Evaluating Light Source Efficacy Under Mesopic Conditions Using Reaction Times

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INTRODUCTION

Luminous efficacy, lumens per watt, is a primary criterion for comparing and specifying light sources. Both luminous flux (in lumens) and power (in watts) are physically measurable quantities, but the former relies on psychophysical experiments designed to determine the spectral sensitivity of the human visual system (Gibson and Tyndall, 1923). These experiments, the results of which determined the photopic spectral luminous efficiency function, V(λ), (CIE, 1924) used relatively high, so-called photopic light levels and measured visual response to small targets imaged in the fovea. The fovea is that part of the retina containing only cone photoreceptors and is responsible for on-axis, high-acuity vision. Strictly speaking then, the efficacy value published for every electric light source represents the effectiveness of that lamp in producing light only for the fovea and only under high light levels.

It has been known for many years that the spectral sensitivity of the human visual system under low light levels is different than that under high light levels (Graham, 1965). At very low levels only the rod photoreceptors function and objects can only be seen off-axis. Electric lighting is not used, however, under these very low, so called, scotopic conditions. At typical nighttime street lighting levels,* both rods and cones are active. There is no definition of light at these, so called, mesopic levels. It is difficult to establish a spectral luminous efficiency function for mesopic vision because the visual spectral sensitivity at mesopic levels shifts with light level. Near 3 cd/m^2, spectral sensitivity outside the fovea will be close to the CIE 10^0 photopic function $V_{10}(\lambda)$; as the light level is decreased to 0.001 cd/m^2 spectral sensitivity will shift toward shorter wavelengths until it approaches the CIE scotopic function V'(λ). Currently there are no accepted standards for evaluating spectral sensitivity in the mesopic region, despite several studies that have been performed to this end (Kinney, 1958; Pollack, 1968; Kokoschka, 1972; Ikeda and Shimonozo, 1981; Sagawa and Takeichi, 1986; McGowan and Rea, 1995). Therefore, the efficacy of light sources for evoking visual response under typical nighttime lighting applications remains undefined.

Several experimental methods have been employed in obtaining luminous efficiency functions. Because the visual system organizes information by employing different channels, different methods produce different functions. Ingling (1977) and Ingling and Tsou (1988) reviewed both psychophysical and electrophysiological data and found that the visual system could be conveniently segregated into two channels, each having different spectral, temporal and spatial characteristics. Kaplan and Shapely (1986) reinforced this proposition through electrophysiological recordings from the lateral geniculate nucleus (LGN) in the primate brain. They described the characteristics of the magnocellular and parvocellular channels. The magnocellular channel has better temporal resolution and reacts more quickly to changes in the visual field (Shiller *et al.*, 1978). This channel is also achromatic in that it does not provide color

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* A survey of roadway luminance values ranged from 0.74 to 0.013 cd/m^2 in the Albany and Troy, NY area.

information. The parvocellular channel has better spatial resolution and provides color information, but is much slower than the magnocellular channel. The methods tapping the magnocellular channel likely result in luminous efficiency functions that follow Abney's law of additivity; the methods tapping the parvocellular channel result in severe departures from additivity (Lennie *et al.*, 1993). Abney's law is a statement of linearity whereby the luminance of a mixture of different colored lights is equal to the sum of the luminances of the components (Graham, 1965). Without linearity, photometry is impossible.

One of the most important methods for obtaining luminous efficiency functions is known as flicker photometry. This was the primary technique used in establishing the V(λ) function (Ives, 1912; Coblentz and Emerson, 1917). This technique very likely isolates the achromatic, magnocellular channel which is more sensitive to rapid temporal changes. Departures from additivity in this technique are very small (Shipley, 1961). Flicker photometry would typically be the method of choice in developing a system of mesopic photometry. However, rods and cones have different critical fusion frequencies (CFF) and, as pointed out by Hough (1968) and Hough and Ruddock (1969), at mesopic levels this technique may measure only cone or only rod responses depending on the light level used and retinal position of the image, not the combined response which is believed to be important to visual perception at mesopic levels.

The other main technique used to obtain luminous efficiency functions is known as heterochromatic brightness matching (Hyde et al., 1918; Gibson and Tyndall, 1923; Bedford and Wyszecki, 1958; Wagner and Boynton, 1972). It was also employed in most studies of mesopic photometry (Palmer, 1966; Ikeda and Shimonozo, 1981; Sagawa and Takeichi, 1986; Trezona, 1991). This technique probably taps the chromatic, parvocellular channel as well as the magnocellular channel. Additivity does not hold with this technique, especially for large visual fields, presumably because of complex, cortical interactions between the chromatic information from the parvocellular channel and the achromatic information from the magnocellular channel. Furthermore, variability in heterochromatic brightness matching is large. These facts have thwarted numerous attempts at developing a system of mesopic photometry with this technique(CIE, 1989).

Few studies have been conducted to investigate spectral sensitivity using reaction times (Pollack, 1968; Lit *et al.*, 1971). In general, electrophysiological data from the mammalian visual system show that as stimulus intensity increases, response latency decreases and response magnitude increases in the visual cortex (Kuhnt, 1967). Psychophysical evidence (Rea and Ouellette, 1988) is consistent with these findings. Pollack (1968) and Lit *et al.* (1971) measured on-axis reaction time to chromatic stimuli of equivalent photopic luminance and found that reaction time depended on luminance only. These studies suggest that reaction time techniques tap only the magnocellular channel, and probably produce functions which follow Abney's Law. Reaction times also have face validity for the lighting industry in that the speed of response is very important to many real-world tasks. Therefore, extending and expanding the reaction time technique to mesopic levels seems to be the best chance for developing a system of mesopic photometry.

The purpose of the research presented here was to add to current knowledge about the response of the human visual system to light under nighttime conditions. The relative luminous effectiveness of two commonly-used nighttime light sources, high-pressure sodium (HPS) and metal halide (MH), were quantified with the reaction time technique. Furthermore, a preliminary model of mesopic photometry was developed to evaluate any light source for nighttime applications.

METHODS

Viewing chamber

Figure 1 shows a schematic diagram of the viewing chamber. A half-cylinder (radius = 75 cm, height = 50 cm) was built with plywood and the inside painted flat white.

