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Mesopic models—from brightness matching to visual performance in night-time driving: a review

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At present, suitable methods to evaluate the visual effectiveness of lighting products in the mesopic region are not available. The majority of spectral luminous efficiency functions obtained to date in the mesopic range have been acquired by heterochromatic brightness matching. However, the most recent studies in the mesopic field have adopted a task performance-based approach. This paper summarizes the major mesopic models proposed so far, presenting in detail the experimental conditions of these studies. The authors represent a research consortium which has adopted the task performance-based approach for night-time driving in which mesopic visual performance has been divided into three subtasks. Data for each sub-task will be generated by using a set of common parameter values and 120 observers. The approach and methods used by the consortium are presented.

1. Photopic, scotopic and mesopic photometry

Photometry provides a method for assessing light in terms of human visual spectral sensitivity. The International Lighting Vocabulary defines photometry as measurement of quantities referring to radiation as evaluated according to a given spectral luminous efficiency function e.g., $V(\lambda)$ or $V'(\lambda)$.[1] Human spectral sensitivity functions are derived from psychophysical experiments which measure spectral sensitivity with certain visual criteria and under a defined set of conditions. Both the psychophysical criteria and the physical conditions of the experiments affect the derived functions.[2]

In the early 1900s several researchers[3–8] worked on defining spectral luminous efficiency for photopic vision. Two main methods were used: heterochromatic brightness matching and flicker photometry. In 1923, Gibson and Tyndall[8] introduced the final curve based on their own step-by-step brightness matching data from 52 observers and the accumulated data of more than 200 observers of other researchers. This $V(\lambda)$ function was adopted by the CIE at its 6th Session in 1924.[9] Since its establishment in 1924, the photopic $V(\lambda)$ function has remained the only function that is used in practical photometry.[10]

At very low light levels, in the scotopic region, the spectral sensitivity of the eye is determined by the rods and is described by the

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$V'(\lambda)$ function, established by the CIE in 1951.[11] The $V'(\lambda)$ is based on the detection threshold data of Wald[12] and on the direct brightness matching data of Crawford.[13] The $V'(\lambda)$ function describes the spectral sensitivity at scotopic levels, which is shifted to shorter wavelengths compared with daylight (photopic) vision.

In the mesopic region, between the photopic and scotopic, both the rods and cones are active and their interaction determines spectral sensitivity. Scotopic vision is generally believed to extend from the minimum visible stimulus up to about 0.001 cd/m,[2,14] which can consequently be considered as the lower limit of the mesopic region. The upper luminance limit of mesopic vision cannot be precisely defined, as it is dependent on several factors, including the size and position of the visual object in the field of view. According to a review by LeGrand[15] the upper luminance limit of mesopic vision is about 5 cd/m^2 with a 3° central field and at least 15 cd/m^2 for a 25° field. According to Kokoschka,[16] the upper luminance limit of the mesopic region extends to about 10 cd/m^2. The CIE definition for the border between mesopic and photopic luminance regions is 'at least several cd/m^2'.[14] The mesopic luminance region covers a wide range of lighting applications including night-time traffic conditions. It is known that neither $V(\lambda)$ nor $V'(\lambda)$ alone are representative of the eye's spectral response in the mesopic range.[14]

At present, manufacturers' data for the luminous flux (lumen) values and luminous efficacy (lm/W) of light sources are based only on the photopic $V(\lambda)$. However, modern lighting technology is very different to that of the early 1900s, when the foundations for the photopic $V(\lambda)$ were laid. New light sources have become available, techniques to distribute light are diverse, and applications of lighting are increasingly wide-ranging, with the result that measurements based on $V(\lambda)$ alone are no longer appropriate in many situations.[17–19] One indicator of the potential differences between photopic and mesopic evaluations is the S/P-ratio, which is a ratio of scotopic-to-photopic luminous flux of a light source. Table 1 shows the S/P-ratios of a high pressure sodium lamp, which is today the most common light source for road lighting, of a daylight metal halide lamp and of a blue, red and white light emitting diode (LED).[20] LEDs for general outdoor lighting are not yet competitive compared to traditional light sources, but major efforts are being put into their development and they are foreseen to be potential alternative light sources for future lighting applications. The S/P ratios suggest, that the high pressure sodium lamp is not necessarily the optimum light source for the low luminance levels encountered in street and road lighting. Light sources with higher content in the blue wavelength region, such as high colour temperature discharge lamps (metal halide), may be more effective for good visual performance in road and street lighting. Similarly, the luminous output of modern LED sources used for traffic signalling show tremendous differences depending on which of the currently available luminous efficiency functions is used. It has been stated that the use of $V(\lambda)$ alone in mesopic photometry generally results in sizeable errors in the assessment of light[14] and it is evident that, with present practice, the effective illuminance produced by light sources in mesopic applications cannot be correctly determined.[21] It is not surprising, therefore, that international pressure for a system of mesopic photometry is steadily increasing.

Table 1 Scotopic to photopic (S/P) luminous flux ratios of light sources

Light source type	S/P-ratio
250 W high pressure sodium	0.60
250 W daylight metal halide	2.40
Red AlInGaP LED	0.04
Blue InGaN LED	14.60
White InGaN+YAG LED	2.43

The aim of this paper is to give a review of the existing mesopic models and discuss the different approaches in developing mesopic models as well as the problems of comparing the existing models. The paper ends with an outline of an experimental method, which is developed by the authors to establish mesopic luminous efficiency functions using a task performance based approach.

