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Light and Lighting

Spectral characteristics of road surfaces and eye transmittance: Effects on energy efficiency of road lighting at mesopic levels

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Received 11 November 2016; Revised 22 May 2017; Accepted 8 June 2017

In 2010, the CIE published a recommended system for mesopic photometry based on visual performance. According to this system, scenes illuminated at mesopic levels with light sources of high S/P ratio, will produce better visual performance than those illuminated with light sources of a lower S/P ratio at equal photopic luminance. However, there could be other factors affected by SPD that, when quantified, could lead to a contradictory final effect. The scope of this paper was to evaluate how road lighting is affected by the spectral road surface reflectance and by the human eye transmittance as people get older. Our results suggest that the benefits of considering the mesopic vision effect for light sources with high S/P ratios are totally counteracted by the other two effects at mesopic luminances between 0.75 cd/m^2 and 1.73 cd/m^2 for people between 20 and 60 years of age, depending on the light source and the age of observers.

1. Introduction

There are three states of sensitivity of the visual system. Photopic vision occurs when eyes are adapted to a luminance above 5 cd/m^2 and the light-sensitive cells called cones are active. It is characterised by the photopic luminous function $V(\lambda)$.¹ At the other extreme, scotopic vision is present when luminance adaptation is below 0.005 cd/m^2 and the rod cells dominate vision. This state of the visual system is represented by scotopic luminous function $V'(\lambda)$.² The intermediate state of the visual system is the mesopic vision (between 0.005 cd/m^2 and 5 cd/m^2). In mesopic vision, both rods and cones are active, so that there is no unique luminous

function, indeed there are an infinite number of curves to describe this state. These curves move from the photopic to the scotopic luminous function with decreasing luminance adaptation.³

The range of minimum maintained luminances recommended for road lighting in most of the world, many of them based on the technical reports developed by the CIE⁴ and the IESNA,⁵ is between 0.3 cd/m^2 and 2 cd/m^2 for roads intended to be used by drivers of motorised vehicles. For roads used by pedestrian and pedal cyclists, the same reports recommend minimum maintained horizontal illuminances between 2 lx and 15 lx which implies a photopic luminance adaptation of between 0.14 cd/m^2 and 1.05 cd/m^2 (considering a $Q_0 = 0.07$, typical of asphalted surfaces), so that, in principle, road lighting applications are within the mesopic visual state.

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Currently, and this has been the case for over 90 years, photometry is based on the photopic luminous efficiency function $V(\lambda)$, i.e. all photometric units are weighted regarding this curve. However, in some night-time situations, the use of $V(\lambda)$ could produce values that may not be visually meaningful because they fall in the mesopic range.⁶ According to research carried out relatively recently, there is a relation, at mesopic levels, between the spectral power distribution (SPD) of the light sources and visual performance,^{7–12} the perception of safety,^{10,13,14} and the perception of comfort.¹⁴ Using some research undertaken with the purpose of developing a model that represents the effect of mesopic vision on brightness (as cited in Fotios *et al.*¹⁰) and some research based on visual performance,^{15–18} in 2010, the CIE defined a method to calculate the mesopic luminous function³ based on the MOVE model¹⁷ and the USP model.¹⁶

The CIE system of mesopic photometry encourages the use of light sources with high scotopic/photopic (S/P) ratios such as metal halides and LED's, because the human eye is more sensitive to short wavelength light in the mesopic range. This implies that the luminous flux of these kinds of light sources could be reduced and would lead to reductions in the cost of installations, lower energy consumption and a lower environmental impact. However, there could be other factors affected by SPD⁶ that, when quantified, could lead to the final effect being contradictory.

The characteristics of the road surface are important in road lighting because the road surface is considered to be the main part of the visual field.¹⁹ Therefore, in most national and international road lighting standards^{5,20} and recommendations,⁴ the road surface luminance is one of most important requirements. The spectral reflectance of road surfaces could have an effect on the visual performance of the driver.⁶ Road surfaces tend to reflect less light in the short

wavelength part of the visual spectrum.^{21–24} This means that sources with a strong emission of light in this wavelength range of the spectrum will produce less reflected light reaching the eye of the observer.^{25,26}

The age of drivers or pedestrians is another aspect that can modify the light reaching the retina according to the spectrum of the light source.⁶ It is well known that the human visual system changes with normal ageing.^{4,27,28} The eye lens become yellower and the consequence is an increase of the spectral absorbance^{27,29} or a decrease of the spectral transmittance.^{30–34} This decrease in ocular transmittance is exacerbated at the short wavelength part of the visual spectrum, while at the long wavelength, it remains practically independent of age and also, it is at this stage where the transmittance is highest.

The scope of this work is to evaluate how the luminance of road lighting installations is affected by the spectral reflectance of road surfaces and by the human eye transmittance response as people get older, at mesopic levels. Our results suggest that the benefits of considering the mesopic vision effect for light sources with high S/P ratios are counteracted, at a certain mesopic luminance, by the effects of the spectral reflectance of road surfaces and by the changes in the spectral transmittance of the human eye.

1.1 CIE recommended system for mesopic photometry³

The aim of the work done by the CIE technical committee TC 1-58 was 'to propose' a model for the basis of performance based mesopic photometry'. For this reason, the CIE system for mesopic photometry was based on the performance of some typical visual tasks typically done at night such as recognition, detection and reaction time rather than on brightness matching.

The most important constraints when developing this system were to maintain additivity and to form a transition between scotopic and photopic luminous efficiency functions ($V'(\lambda)$ and $V(\lambda)$, respectively). This implies a linear combination of these functions in order to calculate the mesopic luminous efficiency function:

$$M(m)V_{\text{mes}}(\lambda) = mV(\lambda) + (1 - m)V'(\lambda) \quad (1)$$

for $0 \leq m \leq 1$

where m is a coefficient that represents the adaptation state and ranges from 0 to 1; $M(m)$ is a function to normalise the maximum value of $V_{\text{mes}}(\lambda)$ to 1.

Coefficient m depends on the photopic luminance of adaptation (L_V) and on the S/P ratio of the light source which is the ratio of the luminous output of a light source evaluated according to the scotopic luminous efficiency function, $V'(\lambda)$, to the luminous output evaluated according to the photopic luminous efficiency function, $V(\lambda)$.

To calculate mesopic luminances from CIE 191:2010, there are two options, one: following an iterative approach (described later in the Method section, equations (11) and (12)) and, two: using a table which shows the percentage differences between the luminance calculated using the mesopic system and the luminance calculated with the photopic luminous efficiency function (Table 1). In both

cases, the S/P ratio of the light source and the photopic luminance of adaptation are needed to calculate mesopic luminance.

Table 1 shows that, when the recommended system of mesopic photometry is used, light sources with S/P ratio > 1 (with a strong emission in the blue part of the visible spectrum) produce luminances higher than those luminances calculated or measured with the photopic luminous efficiency function. On the contrary, when S/P ratio < 1 (with strong emission in the long wavelength region), mesopic luminances are lower than photopic luminances.

Let us suppose two roads classified as ME6 (European standard EN 13201),²⁰ one based on high pressure sodium lighting (HPS) lighting (S/P ratio ~ 0.65) and the second based on metal halide (MH) lighting (S/P ratio ~ 1.45) and both designed to meet the minimum maintained luminance of 0.3 cd/m^2 using the photopic luminous efficiency function. Using the recommended system for mesopic photometry, the effective luminances of these roads would be 0.27 cd/m^2 (HPS) and 0.33 cd/m^2 (MH) (from Table 1). This means that the road illuminated with HPS will require more than 0.3 cd/m^2 of photopic luminance (approximately 0.33 cd/m^2) to reach 0.3 cd/m^2 of effective luminance and, conversely, MH will require less than 0.3 cd/m^2 (approximately 0.27 cd/m^2).