Two apertures on the half-cylinder surface let two paths of partially collimated light into the chamber from the source, S. Light entering through the top aperture, H1, reflected off two angled mirrors, MS, onto the back wall which then diffusely illuminated the rest of the chamber. This aperture provided background luminances for the experiment. The luminance ratio of the brightest to darkest area on the cylindrical viewing surface was 1.06:1.

Light entering the lower aperture, H2, was entirely collected by a mirror, M, and reflected as a small luminous disk onto the back of the viewing chamber. The mirror could be rotated to position the disc either on-axis or off-axis at any angular displacement from the fovea. Neutral density filters placed in filter holders, F1 and F2, were used to adjust the luminance of the background and disc, respectively. The spectral distributions of the background and disc were nearly identical since the same light source was used for both. The disc served as the reaction time target.

An electromechanical shutter, SH, controlled the presentation time of the target. Reaction times were measured by a microprocessor based timer, CDAS, with one ms resolution , which also triggered the opening of the shutter. The shutter opened completely within 10 ms when triggered. A reaction time was the time interval between the triggering of the shutter and depression of the button on a joystick, J, by the subject.

A pencil-drawn circle, 3^0 in diameter with respect to the subject's viewing position was used as a fixation location. The circle was located 13 cm above the chamber floor and at a point that laterally bisected the half-cylinder. The on-axis target used in experiment was flashed at the center of the circle. The cylindrical shape of the chamber provided for a constant viewing distance in the horizontal plane for different lateral viewing angles from the fixation circle.

Light sources and target

The lamps used were a 175-W clear MH lamp and a 400-W clear HPS lamp. Lamp information appears in Table 1.

The diameter of the target disk in the reaction time experiment was 2^0 so that it could be imaged within the fovea, yet it was large enough to be easily seen when viewed off-axis. The luminance of the target (Lt) was adjusted to maintain the same contrast of 0.7 against its background (Lb) for each experimental condition. (Contrast was defined as (Lt - Lb)/Lt). This high contrast made the target clearly visible at all conditions. All reaction time targets were viewed monocularly with the right eye. For each lighting condition reaction times were measured either for the target appearing on-axis or off-axis at an eccentricity of 15^0 to the nasal side of the right eye.

Subjects

Three subjects, AB, YH and YY participated in the experiment. AB and YH were males, 28 years old. YY was a female 31 years old. All had a Snellen acuity of at least 20/20 and normal color vision on the Ishihara Test of Color Blindness. Two of the subjects, AB and YH were highly trained, having experienced many reaction time trials prior to data collection for this experiment. YY was much less experienced. All subjects understood the purpose of the experiment prior to data collection.

Procedures

Eight background luminances (0.003 though 10 cd/m^2), two light sources (MH and HPS) and two target locations (on-axis and off-axis) were employed. It will be noted that the lowest background luminance (0.003 cd/m^2) with the MH source was added to the original experimental design to obtain more complete data at the lowest mesopic luminance levels. Subjects performed trials in two sessions, one per light source. A session consisted of fourteen or sixteen lighting conditions (2 target positions x 7 background luminances for HPS or 8 for MH). Subjects AB and YY performed one block of reaction time trials (20 trials) per lighting condition; subject YH performed three blocks of trials for each condition. For each trial, the target would appear with a randomized foreperiod from 6 to 8 s and would go "off" when the subject responded by depressing the switch, or remain "on" for 2 s if there were no response.

For practical reasons, the subject always performed two blocks of trials successively, one for on-axis and one for off-axis targets, for a given lighting condition. The presentation orders of lighting conditions were randomized for each subject.

A one-minute adaptation period preceded the start of each lighting condition in addition to a five-minute adaptation period to the darkened laboratory at the start of each session.

RESULTS

On-axis detection

Figure 2 shows each subject's on-axis reaction times for the MH and the HPS sources plotted as a function of background luminance. Each point in a figure represents the median reaction time of 20 (AB, YY) or 60 (YH) trials for a given lighting condition. Median values were used rather than mean values in the analysis due to the skewed distribution of reaction times. A single function was obtained for each subject to represent the on-axis reaction times (RT) for both sources as a function of background luminance (L) since there was no systematic difference between light sources at different background luminances. The data for each subject were fitted using a least squares solution following the function:

$$RT = a(p,s,r)/L^{b(p,s,r)} + c(p,s,r) \qquad (1)$$

where a(p,s,r) and c(p,s,r) are coefficients which may vary with target position (p), light source (s) and background luminance range (r). For simplicity of regression analysis, the coefficient b(p,s,r) is assumed constant for retinal position (p), light source (s) and background luminance range (r) and is set equal to 1/3 (Vaughn *et al.*, 1966).

When the background luminance, L, is infinitely high, the first term a in Eq. (1) approaches 0. Thus the coefficient c represents the asymptotic reaction time for a subject. The value of c will be different for different subjects and is determined by the individual's motor, cognitive and minimum visual processing time. It was shown that the 2^0, on-axis reaction time data were not different for each light source so the variable s was not a parameter for the curve fit. When plotted, the data show no discontinuities implying that a single curve is appropriate for the entire range of background luminances. Therefore, r was not a parameter either. By visual extrapolation to higher background luminances, the values of c(p=on-axis) were estimated to be 218, 200 and 230 ms for subject AB, YH and YY, respectively.

The value of a for each subject was determined by a least squares fitting method and is presented in Table 2. The correlation coefficient (R^2) between the fitted curve and the actual median reaction times for each subject is also provided. These coefficients were used in Eq. (1) to produce the corresponding functions in Figure 2.

Off-axis detection

Figure 3 show each subject's off-axis reaction times for the MH and the HPS sources plotted as a function of background luminance. Each point in a figure represents the median reaction time of trials for a lighting condition. For all three subjects there were no apparent systematic differences between reaction times obtained under MH and HPS above approximately 1 cd/m^2. Below this value, reaction times for HPS become systematically longer than those for MH as background luminance decreases. Again, Eq. (1) was used to fit the off-axis reaction time data, though the coefficients a and c now depend on r and s for the off-axis condition. A single function was therefore assumed for high background luminances for both MH and HPS; separate functions were fit to the data obtained with these two sources at low luminances.

