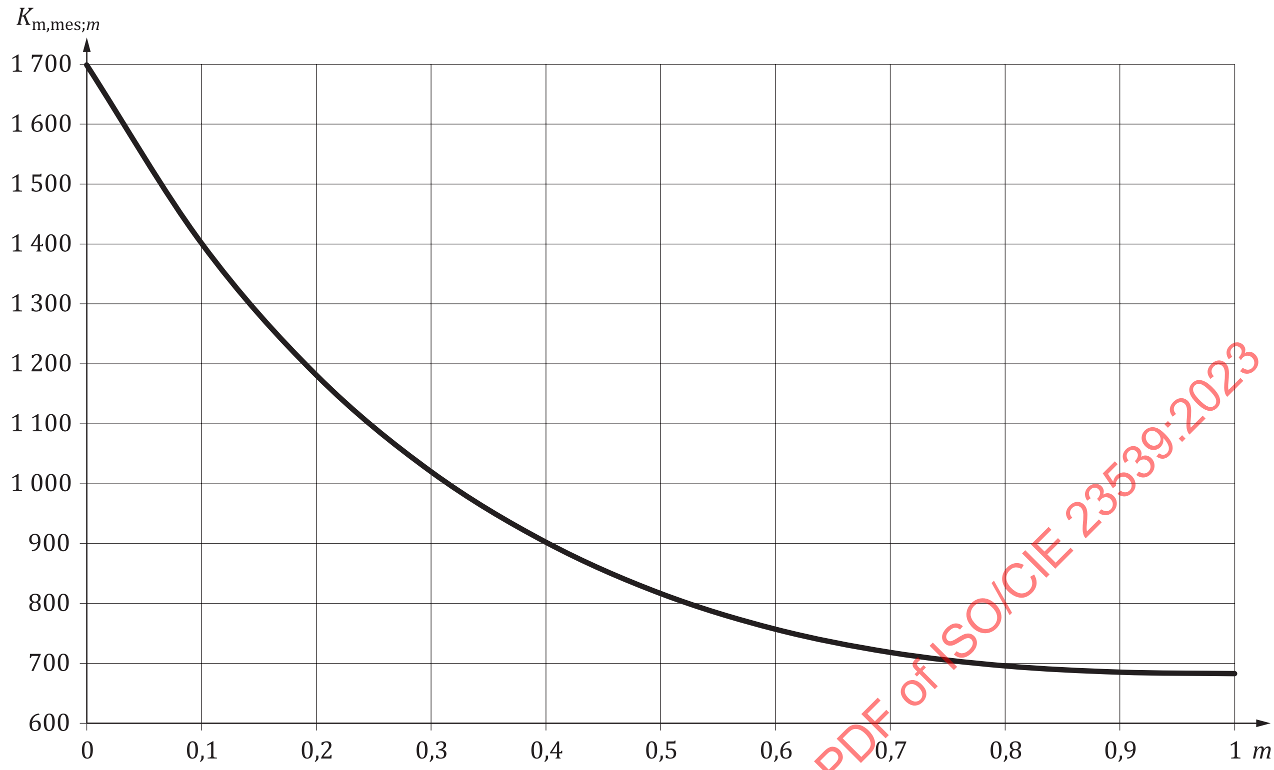
Other mesopic photometric quantities (e.g. mesopic luminous intensity, mesopic luminance, mesopic illuminance) are calculated similarly.

Mesopic photometric quantities shall always be given with indication of the value m in the symbol subscript, e.g. $L_{\text{mes};0,4}$ = 0,12 cd·m^{-2} (see also C.1).

NOTE The numerical values of $V_{\text{mes};0,8}(\lambda)$ are given in Table A.1, to be used as a reference for the check of calculations.

2) The subscript m, in roman, in $K_{\text{m,mes};m}$ refers to "maximum", whereas the subscript m, in italic, represents the variable adaptation coefficient.

3) The determination of adaptation luminance in various application conditions is still under research. An interim recommendation is available in Reference [11].



Key

m adaptation coefficient

$K_{m,mes;m}$ maximum luminous efficacy for mesopic vision, in lm·W^{-1}

Figure 2 — Maximum luminous efficacy for mesopic vision, $K_{m,mes;m}$, as a function of the adaptation coefficient, *m*

7.8 10° photopic luminous flux

The 10° luminous flux, Φ_{10}, is related to spectral radiant flux, $\Phi_{e,\lambda}(\lambda)$, according to Formula (15):

$$\Phi_{10} = K_{m,10} \int_{\lambda} \Phi_{e,\lambda}(\lambda) V_{10}(\lambda) d\lambda \quad (15)$$

where

$K_{m,10}$ is the maximum luminous efficacy for 10° photopic vision;

$V_{10}(\lambda)$ is the spectral luminous efficiency function for 10° photopic vision (see Table 8).

Other photometric quantities for 10° photopic vision (e.g. 10° luminous intensity, 10° luminance, 10° illuminance) are calculated similarly.

8 Physical measurement

8.1 General

Physical measurements of photometric quantities are typically performed either with photometers (8.2) incorporating a single sensor, with a filter adapted to a spectral weighting function or a spectroradiometer (8.3), where the weighting is performed by subsequent calculation (8.3.2). For guidance on the practical realization of the candela and related units used in photometry and radiometry, see the mise en pratique, prepared by CCPR of the CIPM and formally adopted by the CIPM[12].

8.2 Photometers

Photometric measurements can be performed with an appropriately calibrated detector (including all necessary corrections) that conforms to the definition of the specified CIE standard photometric observer or CIE photometric observer. In such a detector the specific spectral luminous efficiency function [$V(\lambda)$, $V'(\lambda)$ or $V_{10}(\lambda)$] is realized in terms of a similar absolute spectral responsivity of the detector. The evaluation of photometers designed to measure light is dealt with in ISO/CIE 19476.[13] Mesopic quantities can be obtained using the combination of $V(\lambda)$- and $V'(\lambda)$-corrected detectors.[14],[15]

In this context, it is important to consider the effect of the spectral mismatch of the photometric detector combined with the spectral power distribution of the light source.

8.3 Spectroradiometers

8.3.1 Spectral measurement

For measurement for photopic vision, scotopic vision, mesopic vision and 10° photopic vision, the use of spectroradiometers is an alternative.[16][17] Spectroradiometers can be used to measure the spectral distribution of the optical radiation and then calculate the photometric quantities, applying the appropriate weighting function $V(\lambda)$, $V'(\lambda)$, $V_{\text{mes};m}(\lambda)$ or $V_{10}(\lambda)$, according to Clause 7. In this case, the integrations usually take the form of numerical summations over the visible spectrum (see 8.3.2).

For spectroradiometers it is important to consider the distortions of the spectrum that can occur in a measurement. Internal stray light and bandpass are among the effects to consider.[18]

8.3.2 Spectral calculations

The tabulated values of luminous efficiency functions at 1 nm intervals are normally sufficient for calculation of photometric quantities, but if intermediate values are required, these shall be obtained from the tabulated values by linear interpolation. Other interpolation methods can produce deviating values, see CIE 167:2005[19] for more details. In this document, values are given for the photopic standard observer $V(\lambda)$ over the spectral range from 360 nm to 830 nm (Table 6), for the scotopic standard observer $V'(\lambda)$ over the spectral range from 380 nm to 780 nm (Table 7) and for the 10° photopic observer $V_{10}(\lambda)$ over the spectral range from 360 nm to 830 nm (Table 8). Values for the standard observers outside these spectral ranges are not defined because, for all practical photometric purposes, the visual contribution of radiation with longer or shorter wavelengths is negligible. For calculations, the values shall be set to zero outside the given spectral ranges. Definitive values of the photometric quantities will be obtained if the summation is carried out at 1 nm intervals and the limits are set to 360 nm and 830 nm in Formulae (9), (11) and (15) and to 380 nm and 780 nm in Formula (10). The formulae of Clause 7 and the measurement procedures according to 8.2 and 8.3.1 can be applied to any of the photometric quantities listed in 4.1. As an example, luminance (for photopic vision) is theoretically given by Formula (16):

$$L_{\text{v}} = K_{\text{m}} \int_{\lambda} L_{\text{e},\lambda}(\lambda) V(\lambda) \, \text{d}\lambda \tag{16}$$

where $L_{\text{e},\lambda}(\lambda)$ is the corresponding spectral radiance. In practice, the integration may be replaced by a summation ($\sum_{\lambda}$) over the specific wavelength range, as shown in Formula (17):

$$L_{\text{v}} = K_{\text{m}} \sum_{\lambda = 360\ \text{nm}}^{830\ \text{nm}} L_{\text{e},\lambda}(\lambda) V(\lambda) \Delta\lambda \tag{17}$$

where $\Delta\lambda$ is the wavelength interval of 1 nm.

9 Tables of values of spectral luminous efficiency functions

9.1 Photopic vision

Table 6 — Values of the spectral luminous efficiency function for photopic vision, $V(\lambda)$ (λ in standard air)

λ/nm	$V(\lambda)$
360	0,000 003 917 000 0
361	0,000 004 393 581 0
362	0,000 004 929 604 0
363	0,000 005 532 136 0
364	0,000 006 208 245 0
365	0,000 006 965 000 0
366	0,000 007 813 219 0
367	0,000 008 767 336 0
368	0,000 009 839 844 0
369	0,000 011 043 230 0
370	0,000 012 390 000 0
371	0,000 013 886 410 0
372	0,000 015 557 280 0
373	0,000 017 442 960 0
374	0,000 019 583 750 0
375	0,000 022 020 000 0
376	0,000 024 839 650 0
377	0,000 028 041 260 0
378	0,000 031 531 040 0
379	0,000 035 215 210 0
380	0,000 039 000 000 0
381	0,000 042 826 400 0
382	0,000 046 914 600 0
383	0,000 051 589 600 0
384	0,000 057 176 400 0
385	0,000 064 000 000 0
386	0,000 072 344 210 0
387	0,000 082 212 240 0
388	0,000 093 508 160 0
389	0,000 106 136 100 0
390	0,000 120 000 000 0
391	0,000 134 984 000 0
392	0,000 151 492 000 0
393	0,000 170 208 000 0
394	0,000 191 816 000 0
395	0,000 217 000 000 0
396	0,000 246 906 700 0
397	0,000 281 240 000 0
398	0,000 318 520 000 0
399	0,000 357 266 700 0
400	0,000 396 000 000 0
401	0,000 433 714 700 0
402	0,000 473 024 000 0
403	0,000 517 876 000 0
404	0,000 572 218 700 0
405	0,000 640 000 000 0
406	0,000 724 560 000 0
407	0,000 825 500 000 0
408	0,000 941 160 000 0
409	0,001 069 880 000 0
410	0,001 210 000 000 0
411	0,001 362 091 000 0
412	0,001 530 752 000 0
413	0,001 720 368 000 0
414	0,001 935 323 000 0
415	0,002 180 000 000 0
416	0,002 454 800 000 0
417	0,002 764 000 000 0
418	0,003 117 800 000 0
419	0,003 526 400 000 0
420	0,004 000 000 000 0
421	0,004 546 240 000 0
422	0,005 159 320 000 0
423	0,005 829 280 000 0
424	0,006 546 160 000 0
425	0,007 300 000 000 0
426	0,008 086 507 000 0
427	0,008 908 720 000 0
428	0,009 767 680 000 0
429	0,010 664 430 000 0
430	0,011 600 000 000 0
431	0,012 573 170 000 0
432	0,013 582 720 000 0
433	0,014 629 680 000 0
434	0,015 715 090 000 0
435	0,016 840 000 000 0
436	0,018 007 360 000 0
437	0,019 214 480 000 0
438	0,020 453 920 000 0
439	0,021 718 240 000 0
440	0,023 000 000 000 0
441	0,024 294 610 000 0
442	0,025 610 240 000 0
443	0,026 958 570 000 0
444	0,028 351 250 000 0
445	0,029 800 000 000 0
446	0,031 310 830 000 0
447	0,032 883 680 000 0
448	0,034 521 120 000 0
449	0,036 225 710 000 0
450	0,038 000 000 000 0
451	0,039 846 670 000 0
452	0,041 768 000 000 0
453	0,043 766 000 000 0
454	0,045 842 670 000 0
455	0,048 000 000 000 0
456	0,050 243 680 000 0
457	0,052 573 040 000 0
458	0,054 980 560 000 0
459	0,057 458 720 000 0
460	0,060 000 000 000 0
461	0,062 601 970 000 0

