




Influence of age and spectral power distribution on mesopic visual sensitivity

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Abstract

The ability of the human visual system to detect stimuli at low illumination levels provides awareness of potential risks. The influence of age and spectral power distribution on mesopic spectral sensitivity is analyzed. Two typical light sources are used, a high-pressure sodium lamp (HPS), with a higher content of long wavelengths, and a metal halide lamp (MH), with a higher content of short wavelengths. Two experiments were performed, using a two-channel Maxwellian-view optical system to measure contrast threshold under different experimental conditions. In Experiment 1, three age groups (young, middle-aged and old, $n = 2$ each), two retinal locations (on-axis and off-axis vision), four background luminances (0.01, 0.07, 0.45, and 3.2 cd/m²), and two photometry systems (photopic and the MES2 systems) were considered. In Experiment 2, contrast threshold measurement was performed with two age groups (young and old, $n = 11$ each), one retinal location (off-axis vision), one background luminance (0.01 cd/m²), and two photometry systems (photopic and the MES2 systems). In on-axis vision, neither age nor spectral power distribution have an effect on the contrast threshold. In off-axis vision, however, a significant interaction between age and spectral power distribution is obtained, albeit only at 0.01 cd/m² with an MH lamp. Only at this lowest background luminance was the greater content of short wavelengths of this lamp responsible for higher rod stimulation in off-axis vision, with the subsequent improvement in detection performance in young subjects. However, the effect of diffused light inside the aged eye counteracted the benefits of increased rod sensitivity for the MH lamp.

Keywords Aging · Visual perception

Today, there is a growing interest in studying the behavior of the human visual system in the mesopic illumination range. Daily perceptual tasks such as nighttime driving should be performed in the best possible operating conditions of the visual system in order to achieve an optimal response, reducing perception errors as well as the possibility of accidents. Perceptual limitations may arise from personal factors such as

age, as well as external factors such as lighting conditions, strongly determined by the design of the light source and the photometry system used in luminance-level calculation.

Light adaptation is widely understood as the combination of a series of mechanisms that occur in the retina (Barrionuevo et al., 2018; Gloriani et al., 2016), and even the processing of luminance changes is a low-level sensory condition (Cole, Kuhn, & Skarratt, 2011). When adaptation luminance changes from photopic to mesopic values, the visual spectral sensitivity curve gradually shifts as a consequence of the transition from a cone response to a rod–cone response (i.e., the Purkinje effect). This change gives rise to an increase in sensitivity to short wavelengths in relation to long wavelengths.

This is why, in the mesopic illumination range, one might expect that street lamps with a greater content of short wavelengths (e.g., metal halide lamps, or MH lamps) in its spectral power distribution (SPD) should be more efficient than those with a greater content of long wavelengths (e.g., high-pressure sodium lamps, or HPS lamps). HPS and MH street lamps are commonly used in many psychophysical experiments and in

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urban lighting (British Standards Institution, 2012), and as such, it is important to document any possible difference in visual performance under these different lighting conditions.

When visual efficiency is compared in experiments using HPS and MH lamps in the mesopic illumination range, it has been shown that, in on-axis vision, contrast threshold or brightness perception is not affected by SPD (Fotios & Cheal, 2007). However, studies addressing the off-axis visual performance found that, for MH lamps, visual reaction-time tasks improve in comparison with HPS lamps (Ashaki & Rea, 2002).

The main aim of this study is to analyze how the SPD of different light sources influence visual performance of different-age subjects. It is well known that visual function declines with aging due to changes in the optical media, the retina, and the postreceptoral pathways (Boyce, 2006; Higgins, Jaffe, Caruso, & Demonasterio, 1988; Owsley, Sekuler, & Siemsen, 1983; Wright & Rea, 1984). Changes in the optical media are usually attributed to transparency loss (Whitaker & Elliot, 1992), increments in intraocular scattering (Vos, 2003), variations in the density and extent of the macular pigment (Chang, Lee, Chen, & Chan, 2002), increased pupil miosis, and lens fluorescence that generates stray light inside the eye. This fluorescence effect is particularly noticeable when employing lamps with a significant proportion of short wavelengths (below 450 nm) in their SPD (Boyce, 2003). Retinal factors may include a reduction in the density of rods and retinal ganglion cells, both of which occur with increasing age (Pearson, Schmidt, Ly-Schroeder, & Swanson, 2006). In addition, central visual pathways show deficits due to aging (Spear, 1993). In general, age-related changes in cognitive function may be mediated by age-related changes in global sensory processing. Humes, Busey, and Craig (2013) concluded that age influences the abilities to extract sensory information from the environment, with observed cognitive deficiencies mediated by such sensory deficits.

In spite of the visual changes with age, further studies on the effect of age on visual functions in relation to the type of illuminant are still needed. In this regard, Fotios and Cheal (2009) find that, at low luminance levels, obstacle detection is improved by using light sources with a significant amount of short-wavelength components in their SPD. Young subjects show better sensitivity at low luminances than did those who are older. Recently, Uttley, Fotios, and Cheal (2017) have found that obstacle detection improves for SPDs with higher a S/P ratio (scotopic-to-photopic luminance ratio), but only at low luminances and in a different way for two different age groups. In that sense, the present study evaluates the effect of aging on visual performance, particularly in conditions of an environment lighted with the luminance levels and light sources typical of street lighting.

The secondary aim of our study is to emphasize the importance of applying a mesopic photometry system when visual

performance is studied under mesopic illumination conditions. From the analysis of the abovementioned studies (Ashaki & Rea, 2002; Fotios & Cheal, 2007), among others, the Commission Internationale de l'Éclairage (CIE) issued a technical report in which a detailed analysis of the different mesopic photometry systems was performed (CIE, 2010). The effect on visual sensitivity of the SPD of different light sources, the luminance level, and degree of retinal eccentricity of young subjects were parameters considered in the development of the MES2 system. A mesopic photometry system that is derived from psychophysical experiments based on visual performance measurements in real-life situations (e.g., contrast threshold and visual reaction time). This photometry system allows the SPD of a light source to be expressed as the S/P ratio. Recent studies, especially those evaluating aging in the mesopic illumination range and off-axis vision (Uttley et al., 2017), continue to use the traditional photopic system measurement at low luminance levels. The present study improves the existing literature by analyzing the effect on visual performance in off-axis vision of luminance, calculated by applying the MES2 system, in different age groups and under the SPD of different light sources.

Therefore, our aim in this study is to analyze the effect of SPD on visual performance in the mesopic illumination range, and to determine whether or not these effects are similar for different age groups. In addition, the effectiveness of the MES2 system is considered in the calculated luminances of two well-differentiated SPDs.

