LBNL-42327
L-213

The Reengineering of Lighting Photometry

S. M. Berman

Energy and Environment Division

Lawrence Berkeley National Laboratory

Berkeley, CA 94720

July 1995

For several generations lighting practitioners have had suspicions that calibrated light meters and photometers do not accurately reflect their perceptions of lit environments even for light which is whiteish in color. The troublesome perceptions arise when comparing lightings of different spectral quality and where the metered photometrics are equal but contrarily where brightness sensation and visual sensitivity are perceived to be different. An observer can readily experience these perceptions of different lightings by comparing the same environment under equally lit photopic conditions by low color temperature lamps (3000°K) versus high color temperature lamps (6000°K) or incandescent lighting versus natural lighting or compare high pressure sodium lighting with metal halide lighting. Vision scientists have tried to resolve this problem by introducing small corrections into the calibration function which are not included in its classic determination based on flicker photometry. These refinements have not resolved the differences and the problem continues to plague lighting practice.

Recently new research carried out at the Lawrence Berkeley National Laboratory (LBNL) and the Abratech Corp. of Sausalito, CA under the auspices of the Department of Energy has identified the likely cause of the discrepancies as well as the underlying visual mechanism. Since these new findings are highly plausible and readily understood, lighting practice can immediately benefit from their incorporation to make lighting more visually effective and energy efficient.

The principal reason for the discrepancy occurs because the standard calibration of photometers is based on measurements of visual efficiency of the human eye, with the field of view undergoing evaluation confined to a mere 2 degrees (some special applications to 10 degrees) of the total visual field. A visual field of 2 degrees covers only two hundredths of one percent of the total visual field that is observable while a 10 degree field covers four tenths of one percent of the total observable visual field. The portion of the retina of the eye which is sensitized by these small fields is densely populated primarily with cone photoreceptors. Outside this portion of the retina the principal photoreceptors are not the cones but instead the rod receptors which in the total retina are of much greater population than the cone receptors. Because the measurement of the rod spectral sensitivity requires conditions of very low light levels it has perhaps been erroneously assumed that rod receptors are not active at normal interior light levels. However, the new findings demonstrate that rod receptors are indeed active at normal interior levels and that they are contributing to brightness perception while providing the dominant control

of pupil size. The new research also shows that at normal interior light levels pupil size determines the ultimate ability to achieve visual performance (acuity, contrast sensitivity and depth of field). Thus the discrepancy between the photometer and experience is simply that the meter is based on the eyes response to the small visual field of 2 degrees while lighting practice is concerned with the full field of view which displays a somewhat different spectral sensitivity. and which could also depend on the specific nature of the visual phenomena.

The new findings mean that both the overall cone spectral sensitivity function, the canonical "photopic" response which provides the photometer calibration and the rod spectral response, the scotopic response must both be included to properly quantify the lit environment. Figure 1 shows both the photopic and scotopic spectral sensitivity functions as they depend on wave length. Whereas the photopic response peaks at 555 nm, the scotopic response peaks at 508 nm and is therefore more sensitive to shorter wave lengths, i.e., more sensitivity to greenish—blue colors. The ratio of scotopic to photopic response at each value of wave length, which varies dramatically over the range of visible spectrum, is also shown in Figure 1.

Because the two different features of human scotopic sensitivity, i.e., the control of pupil size and the contribution to brightness perception are quantitatively different, two modifications of the present calibration function are necessary. These are discussed separately in what follows.

Surprisingly the relevance of pupil size to visual performance at normal interior light levels has not been a part of lighting engineering and the ergonomic consequences have been overlooked. In the eye visual discrimination is affected by two principal components, the first is the refracting media composed of the cornea and lens and the second is the matrix of photoreceptors that populate the retina. Vision scientists have demonstrated the retinal resolution component appears to saturate at the low end of photopic light levels, i.e., at task luminances of order a few candelas per sq. meter. Nevertheless engineering studies have shown a slowly rising but not totally saturating behavior of visual performance as luminances move through the range typical of work environments, 30 to 300 cd/m2. On the basis of the new studies on pupil size and vision we believe that this slow rise in visual performance is primarily due to the decrease in pupil size brought about by simply increasing light level.