Table 1 Extract of CIE mesopic table³

	S/P	Photopic luminance (cd/m^2)									
		0.01	0.03	0.1	0.3	0.5	1	1.5	2	3	5
HPS \sim	0.65	−31%	−20%	−13%	−8%	−6%	−4%	−3%	−2%	−1%	0%
	0.85	−12%	−8%	−5%	−3%	−3%	−2%	−1%	−1%	0%	0%
	1.05	4%	3%	2%	1%	1%	1%	0%	0%	0%	0%
	1.25	18%	13%	8%	5%	4%	3%	2%	1%	1%	0%
MH warm white \sim	1.45	32%	22%	15%	9%	7%	5%	3%	3%	1%	0%

Note: This table shows the percentage differences between mesopic and photopic luminances as a function of the photopic luminance of adaptation and the S/P ratio for high pressure sodium (HPS) and warm white metal halide (MH) discharge light sources.

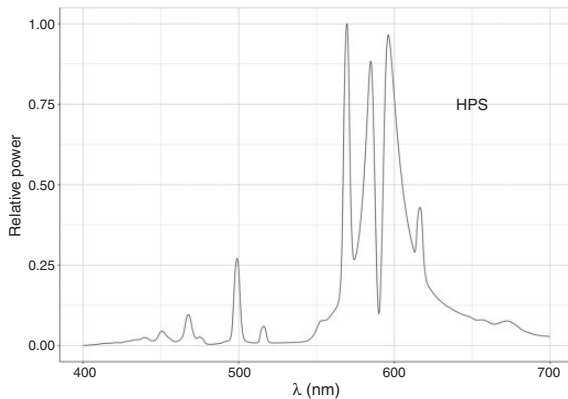


Figure 1 The normalised spectral power distribution (SPD) of the high pressure sodium (HPS) luminaire

However, in road lighting applications, as the road surface reflectance is not uniform across all visible wavelengths, the SPD of the light coming from the light source and the SPD of the reflected light will be different. Therefore, the S/P ratio of the light coming from the road surface will be different from the S/P ratio of the light source and this will affect the calculation of the mesopic luminance. Furthermore, the CIE system for mesopic photometry was developed based on experiments carried out with young observers (aged 19 to 35)^{35–37} and the changes in spectral transmittance with age can also modify the S/P ratio of the light that finally reaches the retina.

2. Method

2.1 SPDs of the light sources

Three different types of luminaires were used in this work: one with a high pressure sodium lamp (HPS), another with a metal halide lamp (MH) and finally a solid state device (LED), considering that currently these light sources are the most used in road lighting applications. The SPDs (spectral irradiances) of these luminaires (Figures 1 to 3) were measured with a spectroradiometer

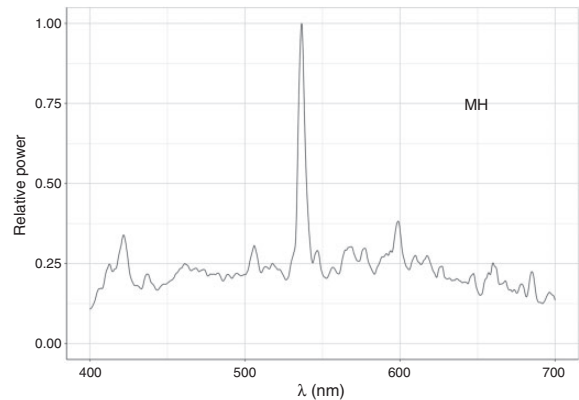


Figure 2 The normalised spectral power distribution (SPD) of the metal halide (MH) luminaire

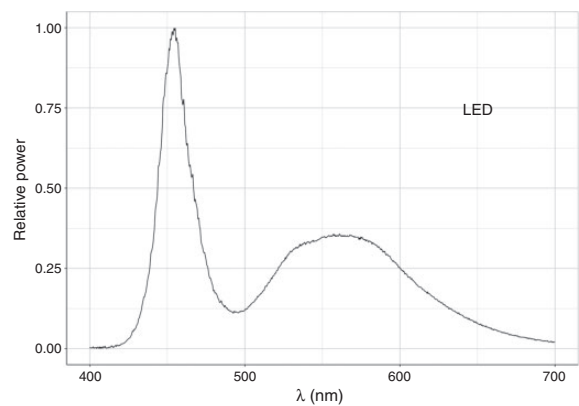


Figure 3 The normalised spectral power distribution (SPD) of the LED luminaire.

JAZ-EL350 (350–1000 nm) from Ocean Optics. The S/P ratios of the luminaires were then calculated from the scotopic and photopic luminous efficiency functions and the SPDs of the luminaires:³ $S/P_{HPS} = 0.58$; $S/P_{MH} = 2.07$; $S/P_{LED} = 2.41$.

2.2 Spectral reflectance of road surfaces

Twenty-two samples ($0.4\text{ m} \times 0.2\text{ m}$) of road surface (M1–M22) were collected in previous work (unpublished) by the Department of Lighting, Light and Vision

of the National University of Tucumán. These samples were extracted from highways in three provinces of Argentina: Buenos Aires, Entre Ríos and Tucumán. Although we do not have an accurate record of the usage time, we know that they have been in use for a period of less than 10 years and greater than a year, except sample M18 which can be considered as new because it has been in use for less than a year. The samples are

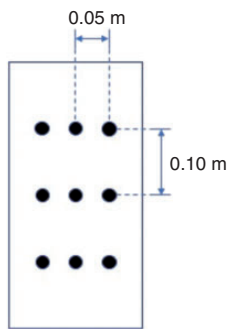


Figure 4 Measurement points on road surface samples

representative of the centre of the traffic lane. All of the samples are asphalt concrete, which essentially consists of asphalt mix and aggregate particles (rock components).

The reflectance of the road surface samples was measured with a spectroradiometer JAZ-EL350 (350–1000 nm) from Ocean Optics. As reference for the reflectance measurements, a white sample (10 mm thick) of polytetrafluoroethylene powder (PTFE) was used whose absolute reflectance is 99.4% throughout the visible spectrum.³⁸ The measurement angle or angle of observation (α) was set for all measurements to 45° . A grid with nine measurement points uniformly distributed was marked on each sample (Figure 4) and then the average was obtained. The average standard deviation relative to the average reflectance of the road surface samples was 19.3%.

The spectral reflectance of all the measured samples showed a similar general performance: reflectance is higher in the long wavelength part of the visual spectrum (Figure 5). These results are consistent with other

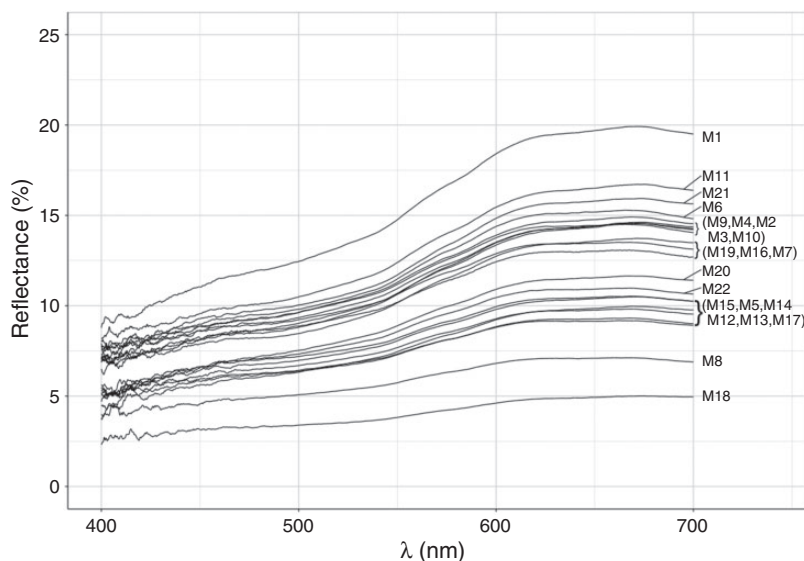


Figure 5 Spectral reflectances of the 22 road surface samples. All samples reflect more light as wavelength increases