The rest of the paper is based on two experiments. In Experiment 1, three age groups (young, middle-aged, and old-aged), two light sources (HPS and MH lamps), two retinal locations (on-axis or fovea and off-axis or 10° temporal retinal eccentricity), four background luminances (0.01, 0.07, 0.45, and 3.4 cd/m²), and two photometry systems (photopic and the MES2 systems) are considered. A second experiment is performed as a consequence of the results found in Experiment 1, but extended to a larger group of young and old-aged subjects in order to obtain greater statistical significance. It is focused on two age groups (young and old-aged), the same light sources (HPS and MH), one retinal location (off axis), one background luminance (0.01 cd/m²), and two photometry systems (photopic and the MES2 systems).

General methods

Apparatus

A two-channel Maxwellian-view optical system was employed. This type of setup provides three significant advantages: It allows obtaining results that do not depend on the pupil variations linked to the luminance or type of illuminant (Berman et al., 1987), it helps to avoid the influence of iris

pigmentation or scattering on the results due to the ocular wall (van den Berg, Ijspeert, & De Waard, 1991), and it allows precise control of the retinal illuminance. An exhaustive description of the experimental setup has been previously published (Matesanz et al., 2011). We only explain here the most relevant features and the specific details concerning this study.

Two concentric beams, coming from the same light source, reached the subject's pupil: a background beam (with luminance L_b) and a probe beam. Henceforth, we refer to the spatial region where both beams were overlapped as "the test" (with luminance L_t). In the subject's pupil, the background and the test subtended 10° and 2° , respectively. In all cases, the subject's fixation was maintained in the proper fixation test during the light adaptation time and during measurement. The fixation test of on-axis measurement consisted of four dim, red fixation points in a diamond configuration, whereas for off-axis measurements, a single dim fixation point was employed. Several shutters controlled the exposure times of the visual stimulus and the fixation points, as well as the delay between them, with an uncertainty in the time control of less than 1 ms. Neutral density filters controlled the luminance of the background and the probe beams in steps of 0.1 log units. The whole instrument was controlled by a computer. During measurement, the subject's head was fixated to the setup by biting on a bite bar made of dental compound. The subject's face was illuminated with infrared LEDs (830 nm), and the pupil was imaged on a CCD camera in order to verify whether its size was greater than the imaged light source in all conditions (2.5-mm diameter). A Pritchard 1980 luminance meter provided the photopic luminance measurement, and the MES2 photometry system was applied to luminance calculation.

Two typical streetlamps were employed: a high-pressure sodium (HPS) lamp and a metal halide (MH) lamp. Their absolute irradiance SPDs are shown in Fig. 1. They were measured by placing the lamp 50 cm from the entrance slit of a spectrometer. An absolute calibration of the spectrometer was performed with a halogen incandescent lamp calibrated by the National Institute of Standards and Technology. From these data, the S/P ratios were calculated following Eq. 6 in the Appendix. These ratios, as well as the correlated color temperatures (CCT), provided by the manufacturer, are summarized in Table 1.

Experiment 1

Participants

Six subjects with normal vision and no previous history of ocular disease participated in this study. All subjects were experienced with psychophysical measurements. A routine eye exam was performed including long-distance refraction, examination with a direct ophthalmoscope and a

biomicroscope, and Ishihara Color Test assessment. These subjects were split into three different age groups: young (24, 26 years old), middle-aged (41, 43 years old), and old-aged group (64, 65 years old). All subjects, including the emmetropic and the users of contact lenses, were compensated with the same type of ophthalmic lenses to prevent transmittance differences in the results due to this factor. The monocular visual acuities ranged from 0.00 to -0.18 log minimum angle of resolution. Written informed consent was provided, and the tenets of the Declaration of Helsinki were followed.

Procedure and measurements

The on-axis measurements provided contrast threshold values that support the validity of the off-axis measurements. Four background luminances (0.01, 0.07, 0.45, and 3.2 cd/m^2), two different lamps (HPS and MH), and one photometry system (photopic system) were considered in on-axis measurements. The same four background luminances and two lamps as well as two photometry systems (photopic and the MES2 systems) were considered in off-axis measurements. For each of these 24 conditions, and for our six participants, contrast thresholds were measured. In order to minimize fatigue effects, measurements were carried out over 4 different days for each participant, one for each combination of lamp and retinal location. The order of the different experimental conditions was randomized for each participant. Previous to each measurement, the subject was dark-adapted ($5 \times 10^{-6} \text{ cd/m}^2$) for 30 minutes. Afterwards, the retinal area under analysis was exposed to the background luminance chosen to light adaptation for 3 minutes.

Measurements were always performed on the right eye while the left eye was occluded. Probe exposure time was 40 ms in all cases. No mydriatic was used, as pupil size was greater than the imaged light source on the pupil entrance plane, under our luminance conditions. The task of the subject was to answer whether or not the probe was detected. The luminance value used to contrast threshold calculation was determined by the method of limits for each subject. The luminances range employed in the experiment for an individual measurement of contrast threshold consisted of six runs (three ascending, three descending), each one with eight different luminances (0.1 log units steps), equaling 48 trials. Previous studies allowed us to prove that the differences between the thresholds obtained with the method of limits and the method of constant stimuli are lower than 0.15 log units, in the most unfavorable case (Matesanz et al., 2011).

Results

In order to analyze the influence of age, type of lamp, and the background luminance in contrast threshold measurement, a

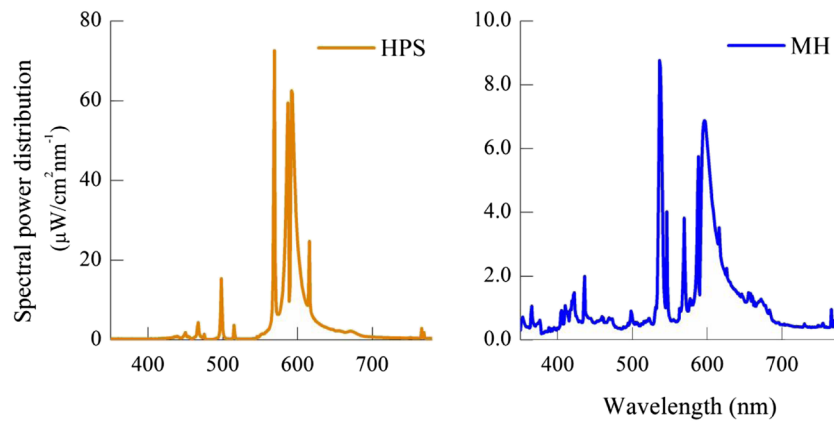


Fig. 1 Absolute irradiance spectral power distributions of the high-pressure sodium (HPS) lamp and metal halide (MH) lamp, measured with the lamp placed 50 cm from the spectrometer entrance

linear mixed model was fitted. With this purpose, age, background luminance, and type of lamp factors were considered as fixed effects, and the interactions between these factors were also considered. First, this model is applied in the on-axis contrast threshold, and results are obtained using photopic photometry. Then, the off-axis contrast thresholds obtained for both photopic and the MES2 photometry systems are analyzed.