Nearly all people, including those with 20/20 vision, have some optical imperfections in their eyes. These imperfections which could be lens or

cornea related cause aberrant light rays to reach the retina i.e., light rays which are not in perfect focus. These aberrant rays function to cause blurring which is not due to lack of retinal resolution but due to the aberrant rays failing to focus at the right place on the retina. As the pupil becomes smaller these aberrant rays are decreased. (See Fig. 2). As long as there is enough light to achieve high retinal resolution then the loss of light from the reduction of aberrant rays will improve vision. This means that when optical quality of the eye is the limiting factor in visual resolution, we have the surprising result that less task light can produce better sight.

To support this conclusion the LBNL/Abractech team has undertaken 9 separate studies of visual performance at normal interior light levels where pupil size is controlled either by spectrum or light level. These studies all take place in a normal sized room lit indirectly by fluorescent lighting with the subjects seated in a comfortable chair viewing the test visual tasks with normal vision. Seven of these studies involved adults between the ages of 20 and 45 years and used variable contrast circular rings with a small fixed size gap whose orientation direction was the visual task. Each of these studies used 12 separate and different subjects with at least 20/30 vision. Another study involved 7 elderly adults in their sixties again with at least 20/30 vision. A somewhat different study tested 12 young adults correctly refracted by an optometrist with common words presented at 100% contrast. Letter size was variable and the accuracy of word reading was evaluated. Pupil sizes of the subjects in all studies were extensively measured during task performance using the techniques of infrared pupilometry. All of these studies demonstrated significant improvement in visual performance for smaller pupils even though task retinal illuminance was considerably less than it was for the larger pupils. Typically a 50% reduction in task retinal illuminance associated with a smaller pupil allowed 30 to 40% improvements in visual performance (contrast sensitivity or acuity). Tasks luminances in these studies ranged from 15 to 80 cd/m^2 so that task retinal illuminance was well in the range of its optimum. These studies clearly demonstrate that the improvement in optical quality of the eye caused by removing the aberrant rays with smaller pupils is the controlling factor in achieving maximum visual performance.

Although smaller pupils can be achieved by simply raising light levels, this brute force method is not the efficient procedure. This is because the pupillary spectral response function is not the same as the function used to calibrate photometers and lightmeters, i.e., the photopic $V(\lambda)$ function. The LBNL/Abratech team has conducted several studies to determine the

pupillary spectral response function which turns out to be slightly dependent on the visual task conditions. Two conditions were studied, the first where subjects fixated on a spot on the room wall located directly in their line of sight and second where subjects watched a pleasant nondescript movie on a very small self-illuminated TV located about 5 feet in front of them. This second condition mimics a CRT or VDT workplace environment.

Illuminance and luminances were varied but confined to the levels typical of building interiors. The results showed that for the first case where subjects simply viewed a fixation point, pupil size was determined by a combination of photopic (P) and scotopic (S) values empirically determined as the quantity $P(S/P)^{0.78\pm0.03}$ The exponent having the value 0.78 means that pupil size is mostly determined by the scotopic spectrum but with a small photopic component. For the second case where the subjects viewed the small TV, pupil size was entirely determined by the scotopic spectrum alone, i.e., the analogous exponent has the value of one instead of 0.78.

Since the scotopic response function peaks at the wave length of 508 nm compared to 555 nm for the photopic response function, lighting deficient in the shorter wave lengths (more redish in color) will be less efficient in producing smaller pupils than lighting with enhanced short-wave length spectral content (blue-green in color). Thus the efficient way to produce smaller pupils is to use lighting with large ratios of scotopic to photopic output (S/P ratio). The S/P ratio varies by a factor 10 for lamps used in general lighting with natural daylight or high CCT daylight fluorescents achieving S/P ratios of about 2.5 compared to the value of 0.23 for the low pressure sodium lamp. Figure (3) shows the S/P value for a number of common lamps.