The data from the less practiced subject, YY, showed much greater variability, making systematic differences less apparent. However, YY's data do not contradict those from AB and YH.

The bifurcation in the off-axis reaction time function at a background luminance below approximately 1 cd/m^2 was also found in other studies. For example, Brooke (1951) measured CFF at different field luminances using a 2^0 circular disc at various retinal positions. These data showed a discontinuity in the CFFs at about 0.5 cd/m^2 for off-axis positions. Hecht *et al.* (1936), used a 19^0 test field and seven different wavelengths in measuring CFF as a function of field luminance. As luminance dropped below about 0.8 cd/m^2 the CFFs for the seven wavelengths began to branch.

By visual inspection of the data of AB and YH there appears to be a separation between HPS and MH below 0.3 cd/m^2, but no clear separation above 1 cd/m^2. The midpoint between these luminances (in log units) is 0.6 cd/m^2. Guided by the literature which describes a rod-cone discontinuity at about this luminance (Brooke, 1951; Hecht *et al.*, 1936), 0.6 cd/m^2 was chosen as a convenient point of bifurcation on the fitting curves in Figures 5 through 7. It was assumed in this analysis that above 0.6 cd/m^2 there is no rod contribution to detection of the 2^0, off-axis target; rods contribute more and more, however, as background luminance drops below this luminance.

It was assumed, again for simplicity in the regression analysis, that b(p,s,r) was equal to 1/3 for all conditions and all subjects. With the assumption that there is no difference between the minimum visual processing time for on-axis and for off-axis detection at high background luminances, the values of c for luminance levels above 0.6 cd/m^2 were again assumed to be 218, 200, and 230 ms for subject AB, YH, and YY, respectively. The values of coefficient a for this high level range can then be solved using a least squares method.

For luminance levels below 0.6 cd/m^2 the values of both variables a and c were solved using a least squares method with the constraint that this curve and the curve for the high luminance levels must intersect at 0.6 cd/m^2.

Tables 3a, b and c present the three sets of coefficients for each subject. These coefficients were used in Eq. (1) to produce the corresponding functions plotted in Figure 3.

It should be noted, that the spectral sensitivity of the peripheral cones is slightly different than that for the foveal cones. S cones are scarce at the fovea and the fovea is covered by the macula lutea (Sekuler and Blake, 1994). The visual effects produced by MH and HPS on these peripheral cones should therefore be slightly different when the radiations from the two lamps are equated in terms of luminance, or in other words, are equated for their visual effects on the foveal cones. This small difference, however, is equivalent to about a 4% to 7% difference in luminance as estimated using the CIE 2^0 and 10^0 1964 luminous efficiency functions (Table 1). This would produce a difference of about 1 ms in reaction times, which is too small to be revealed in this study unless many more trials were conducted.

Relative Efficacies of MH and HPS

Below 0.6 cd/m^2 off-axis reaction times are longer for HPS than for MH at the same background luminance. This difference becomes larger as background luminance decreases. Therefore, below 0.6 cd/m^2 the $V(\lambda)$ function becomes increasingly inappropriate in characterizing visual stimulus for off-axis detection as the background radiance decreases.

The regression functions in Figure 3 can be used to establish an equivalent visual effectiveness for MH and HPS for these experimental conditions. The ratio (R(L)) of the background luminance (L) under HPS, the reference source, to the background luminance of MH can be determined for any criterion reaction time. R(L) is constant and equal to unity above 0.6 cd/m^2 but changes with background luminance below that level. Figure 4 illustrates how R(L) is determined for a background luminance of 0.1 cd/m^2 under HPS. When $R(L = 0.1) = 1.93$, a background luminance of 0.1 cd/m^2 under HPS has an equivalent visual effect (i.e., equivalent reaction time for a flashed 2^0, off-axis target) as that produced at a background luminance of 0.052 cd/m^2 under MH. Table 4 provides values of R(L) for background luminances of 0.01 to 10 cd/m^2 under HPS for subjects AB and YH as well as the average ratios for the two subjects. (The values for subject YY were not included because YY's data were consistent with the other two but more variable.) The values of R(L) for subjects AB and YH are very similar demonstrating that the relative shift in reaction times due to the lighting conditions is about the same for both subjects despite differences in the absolute values of their reaction times.

From the power and lumen ratings for MH and HPS lamps, the relative efficacies, or the efficacy ratio ($ER_{MH/HPS}$), for two lamps at different background luminances can be derived from the values of R(L) in Table 4 and Eq. (2).

$$ER_{MH/HPS} = R(L) * \frac{(\text{MH lumens}) * (\text{HPS watts})}{(\text{MH watts}) * (\text{HPS lumens})} \quad (2)$$

250-W HPS lamps are used widely in outdoor lighting and the efficacy of this lamp can be compared with a 250-W MH lamp at different background luminances. With the initial lumens of 27,500 lm for the HPS and 23,000 lm for the MH (from the GE 9200 Lamp Catalog: 1993), the average values of $ER_{MH/HPS}$ of these two lamps were calculated and presented in Table 5, and graphically as the solid line in Figure 9; $ER_{MH/HPS}$ values for both subjects are also plotted in Figure 5 showing how similar the individual data are to the average.

As shown in Figure 5, above a background luminance of 0.6 cd/m^2, $ER_{MH/HPS} = 0.84$. This is the value of the efficacy ratio under photopic conditions. As background luminance drops below 0.6 cd/m^2 the efficacy ratio increases until it approaches the theoretical scotopic limit. The scotopic efficacy ratio was calculated in the same way as the (photopic) efficacy ratio for the two lamps but the scotopic luminous efficiency function, $V'(\lambda)$, was used instead of $V(\lambda)$. At a typical roadway lighting level of 0.1 cd/m^2, the MH lamp is 60% more efficacious than the HPS, as shown in Figure 5 as well as in Table 5.

Of greater significance than establishing values of $ER_{MH/HPS}$ for these two sources, the estimates of R(L) can be used to establish a family of preliminary mesopic luminous efficiency functions which can further be used to estimate the mesopic luminous efficacy of any light source.