Table 6 *(continued)*

λ/nm	$V(\lambda)$
462	0,065 277 520 000 0
463	0,068 042 080 000 0
464	0,070 911 090 000 0
465	0,073 900 000 000 0
466	0,077 016 000 000 0
467	0,080 266 400 000 0
468	0,083 666 800 000 0
469	0,087 232 800 000 0
470	0,090 980 000 000 0
471	0,094 917 550 000 0
472	0,099 045 840 000 0
473	0,103 367 400 000 0
474	0,107 884 600 000 0
475	0,112 600 000 000 0
476	0,117 532 000 000 0
477	0,122 674 400 000 0
478	0,127 992 800 000 0
479	0,133 452 800 000 0
480	0,139 020 000 000 0
481	0,144 676 400 000 0
482	0,150 469 300 000 0
483	0,156 461 900 000 0
484	0,162 717 700 000 0
485	0,169 300 000 000 0
486	0,176 243 100 000 0
487	0,183 558 100 000 0
488	0,191 273 500 000 0
489	0,199 418 000 000 0
490	0,208 020 000 000 0
491	0,217 119 900 000 0
492	0,226 734 500 000 0
493	0,236 857 100 000 0
494	0,247 481 200 000 0
495	0,258 600 000 000 0
496	0,270 184 900 000 0
497	0,282 293 900 000 0
498	0,295 050 500 000 0
499	0,308 578 000 000 0
500	0,323 000 000 000 0
501	0,338 402 100 000 0
502	0,354 685 800 000 0
503	0,371 698 600 000 0
504	0,389 287 500 000 0
505	0,407 300 000 000 0
506	0,425 629 900 000 0
507	0,444 309 600 000 0
508	0,463 394 400 000 0
509	0,482 939 500 000 0
510	0,503 000 000 000 0
511	0,523 569 300 000 0
512	0,544 512 000 000 0
513	0,565 690 000 000 0
514	0,586 965 300 000 0
515	0,608 200 000 000 0
516	0,629 345 600 000 0
517	0,650 306 800 000 0
518	0,670 875 200 000 0
519	0,690 842 400 000 0
520	0,710 000 000 000 0
521	0,728 185 200 000 0
522	0,745 463 600 000 0
523	0,761 969 400 000 0
524	0,777 836 800 000 0
525	0,793 200 000 000 0
526	0,808 110 400 000 0
527	0,822 496 200 000 0
528	0,836 306 800 000 0
529	0,849 491 600 000 0
530	0,862 000 000 000 0
531	0,873 810 800 000 0
532	0,884 962 400 000 0
533	0,895 493 600 000 0
534	0,905 443 200 000 0
535	0,914 850 100 000 0
536	0,923 734 800 000 0
537	0,932 092 400 000 0
538	0,939 922 600 000 0
539	0,947 225 200 000 0
540	0,954 000 000 000 0
541	0,960 256 100 000 0
542	0,966 007 400 000 0
543	0,971 260 600 000 0
544	0,976 022 500 000 0
545	0,980 300 000 000 0
546	0,984 092 400 000 0
547	0,987 418 200 000 0
548	0,990 312 800 000 0
549	0,992 811 600 000 0
550	0,994 950 100 000 0
551	0,996 710 800 000 0
552	0,998 098 300 000 0
553	0,999 112 000 000 0
554	0,999 748 200 000 0
555	1,000 000 000 000 0
556	0,999 856 700 000 0
557	0,999 304 600 000 0
558	0,998 325 500 000 0
559	0,996 898 700 000 0
560	0,995 000 000 000 0
561	0,992 600 500 000 0
562	0,989 742 600 000 0
563	0,986 444 400 000 0
564	0,982 724 100 000 0
565	0,978 600 000 000 0
566	0,974 083 700 000 0
567	0,969 171 200 000 0
568	0,963 856 800 000 0
569	0,958 134 900 000 0
570	0,952 000 000 000 0
571	0,945 450 400 000 0
572	0,938 499 200 000 0
573	0,931 162 800 000 0
574	0,923 457 600 000 0
575	0,915 400 000 000 0
576	0,907 006 400 000 0
577	0,898 277 200 000 0
578	0,889 204 800 000 0
579	0,879 781 600 000 0
580	0,870 000 000 000 0
581	0,859 861 300 000 0
582	0,849 392 000 000 0
583	0,838 622 000 000 0
584	0,827 581 300 000 0

Table 6 *(continued)*

λ/nm	$V(\lambda)$	λ/nm	$V(\lambda)$	λ/nm	$V(\lambda)$
585	0,816 300 000 000 0	625	0,321 000 000 000 0	665	0,044 580 000 000 0
586	0,804 794 700 000 0	626	0,309 338 100 000 0	666	0,041 758 720 000 0
587	0,793 082 000 000 0	627	0,297 850 400 000 0	667	0,039 084 960 000 0
588	0,781 192 000 000 0	628	0,286 593 600 000 0	668	0,036 563 840 000 0
589	0,769 154 700 000 0	629	0,275 624 500 000 0	669	0,034 200 480 000 0
590	0,757 000 000 000 0	630	0,265 000 000 000 0	670	0,032 000 000 000 0
591	0,744 754 100 000 0	631	0,254 763 200 000 0	671	0,029 962 610 000 0
592	0,732 422 400 000 0	632	0,244 889 600 000 0	672	0,028 076 640 000 0
593	0,720 003 600 000 0	633	0,235 334 400 000 0	673	0,026 329 360 000 0
594	0,707 496 500 000 0	634	0,226 052 800 000 0	674	0,024 708 050 000 0
595	0,694 900 000 000 0	635	0,217 000 000 000 0	675	0,023 200 000 000 0
596	0,682 219 200 000 0	636	0,208 161 600 000 0	676	0,021 800 770 000 0
597	0,669 471 600 000 0	637	0,199 548 800 000 0	677	0,020 501 120 000 0
598	0,656 674 400 000 0	638	0,191 155 200 000 0	678	0,019 281 080 000 0
599	0,643 844 800 000 0	639	0,182 974 400 000 0	679	0,018 120 690 000 0
600	0,631 000 000 000 0	640	0,175 000 000 000 0	680	0,017 000 000 000 0
601	0,618 155 500 000 0	641	0,167 223 500 000 0	681	0,015 903 790 000 0
602	0,605 314 400 000 0	642	0,159 646 400 000 0	682	0,014 837 180 000 0
603	0,592 475 600 000 0	643	0,152 277 600 000 0	683	0,013 810 680 000 0
604	0,579 637 900 000 0	644	0,145 125 900 000 0	684	0,012 834 780 000 0
605	0,566 800 000 000 0	645	0,138 200 000 000 0	685	0,011 920 000 000 0
606	0,553 961 100 000 0	646	0,131 500 300 000 0	686	0,011 068 310 000 0
607	0,541 137 200 000 0	647	0,125 024 800 000 0	687	0,010 273 390 000 0
608	0,528 352 800 000 0	648	0,118 779 200 000 0	688	0,009 533 311 000 0
609	0,515 632 300 000 0	649	0,112 769 100 000 0	689	0,008 846 157 000 0
610	0,503 000 000 000 0	650	0,107 000 000 000 0	690	0,008 210 000 000 0
611	0,490 468 800 000 0	651	0,101 476 200 000 0	691	0,007 623 781 000 0
612	0,478 030 400 000 0	652	0,096 188 640 000 0	692	0,007 085 424 000 0
613	0,465 677 600 000 0	653	0,091 122 960 000 0	693	0,006 591 476 000 0
614	0,453 403 200 000 0	654	0,086 264 850 000 0	694	0,006 138 485 000 0
615	0,441 200 000 000 0	655	0,081 600 000 000 0	695	0,005 723 000 000 0
616	0,429 080 000 000 0	656	0,077 120 640 000 0	696	0,005 343 059 000 0
617	0,417 036 000 000 0	657	0,072 825 520 000 0	697	0,004 995 796 000 0
618	0,405 032 000 000 0	658	0,068 710 080 000 0	698	0,004 676 404 000 0
619	0,393 032 000 000 0	659	0,064 769 760 000 0	699	0,004 380 075 000 0
620	0,381 000 000 000 0	660	0,061 000 000 000 0	700	0,004 102 000 000 0
621	0,368 918 400 000 0	661	0,057 396 210 000 0	701	0,003 838 453 000 0
622	0,356 827 200 000 0	662	0,053 955 040 000 0	702	0,003 589 099 000 0
623	0,344 776 800 000 0	663	0,050 673 760 000 0	703	0,003 354 219 000 0
624	0,332 817 600 000 0	664	0,047 549 650 000 0	704	0,003 134 093 000 0