Analysis of on-axis measurements

On-axis visual system response is cone-mediated, so only photopic photometry seems appropriate to luminance measurement. Contrast threshold (*C*) calculation employing the photopic photometry system was determined from the standard Weber expression, which takes the following form:

$$C = \frac{L_t - L_b}{L_b}, \tag{1}$$

where *L_t* represents the photopic measurement of the test luminance and *L_b* the photopic measurement of the background luminance.

Contrast thresholds for the on-axis condition and for each subject are plotted as a function of *L_b* in log scale in Fig. 2. There is a trend of contrast threshold values to increase as background luminance decreases. The fitted mixed model only reveals a significant influence of the background luminance

factor in contrast thresholds at the lowest value tested (*L_b* = 0.01 cd/m²). No differences are found among the other background luminances or for the interactions studied. The Age × Lamp interaction is the only one close to be significant (*p* = .07) at the lowest background luminance (*L_b* = 0.01 cd/m²) due to different results under the HPS lamp for different age groups.

Analysis of off-axis-measurements

At 10° of temporal eccentricity, visual performance is rod-cone mediated, so the MES2 recommended system was also considered, in addition to photopic contrast threshold calculation (*C*), as different results are expected. Applying the MES2 system, luminance values were corrected according to Eq. 4 shown in the Appendix. Subsequently, the MES2-corrected contrast threshold (*C_m*) was calculated as follows:

$$C_m = \frac{L_{t,m} - L_{b,m}}{L_{b,m}}, \tag{2}$$

where *L_{t,m}* and *L_{b,m}* represent the MES2 corrected test and background luminances, respectively.

In Fig. 3, photopic (Eq. 1) and the MES2 (Eq. 2) calculated contrast thresholds (*C* and *C_m*) for the off-axis condition have been plotted as a function of *L_b* in log scale.

Contrast thresholds increase in a more evident way for the lowest background luminance (0.01 cd/m²), but appear mostly constant for *L_b* ≥ 0.07 cd/m². This increase is observed in all age groups for both photometry systems. It may be the result of the transition from the Weber to the de Vries Rose region of luminances (two different sections of the light-adaptation curve with different dependence on background luminance). However, at the lowest background luminance, contrast threshold results for both lamps are different between photometry systems. Only contrast threshold results for the HPS lamp, whose S/P ratio (0.49) is more different from unity, differ between photometry systems for all age groups.

Table 1 Features of the lamps employed in the study

Lamp type	Model	CCT (K)	S/P ratio	Manufacturer
HPS	150 W Pro SON-T	2000	0.49	Philips
MH	70 W CDO-TT	2800	1.17	Philips

CCT = correlated color temperatures; HPS = high-pressure sodium lamp; MH = metal halide lamp. CCTs were taken from the manufacturer’s literature. S/P ratios were determined from spectral power distribution and Eq. 6 (see the Appendix)

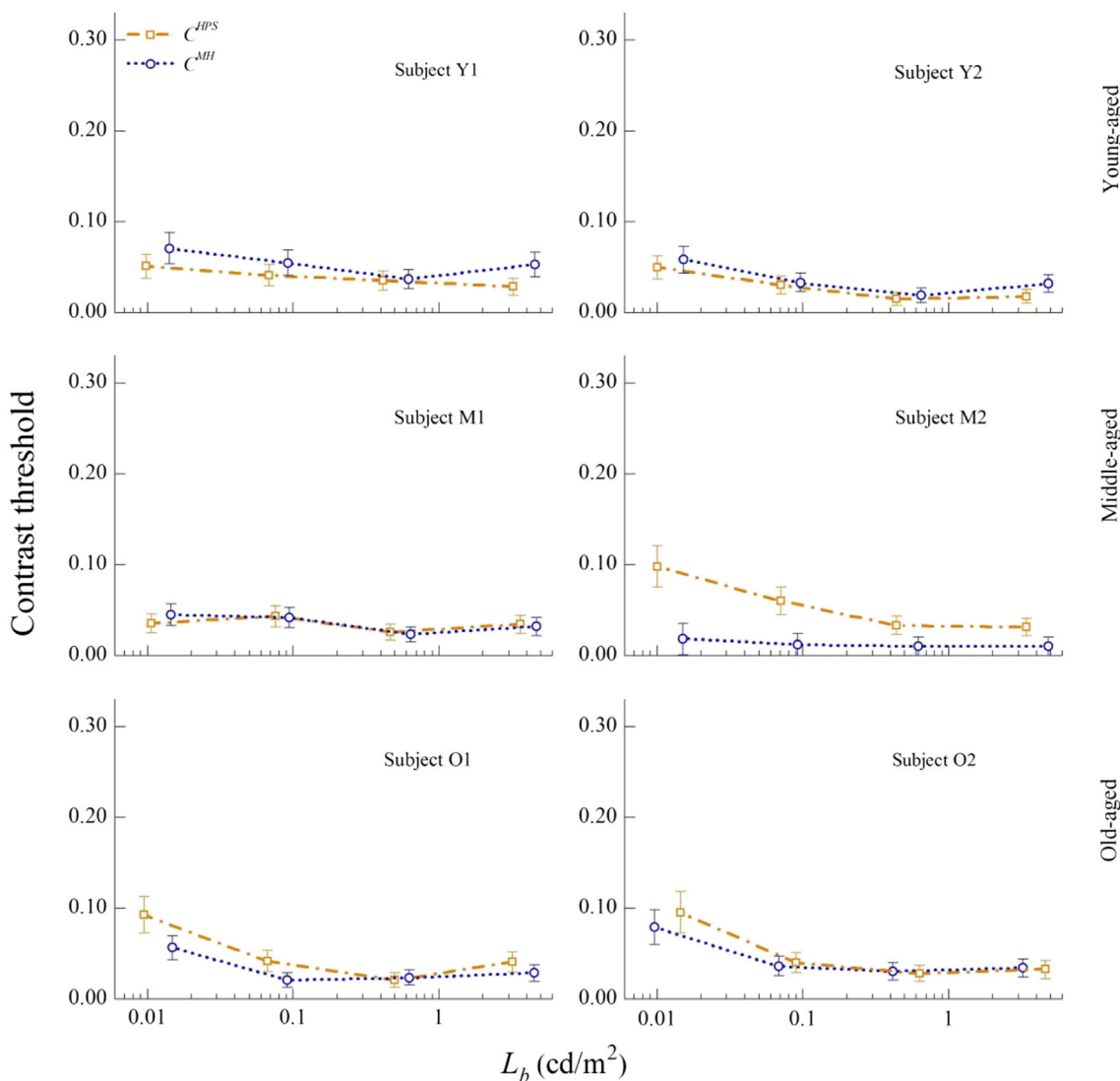


Fig. 2 On-axis contrast thresholds (C) based on photopic photometry for each subject and type of lamp as a function of L_b in log scale. Upper graphs correspond to young (Y1, Y2), intermediate graphs to middle-aged (M1, M2), and the lower ones to old-aged (O1, O2) subjects.