2. Additivity requirements of photometry

One major issue in selecting the visual criteria for defining spectral luminous efficiency functions is the question of additivity. The CIE definition of photometry assumes additivity.[22] Physical photometers are built on the principle of Equation 1, which describes the integration of a radiant power distribution with $V(\lambda)$:[14]

$$L = K_m \int L_{e,\lambda} V(\lambda) d\lambda \tag{1}$$

where L = luminance in cd/m^2; $L_{e,\lambda}$ = spectral radiance in W/m^2 per sr per nm; $V(\lambda)$ = spectral luminous efficiency for photopic vision; K_m = maximum spectral luminous efficacy (683 lm/W).

The integral sign in Equation 1 indicates the requirement that luminance is additive i.e., that the total luminance of a non-monochromatic light is the sum of the spectral radiance of the component wavelengths weighted by $V(\lambda)$. The property of additivity in photometry allows the use of one number to assess the visual effectiveness of light of any radiant energy distribution. However, there are visual tasks for which additivity does not hold e.g., the brightness perception of saturated lights. In the case where two monochromatic or highly saturated stimuli are combined together, the consequent perceived brightness is usually lower than the sum of the component perceived brightnesses. This failure of additivity (known as the Helmholtz-Kohlrausch effect) is thought to be a consequence of cone–cone interactions.[23]

Vision research has provided evidence that the photopic visual system can be suitably described in terms of a chromatic or spectrally opponent system and an achromatic or spectrally non-opponent system.[24] The M- and L-cones are the primary input to the achromatic, or luminance, channel, but there are also arguments that the S-cones contribute to luminance under certain conditions.[25,26] The achromatic signal is an additive response of the cone outputs.[24] The chromatic system, on the other hand, involves the differencing of signals from the cones to form two opponent colour mechanisms.

It has been suggested that the outputs of the achromatic luminance channel and the opponent colour-channels both contribute to brightness perception.[27] The additivity failures associated with the heterochromatic brightness matching method are well known.[22–25] The chromatic system is believed to be responsible for the failure of Abney's law of additivity in visual conditions where both the achromatic and chromatic systems contribute to the response.[23] The mesopic models based on brightness adequately predict the brightness of monochromatic lights. However, the additivity failures become apparent when predictions of the brightness of non-monochromatic lights are made.

In flicker photometry, the minimum flicker adjustments are made at high temporal frequencies. In this case, the chromatic system is not thought to contribute to the visual task as the chromatic pathways have a lower temporal frequency cut-off than the achromatic pathways.[28] It is generally accepted that the perception of flicker is mediated by the achromatic channel and thus, additivity holds for flicker photometry at photopic levels.

In the mesopic range, an additive photometric system[29,30] based on reaction time measurements has been proposed. In this system additivity has been claimed *within* a given adaptation level *only*. The reason is that no model of mesopic photometry can preserve proportionality as there is a gradual shift from the photopic luminous efficiency function to the scotopic luminous efficiency function.[31] But, if additivity holds at a given mesopic light level, then a single luminous efficiency function can be used to integrate radiant flux of any arbitrary spectral power distribution at that light level.[31]

3. Brightness matching and flicker photometry in measuring spectral sensitivity

One question in the fields of lighting and vision research has been what visual criteria should be used in developing spectral luminous efficiency functions. Photometry could be defined against various visual perception or performance measures, such as brightness comparison, flicker resolution, visual search performance, detection threshold, minimally distinct border, reaction time, etc.

The shape of the specific luminous efficiency function that is obtained in a given experiment depends on whether the method used taps the output of the achromatic system, or both the achromatic and chromatic systems. The different characteristics of perception of flicker and brightness are the reason for the different shapes of photopic luminous efficiency functions obtained by the flicker method and the brightness matching method. It is widely accepted that luminous efficiency functions obtained with brightness matching show higher sensitivity to short and long wavelengths than functions obtained with flicker photometry.[23,27,28] The data that were used to derive the CIE $V(\lambda)$ function were based on several experiments using both flicker photometry and step-by-step brightness matching,[3,5–8,32–34] despite the fact that differences between flicker photometry and brightness matching were already recognized at that time.[33] A certain amount of smoothing of the data was carried out in order to form the final $V(\lambda)$ in 1923.[8]

In the 1930s Jainski[35] measured photopic spectral sensitivity for 60 observers with flicker photometry and found a slight shift in the long wavelength region in comparison to the CIE $V(\lambda)$ function. No differences in the derived spectral sensitivity functions were found between Asian and European subjects.[35] In 1995 Enders[36] published his results of the influence of the experimental method on photopic spectral sensitivity. These results showed that the spectral sensitivity functions were either similar to Judd's modified function $V_{\mathrm{M}}(\lambda)$[37] or to the 2° luminous efficiency function for brightness $V_{\mathrm{b},2}(\lambda)$,[38] depending on the method. The methods that utilized high temporal frequencies, like the flicker method and critical flicker frequency, revealed spectral sensitivity functions similar to $V_{\mathrm{M}}(\lambda)$. The methods involving brightness matching (heterochromatic brightness matching, step-by-step brightness matching, achromatic and chromatic threshold) tended to reveal spectral sensitivity functions similar to $V_{\mathrm{b},2}(\lambda)$, as did the method based on measurement of pupil diameter.[36] According to Lennie *et al.*,[39] however, photopic step-by-step brightness matching yields a $V(\lambda)$-like sensitivity function, whereas photopic brightness matching yields a sensitivity function broader than $V(\lambda)$.