When the choices of light levels for interior environments are based on visual performance considerations, the economic consequences of recognizing the role of pupil size and its associated spectral response are substantial. Among fluorescent lamps, a narrow band phosphor lamp with a correlated color temperature (CCT) of 5000°K is 25% more pupillary efficient and hence visually efficient than the ubiquitous cool white lamp based on the exponent of 0.78 and is 33% more visually efficient when based on the condition of a self-illuminated task, i.e., exponent of unity. A fluorescent lamp achieving an S/P ratio 2.5 and with high color rendering index appears as readily possible. Such a lamp would be 50% or 70% more visually efficient than the CW lamp. This enhanced efficacy would allow the substitution of a lamp fixture housing four 32 W lamps by a fixture containing only two 40W lamps but yielding the same visual performance.

Clearly there is the possibility of accruing large energy and cost savings by judicious choice of illuminant.

On the other hand, because the HPS lamp is so scotopically deficient its visual efficiacy is the same as an incandescant lamp. Thus any apparent energy savings would be lost in replacing incandescent lamps with HPS lamps if visual performance were to be maintained.

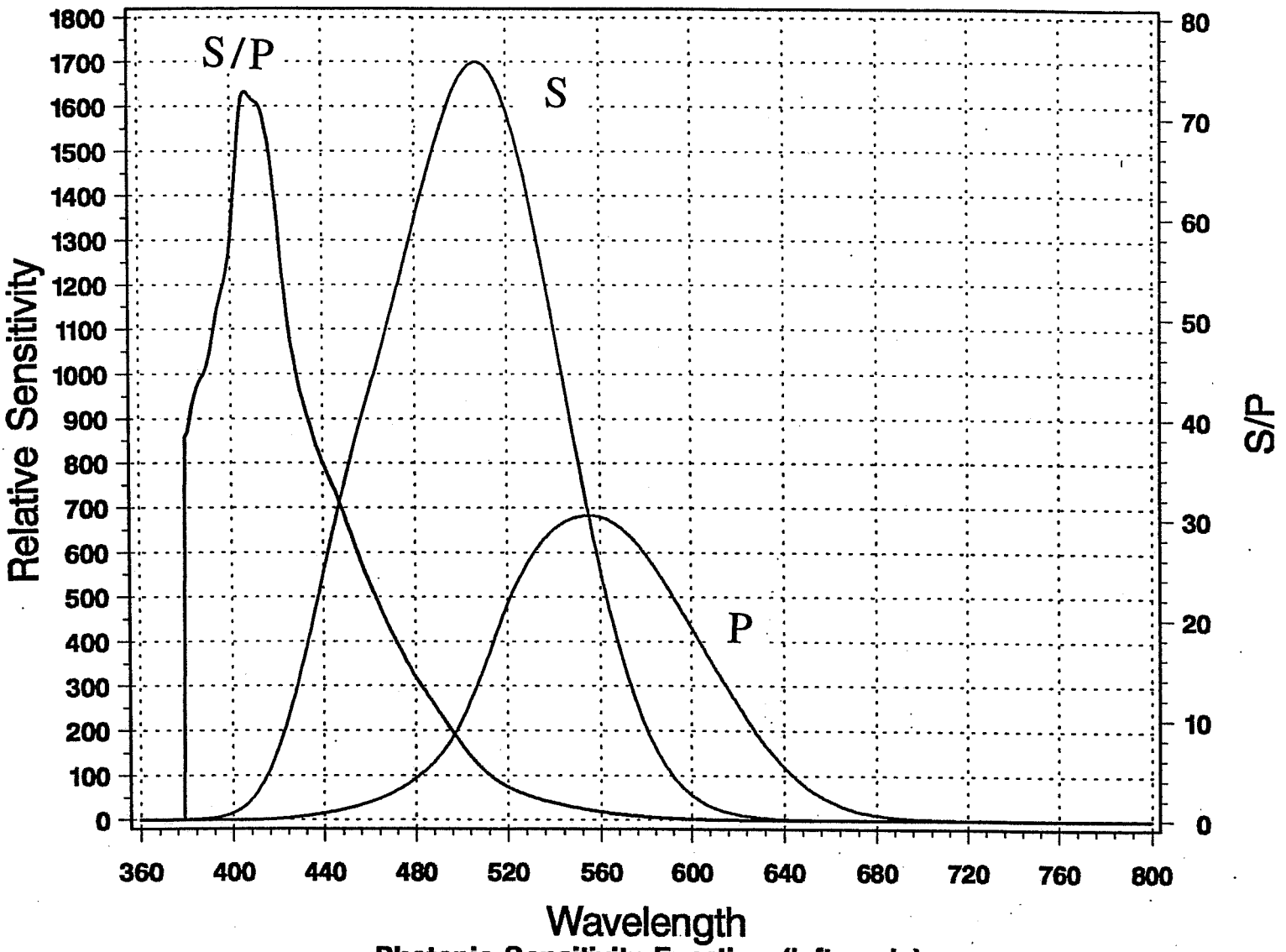
The second aspect of scotopic sensitivity that was mentioned above concerns brightness perception. The LBNL/Abratech team demonstrated that brightness perception in full field of view depends on both the photopic and scotopic components of the lighting. Perceived brightness of a room indirectly lit by two different illuminants was compared, one scotopically enhanced and the other scotopically deficient but both producing about the same whiteish color. The scotopically enhanced luminance was set to be 25% less on the viewed wall than the scotopically deficient lighting as measured by a conventional luminance meter. Nevertheless näive subjects reported that the scotopically enhanced lighting appeared brighter. The same impressions were obtained by an audience of lighting professionals who participated in a similar demonstration at the 1992 National IESNA conference in San Diego, CA.