Squares correspond to results obtained with the HPS lamp and circles to results obtained with the MH lamp. For clarity, data obtained with the MH lamp have been displaced along the horizontal axis. Error bars define the 95% confidence interval of the results

However, for the MH lamp, whose S/P ratio (1.17) approaches unity, the results obtained are similar for both photopic and the MES2 photometry systems for all age groups.

As the MES2 system further defines the spectral sensitivity of the visual system under our experimental conditions, according to CIE (2010), a more in-depth view of the analysis of contrast threshold results obtained using this photometry system is shown in Fig. 4. Age and background luminance influence on contrast threshold was analyzed by considering each lamp separately in statistical analysis. Figure 4 shows the results derived from this analysis, for each age group, as a function of L_b . The upper graph (Fig. 4a) contains the results obtained for the HPS lamp (S/P ratio = 0.49), whereas the lower graph (Fig. 4b) contains those obtained for the MH lamp (S/P ratio = 1.17).

As for the results of the HPS lamp (Fig. 4a), the age effect on contrast thresholds is nonsignificant ($p = .24$), as is the interaction between age and background luminance factors ($p = .46$). In view of this, and taking into account the parsimony principle, a simple linear model (one-way ANOVA) was selected, in which the only explanatory variable is the background luminance—so the fitted model has been depicted in a single solid line for all age groups. The effect of background luminance on contrast thresholds using HPS lamp is significant ($p = .001$), with results showing a decrease as background luminance increases. The main effect of this factor occurs at the lowest background luminance ($L_b = 0.01 \text{ cd/m}^2$), with an estimated mean contrast threshold value of 0.217. This mean value is significantly greater than the estimated one (0.079) for the highest background luminance considered.

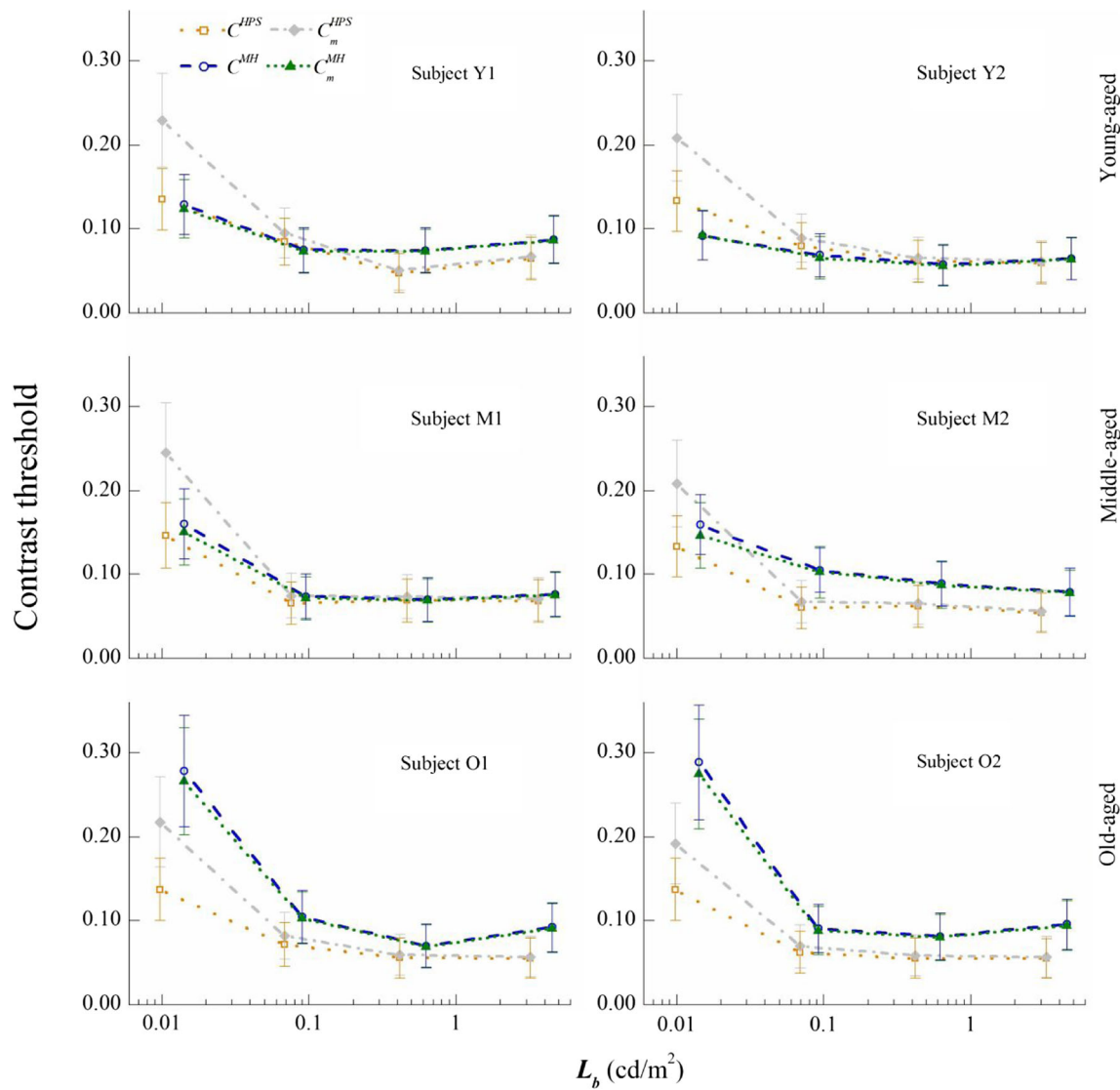


Fig. 3 Off-axis contrast thresholds (C and C_m) based on photopic and the MES2 photometry systems for each subject and type of lamp as a function of L_b in log scale. Upper graphs correspond to young (Y1, Y2), intermediate graphs to middle-aged (M1, M2), and the lower ones to old-aged (O1, O2) subjects. Values obtained by employing photopic or

the MES2 photometry have been identified with the symbols indicated in the upper left graph. For clarity, data obtained with the MH lamp have been displaced along the horizontal axis. Error bars define the 95% confidence interval of the results

The results for the MH lamp have been plotted in Fig. 4b. The fitted mixed model has been depicted for each of the three age groups with a solid line. The observed interaction between the fixed effects, age and background luminance, is significant ($p = .001$). This significant interaction implies that contrast threshold has a strong dependence on background luminance for the different age groups. The biggest difference between age groups is attained at the lowest background luminance ($L_b = 0.01 \text{ cd/m}^2$). In the case of higher background luminances, mean contrast threshold differences among age groups are smaller and nonsignificant, as can be seen from the simultaneous 95% confidence intervals of the mean values of each age group.