In the mesopic region spectral sensitivity is dynamic, showing a strong dependence on the adaptation level. Furthermore, even at the same luminance level sensitivity is dependent on the visual task and its characteristics.[22] It has long been realized that several spectral sensitivity functions are needed to fully describe mesopic vision and that these functions change, both in shape and maximum sensitivity, with changes in light level.[22]

As indicated previously, the lack of brightness–luminance equivalence in the photopic range results from brightness being a combined response of the achromatic and chromatic systems. In the mesopic range the situation is even more complex, due to cone–cone interactions and cone–rod interactions.

At the higher levels of the mesopic region, cone–cone interactions are believed to lead to sub-additivity, where the combined brightness of two coloured stimuli is lower than the sum of the component brightnesses. At the lower mesopic levels it is thought that cone–rod interactions lead to supra-additivity, where the combined effect is greater than the sum of the components.[22,27,40]

Viénot and Chiron compared heterochromatic flicker photometry to direct comparison brightness matching in the mesopic range.[41,42] They state that heterochromatic flicker photometry is a highly problematic method in the mesopic range because of the discontinuities they found in sensitivity over the mid-mesopic region. The fact that the critical flicker fusion frequency (CFF) of human vision is dependent on the adaptation level and that CFF is different for rods and cones[43] may also complicate the applicability of flicker photometry in studying mesopic vision. LeGrand[15] claims that flicker photometry is an unsuitable method for studying peripheral vision as flicker fusion is easily reached in the peripheral retina.

In choosing suitable criteria for the establishment of luminous efficiency functions, the same difficulties that have been encountered in the photopic range remain or are even more complicated in the mesopic range. The non-additivity of brightness matching remains a problem under mesopic conditions. The flicker photometry method, on the other hand, that is claimed to be additive and appropriate for the photopic range, does not appear to be appropriate for the mesopic range.[15,41,42]

4. Proposed mesopic models based on brightness matching

The early works on mesopic luminous efficiency are mostly based on brightness matching, these include studies by Sloan,[44] Weaver,[45] Walters and Wright,[46] Bedford and Wyszecki[47] and Kinney.[48] As the problems of mesopic photometry, like additivity failure, became more obvious to the researchers, different approaches for mesopic research were launched. In 1963, the CIE introduced the concept of equivalent luminance L_{eq}, namely the luminance of the reference stimulus of 555 nm, which appears equal in brightness to the test sample.[40,49]

Table 2 summarizes the major mesopic models that have been introduced so far. The methods used by the different researchers are given, as well as the parameters used in their experimental set-ups to generate their datasets. The viewing conditions are described by the visual angle of the stimulus, stimulus shape and eccentricity and mono/binocularity and the reported pupil conditions. The luminance/radiance and the spectral characteristics of the test and reference field are given. The surrounding field is characterized by its luminance/radiance and spectral characteristics. The number of subjects in each study is also given.

Among the early studies, the works of Walters and Wright[46] and Kinney[48] are summarized in Table 2, as they are the ones frequently referred to in later studies. These two studies used heterochromatic brightness matching to derive mesopic luminous efficiency functions. Measurements were made at several luminance levels, field sizes and eccentricities. None of the early works[44–48] provided a model of mesopic photometry, but they formed a good basis for subsequent studies. The early works found the Purkinje effect at the mesopic levels. Also, the failure of additivity became evident to the researchers, especially at the intermediate mesopic levels. The additivity failures in the direction of supra-additivity were assumed to be due to rod–cone interactions, but these could not, however, be explained in detail. Individual differences were reported in the shapes of the derived mesopic luminous efficiency curves, as well as in the absolute levels of sensitivity.

Table 2 Summary of major mesopic models

Author	Method	System	Viewing conditions					Stimulus				Surrounding			Subjects
			Visual angle	Shape	Eccentricity	Presentation	Viewing	Luminance or radiance of test field	Luminance or radiance of reference field	Spectral characteristics of test field	Spectral characteristics of reference field	Visual angle	Luminance or radiance	Spectral characteristics	No.
Walters, Wright[46] (1942)	HCBM		2°	Square (bipartite)	0° 3° nasal side 10° temporal side	Steady	Artificial pupil (r = 0.628 mm)	Adjustable	0.015, 0.025, 0.031, 0.038, 0.062, 0.092, 0.10, 0.15, 0.25, 0.37, 0.93, 2.3, 5.7, 14, 45 10^{-4} ergs/deg.^{2}/sec	470–700 nm	630 nm				2
Kinney[48] (1964)	HCBM		2° 10°	Circular (solid)	0° 2° (below fovea) 4° (below and nasal side of the fovea)	1 s	Mono-cular (right eye)	Adjustable in 0.1 log unit steps	Surrounding acted as the reference field.	Nearly monochromatic with peaks at 451, 475, 515, 530, 565, 585, 650 nm	Surrounding acted as the reference field.	120°	0.3426, 0.03426 cd/m^2	White (x = 0.33, y = 0.33)	4
Palmer 1st[51,52] (1968)	HCBM	Two-variable system	5°	Circular (bipartite)	0°	Steady	Binocular	Adjustable	Monochromatic test lights (440, 560, 680 nm): 0.001, 0.01, 0.1 cd/m^2 Non-monocrhomatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2	10 nearly monochromatic (hbw 30 nm) with peaks at 410–680 nm (30 nm steps). 10 non-monochromatic: blue, light-blue, cyan, green, white, pink, purple, yellow, orange, red.	2042 K	7°	Monochromatic test lights (440, 560, 680 nm): 0.001, 0.01, 0.1 cd/m^2 Non-monochromatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2	2042 K	16
			15°		0°				Monochromatic test lights: 0.000316–0.316 cd/m^2 (0.5 log unit steps) Non-monochromatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2			21°	Monochromatic test lights: 0.000316–0.316 cd/m^2 (0.5 log unit steps) Non-monochromatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2		