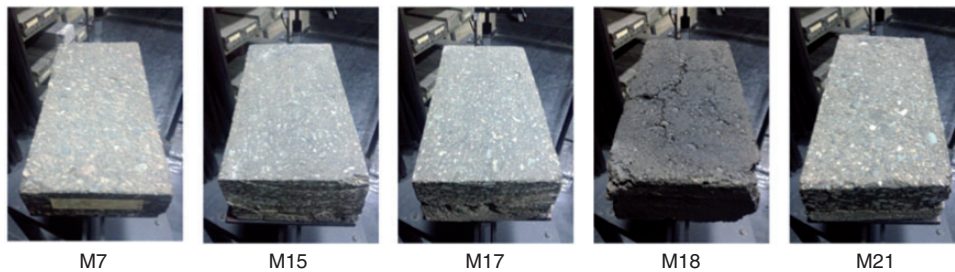


Figure 6 Five of the samples representing the most important differences in reflectance. M18 is a new asphalt concrete sample while the other four have been in use for some years

studies.^{21–24} The reflectance of road surfaces based on asphalt is, generally, very low and, the hydrocarbon components determine the process of absorption, i.e. the shape of the spectral reflectance.^{24,39} (Files of the spectral emissions of the light sources and the spectral reflectances of the road surfaces can be obtained from https://www.facet.unt.edu.ar/luminotecnica/wp-content/uploads/sites/15/2017/06/csv_paper_lrt.zip)

Figure 6 shows five of the samples that represent the diversity of all the collection taking into consideration high reflectance, low reflectance, high gradient of growth and low gradient of growth of the reflectance along the visible spectrum. M18 is a sample of new asphalt concrete road surface, while the other four are samples of road surfaces that have been in use for more than a year. In terms of colour, samples M7 and M21 are yellower than samples M15 and M17 and their reflectance is higher; M21 has the biggest aggregate particles of all of the samples and has the highest reflectance of these samples.

The total reflectance depends on many factors:^{23,24} (a) the colour or lightness of the aggregate particles; (b) the exposure of the aggregate particles; (c) the size of the particles and, (d) the asphalt ageing. According to Herold:²⁴ ‘the vanishing of the complex hydrocarbon components cause’ a general increase in reflectance in all parts of the spectrum’; this explains why the reflectance of

sample M18 is the lowest reflectance among the samples.

2.3 Spectral transmittance of human eye

In 2012, the CIE published ‘A Computerized Approach to Transmission and Absorption Characteristics of the Human Eye’.⁴⁰ This publication was the result of the technical committee TC 6-15 who collected spectral data of eye transmittance and finally compiled them in tabular form. The tabulated data consist of transmittance values in the wavelength range 380 nm to 780 nm and for ages between 1 year and 100 years.

The spectral transmittance curves for people between 20 and 80 were calculated from this technical report (Figure 7). Each decade in Figure 7 is represented by the spectral transmittance curve of the age in the middle of the decade (25, 35, 45, 55, 65 and 75 years old).

There is a significant decrease in spectral transmittance with age. The most evident change occurs at the short wavelength end of the spectrum where, for example, at 500 nm, the transmittance of a human eye at 60–69 years is 25% less than the transmittance of an eye of 20–29 years and 48% less at 450 nm (Figure 7).

The age-related reduction in spectral transmittance is the main reason for the changes in the spectral luminous efficiency function with age.⁴¹ When developed the

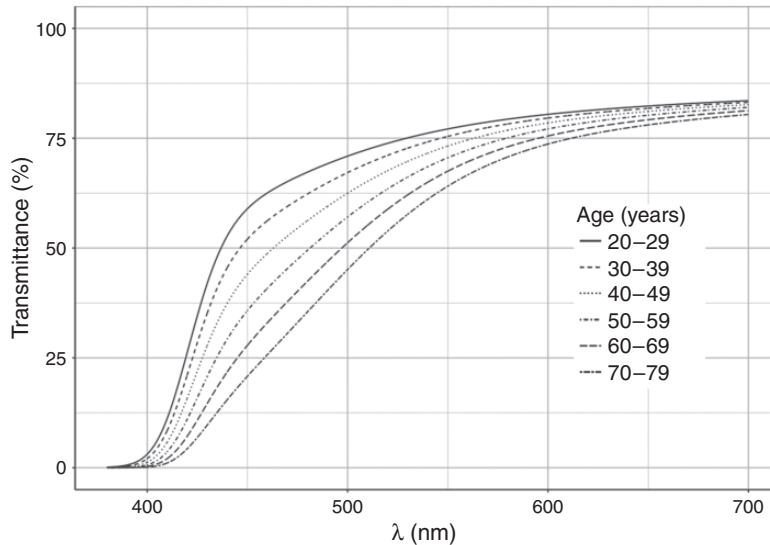


Figure 7 Spectral transmittance of human lens at different ages. Transmittance decreases considerably with ageing, especially between the 400 nm and 550 nm (fitted from the CIE 203:2012 data)

current standard luminous efficiency function, $V(\lambda)$ assumed a specific spectral transmittance of the eye. $V(\lambda)$ was derived with data from 52 observers, most of them young people: 20 observers (20–29 years), 21 observers (30–39 years), 9 observers (40–49 years) and 2 observers (50–59 years).⁴² The average age of the observers was 33 years which could be considered as the reference age for the spectral transmittance. However, Sagawa and Takahashi,⁴¹ after measuring spectral luminous efficiency functions for 91 observers of different ages from 11 to 78 years, showed that the spectral luminous efficiency function for age 25 years fitted best to $V(\lambda)$. For that reason, in this work, the spectral transmittance for the age range 20–29 years (25 years old) has been considered as the reference (100%) and spectral transmittances relative to this transmittance were calculated for the other age ranges (Figure 8).

2.4 Calculation of the mesopic luminance

The mesopic luminance was calculated for all possible combinations of light source, road

surface sample and age range. For these calculations, the road surface was considered as the adaptation field, i.e. the photopic luminance of the road surface was considered as the photopic luminance of adaptation. The following procedure was carried out to calculate the mesopic luminance:

- (1) The spectral photopic and scotopic illuminances ($E_{V,\lambda}$ and $E_{V',\lambda}$, respectively) were calculated in the wavelength interval 380 nm to 780 nm from

$$E_{V,\lambda} = 683 \cdot (SF \cdot E_{e,\lambda}) \cdot V(\lambda) \quad (2)$$

$$E_{V',\lambda} = 1699 \cdot (SF \cdot E_{e,\lambda}) \cdot V'(\lambda) \quad (3)$$

where $E_{e,\lambda}$ is the SPD of the light source or spectral irradiance; SF is a scale factor that affects $E_{e,\lambda}$ in order to always reach the desired photopic luminance calculated in subsection 3 of this procedure.

