Photometry in the dark: time dependent visibility of low intensity light sources

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Abstract: This paper aims at describing the perceived brightness of persistent luminescent materials for emergency signage. In case of emergency, typically, a fully light adapted person is left in the dark, except for the emergency sign. The available photometric models cannot describe visibility of such light source, as they do not consider the slow dark adaptation of the human eye. The model proposed here fully takes into account the shift from photopic to scotopic vision, the related shift in spectral sensitivity and the dark adaptation. The resulting metric is a 'visibility index' and preliminary tests show that it more realistically describes the perceived brightness of persistent luminescent materials than the common photometric standards.

OCIS codes: (120.5240) Photometry; (160.2540) Fluorescent and luminescent materials; (300.6280) Spectroscopy, fluorescence and luminescence; (330.4060) Vision modeling.

References and links

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1. Introduction

For many years, standards for measuring the brightness and color of artificial light sources such as lamps and displays have been well established. The units involved are photometric: they take into account the average human eye sensitivity and color perception. The same photometric quantities are used for specifying low level light sources such as persistent luminescent materials (long afterglow phosphors), although it is realized these are not valid at low light levels [1]. A luminance of 0.32 mcd/m^2 is taken as the visibility threshold for applications and - by definition - any source with this luminance should look equally bright, irrespective of its emission spectrum. However, this is not the case, as the human eye sensitivity shifts from photopic vision at high light levels (corresponding to cone vision) to scotopic vision at low levels (rod vision), both being characterized by a different spectral sensitivity. Therefore, it is a real challenge to describe the eye sensitivity in the intermediate (mesopic) region. Efforts are currently undertaken to describe the actually perceived brightness by means of a unified luminance concept [2, 3]. The present paper aims at a better understanding of human eye behavior in the mesopic and scotopic region, and focuses on persistent luminescent materials as model systems with a high application value [4].

The objective of the current paper is to evaluate the apparent brightness of persistent luminescent materials for emergency signage in case of electricity failures. Typically, a fully light adapted person is left in complete darkness, except for the emergency signs. The currently available photometric models are inappropriate to describe visibility of such weak light sources under these conditions, as they do not take into account the slow dark adaptation of the human eye. The model which is proposed here, fully takes into account the shift from photopic to scotopic vision, the related shift in spectral sensitivity and the temporal effects of dark adaptation.

2. Experimental

In order to mimic a realistic set of brightness levels and decay curves of phosphorescent materials, we used a set of benchmark phosphors which are commercially available (Glotech Int. [5]) and cover the whole visible spectrum. The height normalized emission spectra of the materials are shown in Fig. 1. Phosphor samples were prepared from a 1:5 ratio of phosphor powder and transparent polyurethane varnish, painted as a thick coat on a flat metal plate. Phosphors

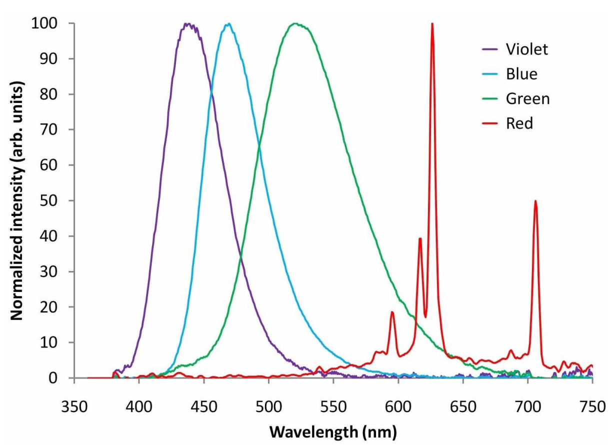

Fig. 1. Reference spectra (measured in steady state) of commercially available persistent luminescent materials, used as benchmarks for model testing.

were excited during 5 min. with 1000 lux from an unfiltered xenon short arc light source, in accordance with the DIN67510 test procedure. The decay of the luminance of the phosphors was measured with an ILT1700 (International Light Technologies) photometer equipped with a

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SPM068 photomultiplier-based calibrated luminance probe (Fig. 2).

