

The Re-engineering of Lighting Photometry

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For several generations lighting practitioners have had suspicions that calibrated light meters and photometers do not accurately reflect their perceptions of lit environments. As an example, clarity of vision and the sensation of brightness can be very different under light sources with differing color characteristics, even though the measured footcandle levels are equal. In order to explain these disparities and provide better information to lighting practitioners, it is necessary to re-examine the visual response to light, thereby better quantifying the effectiveness of light sources.

Our research 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.

This research concludes that the two primary reasons for the discrepancy between measured lighting levels and visual perceptions can be traced to 1) the difference between the very small field of view on which the present photometric units are based and the eye's response to the total visual field as seen in normal conditions and 2) that the testing procedures used to determine these photometric units involves brightness matching only, which does not necessarily result in visual acuity as assumed in general lighting practice. For simplification, this discussion uses the lumen to describe photometric units, although all lighting quantities, i.e. candelas, footcandles, etc., are affected.

The determination of the lumen is based on responses of the eye to brightness comparisons along the visible spectrum in a restricted 2 degrees central field of vision. This very small field of view covers only two hundredths of one percent (.02%) of the total visual field that is observable by the human visual system. The portion of the retina of the eye affected by this small field is densely populated primarily with cone photoreceptors. The brightness sensitivity of the cones is referred to as the *photopic sensitivity function*. The lumen is therefore determined by the photopic sensitivity function only. The rest of the retina is primarily populated with rod photoreceptors, which comprise a much greater population in the overall retina than the cones. For rods, the brightness sensitivity is more pronounced at the blue-green portion of the spectrum, and is referred to as the *scotopic sensitivity function*. Therefore, the lumen includes no rod spectral sensitivity due to the restricted field of vision used in its determination.

Perhaps because the measurement of rod spectral sensitivity requires conditions of very low light levels, it has been erroneously assumed that rod receptors are not active at normal interior light levels. When looking at the total visual field, however, the contribution of the rods have a significant effect on the visual system, even at typical interior light levels, which current lighting practice does not take into account.

The new research demonstrates that rod responses at normal interior lighting levels provide the dominant control of pupil size and contribute to brightness perception. The research concludes that pupil size determines the ultimate ability to achieve visual performance (acuity, contrast sensitivity, and depth of field) at normal interior lighting levels. The research also indicates that visual acuity and brightness perception are distinct responses, contrary to the assumption used in general practice that visual acuity tracks brightness perception.

The results mean that both the photopic and scotopic sensitivity functions should be considered in order to provide a meaningful definition of visually effective light for lighting practice.

A simple approach to include the scotopic sensitivity function is to develop a modifying factor which can be applied to the traditional lumen. The light output of sources is currently expressed solely by using the photopic function as a calibration factor. This gives us photopic lumens, which are published in lamp manufacturers catalogs. Alternatively, by applying the scotopic function as the calibration, we can also determine scotopic lumens. A ratio of scotopic to photopic lumens (S/P) for a given spectral power distribution provides a simple mathematical means to incorporate the sensitivities of both the rods and cones. The S/P ratio for many fluorescent lamps are currently published in the Philips Lamp Specification and Application Guide, and Figure 3 provides the S/P ratio for a number of common lamps.

As previously mentioned, pupil size determines the ultimate ability to achieve visual performance. This conclusion has been reached after undertaking 9 separate studies between 1990 and 1993 of visual performance at normal interior lighting levels, where pupil size is controlled either by color spectrum or light level. The cumulative test sampling includes over 100 adults using precision technologies such as automated infrared pupilometry. All of these studies demonstrated significant improvement in visual performance for smaller pupils.

The reason smaller pupils improve visual performance is that nearly all people, including those with 20/20 vision, have some optical imperfections in their eyes which allow aberrant rays to reach the retina. Aberrant rays of light miss the fovea, causing blurred vision, and the reduction of these aberrant rays by decreasing the pupil size results in improved vision in spite of the fact that the reduced pupil size results in less illumination on the retina (see Figure 4).

The relevance of pupil size to visual performance at normal interior lighting levels has not been fully understood in lighting engineering and design. While lighting practice has traditionally recommended higher lighting levels for the performance of finely detailed tasks, the new findings indicate that the underlying reasons for the associated increase in visual performance are primarily a consequence of achieving smaller pupil size. Although smaller pupils can be achieved by simply raising light levels, the more efficient way of reducing pupil size is to provide lighting that has a color spectrum which is more tuned to the pupil's response.

