Energy Efficiency Consequences of Scotopic Sensitivity

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Introduction

Recent experiments at Lawrence Berkeley Laboratory (LBL) have demonstrated that rod receptors, which are widely thought to be important only for night vision, also contribute actively to vision processes at typical office light levels. At these light levels the studies found that pupil size and brightness perception are strongly affected by rod activity. These results suggest that light sources with scotopically richer spectral content need less photopic luminance to enable a given level of visual performance, visual clarity, and brightness perception. Such phenomena can explain the confusing results of many earlier visual performance studies where performance and visual clarity differences obtained under different lamps could not be explained on the basis of photopic luminance. A re-analysis of these past studies, together with an examination of currently available lamps and phosphors, suggests that there is a substantial opportunity to increase lighting energy efficiency in a highly cost-effective manner solely by considering lamp spectrum.

Background

There is a large variety of lamps available for lighting building interiors. The most common sources, incandescent, fluorescent, and high intensity discharge lamps, produce distinctly different amounts of energy per unit wavelength over the range of the visible spectrum. When environmental needs are essentially achromatic, lamps are primarily judged on their photopic lumen output. The large differences in their various spectral distributions is not generally considered to be important, because photopic luminance (illuminance) is thought to be the primary attribute of the spectral distribution of the source with regards to visual performance. The lumen output is obtained by averaging the wavelength dependent spectral power distribution (SPD) of a lamp over the photopic visual efficiency of the eye [the V(λ) function]. Thus, two lamps, such as an incandescent and a daylight fluorescent, with markedly different spectral distributions, can be considered as equal illuminants if they provide equal photopic light levels as measured by the common light meter.

The human eye is a light sensing system with an aperture (pupil) and a photoreceptive medium (retina). The retina contains two basic types of photoreceptors, cones and rods. The rod photoreceptors are generally associated with night vision and it has been assumed that rods do not participate in the visual process at the light levels typical of building interiors. The cone photoreceptors, which are responsible for seeing fine detail and for color vision, provide the photopic visual spectral efficiency of the eye which is captured by the V(λ) function. Under conditions of very dim light, such as starlight, there is not enough light energy to stimulate cone photoreceptors and there is an absence of color vision, but there is enough to stimulate the rod system as stars can be readily observed. The rod system is known to contain a different photopigment than the cone system and as a result has a different spectral response referred to as the scotopic response.

The scotopic response function V′(λ), differs from the cone spectral response mainly in that its peak wavelength response is at about 508 nm rather than the 555 nm of the V(λ) function. Our new evidence has demonstrated that the rod photoreceptors are not merely involved in night vision, but also participate in important visual functions at light levels typical of interior office environments. Thus photopic illuminance alone does not adequately characterize the visual system spectral response, implying that lighting design for buildings based only on photopic spectral conditions does not capture an important and potentially valuable lighting attribute.

The new evidence

In a series of laboratory lighting studies,[1] we have demonstrated that with almost a full field of view and light levels typical of the interior environment luminances (up to 500 cd/m^2), the mean steady state size of the pupil is predominantly controlled by the scotopic energy content of the ambient lighting. These experiments were based on the responses of approximately 50 adults ranging from 20–40 yrs of age and concluded that the eye functions at these light levels with two spectral responses, the photopic spectrum for the foveal sensitivity and primarily the scotopic spectrum for the light aperture or pupil. Similar results are expected for children and adults older than 40 years and we are planning to explicitly study these populations in the near future. For the

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population studied, we can conclude that two illuminants of different spectral content which provide equal photopic illumination as measured by a light meter, can elicit substantially different pupil sizes. A study of brightness perception in another adult sample found a large rod contribution to perceived brightness,[2] lending additional independent evidence that rods are active and have an effect on vision at typical interior light levels.