Table 6 *(continued)*

λ/nm	$V(\lambda)$	λ/nm	$V(\lambda)$	λ/nm	$V(\lambda)$
705	0,002 929 000 000 0	747	0,000 148 604 400 0	789	0,000 008 009 133 0
706	0,002 738 139 000 0	748	0,000 138 301 600 0	790	0,000 007 465 700 0
707	0,002 559 876 000 0	749	0,000 128 792 500 0	791	0,000 006 959 567 0
708	0,002 393 244 000 0	750	0,000 120 000 000 0	792	0,000 006 487 995 0
709	0,002 237 275 000 0	751	0,000 111 859 500 0	793	0,000 006 048 699 0
710	0,002 091 000 000 0	752	0,000 104 322 400 0	794	0,000 005 639 396 0
711	0,001 953 587 000 0	753	0,000 097 335 600 0	795	0,000 005 257 800 0
712	0,001 824 580 000 0	754	0,000 090 845 870 0	796	0,000 004 901 771 0
713	0,001 703 580 000 0	755	0,000 084 800 000 0	797	0,000 004 569 720 0
714	0,001 590 187 000 0	756	0,000 079 146 670 0	798	0,000 004 260 194 0
715	0,001 484 000 000 0	757	0,000 073 858 000 0	799	0,000 003 971 739 0
716	0,001 384 496 000 0	758	0,000 068 916 000 0	800	0,000 003 702 900 0
717	0,001 291 268 000 0	759	0,000 064 302 670 0	801	0,000 003 452 163 0
718	0,001 204 092 000 0	760	0,000 060 000 000 0	802	0,000 003 218 302 0
719	0,001 122 744 000 0	761	0,000 055 981 870 0	803	0,000 003 000 300 0
720	0,001 047 000 000 0	762	0,000 052 225 600 0	804	0,000 002 797 139 0
721	0,000 976 589 600 0	763	0,000 048 718 400 0	805	0,000 002 607 800 0
722	0,000 911 108 800 0	764	0,000 045 447 470 0	806	0,000 002 431 220 0
723	0,000 850 133 200 0	765	0,000 042 400 000 0	807	0,000 002 266 531 0
724	0,000 793 238 400 0	766	0,000 039 561 040 0	808	0,000 002 113 013 0
725	0,000 740 000 000 0	767	0,000 036 915 120 0	809	0,000 001 969 943 0
726	0,000 690 082 700 0	768	0,000 034 448 680 0	810	0,000 001 836 600 0
727	0,000 643 310 000 0	769	0,000 032 148 160 0	811	0,000 001 712 230 0
728	0,000 599 496 000 0	770	0,000 030 000 000 0	812	0,000 001 596 228 0
729	0,000 558 454 700 0	771	0,000 027 991 250 0	813	0,000 001 488 090 0
730	0,000 520 000 000 0	772	0,000 026 113 560 0	814	0,000 001 387 314 0
731	0,000 483 913 600 0	773	0,000 024 360 240 0	815	0,000 001 293 400 0
732	0,000 450 052 800 0	774	0,000 022 724 610 0	816	0,000 001 205 820 0
733	0,000 418 345 200 0	775	0,000 021 200 000 0	817	0,000 001 124 143 0
734	0,000 388 718 400 0	776	0,000 019 778 550 0	818	0,000 001 048 009 0
735	0,000 361 100 000 0	777	0,000 018 452 850 0	819	0,000 000 977 057 8
736	0,000 335 383 500 0	778	0,000 017 216 870 0	820	0,000 000 910 930 0
737	0,000 311 440 400 0	779	0,000 016 064 590 0	821	0,000 000 849 251 3
738	0,000 289 165 600 0	780	0,000 014 990 000 0	822	0,000 000 791 721 2
739	0,000 268 453 900 0	781	0,000 013 987 280 0	823	0,000 000 738 090 4
740	0,000 249 200 000 0	782	0,000 013 051 550 0	824	0,000 000 688 109 8
741	0,000 231 301 900 0	783	0,000 012 178 180 0	825	0,000 000 641 530 0
742	0,000 214 685 600 0	784	0,000 011 362 540 0	826	0,000 000 598 089 5
743	0,000 199 288 400 0	785	0,000 010 600 000 0	827	0,000 000 557 574 6
744	0,000 185 047 500 0	786	0,000 009 885 877 0	828	0,000 000 519 808 0
745	0,000 171 900 000 0	787	0,000 009 217 304 0	829	0,000 000 484 612 3
746	0,000 159 778 100 0	788	0,000 008 592 362 0	830	0,000 000 451 810 0

9.2 Scotopic vision

Table 7 — Values of the spectral luminous efficiency function for scotopic vision, $V'(\lambda)$ (λ in standard air)

λ/nm	$V'(\lambda)$
380	0,000 589 000 0
381	0,000 665 000 0
382	0,000 752 000 0
383	0,000 854 000 0
384	0,000 972 000 0
385	0,001 108 000 0
386	0,001 268 000 0
387	0,001 453 000 0
388	0,001 668 000 0
389	0,001 918 000 0
390	0,002 209 000 0
391	0,002 547 000 0
392	0,002 939 000 0
393	0,003 394 000 0
394	0,003 921 000 0
395	0,004 530 000 0
396	0,005 240 000 0
397	0,006 050 000 0
398	0,006 980 000 0
399	0,008 060 000 0
400	0,009 290 000 0
401	0,010 700 000 0
402	0,012 310 000 0
403	0,014 130 000 0
404	0,016 190 000 0
405	0,018 520 000 0
406	0,021 130 000 0
407	0,024 050 000 0
408	0,027 300 000 0
409	0,030 890 000 0
410	0,034 840 000 0
411	0,039 160 000 0
412	0,043 900 000 0
413	0,049 000 000 0
414	0,054 500 000 0
415	0,060 400 000 0
416	0,066 800 000 0
417	0,073 600 000 0
418	0,080 800 000 0
419	0,088 500 000 0
420	0,096 600 000 0

λ/nm	$V'(\lambda)$
421	0,105 200 000 0
422	0,114 100 000 0
423	0,123 500 000 0
424	0,133 400 000 0
425	0,143 600 000 0
426	0,154 100 000 0
427	0,165 100 000 0
428	0,176 400 000 0
429	0,187 900 000 0
430	0,199 800 000 0
431	0,211 900 000 0
432	0,224 300 000 0
433	0,236 900 000 0
434	0,249 600 000 0
435	0,262 500 000 0
436	0,275 500 000 0
437	0,288 600 000 0
438	0,301 700 000 0
439	0,314 900 000 0
440	0,328 100 000 0
441	0,341 200 000 0
442	0,354 300 000 0
443	0,367 300 000 0
444	0,380 300 000 0
445	0,393 100 000 0
446	0,406 000 000 0
447	0,418 000 000 0
448	0,431 000 000 0
449	0,443 000 000 0
450	0,455 000 000 0
451	0,467 000 000 0
452	0,479 000 000 0
453	0,490 000 000 0
454	0,502 000 000 0
455	0,513 000 000 0
456	0,524 000 000 0
457	0,535 000 000 0
458	0,546 000 000 0
459	0,557 000 000 0
460	0,567 000 000 0
461	0,578 000 000 0

λ/nm	$V'(\lambda)$
462	0,588 000 000 0
463	0,599 000 000 0
464	0,610 000 000 0
465	0,620 000 000 0
466	0,631 000 000 0
467	0,642 000 000 0
468	0,653 000 000 0
469	0,664 000 000 0
470	0,676 000 000 0
471	0,687 000 000 0
472	0,699 000 000 0
473	0,710 000 000 0
474	0,722 000 000 0
475	0,734 000 000 0
476	0,745 000 000 0
477	0,757 000 000 0
478	0,769 000 000 0
479	0,781 000 000 0
480	0,793 000 000 0
481	0,805 000 000 0
482	0,817 000 000 0
483	0,828 000 000 0
484	0,840 000 000 0
485	0,851 000 000 0
486	0,862 000 000 0
487	0,873 000 000 0
488	0,884 000 000 0
489	0,894 000 000 0
490	0,904 000 000 0
491	0,914 000 000 0
492	0,923 000 000 0
493	0,932 000 000 0
494	0,941 000 000 0
495	0,949 000 000 0
496	0,957 000 000 0
497	0,964 000 000 0
498	0,970 000 000 0
499	0,976 000 000 0
500	0,982 000 000 0
501	0,986 000 000 0
502	0,990 000 000 0

Table 7 *(continued)*

λ/nm	$V'(\lambda)$
503	0,994 000 000 0
504	0,997 000 000 0
505	0,998 000 000 0
506	1,000 000 000 0
507	1,000 000 000 0
508	1,000 000 000 0
509	0,998 000 000 0
510	0,997 000 000 0
511	0,994 000 000 0
512	0,990 000 000 0
513	0,986 000 000 0
514	0,981 000 000 0
515	0,975 000 000 0
516	0,968 000 000 0
517	0,961 000 000 0
518	0,953 000 000 0
519	0,944 000 000 0
520	0,935 000 000 0
521	0,925 000 000 0
522	0,915 000 000 0
523	0,904 000 000 0
524	0,892 000 000 0
525	0,880 000 000 0
526	0,867 000 000 0
527	0,854 000 000 0
528	0,840 000 000 0
529	0,826 000 000 0
530	0,811 000 000 0
531	0,796 000 000 0
532	0,781 000 000 0
533	0,765 000 000 0
534	0,749 000 000 0
535	0,733 000 000 0
536	0,717 000 000 0
537	0,700 000 000 0
538	0,683 000 000 0
539	0,667 000 000 0
540	0,650 000 000 0
541	0,633 000 000 0
542	0,616 000 000 0
543	0,599 000 000 0
544	0,581 000 000 0
545	0,564 000 000 0
546	0,548 000 000 0
547	0,531 000 000 0
548	0,514 000 000 0
549	0,497 000 000 0
550	0,481 000 000 0
551	0,465 000 000 0
552	0,448 000 000 0
553	0,433 000 000 0
554	0,417 000 000 0
555	0,402 000 000 0
556	0,386 400 000 0
557	0,371 500 000 0
558	0,356 900 000 0
559	0,342 700 000 0
560	0,328 800 000 0
561	0,315 100 000 0
562	0,301 800 000 0
563	0,288 800 000 0
564	0,276 200 000 0
565	0,263 900 000 0
566	0,251 900 000 0
567	0,240 300 000 0
568	0,229 100 000 0
569	0,218 200 000 0
570	0,207 600 000 0
571	0,197 400 000 0
572	0,187 600 000 0
573	0,178 200 000 0
574	0,169 000 000 0
575	0,160 200 000 0
576	0,151 700 000 0
577	0,143 600 000 0
578	0,135 800 000 0
579	0,128 400 000 0
580	0,121 200 000 0
581	0,114 300 000 0
582	0,107 800 000 0
583	0,101 500 000 0
584	0,095 600 000 0
585	0,089 900 000 0
586	0,084 500 000 0
587	0,079 300 000 0
588	0,074 500 000 0
589	0,069 900 000 0
590	0,065 500 000 0
591	0,061 300 000 0
592	0,057 400 000 0
593	0,053 700 000 0
594	0,050 200 000 0
595	0,046 900 000 0
596	0,043 800 000 0
597	0,040 900 000 0
598	0,038 160 000 0
599	0,035 580 000 0
600	0,033 150 000 0
601	0,030 870 000 0
602	0,028 740 000 0
603	0,026 740 000 0
604	0,024 870 000 0
605	0,023 120 000 0
606	0,021 470 000 0
607	0,019 940 000 0
608	0,018 510 000 0
609	0,017 180 000 0
610	0,015 930 000 0
611	0,014 770 000 0
612	0,013 690 000 0
613	0,012 690 000 0
614	0,011 750 000 0
615	0,010 880 000 0
616	0,010 070 000 0
617	0,009 320 000 0
618	0,008 620 000 0
619	0,007 970 000 0
620	0,007 370 000 0
621	0,006 820 000 0
622	0,006 300 000 0
623	0,005 820 000 0
624	0,005 380 000 0
625	0,004 970 000 0
626	0,004 590 000 0
627	0,004 240 000 0
628	0,003 913 000 0
629	0,003 613 000 0
630	0,003 335 000 0
631	0,003 079 000 0
632	0,002 842 000 0
633	0,002 623 000 0
634	0,002 421 000 0