- (2) The spectral photopic and scotopic luminance ($L_{V,\lambda}$ and $L_{V',\lambda}$, respectively) were

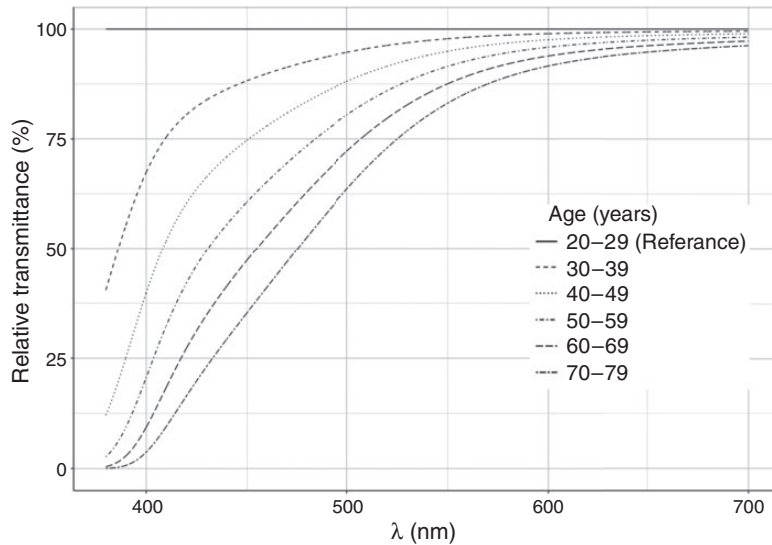


Figure 8 Spectral transmittance of human lens at different ages relative to the spectral transmittance for the age range 20–29 years (25 years old)

calculated in the wavelength interval 380 nm to 780 nm from

$$L_{V,\lambda} = E_{V,\lambda} \cdot q_\lambda \cdot T_\lambda \quad (4)$$

$$L_{V',\lambda} = E_{V',\lambda} \cdot q_\lambda \cdot T_\lambda \quad (5)$$

where T_λ is the relative spectral transmittance of the human eye. For a person in the age range 20–29 years, $T_\lambda = 1$ over the entire spectrum. q_λ is the spectral bidirectional reflectance distribution function (BRDF) of the road surface in the condition of illumination and viewing. As mentioned before, the measurement angle of the spectral reflectance was set to 45° . This angle is not the same as the angle of observation of pedestrians or drivers observing road surfaces in outdoor lighting scenes. However, the spectral behaviour of the BRDF is supposed to be proportional to the measured spectral reflectance. This assumption is based on previous studies showing that the shape of the spectral reflectance curve remains the same at different angles of observation and incidence.^{23,26} As in this work relative differences of the lighting

parameters are evaluated, in this way, the measurement angle of the reflectance will not affect the calculations.⁴³

- (3) The total photopic and scotopic luminance (L_V and $L_{V'}$, respectively) would be

$$L_V = \int_{380}^{780} E_{V,\lambda} \cdot q_\lambda \cdot T_\lambda d\lambda \quad (6)$$

$$L_{V'} = \int_{380}^{780} E_{V',\lambda} \cdot q_\lambda \cdot T_\lambda d\lambda \quad (7)$$

- (4) The S/P ratio of the light coming from the road surface and reaching the retina, $S/P_{rs,T}$ would be

$$S/P_{rs,T} = \frac{L_{V'}}{L_V} \quad (8)$$

- (5) According to CIE 191:2010, the photopic luminance can be converted into mesopic luminance (L_{mes}) with the equations

$$V_{mes}(\lambda) = \frac{m \cdot V(\lambda) + (1 - m) \cdot V'(\lambda)}{M(m)} \quad (9)$$

$$L_{\text{mes}} = \frac{683}{V_{\text{mes}}(\lambda_0)} \int_{380}^{780} L_{e,\lambda} \cdot V_{\text{mes}}(\lambda) d\lambda \quad (10)$$

$m = 0$ when $L_{\text{mes}} \leq 0.005 \text{ cd/m}^2$ and $m = 1$ when $L_{\text{mes}} \geq 5 \text{ cd/m}^2$; $V_{\text{mes}}(\lambda_0)$ is the value of $V_{\text{mes}}(\lambda)$ at 555 nm ; $L_{e,\lambda}$ is the spectral radiance.

- (6) The coefficient m and L_{mes} were calculated by an iterative approach using the following equations³

$$m_0 = 0.5$$

$$L_{\text{mes},n} = \frac{m_{n-1} \cdot L_V + (1 - m_{n-1}) \cdot L_V \cdot V'(\lambda_0)}{m_{n-1} + (1 - m_{n-1}) \cdot V'(\lambda_0)} \quad (11)$$

$$m_n = 0.767 + 0.333 \cdot \log_{10}(L_{\text{mes},n}) \quad (12)$$

where $V'(\lambda_0) = 683/1699$ is the value of scotopic spectral luminous efficiency function at $\lambda_0 = 555 \text{ nm}$.

- (7) L_{mes} values were calculated corresponding to L_V values each 0.01 cd/m^2 in the range from 0.01 cd/m^2 to 5 cd/m^2 .

All these calculations were made using the R language program.⁴⁴

3. Results

3.1 Mesopic vision effect

In order to quantify the effects of the spectral reflectance of the road surfaces and the spectral transmittance of the eye, it was first necessary to calculate only the effects produced by mesopic vision as established in CIE 191:2010 so as to have them as the base case for comparison. For this reason, the mesopic luminance was calculated from a hypothetical flat (in terms of spectral reflectance) road surface and considering the vision of a person in the age range of 20–29 years ($T_\lambda = 1$, all over the visible spectrum). An

arbitrary $q_\lambda = 0.1$ all over the visible spectrum was selected for these calculations.

These two considerations imply that the S/P ratio of the light coming from the road surface and the S/P ratio of the light reaching the retina is the same as the S/P ratio of the light source. The reason for this is that the spectrum of the light reaching the road surface (illuminance, equations (2) and (3)) is not modified either by the reflectance of the road surface or by the eye transmittance (luminance, equations (4) to (7)).

The differences found between L_{mes} and L_V for this specific case (Figure 9) show the mesopic vision effect as predicted by CIE 191:2010. The mesopic luminance obtained with MH and LED luminaires is considerably higher than the mesopic luminance produced by the HPS luminaire, especially for very low photopic luminances. For example, for a $L_V = 0.5 \text{ cd/m}^2$, the mesopic luminance would be for HPS 7.4% lower ($L_{\text{mes,HPS}} = 0.46 \text{ cd/m}^2$); for MH 16.5% higher ($L_{\text{mes,MH}} = 0.58 \text{ cd/m}^2$) and for LED 21.2% higher ($L_{\text{mes,LED}} = 0.61 \text{ cd/m}^2$). Above 3 cd/m^2 , the differences are less than 5%.

Due to the fact that the condition for comparing the results under the three different light sources is that the photopic luminance is the same

$$L_{V,\text{HPS}} = L_{V,\text{MH}} = L_{V,\text{LED}} \quad (13)$$

$$\begin{aligned} & \int_{380}^{780} E_{V,\lambda,\text{HPS}} \cdot q_\lambda \cdot T_\lambda d\lambda \\ &= \int_{380}^{780} E_{V,\lambda,\text{MH}} \cdot q_\lambda \cdot T_\lambda d\lambda \\ &= \int_{380}^{780} E_{V,\lambda,\text{LED}} \cdot q_\lambda \cdot T_\lambda d\lambda \end{aligned} \quad (14)$$

It can be easily inferred that, under these conditions (q_λ and T_λ constant), the photopic