Preliminary mesopic luminous efficiency functions

A mesopic spectral luminous efficiency function, designated $V_m(\lambda)$, forms the basis for calculations of mesopic efficacy. Just like $V(\lambda)$ is dependent upon the experimental conditions used to derive it, $V_m(\lambda)$ will also be a function of the experimental conditions used in its derivation. In this experiment, a 2^0 disk was flashed 15^0 off axis under spectral power distributions of HPS or MH at various photopic luminance levels. Thus, $V_m(\lambda)= F(t, p, s, L)$, where t is the spatial-temporal-contrast characteristics of the target, p is the retinal position of the target, s is the spectral power distribution of the light source, and L is the (photopic) background luminance under the source. The terms t and p are assumed constant for this experiment while s is a discrete variable, HPS or MH, and L is a continuous variable.

Although the visual system is much more complex than modeled below, the following analysis illustrates how a set of mesopic spectral luminous efficiency functions can be derived from reaction time data. As more complete data are obtained, this simple, preliminary model can be modified.

The preliminary model assumes that the luminous efficiency of mesopic vision is an ordered and regular combination of the luminous efficiencies of cones and rods. Since for this experiment, large visual fields were employed, the CIE $V_{10}(\lambda)$ function was chosen to represent the cone spectral response. The model assumes that Abney's law is valid in the mesopic region and that $V_m(\lambda)$, can be expressed by a linear combination of $V_{10}(\lambda)$ and the scotopic function, $V'(\lambda)$. The model is described in Eq. (3).

$$V_m(\lambda)= k_1(L)* [x(L)* V_{10}(\lambda) + (1-x(L)) * V'(\lambda)] \quad (3)$$

where x(L) is a variable between 0 and 1 and depends upon background luminance L; $k_1(L)$ is a normalization constant to ensure the maximum value of $V_m(\lambda)$ at luminance L is equal to unity (1.0).

The average values of R(L) in Table 4 will be used as the basis for determining x(L) in this analysis. Since R(L) varies with background luminance (L) under HPS, $V_m(\lambda)$ and mesopic efficacy are also in terms of L under HPS. R(L) is the ratio of the background luminance under HPS to the background luminance under MH, both of which being associated with a criterion reaction time. Assuming that one may use either $V(\lambda)$ or $V_{10}(\lambda)$ without significantly affecting R(L) for these two sources, then :

$$R(L) \approx [\int P_{HPS}(\lambda) * V_{10}(\lambda) * d\lambda] / [\int P_{MH}(\lambda) * V_{10}(\lambda) * d\lambda] \quad (4)$$

where $P_{HPS}(\lambda)$ and $P_{MH}(\lambda)$ is the spectral power distribution of HPS and MH, respectively.

If the mesopic luminous efficiency function is properly determined, then:

$$1 = [\int P_{HPS}(\lambda) * V_m(\lambda) * d\lambda] / [\int P_{MH}(\lambda) * V_m(\lambda) * d\lambda]$$

By combining Eqs (4) and (5) and rearranging terms:

$$[\int P_{HPS}(\lambda) * V_{10}(\lambda) * d\lambda] / [\int P_{HPS}(\lambda) * V_m(\lambda) * d\lambda] = [\int P_{MH}(\lambda) * V_{10}(\lambda) * d\lambda] / [\int P_{MH}(\lambda) * V_m(\lambda) * d\lambda] * R(L)$$

Substituting $V_m(\lambda)$ in Eq. (6) with Eq. (3) and, again, rearranging terms:

$$R(L) * \{ x(L) + [1-x(L)] * (683/1700) * (S/P)_{HPS} \} = x(L) + [1-x(L)] * (683/1700) * (S/P)_{MH} \qquad (7)$$

where $(S/P)s = [1700 * \int Ps(\lambda) * V'(\lambda) * d\lambda] / [683 * \int Ps(\lambda) * V_{10}(\lambda) * d\lambda]$.

The values of (S/P)s are 1.63 and 0.61 for the MH and HPS used in this experiment, respectively (see Table 1). Substituting (S/P)s in Eq. (7) with these values and rearranging terms:

$$x(L) = 1 - [R(L) - 1]/ [0.755 * R(L) - 0.345] \qquad (8)$$

Values of R(L) can be read or interpolated from Table 4 for any given background luminance from 0.01 to 10 cd/m^2. Thus, the value of x(L) can be determined through Eq. (8) and the mesopic luminous efficiency function, $V_m(\lambda)$, can be obtained from Eq. (3). To link a luminous efficiency function to a luminous efficacy function, a given $V_m(\lambda)$ can be scaled to equal 683 lm/W at 555 nm. Figure 10 shows the mesopic spectral luminous efficacy function at 0.1 cd/m^2 under HPS.+

The mesopic luminance, L_m, of HPS can be calculated with the mesopic luminous efficacy function for a given value of x(L). A useful relationship between the value of x and L_m can thus be obtained and described approximately by Eq. (9).

$$\begin{cases} x(L_m) = 6.01 * L_m^3 - 5.20 * L_m^2 + 2.63 * L_m , & \text{for } L_m < 0.6\ cd/m^2 \\ x(L_m) = 1 , & \text{for } L_m \geq 0.6\ cd/m^2 \end{cases} \qquad (9)$$

Calculating the mesopic luminance and mesopic efficacy of an arbitrary light source, one for which R(L) is not experimentally known, requires an iterative procedure. This complication results from the fact that mesopic functions change for different light source spectra as well as different radiances. An iterative procedure was also put forth by Sagawa and Takeichi (1992). The following computational procedure illustrates the approach.

1. Measure the photopic luminance, L, photopic efficacy, E, for the spectral radiance distribution, $L_e(\lambda)$. Use L as an initial value for L_m.

2. Calculate the value of $x(L_m)$ with Eq. (9).

3. Use the value of $x(L_m)$ in Eq. (3) to determine a mesopic efficiency function, $V_m(\lambda)$.

+ It is necessary to specify the (photopic) luminance and the spectral power distribution because the mesopic luminous efficacy function depends on both.

4. Calculate the mesopic luminance using the following equation:

$$L_m = k_2 \int L_e(\lambda) V_m(\lambda) d\lambda \qquad (10)$$

where k_2 is a scaling factor, equal to $683/V_m(\lambda=555\ \text{nm})$.