Pupil size is important in lighting applications because it affects visual acuity and depth of field, which are important processes underlying visual performance. Visual acuity is the ability to resolve fine detail, and depth of field is the ability to maintain objects in good focus over a range of object distances (the range of distance is defined as the depth of field). Current visual performance models, such as CIE 19/2, the Rea model, and the Clear and Berman model, are based solely either on photopic luminance, or on pupils of fixed size and thus do not capture pupil effects due to spectral differences.[3,4,5]

Laboratory studies have documented the quantitative affects of pupil size on visual performance.[6,7,8] The results that are relevant for light levels typical of the interior environment, where pupil diameters typically range from about 3–5 mm, are summarized as follows:

Reductions in visual acuity occur with increasing pupil size for the normally sighted under conditions of moderate to low contrast, but not necessarily at high contrast. However, many tasks in the workplace do not possess high contrast and changes in acuity are similar to changes in threshold contrast as both are major determinants of visual performance. Moreover, individuals who need optical corrections, i.e., those who should be using spectacles but are not, show decrements in visual acuity even at high levels of contrast. Furthermore, it has been estimated that at least one-third of the nation's working population suffers from uncorrected refractions, i.e., they need spectacles but do not use them. On the basis of both of these phenomena, increased scotopic luminance, with the concomitant smaller pupil size, can lead to improved visual acuity. The basic reason for the improvement is that a smaller pupil reduces the impact of lens aberrations on visual optical quality.

In addition, studies on the effects of pupil size on depth of field have been carried out by Campbell,[8] Ogle and Schwartz,[9] and Tucker and Charman.[10] These studies found that depth of field always increases when pupil size decreases, depending on the size and viewing distance of the task. Thus, smaller pupils improve depth of focus for all populations.

Because of the relationships between pupil size and basic visual functions, our findings on pupil size suggest a strategy for the reduction of workplace lighting energy without a decrement in the visual effectiveness of the illumination. This strategy is based on three premises: existing lighting levels provide a satisfactory level of visual performance; a change of spectrum that provides the same level of effective pupil luminance (see footnote below for definition) will maintain the same level of visual performance because pupil size is maintained; illuminants with significantly higher scotopic lumens per watt than those typically in use are either available or easily achievable.

The first premise is generally accepted and the last premise is straightforward. It is discussed later in this paper. Although some information supports the remaining premise, the concept has not been fully established and is thus, in part, conjecture. If the underlying visual function for performance is depth of focus then the premise clearly applies. However, if the underlying visual function is acuity, then existing studies are inadequate tests. For example, in their study of the effects of luminance on acuity under conditions of natural pupils and high contrast targets, Sheedy, et al.,[11] showed that differences in acuity between their results, and the studies of Konig and Lythgoe could be explained by the differences in measured pupil sizes as determined by visual comparison pupilometry with acuity improving for smaller pupils. However each of these three studies used completely different subjects and such comparisons across subjects are questionable. Furthermore, Shlaer,[12] using an artificial pupil of fixed small diameter of 2 mm showed, that slight improvements in acuity occurred for two young subjects as luminance increased, with its values typical of building interiors. However, he did not study the effects of luminance when pupil size ranged in the 3–4 mm diameter size, which is more typical at levels of building illumination. Thus, vision literature appears to lack the appropriate studies for establishing the level of applicability of the second premise. A study of the tradeoff between pupil size and luminance for high contrast targets using the same subjects and conditions relevant for building interiors would be useful in clarifying this matter. For low to moderate levels of contrast smaller pupil size has been shown to improve acuity.[7] In addition, we have recently shown for natural pupils, fixed target luminance, and contrast ranging from 20–40 percent, smaller pupils have better Landolt-C acuity.[13] The remaining portion of this paper assumes the validity of the second premise and considers our strategy for energy efficiency based on all three above premises.

Consider the group of roughly equal fluorescent lamps listed in **Table 1** that are typical of interior lighting. The first column lists the rated photopic

Table 1—Forty-watt fluorescent lamps

Lamp	Photopic lumens	Scotopic lumens	Effective pupil lumens [P(S/P).78]	Relative Power level for equal pupil sizes	Pupil lumens per watt
Warm-white fluorescent (WW)	3200	3100	3125	136	78
Cool-white fluorescent (CW)	3150	4630	4254	100	106
Narrow-band phosphor fluorescent (5000 K) [NB(5000)]	3300	6468	5578	76	139
Scotopical rich narrow band (SR-NE)	3000	7500	6130	69	153