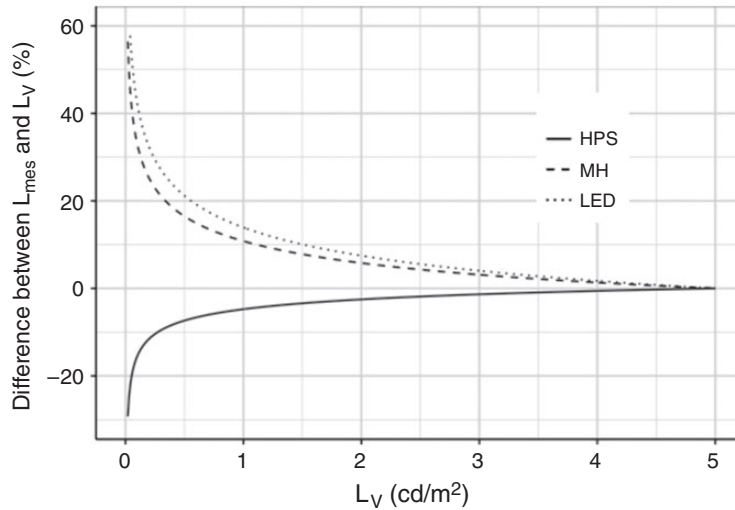


Figure 9 Percentage difference between mesopic luminance and photopic luminance plotted against the photopic luminance. Positive differences indicate that mesopic luminance is higher than photopic luminance while negative differences evidently imply the opposite. When considering only the mesopic vision, MH and LED produce a higher mesopic luminance than HPS all over the mesopic range

illuminance is the same for all three light sources (from equation (14))

$$E_{V,HPS} = E_{V,MH} = E_{V,LED} \quad (15)$$

On the other hand, changing the perspective, the photopic illuminance needed in order to get the same mesopic luminance under the three light sources was calculated as follows

$$L_{mes,HPS} = L_{mes,MH} = L_{mes,LED} \quad (16)$$

This was done using an iterative approach through the variation of the scale factor in equation (2) that affects the SPD of the light sources and then, re-calculating the mesopic luminance until the desired value was obtained. The results of this calculation are shown as percentage differences in photopic illuminance between white light sources (MH and LED) and HPS, using the last one as reference (Figure 10). These differences show that, to get the same mesopic luminance, it is always necessary to have more illuminance

over the road surface when using HPS than when using white light sources; for example, for a $L_{mes} = 0.5 \text{ cd/m}^2$, 21.2% less photopic illuminance with MH and 24.8% less with LED would be required relative to the illuminance that would be needed with HPS.

3.2 Road surface effect

In this case, the mesopic luminance was calculated for the 22 samples of road surface and then the average was obtained. In order to avoid the influence of eye ageing, only the vision of a person in the age range of 20–29 years ($T_\lambda = 1$, all over the visible spectrum) was considered.

The spectral reflectance of the road surface modifies the shape of the light spectrum reaching the road surface (equations (4) to (7)) and, evidently, the S/P ratio of the light coming from the road surface (equation (8)) will be different to the S/P ratio of the light source (Table 2).

The average S/P ratio of the light coming from the road surface samples ($S/P_{ave,rs}$) is

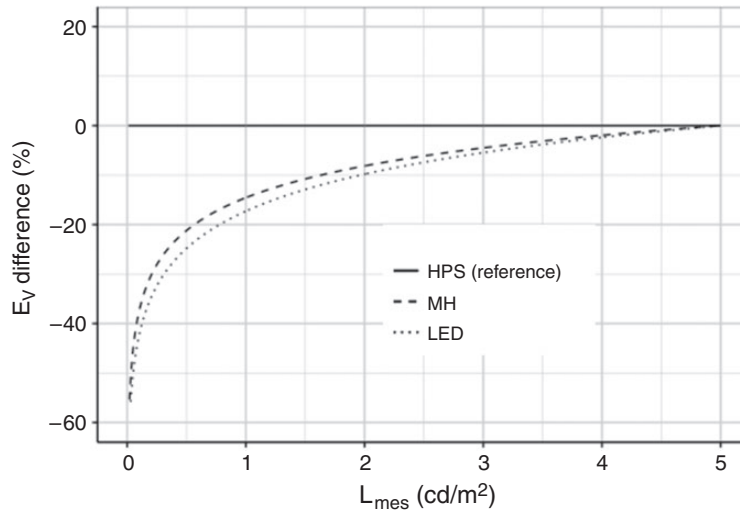


Figure 10 Percentage difference in photopic illuminance plotted against the mesopic luminance level. Having HPS as a reference and considering only the mesopic vision effect, white light sources (MH and LED) require less photopic illuminance (negative percentage) than HPS to get the same mesopic luminance

Table 2 Original S/P ratios of the luminaires and the S/P ratios of the light coming from the road surfaces

	HPS (S/P = 0.58)	MH (S/P = 2.07)	LED (S/P = 2.41)
S/P _{ave,rs}	0.58	1.77	2.02
Relative σ_{rs} (%)	1.37%	1.55%	1.72%
$\frac{S/P_{ave,rs}}{S/P}$	0.86	0.85	0.84

Note: Due to the spectral reflectance of the road surface, S/P ratios tend to decrease.

lower than the original S/P ratio of the light sources. This modification of the S/P ratio affects the calculation of L_{mes} , and therefore the difference between L_{mes} and L_V (Figure 11). For HPS, this difference increases (in a negative way, see Figure 11(a)), while for MH and LED, it is reduced (Figure 11(b) and c)). Both changes mean that mesopic luminance would be lower than the predicted by the CIE 191:2010 when the S/P ratio of the light source is used. However, the impact is not the same for all light sources and, the reduction will be higher for the white light sources than for HPS, e.g. when

$L_V = 0.5 \text{ cd/m}^2$, the difference changes from 21.2% (0.61 cd/m^2) to 15.8% (0.58 cd/m^2) for LED, while for HPS, it will change only from -7.4% (0.46 cd/m^2) to -8.9% (0.45 cd/m^2).

These last results showed the effects of spectral road reflectance under three different lighting installations with the same photopic luminance of adaptation. However, this does not necessarily mean that the light reaching the road surface (illuminance) would be the same. For this reason, the necessary photopic illuminance (E_V) was calculated in order to have the same mesopic luminance (L_{mes}) under the three different lighting installations (Figure 12).

The road surface effect causes a change in the photopic illuminance needed from the three light sources compared with the photopic illuminance when considering only the mesopic vision effect (Figure 12). Relative differences in E_V between MH and LED regarding HPS are not only reduced but, even from a L_{mes} between 1.47 cd/m^2 (for MH) and 1.73 cd/m^2 (for LED), the relative difference