5. Use the resulted value of L_m in Eq. (9) and repeat step 2 through 5 until changes in L_m are negligible. (For test cases using incandescent and fluorescent light sources L_m changed by less than 1% by the third or fourth iteration.)

6. Calculate the mesopic efficacy (E_m) of the source at the mesopic level of L_m:

$$E_m = E * (L_m / L)$$

Obtaining meaningful values of E_m for sources other than MH and HPS, which were determined experimentally in this paper, relies on the assumption that the simple model used to determine V_m in Eq. (3) is accurate. Further research may offer an improved model which could be substituted into this iterative procedure.

CONCLUSIONS

There is no accepted, practical system for mesopic photometry. Lamp lumen ratings provided by manufacturers for nighttime applications do not accurately describe the ability of those lamps to stimulate the human visual system, and in fact can be misleading. Table 5 shows that a conventional MH source is 60% more efficacious than HPS for mesopic, off-axis visual tasks at a typical roadway lighting level of 0.1 cd/m^2, yet the lumen rating for HPS is nearly 20% higher than that for MH. This discrepancy can obscure opportunities for saving energy, because current lamp specifications for outdoor, nighttime applications are largely dependent upon a lamp's lumen rating.

This study lead to the following conclusions:

1. On-axis, foveal vision measured by reaction times has a spectral sensitivity well described by the $V(\lambda)$ function at any lighting level where electric lighting might be used.
2. Off-axis detection has a very different spectral sensitivity than that described by $V(\lambda)$. Below approximately 1 cd/m^2 rods begin to play a role in off-axis detection and their role increases as luminance is reduced. Thus the spectral sensitivity of the peripheral retina changes with background radiance and hence $V(\lambda)$ is inappropriate for many nighttime applications.
3. The use of reaction times to measure the visual effectiveness of different light sources may lead to a practical system of mesopic photometry because reaction times likely follow Abney's Law of light additivity. Reaction time data are consistent with $V(\lambda)$ in the fovea, but indicate a different spectral sensitivity in the periphery, depending upon target and background radiance.
4. The study showed that MH can be more efficacious than HPS at typical roadway lighting levels. A methodology for deriving a family of mesopic spectral luminous efficacy functions was developed which could be used to evaluate any light source for nighttime applications.

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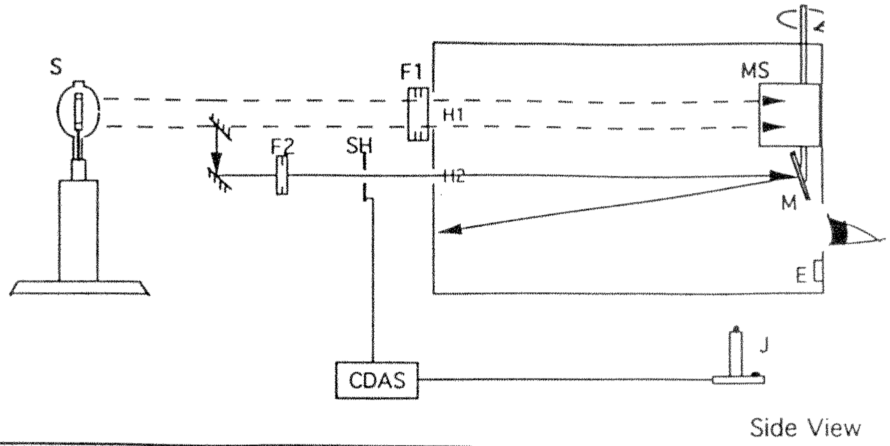
Figure 1. Experimental apparatus.



E = illuminance probe
F1 = neutral density filter for background light
F2 = neutral density filter for target light
H1 = aperture for background light
H2 = aperture for target light
J = joystick
M = mirror
MS = angled mirrors
S = light source
SH = electronic shutter
CDAS = computerized data acquisition system

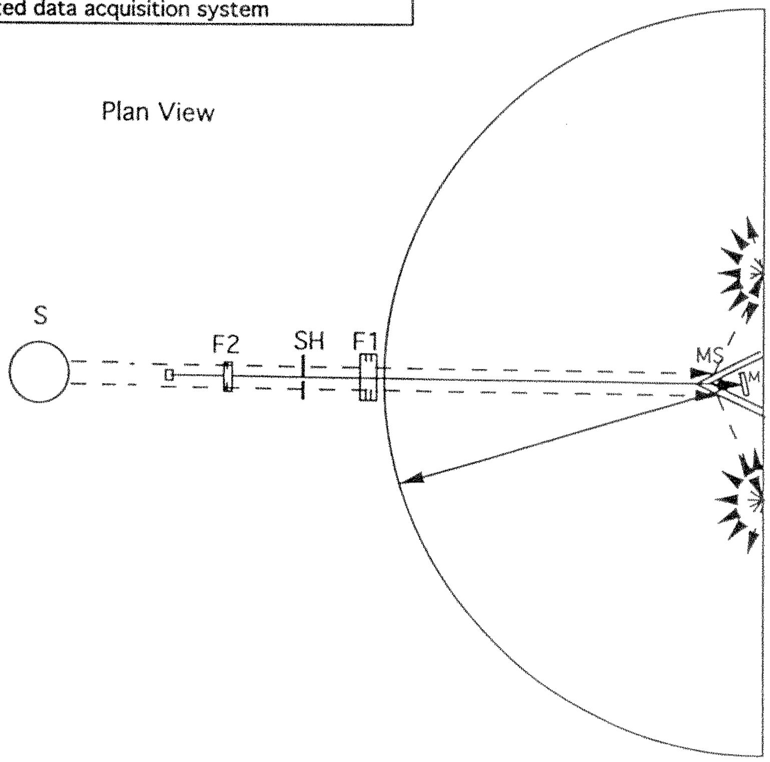


Figure 3. Off-axis detection times plotted against luminance. The error bars show the 25th and 75th percentiles for the data.