Because deciding which illumination is brighter is a much simpler task than determining the brightness equality between two different illuminations and because of various other experimental requirements, the evaluation of the precise combination of photopic and scotopic that determine the "brightness lumen" in full field of view remains ongoing. However from the studies mentioned above a rough estimate can be made of where brightness equality would occur. This yields an expression on how brightness depends on the combination of photopic and scotopic luminance namely $P(S/P)^{0.5}$. In terms of brightness perception this result suggests that 5000° CCT fluorescent lamps could operate with 14% less energy and achieve the same brightness perception as produced by CW lamps while the proposed lamp with the ratio S/P = 2.5 could operate at 30% lower energy while achieveing the same brightness perception as CW illumination.

These findings of scotopic sensitivity at normal interior light levels suggest the need for a reeingineering of lighting photometery that incorporates realistic viewing conditions. The highly cost effective energy and vision benefits that could accrue from this incorporation will advance the ability of lighting practice to achieve a higher level of user satisfaction and confidence.

Figure 1.

Scotopic and Photopic Sensitivity Functions

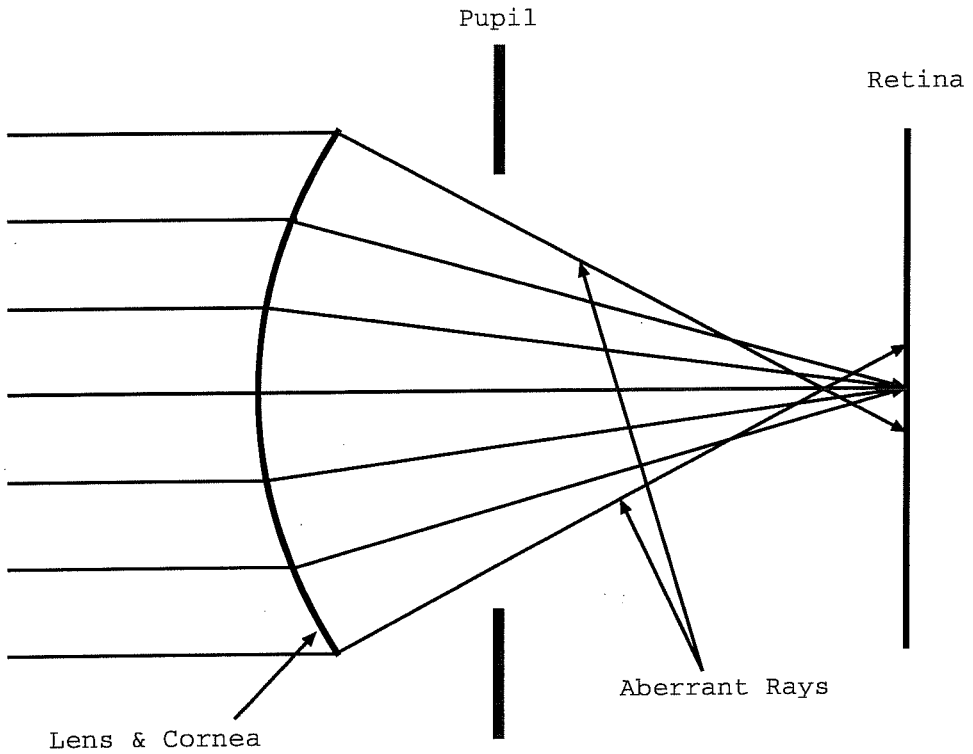


Photopic Sensitivity Function (left scale)

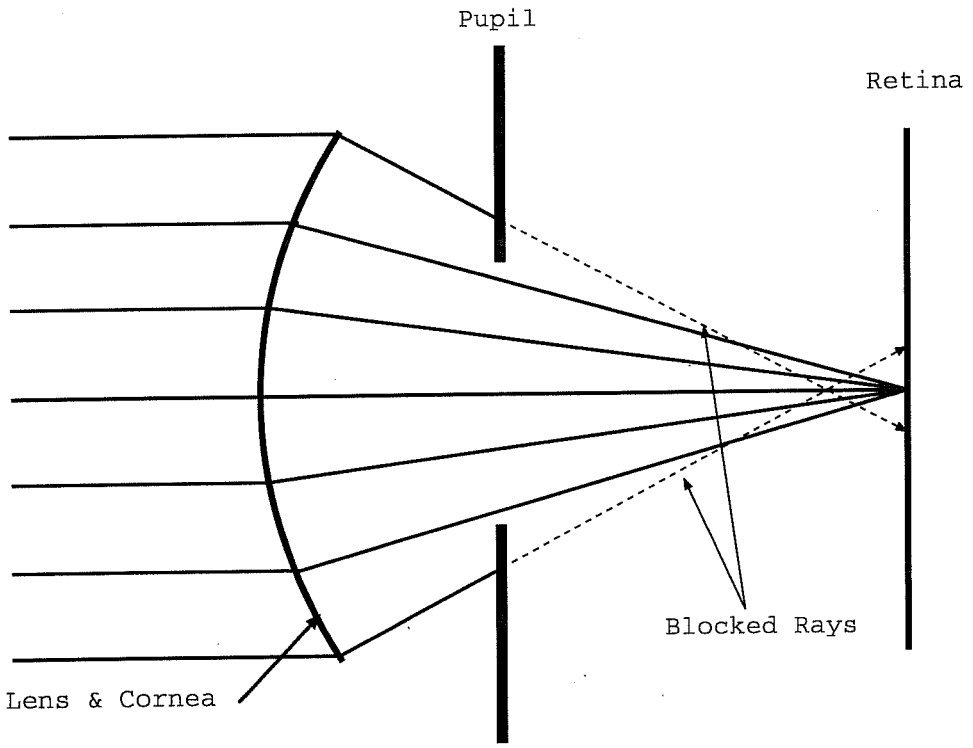
Scotopic Sensitivity Function (left scale)

Scotopic Sensitivity/Photopic Sensitivity (right scale)

Figure 2



A: Light rays from the off-axis portion of the lens system are out of focus, and thereby decrease the retinal image quality.



B: Abberant light rays from the off-axis portion of the lens system are blocked by the pupil, increasing retinal image quality.