Data show that the influence of age in off-axis contrast thresholds is different for the two compared lamps in the mesopic illumination range, using the MES2 photometry system.

Experiment 2

In Experiment 1, a significant interaction between age and SPD was found at the lowest background luminance ($L_b = 0.01 \text{ cd/m}^2$). The aim of Experiment 2 was to involve a greater number of naïve subjects to obtain greater reliability of the results.

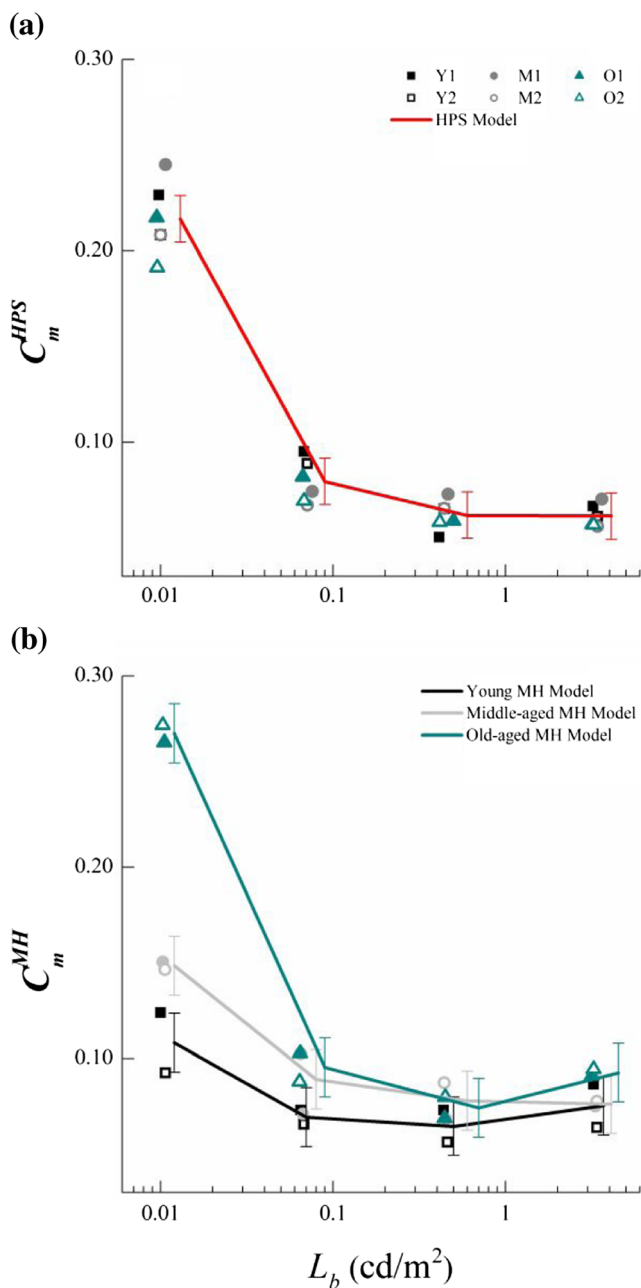


Fig. 4 Off-axis contrast thresholds (C_m) based on the MES2 photometry system as a function of L_b in log scale for the HPS lamp (a) and for the MH lamp (b). Squares, circles, and triangles represent data for the young, middle-aged and old-aged subjects, respectively. Lines join the estimated mean contrast thresholds under the fitted mixed linear model. For clarity, fitted model results have been displaced along the horizontal axis. Error bars define the 95% confidence interval of the mean results

Procedure and measurements

The same protocols and requirements employed in Experiment 1 concerning the subjects' visual capabilities were followed. In addition, the same experimental setup and procedure measurements were also employed. Measurements for each subject were performed in two sessions during 1 single

day. Twenty-two naïve subjects with normal vision participated in this study, split into two age groups, 11 young (24.2 ± 2.6 years old) and 11 old subjects (69 ± 6.4). The interaction between age (young and old) and SPDs (HPS and MH) was studied at fixed background luminance ($L_b = 0.01$ cd/m²) and retinal location (off-axis vision). In addition, two photometry systems (photopic and the MES2 systems) were applied in luminance calculation.

Results

MES2 contrast thresholds

In Experiment 2, the results obtained in Experiment 1 are reinforced by increasing the number of subjects, focusing on contrast threshold measurement in off-axis vision. In addition, the effect size of the significant interactions has been computed by calculation of the Hedges's g statistic. It is a standard and correct effect size statistic appropriate for small samples (Durlak, 2009). The value of the effect size of Pearson's r correlation coefficient (Cohen, 1977) has also been calculated to show the strength of the relationship between the different factors, expressed as a decimal.

Figure 5 shows the off-axis MES2-corrected contrast thresholds of two age groups for a background luminance of 0.01 cd/m² provided by two lamps (HPS and MH).

A significant interaction between age and SPD is found, replicating results shown in Fig. 4 for the lowest background luminance (0.01 cd/m²). For the young group, contrast threshold results between SPDs differ significantly ($p = .001$) ($g = 2.534$; $r = .24$). However, there is nonsignificant effect of SPDs in contrast threshold results of the old-aged group ($p = .855$). An aging effect is observed when comparing results between age groups, the results being greater for the old-aged group in both SPDs ($p = .05$). For the HPS lamp, the mean difference between contrast thresholds of young and old subjects is 0.059 ($p = .023$) ($g = 1.052$; $r = .21$). This difference appears much more pronounced in the case of the MH lamp, in which the mean difference between old and young subjects is 0.162 ($p = .001$) ($g = 2.448$; $r = .24$).

Photopic contrast thresholds

As for photopic contrast thresholds, Fig. 6 shows contrast thresholds without the MES2 system correction for luminance. The same trend is observed as in Fig. 3, regarding the results obtained at the lowest background luminance (0.01 cd/m²). For old-aged subjects, results differ in comparison with the results obtained for the MES2 system (see Fig. 5). However, the differences between photometry systems for young subjects are small.