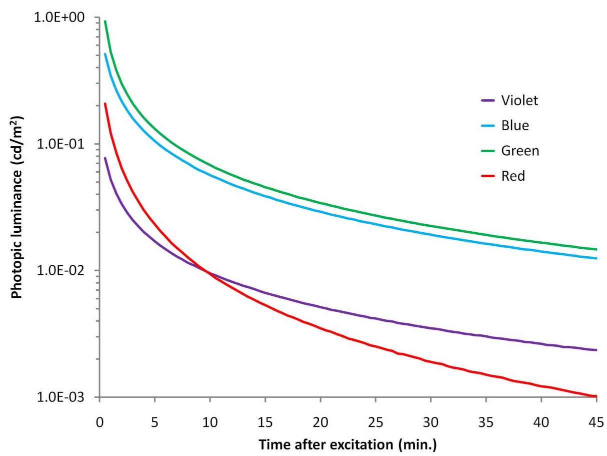

Fig. 2. Luminance decay of the benchmark persistent phosphors, after charging for 5 minutes with 1000 lux of an unfiltered Xe-arc.

3. Results and discussion

The basic unit of photometry, the candela, is defined at a wavelength of 555 nm. In order to take into account the wavelength dependence of the eye sensitivity, this definition is supplemented with the spectral luminous efficiency [6]. In daylight conditions, when the cones of the retina are responsible for color vision, the relative spectral eye sensitivity is specified by $V(\lambda)$. At low light levels, rods are active, and their sensitivity curve is described by $V'(\lambda)$. To enable easy calculation of our model, we have parameterized these tabulated data using a multiple-Gaussian fit [appendix, Eq. (8) and (9)]. For a light source with a spectral distribution $I(\lambda)$, the total visible output under scotopic and photopic conditions is given by:

$$S = K'_m \times \int I(\lambda) V'(\lambda)\, d\lambda \tag{1}$$

$$P = K_m \times \int I(\lambda) V(\lambda)\, d\lambda \tag{2}$$

respectively. For a monochromatic source at 555 nm, both equations should yield the same result, as the candela is defined irrespective of light intensity. A monochromatic source at 555 nm with an optical power of 1 Watt, corresponds to a luminous flux of 683 lumen, following the definition of the candela. As the $V(\lambda)$ curve has a value 1 at 555 nm, the constant K_m equals 683 lm/W. Equation (1) should yield the same flux, therefore:

$$K'_m \times V'(\lambda) = K_m \times V(\lambda) \qquad \text{at} \ \ 555\text{nm} \tag{3}$$

$$K'_m = K_m \times \frac{V(555nm)}{V'(555nm)} = 683lm/W \times \frac{1}{0.402} = 1700lm/W \tag{4}$$

The latter equation means that a 1 Watt monochromatic source at the peak of the $V'(\lambda)$ curve (507 nm) will yield a flux of 1700 lumen under these low light level conditions.

From the numbers given above, one would be tempted to conclude that the eye sensitivity remains the same at 555 nm, decreases for the red and increases for the blue when the light intensity decreases and vision shifts from the photopic to the scotopic regime. The ratio 1700/683 would then be a measure of the ratio of eye sensitivities between rods and cones. However, the ’magic’ number 1700 only stems from the fact that the candela is uniquely defined at 555 nm, irrespective of light intensity. Obviously, it is a necessity for a photometric unit to be valid at all light levels, and to be linear, but it does *not* necessarily accurately describe how different light levels are perceived. Actually, reality is much more complex:

- Above a luminance of the order of 1 cd/m^2, the rods are saturated and do not contribute to vision. Below about 1 mcd/m^2, the cones become inactive. In the intermediate region, the mesopic regime, both types of photo-receptors contribute to vision. It is a field of active research to describe human response in mesopic vision, in view of, for example, improving street lighting [7].

- Rods and cones are not equally distributed over the retina. In the fovea, the central area of the retina which is used for direct vision, the concentration of cones is highest and rods are totally absent. This highly complicates an accurate description of eye sensitivity, since cones are mostly active for direct vision and rods for peripheral vision.

- The eye sensitivity is highly dependent on adaptation to certain lighting conditions [8]. A typical curve for dark adaptation is shown in Fig. 3. The graph shows the threshold of visibility as a function of time. During the first few minutes, the eye sensitivity rapidly increases due to sensitization of the cones and dilatation of the pupils (the graph was obtained with naturally changing pupil size). After 5 to 10 minutes, the cones obtain their maximum sensitivity [9]. The second part of the graph is due to the sensitization of the rods, which gain their ultimate sensitivity after 30-45 minutes. The discontinuity in the graph is described as the cone-rod breakdown. In order to facilitate further modeling, we have fitted continuous curves to both the photopic and scotopic thresholds, which we call PT and ST, respectively [Eqs. (10) and (11) in the appendix]. The curves are typical for human eyes, but variations of about a decade exist among individuals, so they should only be used as approximations. The human eye also becomes less sensitive with age, showing a typical decrease in sensitivity of a factor 200 between the age of 20 to 80 [10]. Figure 3 has been measured with violet light below 460 nm; as an approximation, we have assumed it was measured at a constant wavelength of 460 nm. At other wavelengths, the shape of the curves will be somewhat different, as they should be corrected for the appropriate eye sensitivity using the $V(\lambda)$ and $V'(\lambda)$ curves. This has been done in Eqs. (12) and (13) in the appendix.