Table 7 *(continued)*

λ/nm	$V'(\lambda)$
635	0,002 235 000 0
636	0,002 062 000 0
637	0,001 903 000 0
638	0,001 757 000 0
639	0,001 621 000 0
640	0,001 497 000 0
641	0,001 382 000 0
642	0,001 276 000 0
643	0,001 178 000 0
644	0,001 088 000 0
645	0,001 005 000 0
646	0,000 928 000 0
647	0,000 857 000 0
648	0,000 792 000 0
649	0,000 732 000 0
650	0,000 677 000 0
651	0,000 626 000 0
652	0,000 579 000 0
653	0,000 536 000 0
654	0,000 496 000 0
655	0,000 459 000 0
656	0,000 425 000 0
657	0,000 393 500 0
658	0,000 364 500 0
659	0,000 337 700 0
660	0,000 312 900 0
661	0,000 290 100 0
662	0,000 268 900 0
663	0,000 249 300 0
664	0,000 231 300 0
665	0,000 214 600 0
666	0,000 199 100 0
667	0,000 184 800 0
668	0,000 171 600 0
669	0,000 159 300 0
670	0,000 148 000 0
671	0,000 137 500 0
672	0,000 127 700 0
673	0,000 118 700 0
674	0,000 110 400 0
675	0,000 102 600 0
676	0,000 095 400 0
677	0,000 088 800 0
678	0,000 082 600 0
679	0,000 076 900 0
680	0,000 071 500 0
681	0,000 066 600 0
682	0,000 062 000 0
683	0,000 057 800 0
684	0,000 053 800 0
685	0,000 050 100 0
686	0,000 046 700 0
687	0,000 043 600 0
688	0,000 040 600 0
689	0,000 037 890 0
690	0,000 035 330 0
691	0,000 032 950 0
692	0,000 030 750 0
693	0,000 028 700 0
694	0,000 026 790 0
695	0,000 025 010 0
696	0,000 023 360 0
697	0,000 021 820 0
698	0,000 020 380 0
699	0,000 019 050 0
700	0,000 017 800 0
701	0,000 016 640 0
702	0,000 015 560 0
703	0,000 014 540 0
704	0,000 013 600 0
705	0,000 012 730 0
706	0,000 011 910 0
707	0,000 011 140 0
708	0,000 010 430 0
709	0,000 009 760 0
710	0,000 009 140 0
711	0,000 008 560 0
712	0,000 008 020 0
713	0,000 007 510 0
714	0,000 007 040 0
715	0,000 006 600 0
716	0,000 006 180 0
717	0,000 005 800 0
718	0,000 005 440 0
719	0,000 005 100 0
720	0,000 004 780 0
721	0,000 004 490 0
722	0,000 004 210 0
723	0,000 003 951 0
724	0,000 003 709 0
725	0,000 003 482 0
726	0,000 003 270 0
727	0,000 003 070 0
728	0,000 002 884 0
729	0,000 002 710 0
730	0,000 002 546 0
731	0,000 002 393 0
732	0,000 002 250 0
733	0,000 002 115 0
734	0,000 001 989 0
735	0,000 001 870 0
736	0,000 001 759 0
737	0,000 001 655 0
738	0,000 001 557 0
739	0,000 001 466 0
740	0,000 001 379 0
741	0,000 001 299 0
742	0,000 001 223 0
743	0,000 001 151 0
744	0,000 001 084 0
745	0,000 001 022 0
746	0,000 000 962 0
747	0,000 000 907 0
748	0,000 000 855 0
749	0,000 000 806 0
750	0,000 000 760 0
751	0,000 000 716 0
752	0,000 000 675 0
753	0,000 000 637 0
754	0,000 000 601 0
755	0,000 000 567 0
756	0,000 000 535 0
757	0,000 000 505 0
758	0,000 000 477 0
759	0,000 000 450 0
760	0,000 000 425 0
761	0,000 000 401 0
762	0,000 000 379 0
763	0,000 000 358 0
764	0,000 000 338 2
765	0,000 000 319 6
766	0,000 000 302 1

Table 7 *(continued)*

λ/nm	$V'(\lambda)$	λ/nm	$V'(\lambda)$	λ/nm	$V'(\lambda)$
767	0,000 000 285 5	772	0,000 000 215 9	777	0,000 000 163 8
768	0,000 000 269 9	773	0,000 000 204 2	778	0,000 000 155 1
769	0,000 000 255 2	774	0,000 000 193 2	779	0,000 000 146 8
770	0,000 000 241 3	775	0,000 000 182 9	780	0,000 000 139 0
771	0,000 000 228 2	776	0,000 000 173 1		

9.3 10° photopic vision

Table 8 — Values of spectral luminous efficiency for 10° photopic vision, $V_{10}(\lambda)$ (λ in standard air)

λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$
360	0,000 000 013 398	392	0,000 402 400 000	424	0,027 841 000 000
361	0,000 000 020 294	393	0,000 502 300 000	425	0,029 497 000 000
362	0,000 000 030 560	394	0,000 623 200 000	426	0,031 195 000 000
363	0,000 000 045 740	395	0,000 768 500 000	427	0,032 927 000 000
364	0,000 000 068 050	396	0,000 941 700 000	428	0,034 738 000 000
365	0,000 000 100 650	397	0,001 147 800 000	429	0,036 654 000 000
366	0,000 000 147 980	398	0,001 390 300 000	430	0,038 676 000 000
367	0,000 000 216 270	399	0,001 674 000 000	431	0,040 792 000 000
368	0,000 000 314 200	400	0,002 004 400 000	432	0,042 946 000 000
369	0,000 000 453 700	401	0,002 386 000 000	433	0,045 114 000 000
370	0,000 000 651 100	402	0,002 822 000 000	434	0,047 333 000 000
371	0,000 000 928 800	403	0,003 319 000 000	435	0,049 602 000 000
372	0,000 001 317 500	404	0,003 880 000 000	436	0,051 934 000 000
373	0,000 001 857 200	405	0,004 509 000 000	437	0,054 337 000 000
374	0,000 002 602 000	406	0,005 209 000 000	438	0,056 822 000 000
375	0,000 003 625 000	407	0,005 985 000 000	439	0,059 399 000 000
376	0,000 005 019 000	408	0,006 833 000 000	440	0,062 077 000 000
377	0,000 006 907 000	409	0,007 757 000 000	441	0,064 737 000 000
378	0,000 009 449 000	410	0,008 756 000 000	442	0,067 285 000 000
379	0,000 012 848 000	411	0,009 816 000 000	443	0,069 764 000 000
380	0,000 017 364 000	412	0,010 918 000 000	444	0,072 218 000 000
381	0,000 023 327 000	413	0,012 058 000 000	445	0,074 704 000 000
382	0,000 031 150 000	414	0,013 237 000 000	446	0,077 272 000 000
383	0,000 041 350 000	415	0,014 456 000 000	447	0,079 979 000 000
384	0,000 054 560 000	416	0,015 717 000 000	448	0,082 874 000 000
385	0,000 071 560 000	417	0,017 025 000 000	449	0,086 000 000 000
386	0,000 093 300 000	418	0,018 399 000 000	450	0,089 456 000 000
387	0,000 120 870 000	419	0,019 848 000 000	451	0,092 947 000 000
388	0,000 155 640 000	420	0,021 391 000 000	452	0,096 275 000 000
389	0,000 199 200 000	421	0,022 992 000 000	453	0,099 535 000 000
390	0,000 253 400 000	422	0,024 598 000 000	454	0,102 829 000 000
391	0,000 320 200 000	423	0,026 213 000 000	455	0,106 256 000 000

Table 8 *(continued)*

λ/nm	$V_{10}(\lambda)$
456	0,109 901 000 000
457	0,113 835 000 000
458	0,118 167 000 000
459	0,122 932 000 000
460	0,128 201 000 000
461	0,133 457 000 000
462	0,138 323 000 000
463	0,143 042 000 000
464	0,147 787 000 000
465	0,152 761 000 000
466	0,158 102 000 000
467	0,163 941 000 000
468	0,170 362 000 000
469	0,177 425 000 000
470	0,185 190 000 000
471	0,193 025 000 000
472	0,200 313 000 000
473	0,207 156 000 000
474	0,213 644 000 000
475	0,219 940 000 000
476	0,226 170 000 000
477	0,232 467 000 000
478	0,239 025 000 000
479	0,245 997 000 000
480	0,253 589 000 000
481	0,261 876 000 000
482	0,270 643 000 000
483	0,279 645 000 000
484	0,288 694 000 000
485	0,297 665 000 000
486	0,306 469 000 000
487	0,315 035 000 000
488	0,323 335 000 000
489	0,331 366 000 000
490	0,339 133 000 000
491	0,347 860 000 000
492	0,358 326 000 000
493	0,370 001 000 000
494	0,382 464 000 000
495	0,395 379 000 000
496	0,408 482 000 000
497	0,421 588 000 000
498	0,434 619 000 000

λ/nm	$V_{10}(\lambda)$
499	0,447 601 000 000
500	0,460 777 000 000
501	0,474 340 000 000
502	0,488 200 000 000
503	0,502 340 000 000
504	0,516 740 000 000
505	0,531 360 000 000
506	0,546 190 000 000
507	0,561 180 000 000
508	0,576 290 000 000
509	0,591 500 000 000
510	0,606 741 000 000
511	0,622 150 000 000
512	0,637 830 000 000
513	0,653 710 000 000
514	0,669 680 000 000
515	0,685 660 000 000
516	0,701 550 000 000
517	0,717 230 000 000
518	0,732 570 000 000
519	0,747 460 000 000
520	0,761 757 000 000
521	0,775 340 000 000
522	0,788 220 000 000
523	0,800 460 000 000
524	0,812 140 000 000
525	0,823 330 000 000
526	0,834 120 000 000
527	0,844 600 000 000
528	0,854 870 000 000
529	0,865 040 000 000
530	0,875 211 000 000
531	0,885 370 000 000
532	0,895 370 000 000
533	0,905 150 000 000
534	0,914 650 000 000
535	0,923 810 000 000
536	0,932 550 000 000
537	0,940 810 000 000
538	0,948 520 000 000
539	0,955 600 000 000
540	0,961 988 000 000
541	0,967 540 000 000