Further research has resulted in a pupillary spectral response function which can be quantified by using the S/P ratio. Two separate conditions were studied to simulate work environments, one with a paper task and the other with a CRT task. For the paper task, the pupil size was governed by a combination of photopic (P) and scotopic (S) values which was determined empirically through experimentation as the quantity $P(S/P)^{0.78}$. The exponent having a value 0.78 means that pupil size is mostly determined by the scotopic spectrum but with a small photopic component. For the CRT task, pupil size was governed entirely by the scotopic spectrum alone, i.e. the analogous equation is $P(S/P)$.

These results suggest that light with more energy in the region of highest scotopic sensitivity, i.e. enhanced short wavelength (blue-green) spectral content, will be more effective in producing smaller pupils which in turn means better vision. For tasks which require higher visual acuity, it therefore follows that light sources with this type of spectral distribution are more efficient at producing visually effective light.

The second aspect of scotopic sensitivity that was mentioned above concerns brightness perception. We have demonstrated that brightness perception in full field of view depends on both the photopic and scotopic components of lighting. Perceived brightness of a room indirectly lit by two different light sources was compared, one scotopically enhanced and the other scotopically deficient but both producing the same whitish color. The luminance of the scotopically enhanced lighting on the viewed wall, as measured by a conventional photometer, was set to be 25% less than the scotopically deficient lighting. Nevertheless, naive 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 IESNA conference in San Diego, CA.

The full evaluation of the photopic and scotopic contributions to brightness perception in full field of view is presently ongoing. However, from the studies completed thus far, a rough estimate can be made for how brightness depends on the S/P ratio, namely by the quantity $P(S/P)^{0.5}$.

These findings of scotopic sensitivity at normal interior light levels suggest the need for a re-engineering of lighting photometry that incorporates realistic viewing conditions. The resulting unit of measure may, in fact, be dependent on tasks, as suggested by the research. 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, visual performance, and energy savings.

Examples of Energy and Economic Benefits of the (S/P) Ratio

Applying the S/P ratio can lead to significant energy savings and other economic benefits while maintaining visual effectiveness. The examples below show how easily the S/P ratio can be incorporated into design practice. To evaluate the visual effectiveness of sources, lamp lumens should be modified by applying the task application factor which includes the scotopic sensitivity. The current research has provided factors for modifying lumen ratings for tasks as shown below:

Task	Task Application Factor
Self Illuminated (VDT)	(S/P)
Paper Based	(S/P) 0.78
Brightness Perception	(S/P) 0.5 (approximation)

VDT Office

This example assumes CRT tasks, and the resulting Task Application Factor is S/P. The comparison is between the 3000°K, 75 CRI T8 lamp and the 4100°K, 85 CRI T8 lamp, both of which are typically considered for office lighting applications.

Traditional Calculations		Visual Effectiveness Calculations			
System Lamp	System	S/P	Task	Task	Task

Modified	Watts	Lumens	Efficacy	Ratio*	Application	Modified	
Efficacy		(Photopic)	(Photopic)		Factor	Lumens	
Symbol/Calculation (P(S/P)/W)	(W)	(P)	P/W	(S/P)	(S/P)	P(S/P)	
Lamp							
3000°K, 75 CRI T8	32	2800	88	1.13	1.13	3164	99
4100°K, 85 CRI T8	32	3000	94	1.62	1.62	4860	152

* Values taken from Philips Lamp Specification and Application Guide, 2/96, page 79

Results:

The visual efficacy of the 4100K, 85 CRI lamp is 1.54 times that of the 3000K, 75 CRI lamp.

Designer Discussion:

Ordinarily, the 3000K, 75 CRI lamp would be chosen on the basis of warmer color and lower initial cost. However, the results of the comparison show that the quantity of lamps can be reduced by one-third when using the 4100 K, 85 CRI lamp to obtain the same visual effectiveness for VDT tasks. If the office has mixed tasks, i.e. VDT and paper tasks, the enhanced visual effectiveness would not be this pronounced.

If a design were based on the horizontal illuminance level of 30 footcandles using 3000K, 75 CRI lamps, a one-third fewer 4100K, 85 CRI lamps results in 20 footcandles (as measured with a traditional light meter) and a 33% savings in energy costs. A space illuminated with 4100K at 20 footcandles might be considered contrary to typical design expectations, as we normally associate lower lighting levels with warmer color temperatures. The question of whether this color temperature/illuminance combination is acceptable should be addressed by lighting designers with their clients.