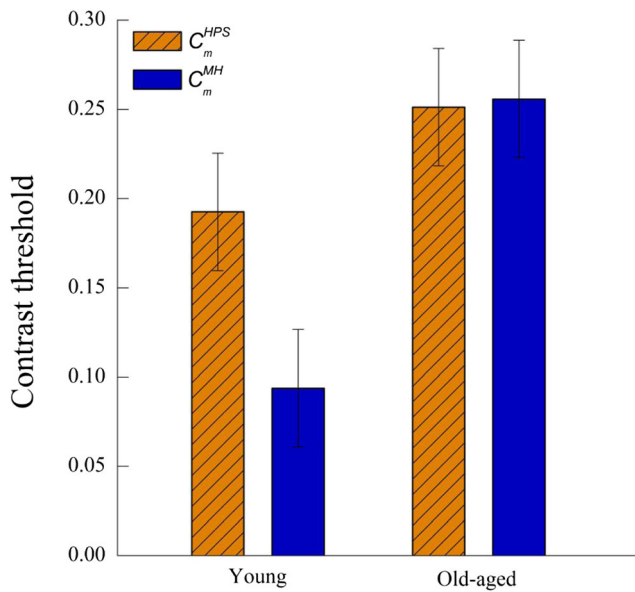


Fig. 5 Mean off-axis contrast thresholds based on the MES2 photometry system and measured for young and old-aged subjects, for HPS and MH lamps, at $L_b = 0.01 \text{ cd/m}^2$. Error bars define 95% confidence interval of the mean results

MES2 versus photopic contrast thresholds

In order to analyze whether the interaction between age and SPD is influenced by photometry, the relationship between mean contrast thresholds obtained for both SPDs and photometry systems has been analyze for young and old-aged groups. For young subjects, lower contrasts thresholds are obtained for the MH lamp when compared with the HPS lamp for both

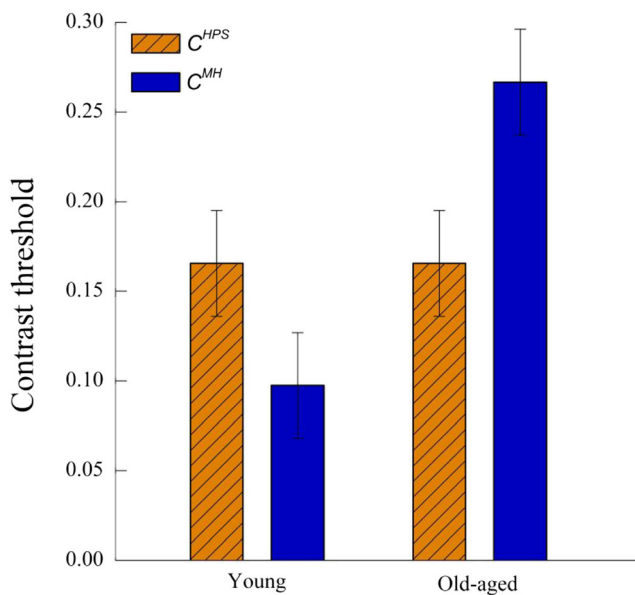


Fig. 6 Mean off-axis contrast thresholds based on the photopic photometry system and measured for young and old-aged subjects, for HPS and MH lamps, at $L_b = 0.01 \text{ cd/m}^2$. Error bars define 95% confidence interval of the mean results

photometry systems. However, for old-aged subjects, lower contrast thresholds are obtained for the HPS lamp in comparison with the MH lamp using both photometry systems. Therefore, the SPD effect in both age groups occurred regardless of the photometry system employed.

Discussion

In this study, we presented the results of two experiments focused on the effect of spectral power distribution and age on contrast threshold in a typical mesopic illumination environment. In addition, the effect on contrast threshold of luminance calculation based on the MES2 mesopic photometry system has been examined in off-axis measurements, as well as the photopic measurement of luminance already established in the literature. Experiment 2 is a consequence of the results obtained in Experiment 1. Its goal has been to obtain greater statistical significance of the most relevant results found in Experiment 1, by measuring contrast threshold in a greater number of naïve subjects.

In Experiment 1, we measured contrast threshold in on-axis and off-axis vision in subjects of three well-differentiated ranges of age, adapted to different levels of mesopic illumination provided by HPS and MH lamps. The photopic contrast threshold results presented in Figs. 2 and 3 show that off-axis results are greater than those measured in on-axis vision, regardless of the subject, age, and type of lamp employed. This result verified the well-known increase in contrast sensitivity in the fovea relative to the peripheral retina.

Spectral power distribution and photometry effect

The first question addressed concerns the influence of the MES2 photometry system applied to the off-axis measurements performed in both experiments. Only significant differences were found between the contrast thresholds obtained with photopic and the MES2 photometry systems for the HPS lamp at the dimmest background luminance (0.01 cd/m^2 ; see Fig. 3). This effect appeared for all ages and subjects of Experiments 1 and 2. However, the influence of the photometry system was absent on the contrast threshold results obtained under the same background luminance provided by the MH lamp, for all ages and subjects of both experiments. The MES2 system calculates the luminance from the photopic one by applying a factor that increases in a sharper way as luminance approaches the lower limit of the validity range of the MES2 photometry system (0.005 cd/m^2). The effect of the MES2 system on luminance calculation, therefore, increases with decreasing luminance level. Thus, at these low luminances, this factor approaches the S/P ratio (e.g., 0.49 for the HPS lamp or 1.17 for the MH lamp). Since Weber contrast is defined as a ratio of luminances, the effects produced in the

contrast domain were notably smaller than for the individual luminances, with the exception of HPS lamp at $L_b = 0.01$ cd/m². In this case, changes from photopic to the MES2 contrast thresholds ranged from 40% to 60%.

In the case of the HPS lamp (see Fig. 4a), contrast thresholds calculated using the MES2 system showed the same functional behavior with background luminance for all subjects, without statistically significant influence of age, even at the lowest background luminance. This figure also shows an almost constant contrast threshold from $L_b = 0.3$ cd/m² upwards (Weber law) and increased values for dimmer background luminances. This was expected when the visual system enters the de Vries Rose region (Laming, 2013). The second experiment confirmed these results for a greater population of young and old subjects, for the HPS lamp, and at $L_b = 0.01$ cd/m² (see Fig. 5 and accompanying text). In order to compare the current results with those of previous studies, it is also important to consider the spatial frequency of the stimuli. If we consider that the fundamental spatial frequency associated with our test size (2°) was around or lower than 0.5 c/deg, the results shown in Fig. 4a are coherent with those previously found in on-axis vision in the photopic illumination range, which could be applied in off-axis vision (Artal, Ferro, Miranda, & Navarro, 1993; Owsley et al., 1983; Ross, Clarke, & Bron, 1985). The studies from Owsley et al. (1983) and Ross et al. (1985) show that on-axis contrast sensitivity declines with age, but not for spatial frequencies around or lower than 1 c/deg. Ross et al. (1985) found similar results in the case of the modulation transfer function, considered as the response of an optical system to sinusoidal stimuli of different spatial frequencies. Concerning the influence of luminance in contrast sensitivity, other authors found that, under mesopic illumination conditions, the significance of the difference in contrast sensitivities between old and young subjects at a spatial frequency of 1.5 c/deg was dependent on the spatial frequency of the test employed (Bühren, Terzi, Bach, Wesemann, & Kohnen, 2006).