Table 2

Lamp (2250 lumens)	Lumens per watt	Ratio S/P	Relative Power level for equal pupil size	Pupil lumens per watt
125-W incandescent	18	1.4	100	23.4
35 Watt HPS	50*	0.4	96	24.5

*(10 W for ballast is included)

lumens for several 40-W (F40, T12) lamps. Because each of these lamps have different phosphors and thus, different spectral power distributions, they will produce different scotopic lumen outputs. These are listed in the second column. The scotopic output can be determined by folding the lamp spectral power distribution with the scotopic sensitivity function V′(λ) as given by Wyszecki and Stiles.[14] Pupil size is then determined by a combination of photopic and scotopic lumens that define the pupil lumen.*

Based on the scotopic and photopic lumen outputs, the third column in **Table 1**, lists the values of the pupil lumens that result from each of the different spectral distributions. The fourth column in **Table 1** shows the relative amounts of power required by these lamps for the condition of equal average pupil size, assigning the value of 100 relative W to the cool-white lamp. The last and most significant column compares the lamps on the basis of pupil lumens per watt which is proposed here as the measure of visual effectiveness per watt. (Some interesting evidence for this proposition is presented in the next section based on several studies published during the last 25 yrs). From the point of view of providing an economic optimum lighting for visual function, the narrow band (5000 K) fluorescent requires 24 percent less energy than the cool-white lamp and 44 percent less energy than the warm-white fluorescent.

Another comparison illustrating the potential importance of this type of analysis is shown in **Table 2** where a 125-W incandescent lamp is compared to a 35-W high pressure sodium lamp. These two lamps provide approximately equal amounts of photopic lumen output but because the HPS lamp uses less than 1/3 the power of the incandescent lamp, substituting it for the incandescent lamp is considered a possible effective strategy for energy savings. On the other hand, as shown in **Table 2**, the large apparent efficiency benefit of the HPS lamp is lost when small pupil size is the preferred condition. Thus according to our analysis, the two lamps would have to operate at about the same power level to supply the same visual effectiveness.

Past studies support pupil size effects

A number of studies comparing lamps with different spectral power distributions have found visual

**Pupil lumens are determined by the factor $P(S/P)^{0.78}$, where P and S are the photopic and scotopic output of the lamp. The ratio of scotopic to photopic luminance (or lumens) is referred to here as the (S/P) ratio. This ratio is a property of the lamp spectral power distribution (SPD) and to the extent that this distribution is independent of lamp intensity (as is the case for most fluorescent lamps) the ratio will be a constant independent of lamp intensity. For lamps whose SPD depends on operating conditions, the (S/P) ratio will have some variation. Generally, the pupil lumen is determined by the measured photopic output multiplied by the S/P ratio which is calculated from the measured SPD, which is then folded with V (λ) and V′(λ). Alternatively, if an accurate scotopic filter were available, which does not appear to be the case, both P and S could be measured and the factor $(S/P)^{0.78}$ determined directly. Although pupil size is predominantly controlled by the level of scotopic luminance, there is a small but significant photopic contribution, which is the reason that the exponent in the expression for pupil lumens is 0.78 ± 0.03 rather than the value 1.0. The standard error in the exponent (± 0.03) is the value 1.0. The standard error in the exponent (± 0.03) is the value determined by our most recent study of 20 subjects.[1]*

function differences of importance to lighting engineers and designers. The explanations proffered for these differences have been confusing or questionable, with the result that the findings have not been widely cited and have not influenced lighting design. A re-examination of those studies suggests that the results are reasonable, and have a simple explanation in terms of scotopically driven pupil size effects. Three of the findings from these early studies are discussed below:

1. Visual Clarity: In 1969, Aston and Bellchambers[15] reported the results of a series of simulation experiments where subjects viewed and compared a pair of identical cabinets containing a number of typical interior furnishings. The cabinets were lighted by a control fluorescent lamp and test fluorescent lamps of different spectral distributions. Four different fluorescent lamps were studied and 33 subjects ranging in age from 22–60 yrs were asked to rate their impression of the cabinets and their contents for visual clarity. The report of this study presents graphs of the various spectral power distributions of the light sources used. These graphs can be digitized and subsequently folded with the scotopic and photopic sensitivity functions to determine lamp (S/P) ratios. The resulting ratios obtained are in good agreement with the values given by Lynes[16] for lamps of the same name. His (presumed measured) values for S/P ratios for the four lamps are Kolorite 1.67, Daylight (3900 K) 1.54, White 1.36, and Warm White 1.13. The ordering of visual clarity was in perfect correspondence to the (S/P) ratio of the various light sources. Higher visual clarity corresponded to the larger scotopic luminance for the fixed photopic luminance of the study. Thus, a likely explanation for the results is that when pupil sizes on average were smaller, greater depth of field was possible and helped to provide the perception of increased clarity. This situation is similar to the photography of a space with some spatial depth detail using two different F-stops for the camera lens. With the larger F-stop (smaller lens pupil), more depth detail will be in focus.

A second visual clarity study[17] comparing nearly full-size rooms confirmed Aston and Bellchamber's findings. In addition, they reported the results of seven skilled observers who determined the illumination levels of Kolorite lamps that produced equal visual clarity and brightness perception when compared to fixed control levels for warm white lamps. They reached a mean reduction for Kolorite level [averaged over the seven observers and the 3 WW levels (200, 400, 600 lx)] of 25.8 percent when equal visual clarity was required and 18.7 percent when equal perceived brightness was required. On the basis of equal pupil lumens and on the S/P values of the two lamps given above, we predict a reduction of 26.3 percent for equal visual clarity, while our very rough estimate of the scotopic contribution to brightness perception[2] predicts a 17 percent reduction.

The authors of these studies on visual clarity and others,[18] have provided perplexing and dubious explanations of these results such as more efficient retinal responses to lamps with narrow bandwave length spectra. However, in retrospect, the results on visual clarity are easily understood in terms of the scotopic spectral effect on pupil size and brightness perception. Flynn (see discussion in DeLaney et al,[19]) has claimed that several factors such as increased color temperature increase visual clarity, but this correlates with higher S/P values and thus decreased pupil size in accordance with our explanation above. Flynn also noted that increased vertical luminances in the periphery increased visual clarity, but this condition also leads to smaller pupil size. Others[19] who have investigated visual clarity have found that it correlates with brightness perception (higher S/P values), and have also found that when lighting conditions have approximately equal S/P values, no apparent differences in visual clarity occur.

Visual clarity probably combines the two different features of scotopically richer light; the increased brightness perception for the same photopic luminance and the greater depth of field resulting from smaller pupils. These studies all indicate that both scotopic and photopic spectrums affect visual function at typical interior light levels, and that scotopically richer illumination is preferred.

2. The Piper Study: Piper[20] presented a study that purported to demonstrate that a group of 24 subjects had a significant decrement in performance on an achromatic visual task performed under standard HPS lighting as compared to fluorescent lighting. This study was considered flawed because of possible unmeasured fluorescence of paper under fluorescent lighting. However, based on our measurements and analysis below, Piper's work appears reasonable and is consistent with the effect of light spectrum on visual performance.

In Piper's experiment, subjects read five-letter nonsense words made out of the lower case letters *a* and *s*. They compared control words at normal reading distance with test words that were placed at the maximum horizontal distance at which all the letters of the words could be distinguished without errors. A combination of speed and accuracy was used as the measure of performance in terms of the number of correct comparisons per second. The results were compared under equal illumination of 50 fc of fluorescent lighting and HPS lighting. The contrast was very high with the letters typed in black ink

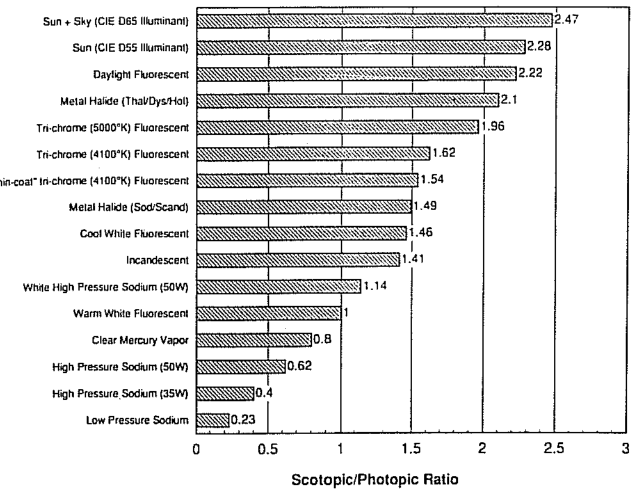

Figure 1—Scotopic/photopic ratios for various light sources

on white matte paper. The decrement in performance under HPS lighting was on average about 4 percent.