Table 2 (*Continued*)

Author	Method	System	Viewing conditions					Stimulus				Surrounding			Subjects
			Visual angle	Shape	Eccentricity	Presentation	Viewing	Luminance or radiance of test field	Luminance or radiance of reference field	Spectral characteristics of test field	Spectral characteristics of reference field	Visual angle	Luminance or radiance	Spectral characteristics	No.
			45°		0°				Monochromatic test lights (440, 560, 680 nm): 0.001, 0.01, 0.1 cd/m^2 Non-monochromatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2			63°	Monochromatic test lights (440, 560, 680 nm): 0.001, 0.01, 0.1 cd/m^2 Non-monochromatic test lights: 0.000316, 0.00316, 0.0316, 0.316 cd/m^2		
Ikeda, Shimozono[50] (1981)	HCBM	Two-variable system	10°	Circular (bipartite)	0°	Steady	Maxwellian view, natural pupil	Adjustable	0.01 – 100 Td (0.5 log unit steps)	400 – 700 nm (hbw about 10 nm) (20 nm steps)	White (x = 0.327, y = 0.345)				2
Trezona[56] (1987)	HCBM	Four-variable system	10°	Circular (bipartite)	0°	Steady	Artificial pupil	Progressively redused from photopic to absolute threshold.	Adjustable	17 monochromatic (436 – 700 nm) 24 non-monochromatic	588 nm				4
Ikeda, Ashizawa[57] (1991)	HCBM	System of equivalent lightness (two variables)	12°	Test field 6° square, Reference field 6° square	0°	Steady		Illuminance: 0.01 – 1000 lx (0.5 log unit steps)	Illuminance: 0.01 – 1000 lx (0.5 log unit steps)	26 colored surfaces illuminated by 5000 K fluorescent lamp.	18 grey surfaces illuminated by 5000 K fluorescent lamp.			Black surface	10
Kokoschka, Bodmann[55] (1991)	HCBM	Four-variable system	3° 9.5° 64°	Circular (bipartite)	0°	Steady		Adjustable	0.003 – 30 Td (1 log unit steps)	399, 430, 459, 479, 503, 550, 578, 599, 618, 660, 698 nm	530 nm				3

Table 2 (*Continued*)

Author	Method	System	Viewing conditions					Stimulus				Surrounding			Subjects
			Visual angle	Shape	Eccentricity	Presentation	Viewing	Luminance or radiance of test field	Luminance or radiance of reference field	Spectral characteristics of test field	Spectral characteristics of reference field	Visual angle	Luminance or radiance	Spectral characteristics	No.
Vienot, Chiron[41] (1992)	HCBM		10°	Circular (bipartite)	0°	Steady	Three-channel Maxwellian view	Adjustable	0.03–100 Td (0.5 log unit steps)	445, 560, 630 nm (hbw 16 nm)	3850 K	30°	0.5 log units lower than the reference field.	3850 K	3
	FP		10°	Circular	0°	Flickering	Three-channel Maxwellian view	Adjustable	0.03–100 Td (0.5 log unit steps)	445, 560, 630 nm (hbw 16 nm)	3780 K	30°	0.5 log units lower than the reference field.	3780 K	3
Nakano, Ikeda[22] (1992)	HCBM	Two-variable system	10°	Circular (bipartite)				Adjustable	0.01–100 Td (1 log unit steps)	4 combinations of two monochromatic wavelenghts of various radiance ratios: 460 and 630 nm, 490 and 610 nm, 470 and 580 nm, 500 and 570 nm	White				2
Sagawa, Takeichi[53,54] (1992)	HCBM	Two-variable system	10°	Circular (bipartite)	0°	Steady	Two-channel Maxwellian view, artificial pupil (r = 1.5 mm)	Adjustable	0.01–100 Td (0.5 log unit steps)	400–700 nm (hbw 6 nm) (10 nm steps)	White (500 W xenon lamp)				24
He *et al.*[29] (1997)	RT	Two-variable system	2°	Circular (solid)	0° 15°	Pulse <2 s	Monocular (right eye)	0.7 contrast against the surrounding	Surrounding acted as the reference field.	400 W High Pressure Sodium (x = 0.5203, y = 0.4187) 175 W Metal Halide (x = 0.3636, y = 0.4005)	Surrounding acted as the reference field.	Half-cylinder r = 75 cm, h = 50 cm	0.003–10 cd/m^2 (0.5 log unit steps)	400 W High Pressure Sodium (x = 0.5194, y = 0.4197) 175 W Metal Halide (x = 0.3706, y = 0.4036)	3

Table 2 (*Continued*)