Figure 4b shows a very different situation, with an influence of age on contrast threshold results. When the same subjects performed the same detection task under the MH lamp, contrast thresholds are clearly dependent on age at $L_b = 0.01$ cd/m². We observed the same increasing trend in contrast thresholds as background luminance decreased (see Fig. 4b), particularly at 0.01 cd/m², but in a much more significant way for old subjects. An age effect on contrast threshold results for the MH lamp was confirmed in the second experiment (see Fig. 5).

When contrast thresholds of Figs. 4, 5, and 6 are observed, a clear interaction appears between the spectral power distribution and age in off-axis vision. Contrast thresholds were different for the young and old-aged groups at 0.01 cd/m² depending on the lamp, although these differences clearly reduced with increasing background luminance as concluded by

comparison of Fig. 4. Several questions arose from the analysis of these values. The first one concerned the relevance of the MES2 photometry system to the results obtained. When contrast thresholds for both photometry systems were analyzed, the effect of the spectral composition and the interaction between this factor and age persist for both photopic and the MES2 photometry systems. Therefore, the MES2 photometry system was neither responsible for the age effects nor could it explain them.

Underlying mechanisms

The next important question we tried to answer concerned the probable underlying mechanisms that could explain the interaction found between the type of lamp and age. Could chromatic aberrations be responsible for these results? It was difficult to find a satisfactory or completely convincing response since the existing studies do not include all these variables (e.g., age, eccentricity, mesopic luminances, spectral power distribution). It is known that aberrations increase with age, the internal optics being unable to balance the corneal aberrations of older people (Berrio, Tabernero, & Artal, 2010). In addition, it is also known that longitudinal chromatic aberration does not increase significantly with eccentricity (Jaeken, Lundström, & Artal, 2011; Rynders, Navarro, & Losada, 1998), while transverse chromatic aberration does so slightly (Ogbo & Bedell, 1987; Winter et al., 2015). However, two arguments lead us to discard the transverse chromatic aberration as responsible for the results shown in Figs. 4 and 5. First, the lamp most likely to be able to emphasize the ocular transverse chromatic aberration is the MH lamp due to its wider spectral composition. However, young and middle-aged subjects appear to benefit from it in terms of contrast sensitivity (see Figs. 2 and 3). Second, Yang, Tai, Laukkanen, and Sheedy (2011) show that the transverse chromatic aberration hardly influences the low-frequency letter recognition task in off-axis vision.

As the Age × Lamp interaction was only evident at the lowest background luminances considered in this study, it seems reasonable to explain it from the point of view of the rod involvement in off-axis detection. Rods show greater sensitivity than cones at short wavelengths; therefore, lower contrast thresholds are expected for the MH lamp as, in fact, was shown for young subjects. In the aged eye, both the transparency loss (mainly for short wavelengths) and scattering increase (van den Berg, 1995). Furthermore, the absence of the macular pigment at 10° of eccentricity ($5^\circ \pm 0.94^\circ$ according to Baptista & Nascimento, 2014; $7.7^\circ \pm 2.0^\circ$ according to Chang et al., 2002) facilitates the scattered light to reach that area of the retina (Baptista & Nascimento, 2014; Chang et al., 2002; Stringham, García, Smith, McLin, & Foutch, 2011). Concerning the transparency loss, it does not influence the contrast of the retinal image, since it affects test and

background in the same way. This is the reason why the explanation given by Sagawa and Takahashi (2001), concerning the changes of crystalline lens density with age, could not explain our results. Furthermore, their experiment was performed in the photopic illumination range (100 phot. Td), where detection is cone mediated. However, the reduction in transparency due to age implies a reduction in retinal illuminance. In a Maxwellian-view experiment like ours, retinal illuminance and luminance are proportional variables connected by a constant (the imaged size of the source at the entrance pupil plane, which is lower than the pupil area). Figure allows us to estimate the effect of transparency reduction in retinal illuminance due to age for both lamps. In order to estimate this reduction, the magnitude $A_i^j = \sum P_e^j(\lambda)V(\lambda)T_i(\lambda)$ was calculated, where $P_e(\lambda)$ represented the normalized lamp spectral power distribution and $T(\lambda)$ the ocular transmittance (Barker, & Brainard, 1991), the index i represented the “old” and “young” subjects, and the index j represented the “HPS” and “MH” lamps. The sums were extended to all wavelengths of the visible spectrum (380 to 780 nm). These magnitudes are proportional to the photopic retinal illuminance and do not depend on the pupil size in a Maxwellian-view experiment like ours. Simple calculations revealed that the ratio was $A_{young}^{HPS}/A_{old}^{HPS} = 1.07$, whereas the same ratio for the MH lamp was 1.10. As expected, retinal illuminance is higher for the young than for the old subjects for these two lamps, but the difference between lamps is small. The effect of this different retinal illuminance on contrast threshold is negligible, particularly when employing the logarithmic scales like those used in Figs. 2, 3, and 4.

Concerning the scattered light, rods certainly do not have the directional selectivity to light as cones have. Therefore, rods are more sensitive to scattered light. When the detection is mostly cone mediated (luminance values above 0.07 cd/m²), calculated contrast thresholds appear similar for the three age groups and the two considered lamps (see Fig. 4). The Stiles–Crawford effect (it describes the directional sensitivity of cones) and the rods’ spectral response could explain this behavior. For luminance values below 0.07 cd/m², and particularly at 0.01 cd/m², detection is rod mediated. As they are more sensitive to short wavelengths and capture greater amount of scattered light, the scattering effects can certainly be larger for the MH lamp than for the HPS lamp. These effects could explain the greater contrast thresholds observed for old subjects at these low luminances and for this lamp.