Our explanation of this result is that HPS lighting has a substantially lower (S/P) ratio than CW fluorescent (see **Figure 1**), leading to larger pupil size and causing smaller depths of field and poorer performance. Piper offers an explanation of his results in which he states the HPS spectrum provides an inadequate stimulus for accommodation. His statement is that "With white light, however, added refractive power for the blue component and reduced refractive power for the red component might allow objects to be focused for closer and farther distances respectively." The essence of this explanation is based on the phenomena that the wavelength best focused on the retina shifts from red to blue as accommodation increases (Ivanoff,[21] Millodot and Sivak[22]). My interpretation of Piper's explanation, based on the results of the latter authors, is that under the blue-deficient HPS light, more of its spectral energy would be out of focus as compared to the CW fluorescent lamp for the accommodation conditions of the Piper tasks. On the other hand, Campbell and Gubisch[23] found that contrast sensitivity increased by about 30 percent for yellow or green monochromatic light as compared to white light when pupil size was controlled by using artificial pupils. This latter effect could oppose the supposed accommodative effect.

Although one cannot rule out Piper's proposition, the alternative explanation in terms of pupil size mediating depth of field changes is more direct and has the added benefit of explaining other studies showing spectral effects on visual performance. As mentioned above, a possible difficulty with Piper's experiment is that the task contrast was not measured separately under the two lightings and that contrast differences resulting from fluorescent whiteners in the typing paper could account for the better performance under fluorescent lighting (HPS lighting having little UV output would not excite the whiteners). Our measurements of black dots and circles on white paper with high rag content indicate contrast differences of less than 1 percent between fluorescent and HPS lamps. Such small differences in contrast at the high contrast levels (about 93 percent) of the Piper experiment are highly unlikely to be the cause of effects of the magnitude of 4 percent. A rough estimate of how much contrast difference would be needed to achieve a 4 percent performance decrement can be made by using typical saturation fits to visual performance tasks such as the simple ogive fits as given in CIE 19/2.[3] Since Piper adjusted the conditions at the task far point to be just at the limit of high accuracy we will assume here that it has the value 99 percent. Using the ogival fit shows that this value would be achieved at a level of VL = 3. A decrement of performance of 4 percent in accuracy would shift the ogive from 99 to 95 percent. This corresponds to a level of VL = 2.7 or a 10 percent reduction in contrast. This amount is an order of magnitude larger than the results of our contrast measurements. In addition, since Piper measured task performance and not just visual performance, we would expect a significant nonvisual component in the measured task times. To find a 4 percent decrement in overall task performance due to changes in visibility would correspond to a much larger visual performance effect. This would make the contrast difference needed to account for Piper's results much greater than the 10 percent estimated above, made without subtracting any factors for the non-visual component. Thus, we believe that Piper's result is far outside the range of possible fluorescence effects.

Another possible confounding condition is flicker, because the HPS lighting has about 95 percent temporal modulation compared to the 30–40 percent in CW fluorescent lamps. However, Piper also compared two different HPS lightings where a blue filter was added to the HPS source to reduce the amounts of blue and blue-green spectral components. At the same illumination level, the filtered HPS produced a 6 percent decrement in performance compared to the unfiltered HPS. The degree of flicker is unaffected by the filter, but the S/P ratio had been further reduced by the presence of the filter, hence average pupil size would be again larger and depth of field further reduced. Thus, Piper's work provides very positive support of our hypothesis that the pupil size dilation under HPS lighting as compared to CW fluorescent lighting will reduce depth of field and result in poorer performance.