Author	Method	System	Viewing conditions					Stimulus				Surrounding			Subjects
			Visual angle	Shape	Eccentricity	Presentation	Viewing	Luminance or radiance of test field	Luminance or radiance of reference field	Spectral characteristics of test field	Spectral characteristics of reference field	Visual angle	Luminance or radiance	Spectral characteristics	No.
He *et al.*[30] (1998)	BSM	Two-variable system	1.6°	Circular (solid)	12° to right (The target in the left viewing field 2° below the visual horizon and in the right field 2° above)	Pulses of 1 s with variable ms delays	Binocular	When on $\rho = 0.95$ When off $\rho = 0.05$	When on $\rho = 0.95$ When off $\rho = 0.05$	When on: white When off: black	When on: white When off: black		Left test field: 0.3, 3, 10 Td, Right reference field: adjustable	Left test field: 436, 470, 510, 546, 630 nm, (hbw max 10 nm) Right reference field: Monochromatic 589 nm low-pressure sodium	1
Hurden *et al.* phase 1[63,64] (1999)	ST	Empirical search time equation	2°	Modified Landolt C (90° sector removed)	Random within the display	< 12 s	Binocular, natural pupil	The stimuli consisted of one target and 48 distractor elements each of which had a unique visual contrast and colour difference against the surrounding.				Computer display	0.044–10 cd/m^2	Uniform achromatic ($x = 0.305$, $y = 0.323$)	15
Hurden *et al.* phase 2[64] (2002)	Conspicuity matching	Conspicuity model based on matching achromatic luminance contrast	3°	Modified Landolt C (90° sector removed)	7°	500 ms	Binocular, natural pupil (pupil size recorded)	Scotopic and photopic contrast against the surrounding	Achromatic contrast against the surrounding	Chromatic difference against the surrounding	Uniform achromatic ($x_{10} = 0.306$, $y_{10} = 0.326$)	27° × 22°	6 light levels 0.0038–10 cd/m^2	Uniform achromatic ($x_{10} = 0.306$, $y_{10} = 0.326$)	5
	ST (Visual Search)		Target 2.5° Distractors 2°–3°	Modified Landolt C (45° sector removed)	Inside 22° diameter (<11°)	< 8 s	Binocular, natural pupil	The stimuli consisted of one target and 19 distractor elements each of which had photopic and scotopic contrasts and colour difference against the surrounding.				27° × 22°	0.012, 0.046, 1.1, 10 cd/m^2	Uniform achromatic ($x_{10} = 0.306$, $y_{10} = 0.326$)	4
	Pre-attentive research orientation discrimination		1° × 0.18°	line	7°	133.3 ms	Binocular, natural pupil	The stimuli consisted of one target and 19 distractor elements each of which had photopic and scotopic contrasts and colour difference against the surrounding.				18° × 18°	0.1, 1, 10 cd/m^2	Uniform achromatic ($x_{10} = 0.306$, $y_{10} = 0.326$)	4

Table 2 (*Continued*)

Author	Method	System	Viewing conditions					Stimulus				Surrounding			Subjects
			Visual angle	Shape	Eccentricity	Presentation	Viewing	Luminance or radiance of test field	Luminance or radiance of reference field	Spectral characteristics of test field	Spectral characteristics of reference field	Visual angle	Luminance or radiance	Spectral characteristics	No.
Kurtenbach *et al.*[65] (1999)	ADT	Four-variable system, incl. opponent channels, modelling the spectral sensitivity curves	2°	Circular (solid)	5°	2 s	Monocular	Adjustable	0.47–15 Td	420–680 nm (hbw 4 nm) (10 nm steps)	6000 K	8° circular background	0.47, 1.49, 4.7, 15 Td	6000 K	3

HCBM: Heterochromatic Brightness Matching; FP: Flicker Photometry; RT: Reaction Time; BSM: Binocular Simultaneity; Method ST: Search Time; ADT: Achromatic Detection Threshold

Table 2 presents three two-variable mesopic models, based on heterochromatic brightness matching, which have been proposed to CIE.[22,40] In addition, a two-variable model of Ikeda and Shimozono[50] (also based on heterochromatic brightness matching) is given, which uses a theoretical photopic luminous efficiency function based on the brightness matching data of their own studies. Ikeda and Shimozono state that the success of their formula stems from the use of a photopic luminous efficiency function determined by their own brightness matching data and not on $V(\lambda)$, which is determined for a 2° field and is partly based on flicker photometry.[50] Palmer's first model[51,52] is a linear combination of the CIE photopic luminance based on $V_{10}(\lambda)$, the CIE photopic luminous efficiency function for 10° field, and CIE scotopic luminance. Palmer's second model[22,40] is a non-linear combination of the same functions. The other two-variable models are geometrically-weighted means of the photopic and scotopic luminances. The Sagawa–Takeichi[53,54] model uses the CIE photopic luminance and CIE scotopic luminance as inputs and the Nakano–Ikeda[22] model uses CIE photopic luminance based on $V_{10}(\lambda)$ and CIE scotopic luminance as inputs. The two-variable models of Sagawa–Takeichi and Nakano–Ikeda also add the chromatic response into their mesopic model.

Two four-variable models[55,56] proposed to CIE are summarized in Table 2. These models are also based on heterochromatic brightness matching. The Kokoschka–Bodman[55] model is a linear weighted sum of the target's CIE 1964 tri-stimulus values for a 10° field, X_{10}, Y_{10}, Z_{10}, and its CIE scotopic luminance, taking into account the chromatic contribution. The equivalent luminance is obtained through iterative calculation. The Trezona[56] model is a hyperbolic tangent function with polynomial functions of CIE 1964 tri-stimulus values X_{10}, Y_{10}, Z_{10}, and $V'(\lambda)$. It does not assume additivity, and it allows independent and interactive behaviour for all four receptor types (long wavelength sensitive-cones, middle wavelength sensitive-cones and short wavelength sensitive-cones, plus rods).[56]

The Ikeda–Ashizawa model[57,58] of mesopic lightness is fundamentally different from the earlier mesopic models. It is based on studies of object colours and it calculates the equivalent lightness rather than equivalent luminance. Despite the different approach of the Ikeda–Ashizawa model, it has been acknowledged for its unique way of separating the achromatic and chromatic contributions to brightness. Viénot and Chiron[41] used both brightness matching and flicker photometry to derive mesopic luminous efficiency functions and found differences in the derived functions based on the method used.