Experimental limitations

In order to assess the extent of these findings and their impact on daily life, we addressed the question concerning the influence of the Maxwellian nature of the experimental arrangement employed in this experiment on them. In other words, could these results be extrapolated to real-life conditions? The

Maxwellian-view arrangement introduced two main differences with natural viewing conditions: the monocular view and an effective pupil difference from real pupil under mesopic illumination conditions. To our knowledge, there is no evidence in the literature of the relationship between the binocular summation effect and the spectral composition of the light source, so we rejected this improbable explanation and concentrated on the effect of the pupil size on the results. The image of the light source formed by our experimental setup in the pupil entrance plane was a circle of 2.5-mm diameter. This size was lower than a real pupil at mesopic illumination levels, but more similar to the pupil size of the oldest group due to the typical senile miosis of the elderly. This means that, for the old subjects, going from the Maxwellian to the natural viewing conditions does not imply great changes in the measured contrast thresholds. In the case of the young subjects, the situation was different. At these low luminances, going from Maxwellian to natural viewing conditions means a change in the pupil size from 2.5-mm diameter to approximately 7 mm, according to the literature (Watson & Yellott, 2012). The influence of pupil size on contrast sensitivity functions can be ignored at these low spatial frequencies (Strang, Atchison, & Woods, 1999). However, in terms of retinal illuminance, this pupil size change would produce an increment in retinal illuminance by a factor of approximately $(7/2.5)^2 \approx 8$. In these natural viewing conditions, we could find contrast thresholds at $L_b = 0.01$ cd/m² that could be very close to those currently measured at $L_b = 0.07$ cd/m² in our Maxwellian experiment. For the young subjects, this means a very significant reduction in the measured contrast thresholds for the HPS lamp and less significant for the MH lamp, according to Fig. 4. Otherwise, our results and predictions agree with those recently published by Uttley et al. (2017). In their study, the ability in obstacle detection has been measured under different mesopic luminance conditions, S/P ratios, and ages. Their experiment performed under natural viewing conditions confirms that, only for illuminances lower than 0.2 lux, do significant differences in obstacle detection appear for different spectral power distributions and ages.

Coming from basic research accomplished in controlled conditions, the abovementioned limitations may make it difficult to generalize our results to a natural viewing situation. Further research is focusing on visual performance assessment under more realistic environmental conditions, as our experimental setup also allows working with natural pupil sizes and performing more applied research.

Conclusions

The findings of this study offer evidence of the effects of the spectral power distribution of the light source in off-axis contrast threshold at mesopic illumination levels. The comparison

between the results obtained employing the photopic and the MES2 photometry systems leads us to affirm that the MES2 system is not responsible for the interactions found between age and spectral power distribution, in terms of luminance calculation. However, the MES2 photometry system better defines the luminances used to calculate contrast threshold, as important parameters such as spectral power distribution, luminance level, and eccentricity, not age, are taken into account. In these conditions, the aged eye manifests increased contrast thresholds due to the greater scattered and captured light, particularly more so the greater the content of short wavelengths in the spectral power distribution of the lamp.

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Appendix

The CIE-recommended (CIE, 2010) system for mesopic photometry describes spectral luminous efficiency, $V_{mes}(\lambda)$, in the mesopic illumination range as a linear combination of the photopic spectral luminous efficiency function, $V(\lambda)$, and the scotopic spectral luminous efficiency function, $V'(\lambda)$. This mesopic photometry system establishes a gradual transition between these two functions throughout the mesopic illumination region that depends on the visual adaptation conditions. It has an upper luminance limit of 5 cd/m² and a lower luminance limit of 0.005 cd/m². This intermediate system is denoted as the MES2 system and defines the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, as a convex linear combination:

$$M(m)V_{mes}(\lambda) = mV(\lambda) + (1-m)V'(\lambda), \tag{3}$$

where, $M(m)$ is a normalizing constant such that the mesopic spectral luminous efficiency function, $V_{mes}(\lambda)$, attains a peak value of 1.

The coefficient of adaptation's, m , value depends on the visual adaptation level of the eye and the spectral characteristics of the adaptation field (S/P ratio).

Thus, the mesopic luminance, L_{mes} , is given by:

$$L_{mes} = \frac{V(\lambda_0)mL_p + (1-m)L_sV'(\lambda_0)}{V(\lambda_0)M + (1-m)V'(\lambda_0)}, \tag{4}$$

where, $V(\lambda_0)$ is the value of the photopic spectral sensitivity function at $\lambda_0 = 555$ nm, calculated as $V(555) = 1$.

L_p and L_s are the photopic and scotopic luminances, respectively. They are obtained by:

$$L_p = 683 \int_{380}^{780} V(\lambda)E(\lambda)d\lambda \quad L_s = 1700 \int_{380}^{780} V'(\lambda)E(\lambda)d\lambda,$$

where, $E(\lambda)$ is the spectral radiance of a given light source (in Wm⁻² sr⁻¹ nm⁻¹) in the visible range (380–780 nm).

The relationship between mesopic luminance, L_{mes} , and coefficient of adaptation, m , is also provided by CIE (2010):

$$m = a + b \log L_{mes}, \tag{5}$$

where a and b are parameters that have the values 0.767 and 0.334, respectively. These values are attained when the L_{mes} value is close to the limits set for the MES2 system (0.005 and 5 cd/m²):

If $L_s \leq 0.005$ cd/m², then $m = 0$ and $L_{mes} = L_s$. Then, Eq. 5 takes the form: $0.005 = 10^{-a/b}$.

If $L_p \geq 5$ cd/m², then $m = 1$ and $L_{mes} = L_p$. Then, Eq. 5 takes the form: $5 = 10^{(1-a)/b}$. And by solving these equations, the values of parameters a and b are defined.

The coefficient of adaptation m is determined using an iterative fixed-point method based on Eqs. 4 and 5. This iteration process starts from photopic and scotopic luminance values, L_p and L_s , for a given m value of 0.5, and then the Eqs. 4 and 5 are repeated till two consecutive values, m_n and m_{n+1} , are close enough that their difference is less than a fixed tolerance:

$$|m_{n+1} - m_n| \leq \epsilon.$$

Therefore, the S/P ratio for a given spectral power distribution is given as follows:

$$S/P\text{-ratio} = \frac{K'_m \int_0^x S_\lambda(\lambda)V'(\lambda)d\lambda}{K_m \int_0^x S_\lambda(\lambda)V(\lambda)d\lambda}. \tag{6}$$

$K'_m \approx 1700 \text{ lmW}^{-1}$ is the maximum value of the spectral luminous efficacy for scotopic vision, $K'(\lambda)$; $K_m \approx 683 \text{ lmW}^{-1}$ is the maximum value of the spectral luminous efficacy for photopic vision, $K(\lambda)$; $S_\lambda(\lambda)$ is the spectral power distribution of the light source.

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