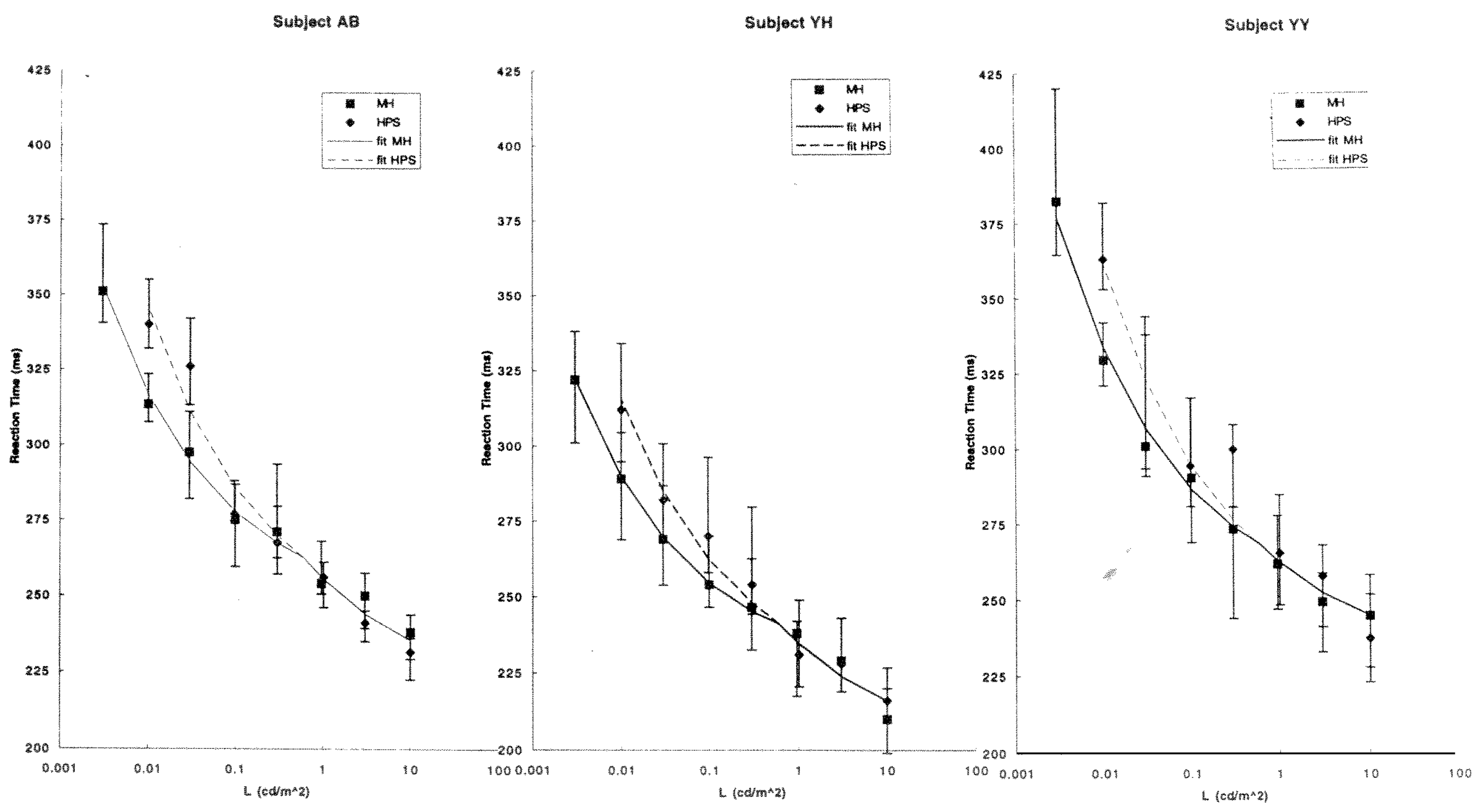


Figure 3. Off-axis detection times plotted against luminance. The error bars show the 25th and 75th percentiles for the data.