A CIE report in 2001[40] updated the earlier CIE 1989 report[22] on mesopic photometry and added a newly proposed model of mesopic photometry. In the new report six models based on heterochromatic brightness matching for 10° fields were assessed by the CIE. The new Ikeda–Ashizawa model was also introduced in the report, but as it is a model for equivalent lightness of object colours the testing could not be directly applied to this model. The models of Palmer (Palmer 1st and 2nd), Sagawa–Takeichi, Nakano–Ikeda, Kokoschka–Bodmann and Trezona were tested in their ability to provide assessments of brightness.[40] The testing was made with the data from seven heterochromatic brightness matching experiments. The procedure for testing the proposed models was based on a concept of residual error between the system equivalent luminance for test and reference stimuli. The residual error does not answer the question ‘Which of the systems produces the most correct values of equivalent luminance for the testing data?’,[40] but rather addresses a more simple question ‘Which of the systems comes closest to predicting the equivalence of pairs of stimuli which have been judged experimentally to be equally bright?’[40] This is a consequence of the fact that each system equivalent luminance for the test stimulus depends on the reference stimulus. Each data set has used its own reference stimulus. Thus in the CIE testing, two models may be found equally accurate, even though the values of equivalent luminance for each test stimulus differed. The comparison led to a statement that all of the proposed models are superior to the presently available measures based on $V_{10}(\lambda)$ or $V'(\lambda)$. However, it was concluded that it was not possible to find one best model and the report made no recommendation for a new CIE supplementary system of photometry. The ‘Mesopic photometry (TC1-21) minority report’ included in the CIE 2001 report[40] concludes that it is premature to consider the publication of a CIE Technical Report on mesopic photometry, as the existing mesopic data need to be examined and new data accumulated. This minority report acknowledged the generation of new data sets to accompany the existing proposed mesopic models.[40]

One difficulty in comparing the predictions of different mesopic models is that different models are based on different data sets from different experimental conditions as shown in Table 2. This concerns the choice of stimulus size and eccentricity as well as the surrounding field size. Also, the lack of common luminance level values and similar spectral characteristics complicates comparisons. Moreover, the models based on brightness matching data are based on different choices of the reference stimulus as shown in Table 2. Also, the use of natural or artificial pupils is not consistent among the different experiments.

5. Mesopic models based on a performance-based approach

The existing brightness-based mesopic models provide much data on the sensitivity changes of the visual system with decreasing light levels. Direct comparison brightness matching can be categorized as a fundamental visual task. It is claimed that brightness comparison of objects or light sources is one of the most fundamental criteria in the illuminating engineering field.[59] But the steady visual assessment of brightness is not the most important mesopic visual task in practical lighting applications, although the brightness matching models for a 10° field have been compared with a measure of perceived conspicuity in the mesopic range.[60] In practical lighting applications, the detection and recognition of visual objects at or near visual threshold, and the reaction time needed to perceive objects in the visual field, are more relevant than the visual assessment of brightness. These tasks involve visual mechanisms that are different from the mechanisms responsible for heterochromatic brightness matching. Therefore, it is difficult, if not impossible, to establish a link between visual task performance and brightness-based models, although brightness contrast is also important in perceiving an object.

Visual task processing includes several fundamental stages or sub-tasks such as search, detection, perception and recognition. In night-time driving, which is one of the key tasks performed under mesopic conditions, flicker photometry and direct brightness matching are not representative of the visual sub-tasks undertaken. Rather, visual performance during driving consists of a series of other sub-tasks. It has recently been discussed that there should be more understanding of the factors that affect visual performance in the mesopic range and that these factors should be considered in new approaches for developing models for mesopic vision.[17,61,62] Within the last 4 years, the CIE has recognized the merit of this approach, through the establishment of a technical committee (TC1-58) to propose a model for the basis of performance-based mesopic photometry. The most recent works in the mesopic field have adopted this task performance-based approach, which is closer to practical applications than brightness matching. Three recently introduced mesopic models[29,30,63–65] based on task performance are summarized in Table 2.

He *et al*.[29,30] employed conventional reaction time measurements and a binocular simultaneity technique to obtain mesopic spectral luminous efficiency functions and to develop a system of mesopic photometry. The authors claimed that their reaction time measurements obeyed the laws of additivity within a given adaptation level if stimulus radiance was adjusted to achieve the criterion reaction time. The He *et al*. system is a linear combination of the CIE $V_{10}(\lambda)$ and $V'(\lambda)$ functions. The authors suggest that their simple system echoes the additive nature of an achromatic channel that sums the outputs of the L- and M-cones and the rods and it is thus acceptable for photometry.[30] The authors also state that the reaction times, from a practical perspective, are a good performance measure for realistic situations like car driver hazard-detection responses.[30] The He *et al*. system is indeed attractive for practical photometry, as it provides a means to calculate mesopic luminances and to evaluate the efficacy of light sources for off-axis visual tasks at mesopic light levels. However, as the authors of the He *et al*. system also acknowledge, further validation of the derived luminous efficiency functions is needed, as the experimental data is based on only four observers and on limited spectral conditions. Furthermore, the number of four observers was distributed to two experiments; the reaction time experiments of the He *et al*. system were made for three observers using two different broadband spectral lights and the binocular simultaneity method experiments were made for one subject using five different monochromatic lights.