λ/nm	$V_{10}(\lambda)$
542	0,972 230 000 000
543	0,976 170 000 000
544	0,979 460 000 000
545	0,982 200 000 000
546	0,984 520 000 000
547	0,986 520 000 000
548	0,988 320 000 000
549	0,990 020 000 000
550	0,991 761 000 000
551	0,993 530 000 000
552	0,995 230 000 000
553	0,996 770 000 000
554	0,998 090 000 000
555	0,999 110 000 000
556	0,999 770 000 000
557	1,000 000 000 000
558	0,999 710 000 000
559	0,998 850 000 000
560	0,997 340 000 000
561	0,995 260 000 000
562	0,992 740 000 000
563	0,989 750 000 000
564	0,986 300 000 000
565	0,982 380 000 000
566	0,977 980 000 000
567	0,973 110 000 000
568	0,967 740 000 000
569	0,961 890 000 000
570	0,955 552 000 000
571	0,948 601 000 000
572	0,940 981 000 000
573	0,932 798 000 000
574	0,924 158 000 000
575	0,915 175 000 000
576	0,905 954 000 000
577	0,896 608 000 000
578	0,887 249 000 000
579	0,877 986 000 000
580	0,868 934 000 000
581	0,860 164 000 000
582	0,851 519 000 000
583	0,842 963 000 000
584	0,834 393 000 000

Table 8 *(continued)*

λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$
585	0,825 623 000 000	628	0,305 936 000 000	671	0,029 739 500 000
586	0,816 764 000 000	629	0,294 737 000 000	672	0,027 791 800 000
587	0,807 544 000 000	630	0,283 493 000 000	673	0,025 955 100 000
588	0,797 947 000 000	631	0,272 222 000 000	674	0,024 226 300 000
589	0,787 893 000 000	632	0,260 990 000 000	675	0,022 601 700 000
590	0,777 405 000 000	633	0,249 877 000 000	676	0,021 077 900 000
591	0,766 490 000 000	634	0,238 946 000 000	677	0,019 650 500 000
592	0,755 309 000 000	635	0,228 254 000 000	678	0,018 315 300 000
593	0,743 845 000 000	636	0,217 853 000 000	679	0,017 068 600 000
594	0,732 190 000 000	637	0,207 780 000 000	680	0,015 905 100 000
595	0,720 353 000 000	638	0,198 072 000 000	681	0,014 818 300 000
596	0,708 281 000 000	639	0,188 748 000 000	682	0,013 800 800 000
597	0,696 055 000 000	640	0,179 828 000 000	683	0,012 849 500 000
598	0,683 621 000 000	641	0,171 285 000 000	684	0,011 960 700 000
599	0,671 048 000 000	642	0,163 059 000 000	685	0,011 130 300 000
600	0,658 341 000 000	643	0,155 151 000 000	686	0,010 355 500 000
601	0,645 545 000 000	644	0,147 535 000 000	687	0,009 633 200 000
602	0,632 718 000 000	645	0,140 211 000 000	688	0,008 959 900 000
603	0,619 815 000 000	646	0,133 170 000 000	689	0,008 332 400 000
604	0,606 887 000 000	647	0,126 400 000 000	690	0,007 748 800 000
605	0,593 878 000 000	648	0,119 892 000 000	691	0,007 204 600 000
606	0,580 781 000 000	649	0,113 640 000 000	692	0,006 697 500 000
607	0,567 653 000 000	650	0,107 633 000 000	693	0,006 225 100 000
608	0,554 490 000 000	651	0,101 870 000 000	694	0,005 785 000 000
609	0,541 228 000 000	652	0,096 347 000 000	695	0,005 375 100 000
610	0,527 963 000 000	653	0,091 063 000 000	696	0,004 994 100 000
611	0,514 634 000 000	654	0,086 010 000 000	697	0,004 639 200 000
612	0,501 363 000 000	655	0,081 187 000 000	698	0,004 309 300 000
613	0,488 124 000 000	656	0,076 583 000 000	699	0,004 002 800 000
614	0,474 935 000 000	657	0,072 198 000 000	700	0,003 717 740 000
615	0,461 834 000 000	658	0,068 024 000 000	701	0,003 452 620 000
616	0,448 823 000 000	659	0,064 052 000 000	702	0,003 205 830 000
617	0,435 917 000 000	660	0,060 281 000 000	703	0,002 976 230 000
618	0,423 153 000 000	661	0,056 697 000 000	704	0,002 762 810 000
619	0,410 526 000 000	662	0,053 292 000 000	705	0,002 564 560 000
620	0,398 057 000 000	663	0,050 059 000 000	706	0,002 380 480 000
621	0,385 835 000 000	664	0,046 998 000 000	707	0,002 209 710 000
622	0,373 951 000 000	665	0,044 096 000 000	708	0,002 051 320 000
623	0,362 311 000 000	666	0,041 345 000 000	709	0,001 904 490 000
624	0,350 863 000 000	667	0,038 750 700 000	710	0,001 768 470 000
625	0,339 554 000 000	668	0,036 297 800 000	711	0,001 642 360 000
626	0,328 309 000 000	669	0,033 983 200 000	712	0,001 525 350 000
627	0,317 118 000 000	670	0,031 800 400 000	713	0,001 416 720 000

Table 8 *(continued)*

λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$	λ/nm	$V_{10}(\lambda)$
714	0,001 315 950 000	753	0,000 080 048 000	792	0,000 006 185 700
715	0,001 222 390 000	754	0,000 074 751 000	793	0,000 005 810 700
716	0,001 135 550 000	755	0,000 069 819 000	794	0,000 005 459 000
717	0,001 054 940 000	756	0,000 065 222 000	795	0,000 005 129 800
718	0,000 980 140 000	757	0,000 060 939 000	796	0,000 004 820 600
719	0,000 910 660 000	758	0,000 056 942 000	797	0,000 004 531 200
720	0,000 846 190 000	759	0,000 053 217 000	798	0,000 004 259 100
721	0,000 786 290 000	760	0,000 049 737 000	799	0,000 004 004 200
722	0,000 730 680 000	761	0,000 046 491 000	800	0,000 003 764 730
723	0,000 678 990 000	762	0,000 043 464 000	801	0,000 003 539 950
724	0,000 631 010 000	763	0,000 040 635 000	802	0,000 003 329 140
725	0,000 586 440 000	764	0,000 038 000 000	803	0,000 003 131 150
726	0,000 545 110 000	765	0,000 035 540 500	804	0,000 002 945 290
727	0,000 506 720 000	766	0,000 033 244 800	805	0,000 002 770 810
728	0,000 471 110 000	767	0,000 031 100 600	806	0,000 002 607 050
729	0,000 438 050 000	768	0,000 029 099 000	807	0,000 002 453 290
730	0,000 407 410 000	769	0,000 027 230 700	808	0,000 002 308 940
731	0,000 378 962 000	770	0,000 025 486 000	809	0,000 002 173 380
732	0,000 352 543 000	771	0,000 023 856 100	810	0,000 002 046 130
733	0,000 328 001 000	772	0,000 022 333 200	811	0,000 001 926 620
734	0,000 305 208 000	773	0,000 020 910 400	812	0,000 001 814 400
735	0,000 284 041 000	774	0,000 019 580 800	813	0,000 001 708 950
736	0,000 264 375 000	775	0,000 018 338 400	814	0,000 001 609 880
737	0,000 246 109 000	776	0,000 017 177 700	815	0,000 001 516 770
738	0,000 229 143 000	777	0,000 016 093 400	816	0,000 001 429 210
739	0,000 213 376 000	778	0,000 015 080 000	817	0,000 001 346 860
740	0,000 198 730 000	779	0,000 014 133 600	818	0,000 001 269 450
741	0,000 185 115 000	780	0,000 013 249 000	819	0,000 001 196 620
742	0,000 172 454 000	781	0,000 012 422 600	820	0,000 001 128 090
743	0,000 160 678 000	782	0,000 011 649 900	821	0,000 001 063 680
744	0,000 149 730 000	783	0,000 010 927 700	822	0,000 001 003 130
745	0,000 139 550 000	784	0,000 010 251 900	823	0,000 000 946 220
746	0,000 130 086 000	785	0,000 009 619 600	824	0,000 000 892 630
747	0,000 121 290 000	786	0,000 009 028 100	825	0,000 000 842 160
748	0,000 113 106 000	787	0,000 008 474 000	826	0,000 000 794 640
749	0,000 105 501 000	788	0,000 007 954 800	827	0,000 000 749 780
750	0,000 098 428 000	789	0,000 007 468 600	828	0,000 000 707 440
751	0,000 091 853 000	790	0,000 007 012 800	829	0,000 000 667 480
752	0,000 085 738 000	791	0,000 006 585 800	830	0,000 000 629 700

Annex A
(informative)

Example of a spectral luminous efficiency function for mesopic vision

Table A.1 — Values of spectral luminous efficiency for mesopic vision at m = 0,8; $V_{mes;0,8}(\lambda)$ (λ in standard air), as an example[a]

λ/nm	$V_{mes;0,8}(\lambda)$
360	0,000 003 493 3
361	0,000 003 918 3
362	0,000 004 396 3
363	0,000 004 933 6
364	0,000 005 536 6
365	0,000 006 211 5
366	0,000 006 968 0
367	0,000 007 818 9
368	0,000 008 775 4
369	0,000 009 848 4
370	0,000 011 049 7
371	0,000 012 383 8
372	0,000 013 874 1
373	0,000 015 556 1
374	0,000 017 465 4
375	0,000 019 637 9
376	0,000 022 152 9
377	0,000 025 007 6
378	0,000 028 120 0
379	0,000 031 405 5
380	0,000 166 101 8
381	0,000 186 458 6
382	0,000 209 502 4
383	0,000 236 413 1
384	0,000 267 703 6
385	0,000 304 111 3
386	0,000 347 225 5
387	0,000 397 272 8
388	0,000 455 282 3
389	0,000 522 286 6
390	0,000 599 527 3
391	0,000 688 245 8
392	0,000 790 368 3
393	0,000 908 508 0
394	0,001 045 277 8
395	0,001 203 513 8
396	0,001 388 486 6
397	0,001 599 696 8
398	0,001 840 292 5
399	0,002 115 642 6
400	0,002 424 418 1
401	0,002 772 415 9
402	0,003 166 431 8
403	0,003 612 218 0
404	0,004 119 967 9
405	0,004 699 901 9
406	0,005 357 228 2
407	0,006 098 278 8
408	0,006 926 032 3
409	0,007 841 237 8
410	0,008 846 874 2
411	0,009 945 679 1
412	0,011 152 902 9
413	0,012 459 083 2
414	0,013 877 035 6
415	0,015 410 684 0
416	0,017 082 671 9
417	0,018 874 520 6
418	0,020 795 326 9
419	0,022 876 482 7
420	0,025 104 789 1
421	0,027 509 355 2
422	0,030 040 417 4
423	0,032 733 684 1
424	0,035 580 272 9
425	0,038 526 710 1
426	0,041 569 169 7
427	0,044 754 945 2
428	0,048 040 381 7
429	0,051 404 111 3
430	0,054 891 643 6
431	0,058 457 299 6
432	0,062 122 286 6
433	0,065 865 227 9
434	0,069 664 755 2
435	0,073 544 100 6
436	0,077 483 599 4
437	0,081 480 852 6
438	0,085 506 929 5
439	0,089 577 490 4
440	0,093 663 604 7
441	0,097 738 883 4
442	0,101 832 908 2
443	0,105 933 800 1
444	0,110 074 244 2
445	0,114 220 101 7
446	0,118 443 619 0
447	0,122 521 787 2
448	0,126 880 513 7
449	0,131 076 170 5
450	0,135 333 987 3
451	0,139 656 354 2
452	0,144 045 304 6
453	0,148 279 675 4
454	0,152 807 161 3
455	0,157 183 626 1