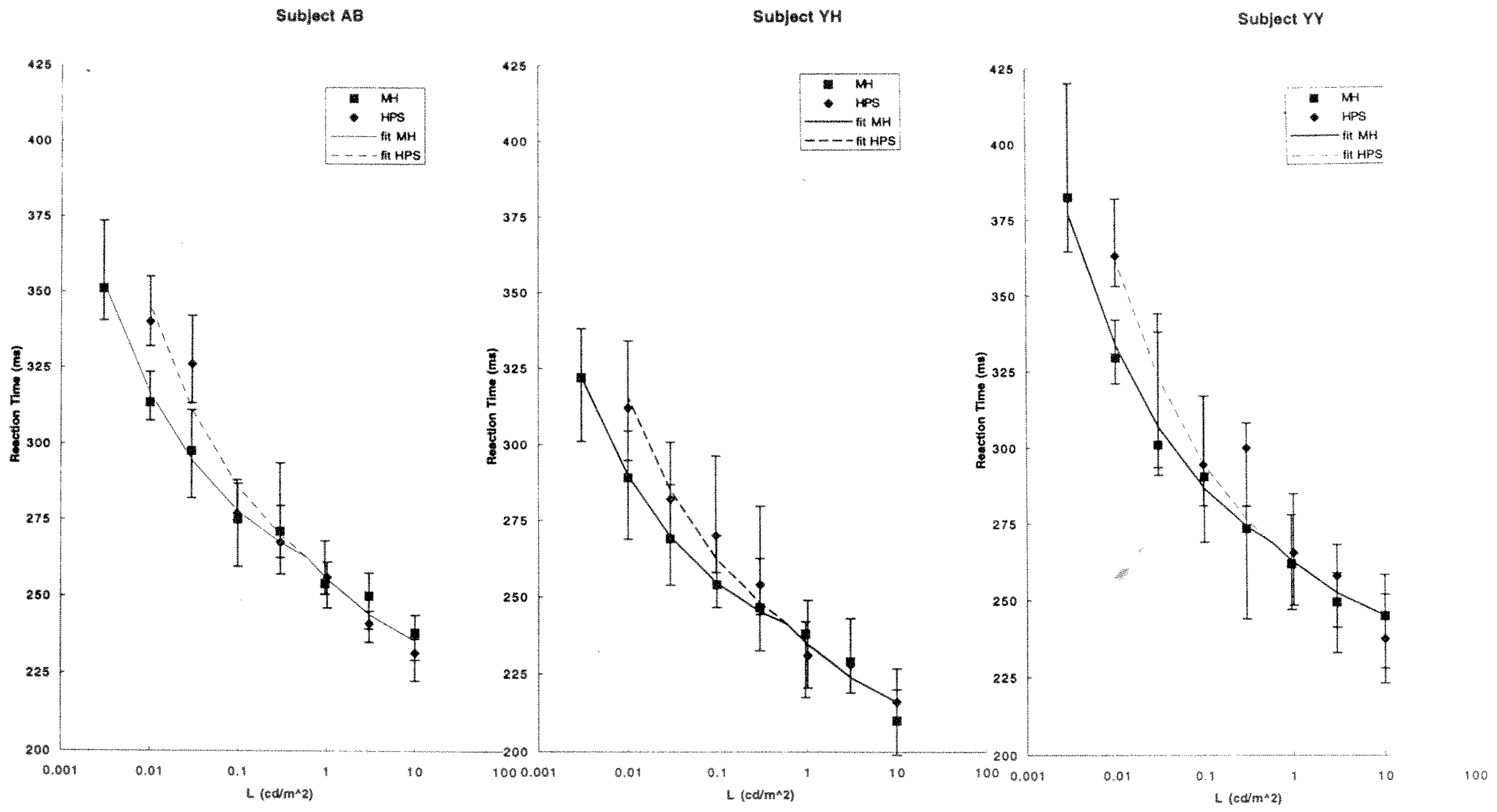


Figure 4. Determination of R(L) at an HPS luminance of 0.1 cd/m^2. At this luminance, R(L)= 0.1/0.052 = 1.93.

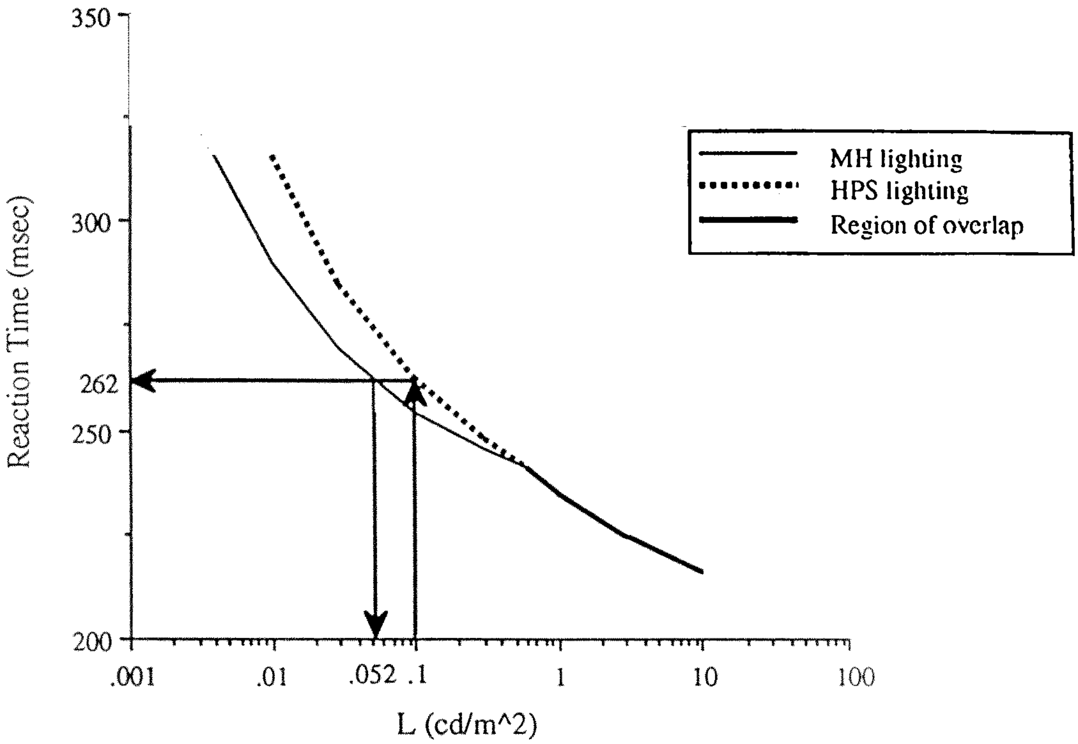


Figure 5. Graph of $ER_{MH/HPS}$ ratios for subjects AB and YH. The line is the average ratio for each luminance.

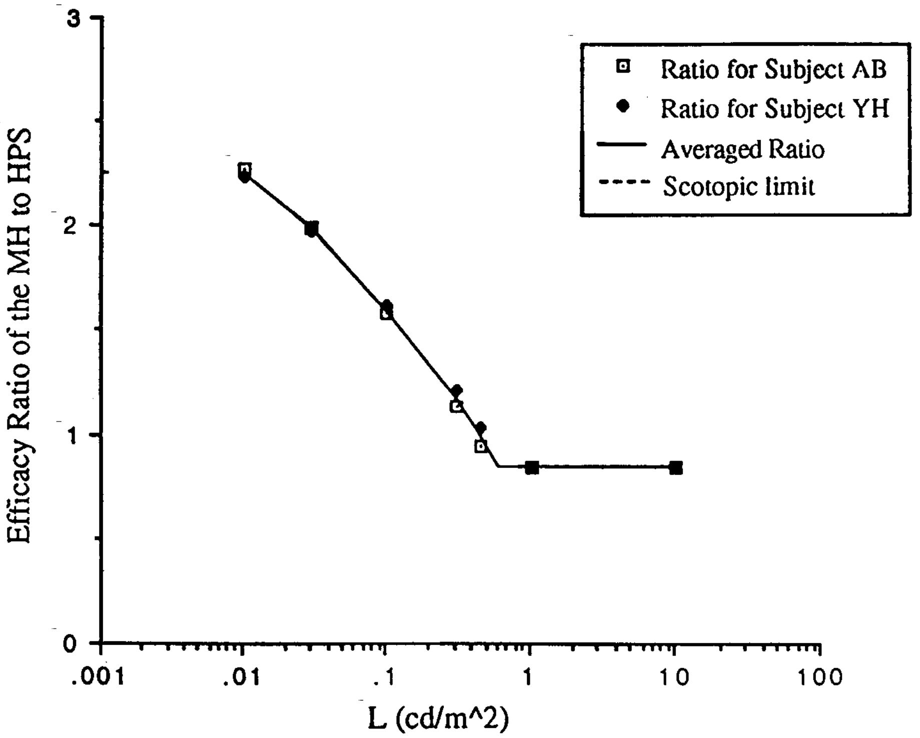


Figure 6. Graph of mesopic luminous efficacy function for a field stimulus equivalent to 0.1 cd/m² of HPS illumination (dashed line). The dotted line is the scotopic luminous efficacy function, and the solid line is the 10° photopic luminous efficacy function.