Hurden *et al*.[63,64] have also introduced new methods for defining a mesopic system. They produced two empirical models, the first was designed to predict search time measurements for a computer-controlled visual task, and was based on results from 15 observers, the second described the conspicuity of a coloured target under mesopic conditions in terms of an equally conspicuous achromatic target, which was based on data from five observers. In this case, the achromatic target was a grey target with the same relative spectral power distribution as the background. The conspicuity model was found to predict visual search behaviour and performance in an orientation discrimination task with reasonable success. This finding led to the suggestion by Hurden *et al*. that conspicuity is a basic visual process that is common to a number of different visual tasks, and that the spectral response obtained using a conspicuity matching method might make a good basis for performance photometry. The results of the Hurden *et al*. work are not directly comparable with the studies of the other research groups, as they do not provide a mesopic luminous efficiency curve or a system of mesopic photometry. Their empirical models describe the relationship between, in the first case, target plus background luminance (photopic and scotopic) and search time, and in the second case, target plus background luminance (photopic and scotopic) and the luminance contrast of an achromatic target with equal conspicuity.

Kurtenbach *et al*.[65] determined achromatic detection thresholds for three normal observers (as well as deuteranopes and tritanopes) in the mesopic region. In this case, 'achromatic' means that the detection criterion was the detection itself, without considering whether any chromaticity was seen. The resulting spectral sensitivity curves of the normal observers could not be described completely by linear combinations of $V(\lambda)$ (or $V_{10}(\lambda)$) and $V'(\lambda)$. To obtain a satisfactory description, another linear combination of $S(\lambda)$, the short-wavelength sensitive cone sensitivity function, and $|L-M|(\lambda)$, a colour opponent signal, had to be added. This yielded a four-part linear combination. The findings of Kurtenbach *et al*. indicated that the performance-based approach could also contain colour-opponent factors in certain tasks, and, that a more detailed performance-based experimental analysis was necessary. Further studies should decide whether these factors are relevant from the point of view of a usable mesopic photometry or whether a simple linear combination of the CIE $V_{10}(\lambda)$ and $V'(\lambda)$ functions could be used.

6. Multi-technique system using a performance-based approach

The authors of the present paper formed a research consortium which has adopted a performance-based approach for developing new mesopic scales,[66] based on a comprehensive experimental data-set. In this work, emphasis has been placed on night-time driving performance and the attempt to describe luminous efficiency in a realistic way, via empirical modelling of the experimental data generated in the work. The approach starts by identifying the relevant visual tasks of night-time driving. Three key visual tasks have been isolated and the consortium has then developed experimental techniques to quantify the visibility of targets when performing each of these tasks. The aim of the multi-technique system is to generate new task-specific spectral sensitivity data and to use the new data in developing (empirically) the corresponding mesopic spectral sensitivity functions. Within the study the task of night-time driving has been divided into three constituent subtasks, which are characterized by the questions for which they provide visual information:

Can it be seen?—How quickly?—What is it?

The first subtask—*Can it be seen?*—is related to detection threshold i.e., the minimum luminance contrast of a target against its surroundings that is necessary for the observers to become aware of objects in their visual field. Achromatic threshold i.e., increment and/or decrement of visual target's intensity around the threshold to detect the target, is the method used to generate data for the first sub-task. Achromatic threshold data will be generated using a sustained presentation (>3 s) with three different experimental settings: uniform hemisphere, large homogeneous screen and screen with computer-controlled projector.

The second subtask—*How quickly?*—is related to reaction times i.e., the time between the onset of a visual stimulus and the detection response of that stimulus under conditions where the observer is instructed to respond manually by pressing a button as quickly as possible. In night-time driving conditions reaction times play an important role for safe driving.[67] In the present work, reaction times will be measured for a number of coloured targets with different spectral characteristics. Reaction time data will be generated with four different experimental settings: large uniform hemisphere, computer controlled cathode ray tube (CRT) display, driving simulator and large homogeneous screen.

The third subtask—*What is it?*—is related to recognition and identification of the target i.e. the perception of fine details. Experimental settings for measuring achromatic recognition threshold and visual acuity will be used. Achromatic recognition threshold will be measured by increasing and decreasing the visual target's intensity around the threshold to recognise the target. Two experimental settings will be used to generate data for the third sub-task, these are a screen with computer-controlled projector and a head-up display (device to present computer-generated images in the driver's field of view).

The aim is to develop mesopic spectral sensitivity functions based on different visual criteria. For each visual sub-task, data will be simultaneously generated in two to four laboratories using different experimental methods in each location. This approach differs from earlier techniques. The consortium has developed an alternate multi-technique system where the visual performance of driving is described with three different sub-tasks.

The issue of additivity in mesopic photometry differs from the situation for either photopic or scotopic photometry. Due to the dependence of mesopic spectral sensitivity on the state of adaptation of the eye, additivity can only apply within a given adaptation level. Failures of additivity in the mesopic range have been discussed by Berman and Clear.[31] Berman and Clear went on to argue that additivity is not necessary for a system of mesopic photometry based on the standard photopic and scotopic luminous efficiency functions, $V(\lambda)$ and $V'(\lambda)$, as is demonstrated by He *et al*.[30] It would, nevertheless, be an advantage to have a system of mesopic photometry that did not suffer from the additivity failures inherent in comparisons of the brightness of monochromatic and broadband lights, for a given level of adaptation. To this end, the consortium has chosen visual tasks that approach additivity under photopic conditions. For example, measurements of absolute threshold for small brief stimuli,[68] increment threshold for small brief stimuli[69] and Landolt C visual acuity[70] have been shown to be additive. The consortium acknowledge, however, that the desire to represent the driving situation more realistically has led to the selection of stimulus parameters that may result in deviations from additivity for the threshold task. There has been no investigation into the additivity of reaction times, but the merits of reaction time as a promising method of producing additive spectral luminous efficiency functions has been discussed.[30,39]