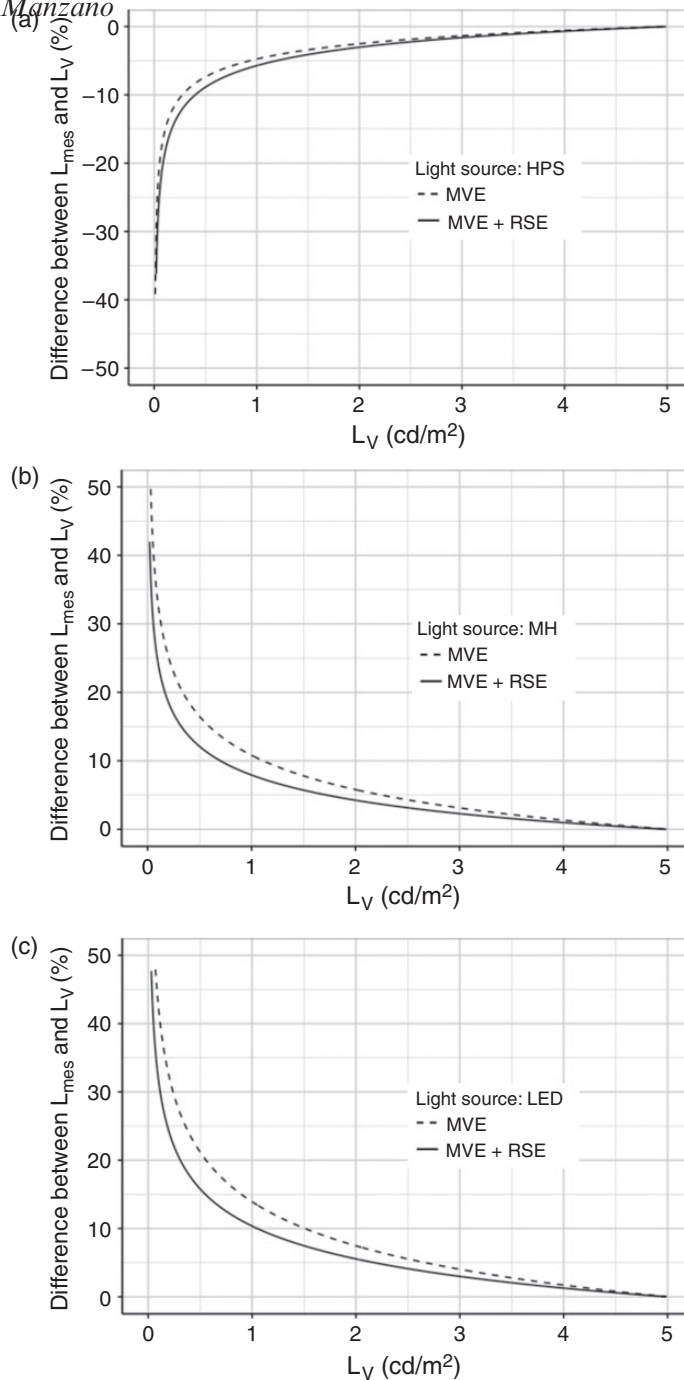


Figure 11 Percentage difference between mesopic luminance and photopic luminance plotted against the photopic luminance. The road surface affects the difference between L_{mes} and L_v . In general terms, the mesopic luminance will be lower than the one calculated considering only the mesopic vision effect for all light sources. However the reduction is higher for white light sources (b) and (c) than for HPS (a)
Note: MVE: Mesopic Vision Effect; RSE: Road Surface Effect

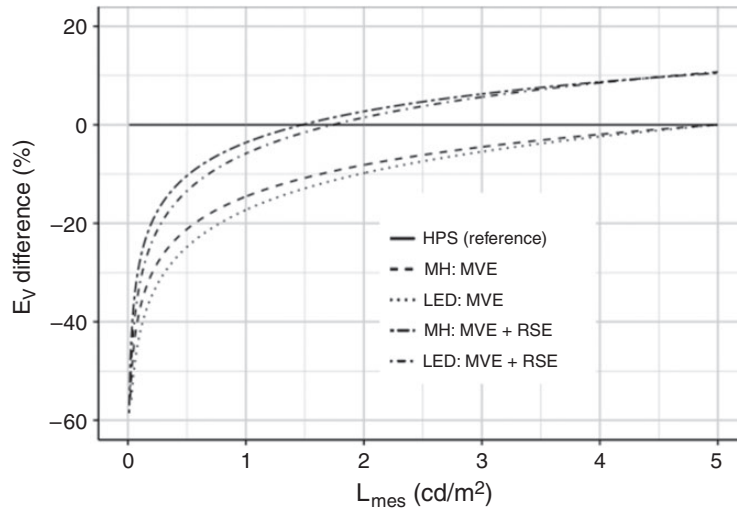


Figure 12 Percentage difference in photopic illuminance between white light sources and HPS (reference) plotted against the mesopic luminance. Road surface effect not only reduces the difference in E_V between white light sources and HPS but from a certain L_{mes} , the difference is now in favour of HPS (E_V difference positive)
 Note: MVE: Mesopic Vision Effect; RSE: Road Surface Effect

Table 3 Original S/P ratios of the luminaires and the S/P ratios of the light coming from the road surfaces for people in the age range 40–49 and 60–69 years

	HPS (S/P = 0.58)	MH (S/P = 2.07)	LED (S/P = 2.41)
$S/P_{ave, T40-49}$	0.48	1.67	1.86
Relative $\sigma_{T40-49}(\%)$	1.31%	1.52%	1.67%
$\frac{S/P_{ave, T40-49}}{S/P}$	0.84	0.80	0.77
$S/P_{ave, T60-69}$	0.45	1.50	1.65
Relative $\sigma_{T60-69}(\%)$	1.21%	1.48%	1.59%
$\frac{S/P_{ave, T60-69}}{S/P}$	0.78	0.74	0.68

Note: Due to changes in spectral transmittance of the human eye with ageing, S/P ratios tend to decrease as age increases.

becomes positive which implies that more photopic illuminance from white light sources is needed compared with the one needed using HPS in order to get the same mesopic luminance.

3.3 Eye transmittance effect

Finally, in addition to the mesopic effect and the road surface effect, the changes in spectral eye transmittance with age were also

considered. Spectral transmittance of the eye also modifies the light spectrum reaching the eye (luminance) compared with the spectral illuminance over the road surface (equations (4) to (7)). The result of this modification is a reduction in the S/P ratio of the light that reaches the retina. S/P ratios for people in the age range 40–49 ($S/P_{ave, T40-49}$) and 60–69 ($S/P_{ave, T60-69}$) are shown in Table 3.

However, the reduction in S/P ratios is not the same for each light source: the higher the S/P ratio of the light source, the higher the reduction with ageing (Table 3). Due to this reduction in S/P ratios, the difference between L_{mes} and L_V decreases for white light sources and increases negatively for HPS, e.g. for a $L_V = 0.5 \text{ cd/m}^2$ with LED, the difference changes from 21.2% (0.61 cd/m^2) to 13.4% (0.57 cd/m^2 , 40–49 years) and to 9.8% (0.55 cd/m^2 , 60–69 years), while for HPS, it will change only from -7.4% (0.46 cd/m^2) to -9.2% (0.453 cd/m^2 , 40–49 years) and to -9.8% (0.451 cd/m^2 , 60–69 years) (Figure 13).