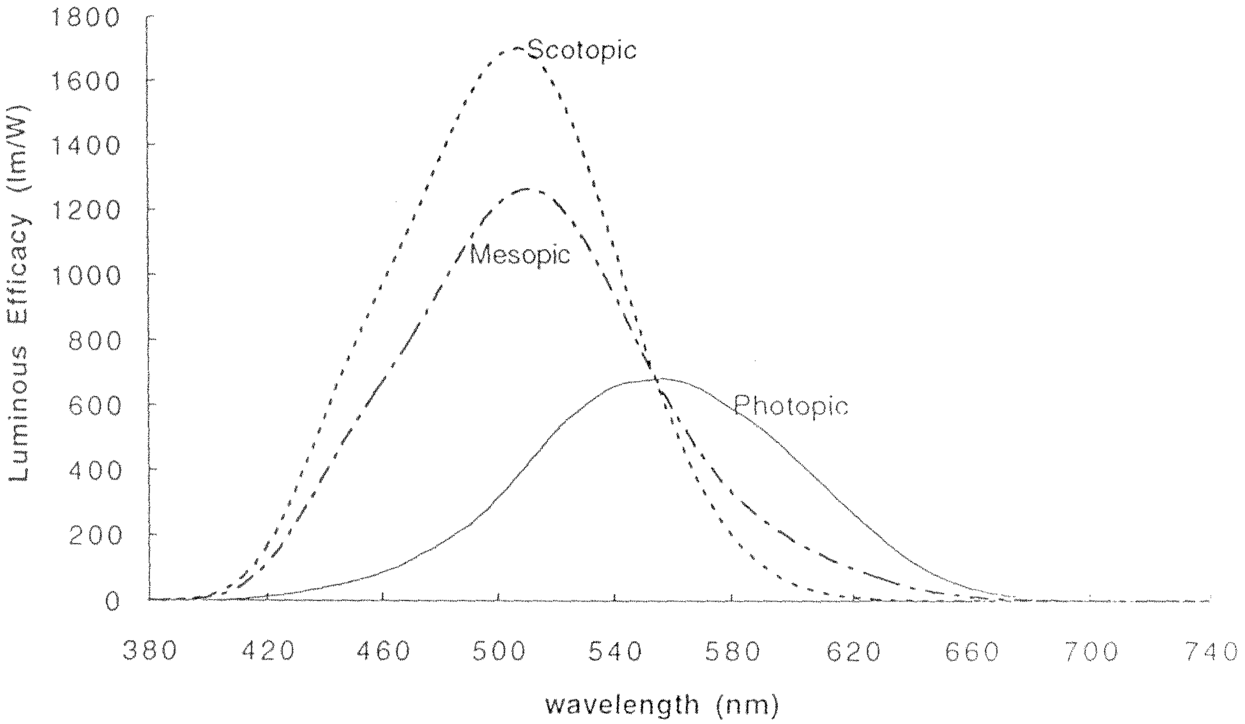


Table 1. Color properties of background and target in experiment using HPS and MH lamps.

Source	Location	Chromaticity, CIE 2°		CCT	Scotopic/ Photopic	CIE 10°/ 2°
		x	y	(K)	(10°) ratio	ratio
HPS 400 Watt	Background	0.5194	0.4197	2102	0.61	1.04
	Target	0.5203	0.4187	2088	0.61	1.04
MH 175 Watt	Background	0.3706	0.4036	4426	1.63	1.07
	Target	0.3636	0.4005	4599	1.67	1.07

Table 2. Coefficients for the **on-axis data.**

	Subject AB	*Subject YH*	*Subject YY*
a $(ms*(cd/m^2)^{1/3})$	30	23	27
b	1/3	1/3	1/3
c (ms)	218	200	230
R^2	0.96	0.98	0.93

Table 3a. Coefficients for the **off-axis data above 0.6 cd/m²**.

	Subject AB	*Subject YH*	*Subject YY*
a (ms*(cd/m²)$^{1/3}$)	37	35	33
b	1/3	1/3	1/3
c (ms)	218	200	230
R^2	0.85	0.83	0.85

Table 3b. Coefficients for the **off-axis data under HPS and below 0.6 cd/m²**.

	Subject AB	*Subject YH*	*Subject YY*
a (ms*(cd/m²)$^{1/3}$)	24	21	27
b	1/3	1/3	1/3
c (ms)	234	216	236
R^2	0.91	0.99	0.75

Table 3c. Coefficients for the **off-axis data under MH and below 0.6 cd/m²**.

	Subject AB	*Subject YH*	*Subject YY*
a (ms*(cd/m²)$^{1/3}$)	16	14	19
b	1/3	1/3	1/3
c (ms)	244	224	246
R^2	0.92	0.99	0.98

Table 4. Values of R(L) for subjects AB and YH at each luminance

Luminance level of HPS (cd/m^2)	Ratio of the MH to HPS luminance (R(L))		
	Subject AB	Subject YH	R(L) (average)
10.0	1	1	1
3.0	1	1	1
1.0	1	1	1
0.3	1.35	1.44	1.395
0.1	1.89	1.93	1.910
0.03	2.37	2.36	2.365
0.01	2.71	2.66	2.685

Table 5. Values of $ER_{MH/HPS}$ for 250-W MH and 250-W HPS for several luminances.

Luminance Level (HPS) (cd/m^2)	Efficacy Ratio of the MH to HPS
10.0	0.84
3.0	0.84
1.0	0.84
0.45	1.00
0.3	1.17
0.1	1.60
0.03	1.99
0.01	2.25