The next question is how the human eye will interpret the intensity and color of a weak light source as a function of time. Due to the complexities of our visual system, it is not possible to describe this in a single set of equations. Therefore, we will limit ourselves to a simple case which is, however, of practical significance:

Consider a person in a well-lit room, subject to (very bright) 5000 cd/m^2 white light, for which Fig. 3 is valid. As typical illumination levels indoors are much lower, we are thus considering a worst case scenario in terms of dark adaptation. If the electricity fails, the test person is left in complete darkness, except for the afterglow phosphor emergency exit signs.

In order to assess the visibility or ’brightness’ of the phosphors, their luminance should be compared to the visibility thresholds calculated in Eqs. (12) and (13). Which of the two spectral luminous efficiency curves, photopic or scotopic, should be used in this case? For mesopic vision, in the luminance range typically from 0.001 to 1 cd/m^2, several models have been proposed to describe the transition from cone to rod vision ([2, 7, 11, 12]). These models obviously cannot be used here, as they all use the 1700/683 ratio and do not take into account dark adaptation. Nevertheless, we will use the same way of mixing information from rods

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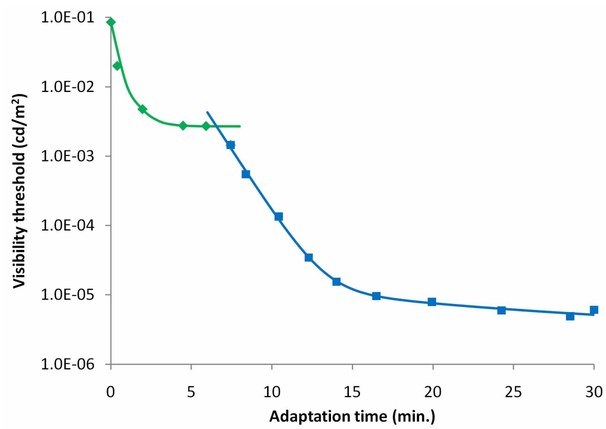

Fig. 3. Dark adaptation of the human eye using violet light (wavelengths below 460 nm), after light adaptation to about 5000 cd/m^2. Adapted from [8].

and cones as the simplest of the models [2]. The mixing parameter X describes the relative contribution of photopic and scotopic vision:

$$X = \frac{L}{0.599} - \frac{0.001}{0.599} \tag{5}$$

valid for a luminance between 0.600 and 0.001 cd/m^2. Above 0.600 cd/m^2, X = 1 and below 0.001 cd/m^2, X = 0. In the original model by Rea, the 'unified' luminance L is found from a linear combination of S and P [Eqs. (1) and (2)]:

$$L = 0.834P - 0.335S - 0.2 + \left(0.696P^2 - 0.333P - 0.56SP + 0.113S^2 + 0.537S + 0.04\right)^{1/2} \tag{6}$$

In the present model, we will only use L for calculating the mixing parameter X, and then replace S and P by a scotopic and photopic 'luminance above threshold'. This leads to the following tentative 'visibility index' VI:

$$VI\left(I\left(\lambda\right),t\right) = X \times \frac{P}{PT_{I(\lambda)}\left(t\right)} + \left(1 - X\right) \times \frac{S}{ST_{I(\lambda)}\left(t\right)} \tag{7}$$

where we have made the assumption that the brightness of a source is only dependent on the ratio between its luminance and the visibility threshold. If we apply this equation to our benchmark persistent phosphor materials, we obtain figure 4.

It is clear from Figs. 2 and 4 that the predicted apparent brightness is entirely different from the photopic luminance. The most important effect is the wavelength shift of the eye sensitivity towards the blue; indeed, violet and red emitting phosphors have a similar (photopic) luminance at all times (Fig. 2), while, except for the very first minutes of the decay curve, the red phosphor has a visibility index which is almost 3 orders of magnitude lower than the violet one (Fig. 4).

The luminance of all persistent phosphors follows a non-exponential decay [13] (Fig. 2). Despite this rapid decay, the visibility first increases with time, and then remains constant for tens of minutes. The initial increase is due to the fact that the eye sensitivity increases faster than the phosphor materials decay. After the rod-cone breakdown, the eye sensitivity keeps increasing at a slower rate (Fig. 3), which then almost perfectly compensates for the decreasing light output of the phosphor materials. This is an effect which is observed in practice, but cannot be described using the usual photometric quantities.