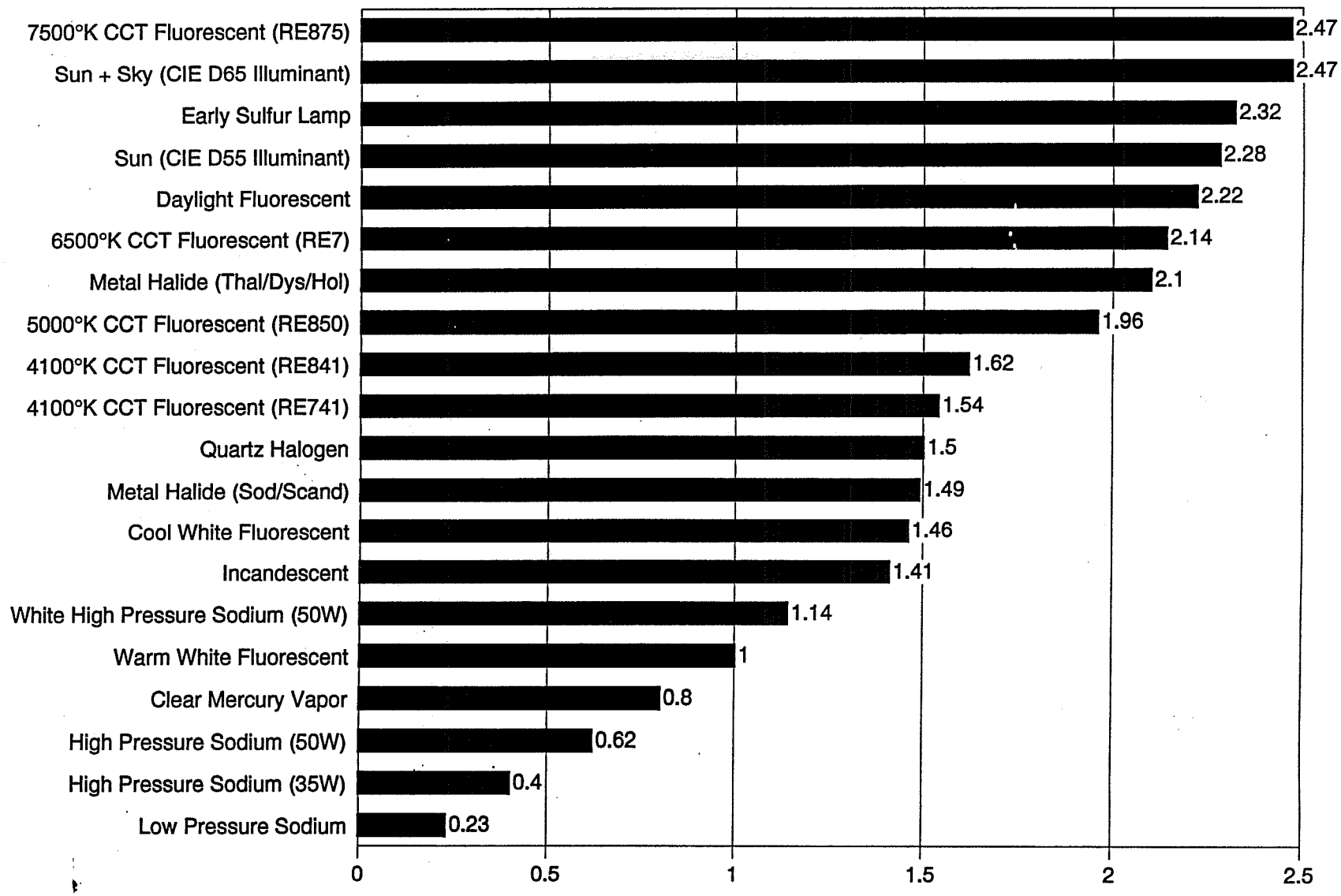


Figure 3: Scotopic/Photopic Ratios for Various Light Sources

Dr. Sam Berman is a Senior Scientist and the originator of the Lighting Systems Research Group, Lawrence Berkeley National Laboratory, Energy and Environment Division, Berkeley, CA 94720 USA.

Acknowledgements

We thank Francis Rubinstein for Figure 3. This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technologies, Building Equipment Division of the U.S. Department of Energy under Contract No. DE-ACO3-76SFOOO98.

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