Industrial Facility

This example assumes paper tasks, and the resulting Task Application Factor is (S/P) 0.78. The comparison is between a 310 watt high pressure sodium lamp, a 400 watt metal halide lamp, and (10)-5000K, 82 CRI T10 fluorescent lamps. The specific fluorescent lamp chosen for this example has a very high S/P ratio to underscore the potential visual benefit there may be when using this design approach.

Traditional Calculations			Visual Effectiveness Calculations			
System	Lamp	System	S/P	Task	Task	Task

Modified	Watts	Lumens	Efficacy	Ratio*	Application	Modified	
Efficacy		(Photopic)	(Photopic)		Factor	Lumens	
Symbol/Calculation (P(S/P)/W)	(W)	(P)	P/W	(S/P)	(S/P)	P(S/P)	
Lamp							
310 Watt HPS	365	37,000	101	0.62	0.69	25,530	70
400 Watt MH	455	36,000	79	1.49	1.36	48,960	108
(10) F40T10 FLR, 5000K, 82 CRI.	400	37,000	93	1.85	1.62	59,940	150

* Values taken from Philips Lamp Specification and Application Guide, 2/96, page 79

Results:

The efficacy of metal halide is 1.54 times that of high pressure sodium.

The efficacy of the 5000K, 85 CRI T10 lamp is 2.14 times that of high pressure sodium.

Designer Discussion:

High pressure sodium is used in many industrial applications due to its presumed efficiency. However, there are many visual concerns about using this source in indoor applications, particularly with regard to the poor color quality. The results of this calculation quantify the perceptions of many lighting designers, in that HPS results in a lower perceived lighting level than the illuminance meter would indicate. Both metal halide and fluorescent sources appear to be much more efficient than high pressure sodium when considering the paper tasks. This could lead to significant energy savings and increased visual effectiveness.

Summary

The examples above demonstrate how the S/P ratio can be used in lighting design practice to determine a new lighting quantity which, although is task variable, is easily calculated. The research conducted thus far demonstrates that controlling pupil size through spectral power distribution provides a method for calculation resulting in dramatic changes in the visual efficacies of sources. While the benefits to energy efficiency based on visual effectiveness are clearly shown, further research is needed to evaluate psychological concerns surrounding scotopically enhanced lighting. Such things as color acceptance and preference, as well as visual comfort, should be considered along with the energy aspects in any design to achieve a comprehensive IES recommended standard practice.

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Scotopic/Photopic Ratios for Various Light Sources

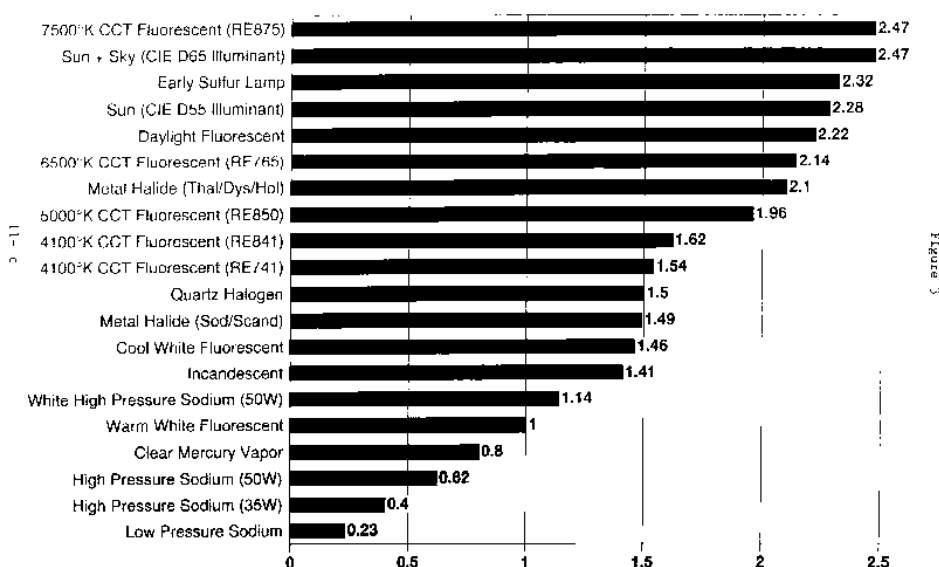


FIGURE 2
Scotopic & Photopic Sensitivity Functions