Table A.1 *(continued)*

λ/nm	$V_{mes;0,8}(\lambda)$
456	0,161 637 099 8
457	0,166 166 984 7
458	0,170 766 574 5
459	0,175 429 162 6
460	0,179 925 087 0
461	0,184 698 091 5
462	0,189 313 760 8
463	0,194 231 766 7
464	0,199 242 923 4
465	0,204 138 054 0
466	0,209 369 481 9
467	0,214 720 770 5
468	0,220 205 832 5
469	0,225 838 580 2
470	0,231 855 881 6
471	0,237 819 985 7
472	0,244 177 151 5
473	0,250 483 724 2
474	0,257 187 728 5
475	0,264 068 491 9
476	0,270 919 468 5
477	0,278 181 039 9
478	0,285 599 571 9
479	0,293 144 386 0
480	0,300 784 803 4
481	0,308 504 771 2
482	0,316 346 472 8
483	0,324 143 315 8
484	0,332 397 841 8
485	0,340 720 592 2
486	0,349 365 111 9
487	0,358 341 300 3
488	0,367 674 574 2
489	0,377 167 573 4
490	0,387 068 581 1
491	0,397 413 627 0
492	0,407 994 738 3
493	0,419 028 895 0
494	0,430 510 300 5
495	0,442 209 934 9
496	0,454 325 247 5
497	0,466 685 008 5
498	0,479 399 357 9
499	0,492 801 212 9
500	0,507 000 802 6
501	0,521 628 556 1
502	0,537 042 539 9
503	0,553 106 751 1
504	0,569 461 785 4
505	0,585 748 684 6
506	0,602 541 603 5
507	0,619 200 570 8
508	0,636 220 815 1
509	0,653 205 654 2
510	0,670 873 093 7
511	0,688 548 381 3
512	0,706 333 719 8
513	0,724 328 904 0
514	0,742 187 906 9
515	0,759 787 746 4
516	0,777 085 169 0
517	0,794 218 139 7
518	0,810 777 847 1
519	0,826 578 435 7
520	0,841 657 005 3
521	0,855 645 411 6
522	0,868 825 113 7
523	0,881 092 838 7
524	0,892 568 269 0
525	0,903 594 042 6
526	0,913 993 043 8
527	0,923 924 195 1
528	0,933 119 415 0
529	0,941 756 532 6
530	0,949 567 466 3
531	0,956 756 265 0
532	0,963 357 174 7
533	0,969 181 842 5
534	0,974 487 826 6
535	0,979 309 819 0
536	0,983 666 1018
537	0,987 329 349 9
538	0,990 522 251 0
539	0,993 467 582 3
540	0,995 719 254 4
541	0,997 508 338 5
542	0,998 847 230 9
543	0,999 741 906 7
544	0,999 975 474 9
545	1,000 000 000 0
546	0,999 814 857 8
547	0,998 990 635 9
548	0,997 781 860 3
549	0,996 220 101 7
550	0,994 559 975 0
551	0,992 562 918 0
552	0,990 010 077 6
553	0,987 569 785 1
554	0,984 569 874 3
555	0,981 450 102 6
556	0,977 844 198 7
557	0,974 029 786 9
558	0,969 901 453 7
559	0,965 463 034 0
560	0,960 670 650 1
561	0,955 476 232 9
562	0,949 962 186 7
563	0,944 122 358 0
564	0,937 995 273 3
565	0,931 574 957 6
566	0,924 871 756 0
567	0,917 904 396 7
568	0,910 667 796 3
569	0,903 134 665 1
570	0,895 300 098 1
571	0,887 184 874 7
572	0,878 800 677 8
573	0,870 162 133 2
574	0,861 239 275 8
575	0,852 091 322 6
576	0,842 710 603 8
577	0,833 119 771 7
578	0,823 289 753 0

Table A.1 *(continued)*

λ/nm	$V_{mes;0,8}(\lambda)$	λ/nm	$V_{mes;0,8}(\lambda)$	λ/nm	$V_{mes;0,8}(\lambda)$
579	0,813 236 065 3	620	0,341 427 361 1	661	0,051 251 881 7
580	0,802 907 339 7	621	0,330 530 099 0	662	0,048 178 244 0
581	0,792 327 031 1	622	0,319 630 964 1	663	0,045 247 556 4
582	0,781 541 068 4	623	0,308 777 133 7	664	0,042 457 393 2
583	0,770 531 525 9	624	0,298 013 555 7	665	0,039 805 270 7
584	0,759 369 749 4	625	0,287 382 948 4	666	0,037 285 735 3
585	0,748 037 991 6	626	0,276 897 886 4	667	0,034 898 029 1
586	0,736 573 352 4	627	0,266 574 868 5	668	0,032 646 695 8
587	0,724 968 340 3	628	0,256 462 900 2	669	0,030 536 257 0
588	0,713 294 390 4	629	0,246 613 528 9	670	0,028 571 301 2
589	0,701 533 666 3	630	0,237 076 384 6	671	0,026 751 970 9
590	0,689 712 833 3	631	0,227 889 904 6	672	0,025 067 836 4
591	0,677 855 257 3	632	0,219 031 570 5	673	0,023 507 567 1
592	0,665 988 049 6	633	0,210 461 205 7	674	0,022 059 796 7
593	0,654 087 755 3	634	0,202 138 633 7	675	0,020 713 145 5
594	0,642 153 304 2	635	0,194 023 677 9	676	0,019 463 676 1
595	0,630 183 715 3	636	0,186 102 827 1	677	0,018 303 148 1
596	0,618 183 537 0	637	0,178 386 292 7	678	0,017 213 707 3
597	0,606 168 376 0	638	0,170 868 144 1	679	0,016 177 575 1
598	0,594 144 653 5	639	0,163 542 004 8	680	0,015 176 915 2
599	0,582 127 708 9	640	0,156 402 613 0	681	0,014 198 198 5
600	0,570 130 651 9	641	0,149 441 719 4	682	0,013 245 946 7
601	0,558 167 305 8	642	0,142 660 661 7	683	0,012 329 555 0
602	0,546 240 435 2	643	0,136 067 154 2	684	0,011 458 334 1
603	0,534 344 600 0	644	0,129 669 044 9	685	0,010 641 688 2
604	0,522 478 730 0	645	0,123 473 869 6	686	0,009 881 374 3
605	0,510 639 436 4	646	0,117 481 762 2	687	0,009 171 756 0
606	0,498 821 546 4	647	0,111 690 939 1	688	0,008 511 067 5
607	0,487 043 788 5	648	0,106 106 483 5	689	0,007 897 647 8
608	0,475 323 553 0	649	0,100 733 166 9	690	0,007 329 735 6
609	0,463 682 600 6	650	0,095 575 894 1	691	0,006 806 401 1
610	0,452 138 143 2	651	0,090 638 277 0	692	0,006 325 789 3
611	0,440 703 915 1	652	0,085 912 235 8	693	0,005 884 825 6
612	0,429 370 284 5	653	0,081 384 963 9	694	0,005 480 413 4
613	0,418 130 830 3	654	0,077 043 476 3	695	0,005 109 473 4
614	0,406 974 672 3	655	0,072 875 011 1	696	0,004 770 266 7
615	0,395 897 618 8	656	0,068 872 638 9	697	0,004 460 229 2
616	0,384 908 142 3	657	0,065 035 133 3	698	0,004 175 060 2
617	0,373 999 821 6	658	0,061 358 427 7	699	0,003 910 499 0
618	0,363 138 321 6	659	0,057 838 388 5	700	0,003 662 222 4
619	0,352 291 536 6	660	0,054 470 904 3	701	0,003 426 924 1