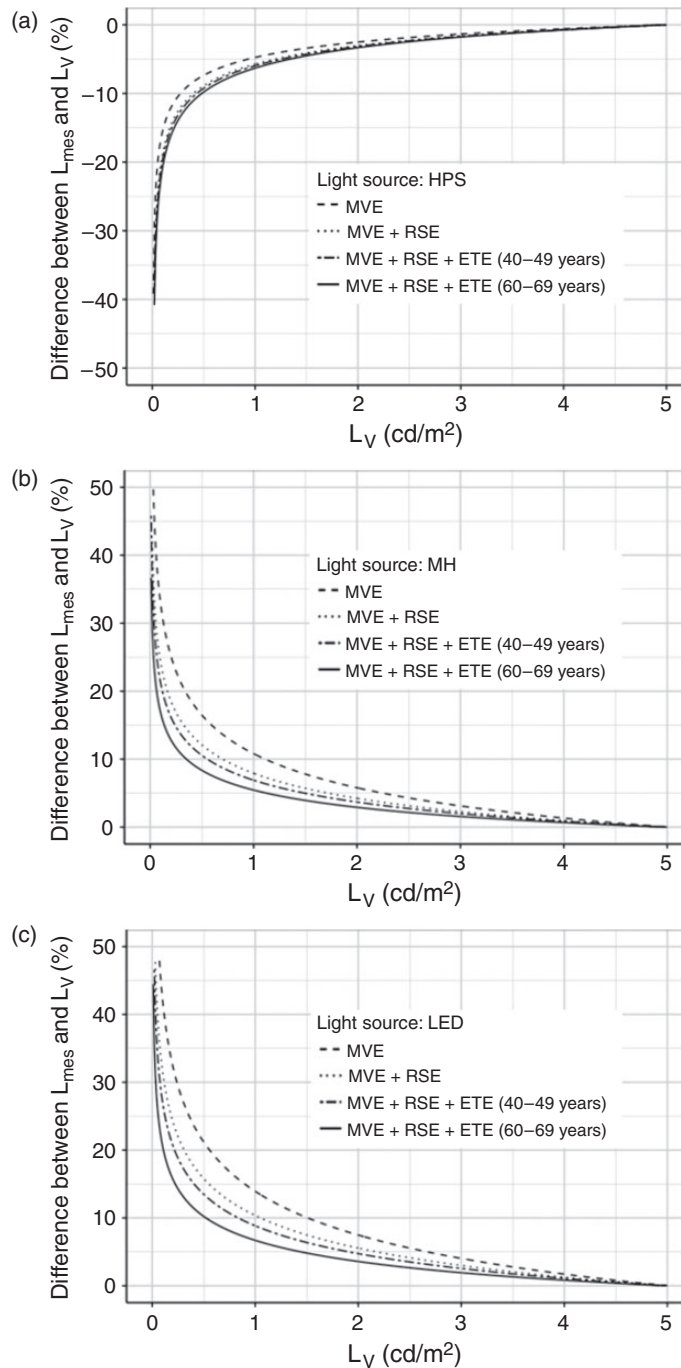


Figure 13 Percentage difference between mesopic luminance and photopic luminance plotted against the photopic luminance. The eye transmittance effect exacerbates the reduction of the mesopic luminance regarding the photopic luminance. The reduction will be higher for MH (b) and LED (c) than HPS (a)

Note: MVE: Mesopic Vision Effect; RSE: Road Surface Effect; ETE: Eye Transmittance Effect

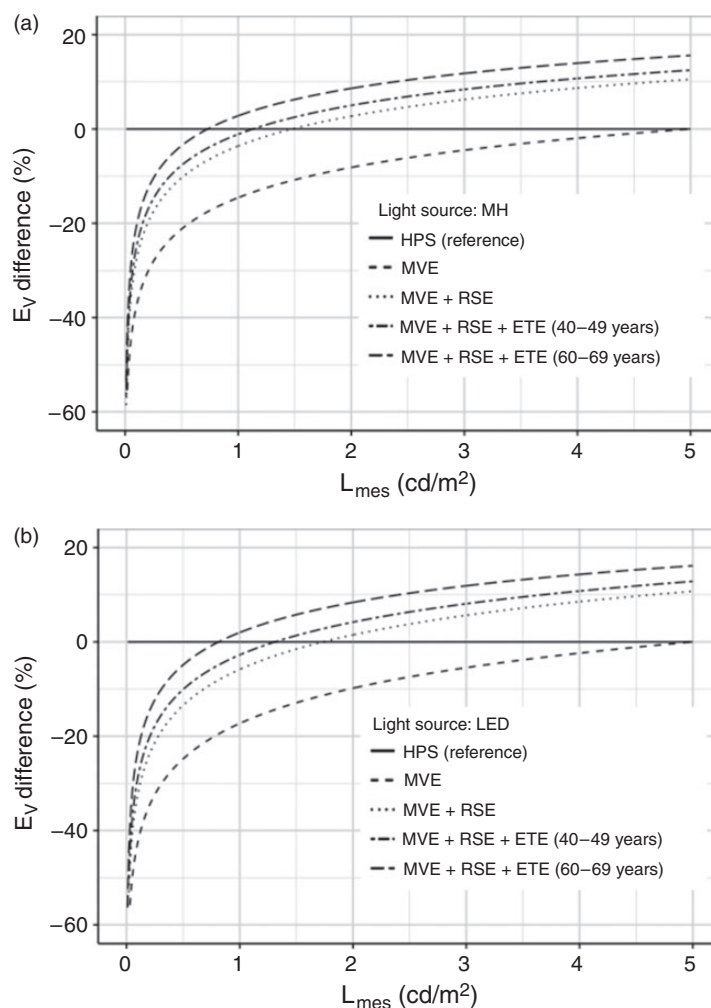


Figure 14 Percentage difference in photopic illuminance regarding HPS light source (reference) plotted against the mesopic luminance. The difference in photopic illuminance between MH (a), LED (b) and HPS, decreases dramatically when the road surface and eye transmittance effects are taken into consideration and there are even certain values of mesopic luminance which turn this difference positive, i.e. more photopic illuminance is needed from these light sources (MH and LED) in order to have the same mesopic luminance

Note: MVE: Mesopic Vision Effect; RSE: Road Surface Effect; ETE: Eye Transmittance Effect

Considering the condition of having the same mesopic luminance under the three different luminaires, the necessary photopic illuminance was calculated for people in the age range 40–49 and 60–69 (Figure 14). The results have shown that there is a specific mesopic luminance from which more photopic illuminance is needed when illuminating with

MH and LED than with HPS, e.g. for the age range 40–49, from 1.13 cd/m^2 (MH) to 1.32 cd/m^2 (LED), more photopic illuminance is needed with these two light sources than with HPS in order to have the same mesopic luminance. Similarly, for the age range 60–69 years, these values decrease even more: 0.75 cd/m^2 (MH) and 0.84 cd/m^2 (LED).

Table 4 Percentage differences between mesopic and photopic luminances

Photopic luminance (cd/m ²)													
	S/P	0.3	0.4	0.5	0.6	0.75	0.8	0.9	1	1.1	1.2	1.5	2
(a) Mesopic vision effect													
HPS	0.58	−9.6%	−8.3%	−7.4%	−6.6%	−5.8%	−5.5%	−5.1%	−4.8%	−4.4%	−4.1%	−3.4%	−2.5%
MH	2.07	21.2%	18.5%	16.5%	14.9%	13.1%	12.6%	11.6%	10.8%	10.1%	9.4%	7.8%	5.8%
LED	2.41	27.2%	23.7%	21.2%	19.2%	16.8%	16.2%	15.0%	13.9%	13.0%	12.2%	10.1%	7.5%
(b) Road surface effect													
HPS	0.58	−11.6%	−10.0%	−8.9%	−8.0%	−7.0%	−6.7%	−6.2%	−5.7%	−5.3%	−5.0%	−4.1%	−3.0%
MH	2.07	15.6%	13.6%	12.1%	10.9%	9.6%	9.2%	8.5%	7.9%	7.4%	6.9%	5.7%	4.2%
LED	2.41	20.3%	17.7%	15.8%	14.3%	12.5%	12.0%	11.1%	10.4%	9.7%	9.0%	7.5%	5.6%
(c) Eye transmittance effect (40–49 years old)													
HPS	0.58	−12.1%	−10.4%	−9.2%	−8.3%	−7.3%	−7.0%	−6.4%	−6.0%	−5.6%	−5.2%	−4.3%	−3.2%
MH	2.07	13.6%	11.8%	10.6%	9.5%	8.4%	8.0%	7.4%	6.9%	6.4%	6.0%	5.0%	3.7%
LED	2.41	17.3%	15.1%	13.5%	12.2%	10.7%	10.3%	9.5%	8.8%	8.2%	7.7%	6.4%	4.7%
(d) Eye transmittance effect (60–69 years old)													
HPS	0.58	−12.8%	−11.0%	−9.8%	−8.8%	−7.7%	−7.4%	−6.8%	−6.3%	−5.9%	−5.5%	−4.5%	−3.3%
MH	2.07	10.8%	9.4%	8.4%	7.6%	6.6%	6.3%	5.9%	5.5%	5.1%	4.8%	3.9%	2.9%
LED	2.41	13.2%	11.5%	10.2%	9.3%	8.1%	7.8%	7.2%	6.7%	6.2%	5.8%	4.8%	3.6%

Note: Differences are presented as a function of the relevant photopic luminance required by road lighting standards and the S/P ratios of the light sources.

4. Discussion

Comparisons have been made based on two conditions: first, light sources providing the same photopic luminance and second, light sources producing the same mesopic luminance.