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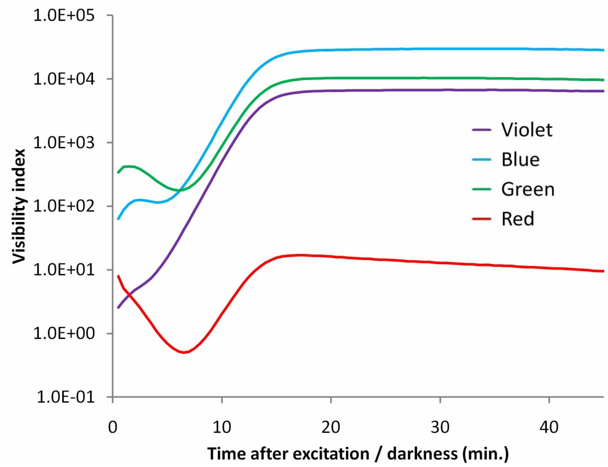

Fig. 4. Apparent brightness, called 'visibility index' VI, of the benchmark persistent phosphors, after charging for 5 minutes with 1000 lux of an unfiltered Xe-arc. The observer is fully light adapted at time zero.

4. Conclusion

For several years, both individual researchers and standards organizations like the CIE (International Commission on Illumination), have undertaken research to develop better photometric practices in low light level conditions. This has led to several models which extend photometry into the mesopic region [7]. However, such models do not take into account the slow dark adaptation of the human eye and therefore provide no accurate description of observed brightness in the case of slowly decaying light intensities. Due to the intricacies of human vision and its complex dependence on background illumination, light/dark adaptation, wavelength, age, angular dependence, ... it is not possible to describe perceived brightness in a single set of equations or a single unit. Therefore we limited ourselves to the simple case of a fully light adapted observer who is suddenly left in complete darkness, except for some low intensity persistent luminescent materials as emergency exit signs.

The proposed preliminary model takes into account the contribution of both rods and cones, their respective spectral sensitivities and dark adaptation behavior, and is summarized in a visibility index. While the model has to be refined in several ways, and made applicable to more realistic situations, it gives a much more reasonable description of the actually observed brightness than the currently used photometric quantities.

From the results obtained, it is seen that the visibility index of typical persistent phosphors is low during the first minutes, and then increases to a constant level. Therefore, it might be advantageous to include an additional high brightness phosphor with a short decay time (of the order of 10 minutes) in emergency lighting applications, in order to correct for this initial lack of brightness.

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Appendix

The tables for $V(\lambda)$ and $V'(\lambda)$ [6] were fit to multiple Gaussian functions as follows:

$$V(\lambda) = 0.23919\exp\left[-\frac{(\lambda-530.52)^2}{850.73}\right] + 0.91063\exp\left[-\frac{(\lambda-565.62)^2}{3323.3}\right] + 0.03101\exp\left[-\frac{(\lambda-463.87)^2}{658.13}\right] \quad (8)$$

$$V'(\lambda) = 0.99927\exp\left[-\frac{(\lambda-507.05)^2}{2522.3}\right] + 0.18215\exp\left[-\frac{(\lambda-449.42)^2}{646.47}\right] \quad (9)$$

where wavelengths are given in nanometer.

The following curves were fit to the dark adaptation curves of Fig. 3. The fits correspond to the continuous curves in the figure.

$$PT_{460}(t) = 0.00270 + 0.05326\exp(-t/0.03142) + 0.0292\exp(-t/0.74034) \quad (10)$$

$$ST_{460}(t) = 2.98\times10^{-6} + 0.60056\exp(-t/1.2124) + 1.97\times10^{-5}\exp(-t/13.586) \quad (11)$$

when the adaptation time is given in minutes and the threshold is in cd/m^2. Subscripts 460 are used, as the adaptation curve was recorded for blue light below 460 nm.

In case of a light source with an arbitrary wavelength distribution $I(\lambda)$, the equations describing the threshold become:

$$PT_{I(\lambda)}(t) = PT_{460}(t) \times V(460nm) \times \frac{\int I(\lambda)\,d\lambda}{\int I(\lambda)V(\lambda)\,d\lambda} \quad (12)$$

$$ST_{I(\lambda)}(t) = ST_{460}(t) \times V'(460nm) \times \frac{\int I(\lambda)\,d\lambda}{\int I(\lambda)V'(\lambda)\,d\lambda} \quad (13)$$

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