Table A.1 *(continued)*

λ/nm	$V_{mes;0,8}(\lambda)$	λ/nm	$V_{mes;0,8}(\lambda)$	λ/nm	$V_{mes;0,8}(\lambda)$
702	0,003 204 307 5	745	0,000 153 532 1	788	0,000 007 662 9
703	0,002 994 608 9	746	0,000 142 709 8	789	0,000 007 142 7
704	0,002 798 082 6	747	0,000 132 727 0	790	0,000 006 658 1
705	0,002 614 984 8	748	0,000 123 529 6	791	0,000 006 206 7
706	0,002 444 588 9	749	0,000 115 037 5	792	0,000 005 786 1
707	0,002 285 441 0	750	0,000 107 188 1	793	0,000 005 394 4
708	0,002 136 669 5	751	0,000 099 918 8	794	0,000 005 029 3
709	0,001 997 431 6	752	0,000 093 185 4	795	0,000 004 689 0
710	0,001 866 837 6	753	0,000 086 948 4	796	0,000 004 371 5
711	0,001 744 163 0	754	0,000 081 152 5	797	0,000 004 075 4
712	0,001 628 988 7	755	0,000 075 752 9	798	0,000 003 799 3
713	0,001 520 964 5	756	0,000 070 704 3	799	0,000 003 542 0
714	0,001 419 736 0	757	0,000 065 980 8	800	0,000 003 302 3
715	0,001 324 935 3	758	0,000 061 567 2	801	0,000 003 078 7
716	0,001 236 105 4	759	0,000 057 447 2	802	0,000 002 870 2
717	0,001 152 876 1	760	0,000 053 604 1	803	0,000 002 675 7
718	0,001 075 046 8	761	0,000 050 015 4	804	0,000 002 494 5
719	0,001 002 421 3	762	0,000 046 660 8	805	0,000 002 325 7
720	0,000 934 803 4	763	0,000 043 527 6	806	0,000 002 168 2
721	0,000 871 945 5	764	0,000 040 606 0	807	0,000 002 021 3
722	0,000 813 486 6	765	0,000 037 884 5	808	0,000 001 884 4
723	0,000 759 045 5	766	0,000 035 348 7	809	0,000 001 756 8
724	0,000 708 255 8	767	0,000 032 985 3	810	0,000 001 637 9
725	0,000 660 724 6	768	0,000 030 782 6	811	0,000 001 527 0
726	0,000 616 157 6	769	0,000 028 727 2	812	0,000 001 423 5
727	0,000 574 402 5	770	0,000 026 808 5	813	0,000 001 327 1
728	0,000 535 290 3	771	0,000 025 013 9	814	0,000 001 237 2
729	0,000 498 642 2	772	0,000 023 337 2	815	0,000 001 153 5
730	0,000 464 315 1	773	0,000 021 770 3	816	0,000 001 075 4
731	0,000 432 095 1	774	0,000 020 309 7	817	0,000 001 002 5
732	0,000 401 866 1	775	0,000 018 947 4	818	0,000 000 934 6
733	0,000 373 565 3	776	0,000 017 677 9	819	0,000 000 871 4
734	0,000 347 112 5	777	0,000 016 493 3	820	0,000 000 812 4
735	0,000 322 453 8	778	0,000 015 389 1	821	0,000 000 757 4
736	0,000 299 491 4	779	0,000 014 359 9	822	0,000 000 706 1
737	0,000 278 118 0	780	0,000 013 399 4	823	0,000 000 658 2
738	0,000 258 235 3	781	0,000 012 473 9	824	0,000 000 613 7
739	0,000 239 736 5	782	0,000 011 640 1	825	0,000 000 572 1
740	0,000 222 549 5	783	0,000 010 860 6	826	0,000 000 533 4
741	0,000 206 568 0	784	0,000 010 133 8	827	0,000 000 497 3
742	0,000 191 737 9	785	0,000 009 453 3	828	0,000 000 463 6
743	0,000 177 987 8	786	0,000 008 816 5	829	0,000 000 432 2
744	0,000 165 273 3	787	0,000 008 220 2	830	0,000 000 402 9

[a] For other *m* values, use Formula (1).

Annex B
(informative)

Supplementary information on mesopic vision

Table B.1 shows the values of the maximum luminous efficacy for mesopic vision for specific values of *m*, which can be used to check implementations of the calculations of Formulae (1) and (2).

Table B.1 — Values of maximum luminous efficacy for mesopic vision, $K_{\mathrm{m,mes};m}$, at specific *m* values[a]

m	$K_{\mathrm{m,mes};m}$ lm·W^{-1}
0	1 700,13
0,1	1 402,22
0,2	1 181,84
0,3	1 020,44
0,4	902,64
0,5	816,88
0,6	757,24
0,7	718,49
0,8	695,95
0,9	685,46
1,0	683,00

[a] For other *m* values use Formulae (1) and (7).

Annex C
(informative)

Background of the CIE system of physical photometry

C.1 Evolution of the photometric base unit

Historically and up until about 1950, photometry was mainly conducted by humans visually comparing light sources, such as stars, candles, gas flames, tungsten lamps and gas-discharge lamps. The fact that light was measured by using the human eye to compare a known standard light source to an unknown light source led to the tradition of regarding luminous intensity as the fundamental photometric quantity. The earliest standard light sources were candles, and the name candela has been preserved for the photometric base unit in the SI[20]. The candela has been a base unit of the SI since the inception of that system. It remained a base unit even after it was linked to the derived SI unit of radiant flux, the watt, in 1979, and will continue as such in the foreseeable future, after the redefinition of the SI in 2019.

In 1948 the various units of luminous intensity that had been used in countries around the world were replaced by a definition using the radiation from a blackbody of freezing platinum. Prepared by the CIE and the CIPM, this definition, although precise, was found to be difficult to realize. The 1979 definition of the candela in terms of monochromatic radiation (rather than broadband radiation of the kind usually encountered in photometry) resulted from an analysis of the state of the art in photometry and radiometry at the time of the redefinition by members of the Comité Consultatif de Photométrie et Radiométrie (CCPR) of the Conférence Générale des Poids et Mesures (CGPM)[21]. The constant 683 cd·sr·W^{-1} was defined as the luminous efficacy for monochromatic radiation at the frequency of 540 × 10^{12} Hz and by convention used as the maximum luminous efficacy for photopic vision, K_m, required to maintain the candela at its previous level. It became the defined constant that linked physical photometry and optical radiometry. It was also realized at that time that the new definition would increase the magnitude of the existing realization of the luminous intensity for scotopic vision by some 3 %, but this small change was felt to be acceptable.

In 2018, the CGPM adopted a new approach for the SI based on seven defined constants.[22] In the SI[6] the definition of the candela was reformulated by introducing the constant K_{cd} = 683 lm·W^{-1}, which is the luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz. Following this revision, the definitions of the photometric units (lm, cd, and lx) are now linked to the respective radiometric units (W, W·sr^{-1}, and W·m^{-2}) through the relevant defining constants.

The definition applies to photopic, scotopic, mesopic and 10° vision. At the fixed reference point corresponding to the specified frequency 540 × 10^{12} Hz, the values of the luminous efficacy functions for photopic vision, $K(\lambda)$, and for scotopic vision, $K'(\lambda)$, are both equal to 683 cd·sr·W^{-1} (683 lm·W^{-1}). Owing to the choice of a defining frequency (rather than a wavelength) the candela is independent of the medium of light propagation. This allows for further advances in photometry without necessitating a redefinition of the SI base unit. However, it is useful to have the definition of λ_{cd} in mind, which is the wavelength at 540 × 10^{12} Hz according to the definition of the unit candela (555,017 nm in standard air).

The 2019 revision of the definition of the candela does not make a numerical difference in the calculations of the photometric quantities. The most notable qualitative change occurring within photometric and radiometric practice comes as a consequence of a change of the Planck constant and the Boltzmann constant in the revised SI system. This caused the assigned temperature of CIE standard illuminant A to decrease by 46 mK, which can cause a 1 K change due to numerical rounding. This is dealt with in ISO/CIE 11664-2[23] where the assigned temperature is now rounded to 2 855,5 K in place of the previous value of 2 856 K.

C.2 Spectral response of the human eye

The response of the human visual system to light is strongly dependent on the wavelength of the light incident on the eye. The origin of the spectral luminous efficiency functions was the realization that equal amounts of radiant flux from different parts of the visible spectrum yield different levels of excitement to the visual system. To quantify this, measurements of the spectral luminous efficiencies of different human observers were begun with the work of Coblentz and Emerson.[24] It was soon recognized that the visual response varies spectrally from observer to observer. These variations caused deviations in results when different human observers visually compared light sources. The way to minimize these deviations would be to perform photometric measurements photoelectrically with detectors whose spectral responsivity should be based on internationally accepted average spectral luminous efficiency functions. For this to happen, unambiguous and consistent photometric scales would have to be introduced for worldwide use. By 1924, additional measurements of the spectral luminous efficiency of individual observers had been performed, three by the flicker method and two by direct comparison of light from adjacent portions of the spectrum ("step-by-step method").[25] This enabled the CIE to adopt standardized response functions. The first of the standard functions so defined was $V(\lambda)$.

Other studies revealed that the spectral response of the human eye changes as the luminance of objects is reduced. Because the principal active elements for scotopic vision (the rod receptors of the retina) are less sensitive to red light, the response for scotopic vision is blue-shifted by approximately 50 nm with respect to the $V(\lambda)$ curve that applies to photopic (cone) vision. In 1951, the CIE adopted the supplementary standard spectral luminous efficiency function, $V'(\lambda)$, for scotopic vision at luminance levels less than some hundredths of a candela per square metre. The CIE standard spectral luminous efficiency functions, $V(\lambda)$ and $V'(\lambda)$, have been officially ratified by the CIPM[26][27].

In 2010, the CIE defined the spectral luminous efficiency functions for mesopic vision based on visual performance.[10] These mesopic spectral luminous efficiency functions are to be used at intermediate luminance levels and are a weighted average of the standard functions for photopic and scotopic vision, $V(\lambda)$ and $V'(\lambda)$, respectively, depending upon the state of adaptation for the given visual conditions.

C.3 Supplementary remarks

Although the CIE system of physical photometry is a universally accepted, proven system that is unlikely to be changed in the near future, it should be noted that it is based on conventions which are supported by only a limited number of measurements made a fairly long time ago. The human visual response to optical radiation of different wavelengths is complex and not yet fully understood. For example, luminance is intended to correlate with the perception of brightness. However, in photopic vision, it does so only for lights having the same colour. It has been established experimentally that lights having identical photopic luminances or photopic luminous intensities but different colours, i.e. different values for the chromaticity coordinates are in general not perceived as equally bright. The brightness differences depend on the colours involved.

It is also known that the spectral luminous efficiency function for photopic vision, $V(\lambda)$, underestimates the visual response in the blue region and an improved function, known as the CIE 1988 modified 2° spectral luminous efficiency function for photopic vision, $V_M(\lambda)$, was recommended by the CIE as a supplement to, and not a replacement of, $V(\lambda)$.[9] The physiology-based function, known as the cone-fundamental-based spectral luminous efficiency function, $V_F(\lambda)$, is based on the latest research[5] and is considered to provide further improvements. The $V_F(\lambda)$ functions are not yet recognized by the CIPM and are used only for research purposes to measure perceived brightness more accurately. Benefits and impacts of the new luminous efficiency functions will be evaluated in the near future. The values of the cone-fundamental-based spectral luminous efficiency functions are reported in Annex E.

Annex D
(informative)

Guidance on valid description of photometric values

Table D.1 gives some examples of valid descriptions of photometric values conforming with this document.

Table D.1 — 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[a]	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[b]	$L_{mes;0,614}$ = 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[c]	$\Phi_{mes;0,479}$ = 30,0 lm
Photopic luminous flux using the CIE 10° photopic photometric observer function is 5 000 lm	Φ_{10} = 5 000 lm

[a] Where no qualifying descriptor is given, as in this case, it is assumed that the quantity is a photopic quantity.

[b] See CIE 191:2010, Table A.1a for determination of m = 0,614 for these adaptation conditions.

[c] See CIE 191:2010, Table A.1a for determination of m = 0,479 for these adaptation conditions.

Annex E
(informative)

Cone-fundamental-based spectral luminous efficiency functions

Since colorimetry was established in 1931, considerable improvements in the metrology of the colour stimulus and immense advances in the knowledge of colour vision have been made.

The CIE provides recommendations concerning colorimetry which can be found in CIE 015:2018,[28] with colour-matching functions specified by ISO/CIE 11664-1:2019.[29] However, the colour sensation results from physiological processes, the first of which is the capture of photons by the cones of the retina. For some purposes a more precise model of the fundamental sensitivities of the cones could be needed to accurately specify a colour stimulus from a given spectral power distribution.