As noticed earlier, the comparison of different mesopic models is difficult when different experimental parameters are used. Compared to the existing mesopic models and systems, the merit of the work adopted by the consortium is the use of a common set of parameter values as the basis of each particular data set generated in different test locations. Joint values for target eccentricity (0° and 10°), target size (2° and 0.3°), background luminance (0.01, 0.1, 1, 10 cd/m^2

photopic) and target presentation will be used in the different experimental settings. In driving, both foveal vision and peripheral vision are needed. The use of the 10° target eccentricity in the experiments is based on findings of eye-fixation behaviour in night-time driving and also to be comparable with the $V'(\lambda)$, which is partly based on brightness matching data for a centrally viewed 20° field.[13] The joint background luminance values cover the upper part of the mesopic region, which is of prime importance for night-time driving. As the vision experiment data of several research groups will be generated with common parameter values, the comparison and combination of the results will be easier than with individual research studies based on different parameter combinations. The experiments will be carried out under varied spectral conditions using quasi-monochromatic (half-band width = 10 nm), narrow-band (half-band width = 15–35 nm) and broadband spectral lights for the target and the background. The high number of observers (120) compared with earlier studies will ensure that the empirically-modelled spectral sensitivity curves are more representative of an average observer and will also increase the precision of the modelling process.

The general aim of photometry is to quantify light in various stimulus and observation conditions. Thus, the visual criteria that are used in deriving spectral luminous efficiency functions should describe the visual response in a wide range of visual conditions. Yet, one cannot assume that any single photometric system can characterize visual response in all lighting and viewing conditions. The consortium has defined and selected a set of parameter values, which are believed to be relevant in night-time driving conditions. By building the experimental data on three different visual sub-tasks instead of one visual criterion, the findings will cover a wider perspective of the visual tasks undertaken in practical situations.

7. Summary

Mesopic lighting applications are of substantial practical interest as they include road lighting, outdoor lighting, other night-time traffic environments, emergency lighting, and many other applications. It is especially the higher part of the mesopic luminance region that is of utmost importance for practical applications (e.g., traffic lighting) and for which new measurement scales and a practical system of mesopic photometry are very much needed.

Modern society and lighting technology need new dimensioning methods to accompany the $V(\lambda)$ function, dating from 1924. New developments and advances in lighting technology set constantly growing demands for better measurement precision. An internationally accepted system of mesopic photometry would promote the development and manufacture of mesopically optimized products, and would enhance the quality and performance of mesopic lighting installations. This all relates to better energy-efficiency, visual effectiveness and safety in mesopic lighting applications.

Brightness matching has been the major method in establishing mesopic models and systems. The most recent works in the mesopic field have adopted a different approach, which is to concentrate on task performance. The authors represent a research consortium which has adopted a performance-based approach for developing new mesopic scales. Visual performance of night-time driving has been described with three sub-tasks. For each sub-task, data is currently being generated in two to four laboratories using a different experimental set-up. As the data to establish new mesopic functions will be generated simultaneously in five different laboratories, they are expected to have good validity from a practical point of view. Also, the adoption of common parameter values in each test location will enable data comparison and combination from different test locations. It is foreseen that by the development of links to visual tasks and mesopic visual performance, this performance-based approach will offer new and alternate solutions for developing mesopic photometry. The results will represent a further contribution to the development of mesopic photometry, and will soon be presented to the international lighting community. The results will be integrated in the CIE TC1-58 work and will form a major input for this TC, which aims to propose a model for the basis of performance-based mesopic photometry.

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Discussion

Comment on 'Mesopic models—from brightness matching to visual performance in night-time driving: a review' by M Eloholma, M Viikari, L Halonen, H Walkey, T Goodman, J Alferdinck, A Frieding, P Bodrogi and G Várady

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This paper summarizes the history of the measurement of visual sensitivity to identify the problems inherent in mesopic photometry. In doing so it provides a useful review of the current state of play. However, I would like the authors' clarification of several points to aid my understanding of this work.

The authors state that 'New light sources have become available, techniques to distribute light are diverse, and applications of lighting are increasingly wide-ranging, with the result that measurements based on $V(\lambda)$ alone are no longer appropriate…' The application of lighting is important i.e., the use of $V(\lambda)$ is not appropriate for night time outdoor lighting, but I would like the authors to clarify why new light sources and distribution technologies render the $V(\lambda)$ assessment inappropriate.

It is noted that a difficulty in comparing the predictions made by different mesopic models is that different models are based on different data sets from different experimental conditions, e.g. choice of stimulus size and eccentricity. Are the authors aware of any data available with which to estimate the size and significance of such differences? It is pleasing to see that this consortium is adopting a common set of experimental parameters, thus enabling better comparisons of data from different laboratories: perhaps their work should also investigate the effect of different experimental conditions so that better use could be made of the existing data.

I would like the authors to clarify why they report that no differences were found in spectral sensitivity between Asian and European subjects. If this is relevant to the quest for a system of mesopic photometry the authors should comment on differences in spectral sensitivity between people of different nationalities.

The authors state that 'In practical lighting applications, the detection and recognition of visual objects at or near visual threshold, and the reaction time needed to perceive objects in the visual field, are more relevant than the visual assessment of brightness.' Since brightness is linked to the perception of safety, then there are conditions when brightness is at least equally as important as detection, reaction time etc, and should not be relegated.

The mesopic models discussed by the authors are based on the response to monochromatic lights. The research proposed by the authors has a very practical application, in which broadband light sources would be used, yet it is not clear whether the proposed work intends to use broadband or monochromatic lights.

Furthermore, it would be interesting to find out whether the reviewed models predict the results of experimental work using broadband lights, such as the studies by Ferguson and Stevens[1] and Boyce and Bruno.[2]