Under the first condition, the changes of S/P ratio have been analysed. Due to the effects of spectral reflectance of road surfaces and the spectral transmittance of the eye, S/P ratios of the light reaching the retina tend to become lower than the original S/P ratio of the light source. Despite this reduction which occurs with all light sources, the degree of impact is different and it is evident that the white light sources are the most affected. This implies that less mesopic luminance will be perceived than predicted by CIE 191:2010 when these effects are not considered.

The differences found between photopic and mesopic (or effective) luminance regarding the photopic luminance for the different effects and for the relevant photopic luminances required in standards by CIE, CEN and IESNA are shown in Table 4. Table 4(a)

shows the differences as predicted by the CIE 191:2010 for the luminaires used in this work. Accordingly, at equal photopic illuminance over the road, MH and LED luminaires would always provide a mesopic luminance higher than the mesopic luminance produced by an HPS luminaire. For the specific range of applications in road lighting situations, a road illuminated with a MH luminaire, such as the one used in this work, would represent a mesopic luminance between 31% and 8% above the luminance provided by an HPS luminaire and between 37% and 10% above the road illuminated by an LED luminaire (Table 4(a)).

The benefits of using white light sources over HPS are true in the case of a luminance coming from a surface that reflects the light of all wavelengths equally and for young people (aged 20–29 years). However, road surfaces do not have that spectral characteristic and people continue to drive up to the age of 70 and more.

Our results have shown that the difference between photopic and mesopic luminances for the HPS luminaire increases when road

Table 5 Percentage differences of photopic illuminance between white light sources and HPS, having HPS as a reference

		Mesopic luminance (cd/m ²)											
	S/P	0.3	0.4	0.5	0.6	0.75	0.8	0.9	1	1.1	1.2	1.5	2
(a) Mesopic vision effect													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	-26.2%	-23.4%	-21.2%	-19.4%	-17.3%	-16.7%	-15.6%	-14.6%	-13.7%	-12.9%	-10.8%	-8.1%
LED	2.41	-30.4%	-27.2%	-24.8%	-22.8%	-20.4%	-19.7%	-18.4%	-17.3%	-16.3%	-15.3%	-12.9%	-9.8%
(b) Road surface effect													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	-15.6%	-12.6%	-10.3%	-8.5%	-6.4%	-5.7%	-4.6%	-3.6%	-2.7%	-1.9%	0.1%	2.7%
LED	2.41	-19.3%	-16.0%	-13.4%	-11.4%	-9.0%	-8.3%	-7.0%	-5.8%	-4.8%	-3.9%	-1.5%	1.5%
(c) Eye transmittance effect (40 years old)													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	-12.9%	-9.9%	-7.7%	-5.9%	-3.8%	-3.2%	-2.1%	-1.1%	-0.3%	0.5%	2.5%	5.0%
LED	2.41	-15.7%	-12.5%	-10.1%	-8.1%	-5.7%	-5.1%	-3.8%	-2.8%	-1.8%	-0.9%	1.4%	4.2%
(d) Eye transmittance effect (60 years old)													
HPS	0.58	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
MH	2.07	-8.6%	-5.7%	-3.5%	-1.8%	0.2%	0.8%	1.9%	2.8%	3.6%	4.4%	6.3%	8.6%
LED	2.41	-10.3%	-7.2%	-4.9%	-3.0%	-0.8%	-0.2%	1.0%	2.0%	2.9%	3.7%	5.8%	8.4%

Note: Differences are presented as a function of the mesopic luminance and the S/P ratio of the light source. When the differences become positive the values are shaded.

surfaces characteristics and eye transmittance are considered (Table 4(b) to (d)), while for the MH and LED, this difference decreases. The final effect is that the total difference between the white light sources and the HPS luminaire is reduced: for example, in the worst case, for a person in the age range 60–69 years, the difference between LED and HPS for a photopic luminance of 0.3 cd/m² is reduced from 37% to 26% and from 10% to 7% for a photopic luminance of 2 cd/m² (see Table 4(a) and (d)). However, having the same photopic luminance with the three light sources does not mean that the illuminance on the road surface will be the same unless the road surface reflectance is spectrally flat. As the reflectance of real road surfaces does not meet this characteristic, the perspective was changed and how much photopic illuminance would be necessary to get the same mesopic luminance was calculated.

Under this second condition, the photopic illuminance of the HPS luminaire was taken as a reference (0%). First, the difference in photopic illuminance was evaluated when

considering, as under the first condition, a hypothetical spectrally flat road surface and a person in his/her 20s; in this case, MH and LED sources require less illuminance to produce the same mesopic luminance as HPS (Table 5(a)). This was expected because this kind of road surface does not modify the SPD, and therefore the same photopic luminance is produced by the same photopic illuminance independent of the light source.

So, when real road surfaces were used to calculate mesopic luminance, it was found that at low mesopic levels of luminance, white light sources still require less photopic illuminance than HPS to produce the same mesopic luminance but, after a certain mesopic luminance, this situation is reversed and less illuminance from HPS is needed than from the other sources (Table 5(b)). For example, to produce a mesopic luminance of 1.5 cd/m² and 2 cd/m² with MH and LED luminaires, respectively, differences become positive which means a higher photopic illuminance is needed from these luminaires than from HPS. This performance can be

explained by the shape of the spectral reflectance, which reflects less light in the short wavelength part of the visible spectrum (Figure 5) and, as MH and LED sources have a higher emission of light in these wavelengths than HPS, the resulting luminance will be lower.

In the same way, the human eye transmits less light for wavelengths below 550 nm and even less with ageing. This contributes to reducing the differences in photopic illuminance and also in reducing even more the mesopic luminance value from which HPS requires less photopic illuminance to get the same mesopic luminance as the white light sources (Table 5(c) and (d)). For example, at age 60 years, after only a mesopic luminance 0.75 cd/m^2 for MH and 0.9 cd/m^2 for LED, differences become positive.

5. Conclusions

The CIE recommended system for mesopic photometry encourages the use of light sources with high S/P ratios, such as MH and LED light sources, because the human eye is more sensitive to white light at mesopic levels. This would lead to reductions in the cost of installations, lower energy consumption and a lower environmental impact. However, it has been shown in this work that there are other factors affected by SPD that work in an opposite mode to the mesopic vision effect and suggest that light sources with a low S/P ratio will actually be more efficient than expected in reaching the retina of the human eye.

The shorter the wavelength emission from a light source, the less light is reflected from the road surface. A similar effect occurs when the spectral transmittance of the human eye is considered and this tends to be exacerbated as age increases.

In a first analysis, at equal photopic luminance under the three light sources, the results of this work have shown that these two

factors affect and, essentially, reduce the S/P ratio of the light that, finally, reaches the retina. This reduction implies significant differences in the calculation of the mesopic luminance. The final effect is that the mesopic luminance under the three light sources will be lower than expected when changes in the S/P ratio are not considered. However, the reductions will be higher for the MH and LED light sources than for the HPS light source.

In a second analysis, at equal mesopic luminance under the three light sources, the differences in photopic illuminance reaching the road surface were quantified. The results have shown that, from certain mesopic luminances, the effects of road surface reflectance and eye transmittance weigh more than the mesopic vision effect and the consequence is that, above these values, more photopic illuminance is required from the MH and LED luminaires than from the HPS luminaires.

Due to the fact that the road surface is considered as the main part of the adaptation field for observers and that the age average of the world population is expected to grow considerably in the next 30 years,⁴⁵ these two factors need to be taken into consideration when designing road lighting installations.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was carried out with support from Universidad Nacional de Tucumán, grant reference PIUNT E523; CONICET from

Argentina; CONACYT from Mexico; SEP from Mexico and the Mexican Government.

Acknowledgements

We would like to thank H. Kairuz and the Department of Lighting, Light and Vision for the use of the road surface samples collection.

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