CIE 170-1:2006[30] provides the scientific community with cone fundamentals, which are the relative spectral sensitivities of the long-wave sensitive (LWS), middle-wave sensitive (MWS) and short-wave sensitive (SWS) cones as measured at the entrance of the eye. The cone fundamentals have been derived from the best set of colour-matching functions experimentally collected on a 10° field. In particular, the 2° cone fundamentals, which have been reconstructed from the 10° data by guidance of psychophysical data for 2° field size, represent the best proposal available today.

CIE 170-2:2015[5] provides the user with practical colorimetric tools, in the form of cone-fundamental-based chromaticity diagrams, which establish a link between colorimetry and physiology. This concept, which has been developed by several scientists over a long period, is a modern CIE approach that will improve the understanding of colour.

On the basis of the purely energy-based 2° cone fundamentals $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$, a cone-fundamental-based spectral luminous efficiency function $V_{\mathrm{F}}(\lambda)$ can be defined as a linear combination of $\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ according to Formula (E.1):

$$V_{\mathrm{F}}(\lambda) = \alpha\ \bar{l}\ (\lambda) + \beta\ \bar{m}\ (\lambda) + \gamma\ \bar{s}\ (\lambda) \tag{E.1}$$

where α, β and γ are weighting constants. It is, however, a basic assumption that the S-cone system does not notably contribute to luminance and Formula (E.1) thus reduces to a linear combination of $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$. The determination of the weighting constants is outlined in CIE 170-2:2015,[5] stating that for the 2° cone-fundamental-based spectral luminous efficiency function $V_{\mathrm{F}}(\lambda)$ is calculated according to Formula (E.2):

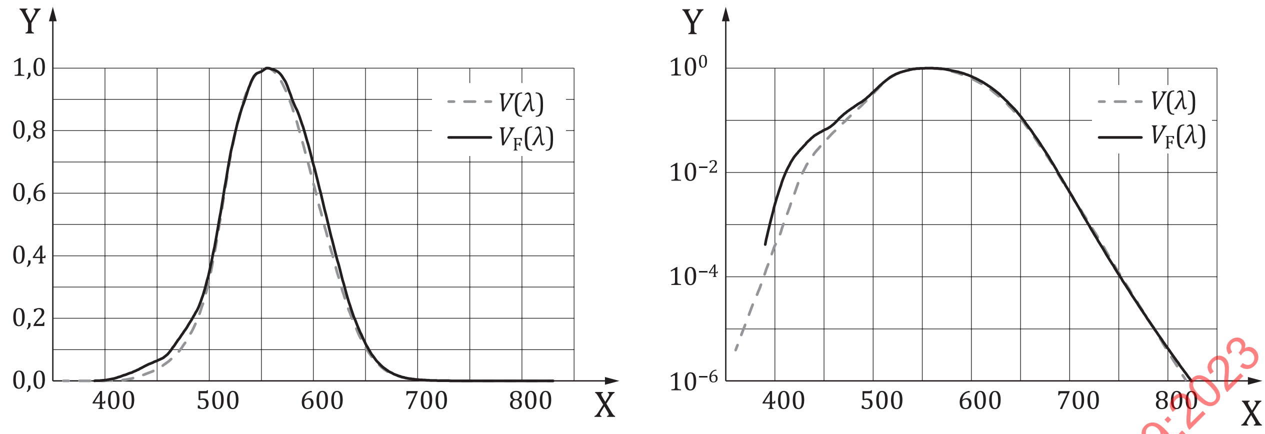
$$V_{\mathrm{F}}(\lambda) = 0{,}689\,902\,72\,\bar{l}(\lambda) + 0{,}348\,321\,89\,\bar{m}(\lambda) \tag{E.2}$$

$V_{\mathrm{F}}(\lambda)$ is normalized to unity peak at 556,1 nm and the values are reported in Table E.1 and illustrated in Figure E.1.

The cone-fundamental-based spectral luminous efficiency function for 10° field size $V_{\mathrm{F},10}(\lambda)$ is calculated according to Formula (E.3):

$$V_{\mathrm{F},10}(\lambda) = 0{,}692\,839\,32\,\bar{l}_{10}(\lambda) + 0{,}349\,675\,67\,\bar{m}_{10}(\lambda)\,. \tag{E.3}$$

$V_{\mathrm{F},10}(\lambda)$ is normalized to unity peak at 555,7 nm and the values are reported in Table E.2 and illustrated in Figure E.2.



a) Linear scale **b) Logarithmic scale (to base 10)**

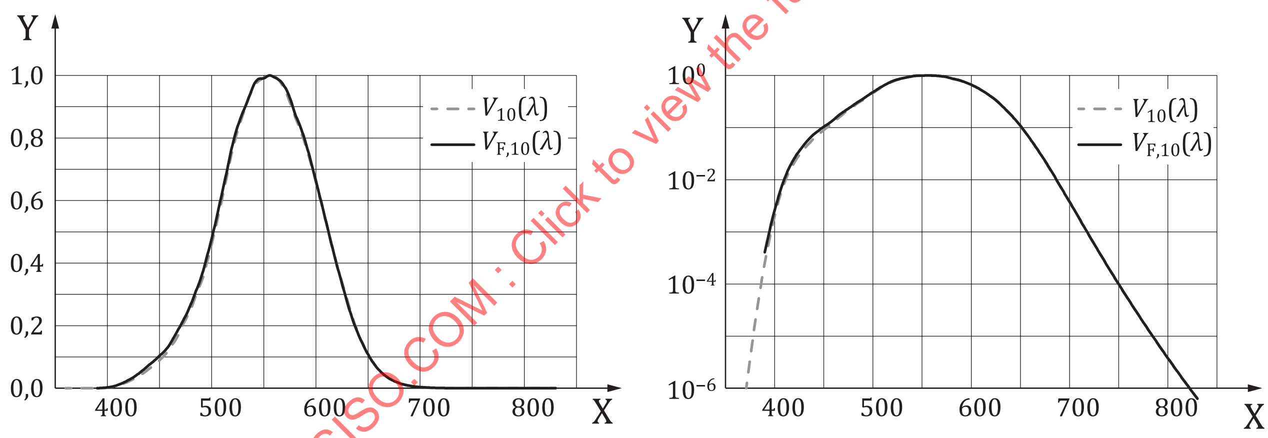
Key

λ wavelength in nm

$V(\lambda)$ spectral luminous efficiency for photopic vision

$V_F(\lambda)$ 2° cone-fundamental-based spectral luminous efficiency

Figure E.1 — 2° cone-fundamental-based spectral luminous efficiency function, $V_F(\lambda)$, and spectral luminous efficiency function for photopic vision, $V(\lambda)$



a) Linear scale **b) Logarithmic scale (to base 10)**

Key

λ wavelength in nm

$V_{10}(\lambda)$ spectral luminous efficiency for 10° photopic vision

$V_{F,10}(\lambda)$ 10° cone-fundamental-based spectral luminous efficiency

Figure E.2 — 10° cone-fundamental-based spectral luminous efficiency function, $V_{F,10}(\lambda)$, and spectral luminous efficiency function for 10° photopic vision, $V_{10}(\lambda)$

Table E.1 — Cone-fundamental-based spectral luminous efficiency function for 2° field size

λ/nm	$V_F(\lambda)$
390	0,000 414 616 100
391	0,000 502 833 300
392	0,000 608 499 100
393	0,000 734 443 600
394	0,000 883 738 900
395	0,001 059 646 000
396	0,001 265 532 000
397	0,001 504 753 000
398	0,001 780 493 000
399	0,002 095 572 000
400	0,002 452 194 000
401	0,002 852 216 000
402	0,003 299 115 000
403	0,003 797 466 000
404	0,004 352 768 000
405	0,004 971 717 000
406	0,005 661 014 000
407	0,006 421 615 000
408	0,007 250 312 000
409	0,008 140 173 000
410	0,009 079 860 000
411	0,010 056 080 000
412	0,011 064 560 000
413	0,012 105 220 000
414	0,013 180 140 000
415	0,014 293 770 000
416	0,015 450 040 000
417	0,016 640 930 000
418	0,017 853 020 000
419	0,019 070 180 000
420	0,020 273 690 000
421	0,021 448 050 000
422	0,022 600 410 000
423	0,023 747 890 000
424	0,024 912 470 000
425	0,026 121 060 000
426	0,027 399 230 000
427	0,028 749 930 000

λ/nm	$V_F(\lambda)$
428	0,030 169 090 000
429	0,031 651 450 000
430	0,033 190 380 000
431	0,034 779 120 000
432	0,036 414 950 000
433	0,038 095 690 000
434	0,039 818 430 000
435	0,041 579 400 000
436	0,043 370 980 000
437	0,045 171 800 000
438	0,046 954 200 000
439	0,048 687 180 000
440	0,050 336 570 000
441	0,051 876 110 000
442	0,053 322 180 000
443	0,054 706 030 000
444	0,056 063 350 000
445	0,057 433 930 000
446	0,058 851 070 000
447	0,060 308 090 000
448	0,061 786 440 000
449	0,063 265 700 000
450	0,064 723 520 000
451	0,066 147 490 000
452	0,067 572 560 000
453	0,069 049 280 000
454	0,070 632 800 000
455	0,072 383 390 000
456	0,074 359 600 000
457	0,076 593 830 000
458	0,079 114 360 000
459	0,081 953 450 000
460	0,085 148 160 000
461	0,088 726 570 000
462	0,092 660 080 000
463	0,096 897 230 000
464	0,101 374 600 000
465	0,106 014 500 000

λ/nm	$V_F(\lambda)$
466	0,110 737 700 000
467	0,115 511 100 000
468	0,120 312 200 000
469	0,125 116 100 000
470	0,129 895 700 000
471	0,134 629 900 000
472	0,139 330 900 000
473	0,144 023 500 000
474	0,148 737 200 000
475	0,153 506 600 000
476	0,158 364 400 000
477	0,163 319 900 000
478	0,168 376 100 000
479	0,173 536 500 000
480	0,178 804 800 000
481	0,184 181 900 000
482	0,189 655 900 000
483	0,195 210 100 000
484	0,200 825 900 000
485	0,206 482 800 000
486	0,212 182 600 000
487	0,218 027 900 000
488	0,224 158 600 000
489	0,230 730 200 000
490	0,237 916 000 000
491	0,245 870 600 000
492	0,254 602 300 000
493	0,264 076 000 000
494	0,274 249 000 000
495	0,285 068 000 000
496	0,296 483 700 000
497	0,308 501 000 000
498	0,321 139 300 000
499	0,334 417 500 000
500	0,348 353 600 000
501	0,362 960 100 000
502	0,378 227 500 000
503	0,394 135 900 000