3. The Blackwell Study: In 1985 H.R. Blackwell[24] conducted a visual performance study where he compared the performance of five subjects under four different lamps; metal halide, HPS, clear mercury and incandescent. The task involved finding a single Landolt-C somewhere in a 5 degree field of view and choosing which of eight randomly presented compass point directions contained the opening in the C. The report does not provide summaries of the data, but instead invokes the CIE visual performance model and incorporates the data directly into this model. Examination of the 1981 CIE model shows that the relative ordering of the mean performance results under the different lamps is not affected by applying the model to the data. The reported ordering of performance was, from best to worst: metal halide, incandescent, clear mercury, and HPS. Blackwell provides a graph for the spectral power distribution of the metal halide used in his study. This graph was digitized and the S/P ratio determined as above. The S/P value obtained for this metal halide lamp is 2.1, while values of the S/P ratio for the other lamps are listed in **Figure 1**. (Note that the S/P ratio for the 50-W HPS lamp in **Figure 1** is larger than that for the 35-W lamp used in **Table 2**, because the higher wattage lamp operates at a higher pressure and has a wider spectral distribution than the lower wattage lamp.) The relative ordering given by Blackwell is the same as the relative ordering in the S/P values for the four lamps. Because the three gas discharge lamps all have flicker modulations close to 100 percent while the incandescent lamp modulations are on the order of 5 percent, there is the possibility that flicker was not properly controlled. Nevertheless, the relative performance ordering for the three gas discharge lamps (flicker conditions the same) follows the relative S/P values for those lamps.

Blackwell offers an explanation of his results based on competitive effects of three separate mechanisms producing results in opposite directions. These mechanisms are the often claimed deficiency in the CIE V(λT) weighting function in the far blue (400–450 nm), chromatic aberration effects, and inappropriate focusing for narrow band sources. The interpretation of Blackwell's results based on the pupil size response to lamp spectrum is much simpler, requiring fewer additional assumptions.

It should be emphasized that pupil size was not directly measured in the Blackwell study or any of the other studies described above. Nevertheless, an explanation based on the pupil size response to the spectral content of the various illuminants is highly compelling. This explanation is also consistent with our understanding of the elementary optics of the visual system and provides a parsimonious description of numerous reports of differential responses to different lamp types. New experiments are being designed to explicitly test our hypothesis with pupil size measurement an integral component of the variables being studied. In addition, specific field studies with realistic environments and tasks should be undertaken to test the generalizability of the pupil size hypothesis proposed here.

Potential economic benefits of scotopically rich lighting

Because scotopically richer illumination appears to be the preferred spectrum for smaller pupil size and greater brightness perception in interior lighting conditions, it is our proposition that lamps with high scotopic output for a given input power will be more cost-effective than lamps of low scotopic output for the same level of input power. Based on the strategy mentioned above and the three premises which use the pupil lumen as the measure of visual effectiveness, we see from **Table 1** that replacement of the ubiquitous cool-white lamp by a high color temperature, narrow band (NB) lamp would elicit the same pupil size with 24 percent less power. The interpretation of this result is that the same visual effectiveness is obtained with 24 percent less power, and is therefore an excellent strategy to achieve cost-effective lighting energy efficiency. Thus, the common four-lamp fixture containing four 40-W cool-white lamps could be replaced by a new fixture with three narrow band 40-W lamps and achieve the same visual effectiveness. The difference in cost between four CW lamps and three NB lamps is about $10. At typical operating conditions of 3000 hrs and $0.08/kWh, the payback is about one year. For a lamp with a 5-yr lifetime, this should be a good return on investment.

On a national basis, a 24 percent improvement in fluorescent lighting efficiency as a consequence of switching to narrow band phosphor lamps has the potential of an annual reduction in electricity usage of some 53 billion kWh and a possible annual savings of $4.23 billion. Furthermore the electrical power demand saved by replacing the four-lamp CW fixture with the visually equivalent light output three-lamp NB fixture is approximately 40 W (including the additional ballast power savings). Looked at from the view of avoided generating capacity at $1–2/W, the three-lamp NB system avoids $40–80 in electrical generating costs. The added consumer cost for NB lamps over the 25-yr life span of new electrical generating capacity essentially cancels the cost of the added generating capacity. Thus, if instead of adding generating capacity the equivalent investment was made in the more efficacious NB lamp system, society would have instant payback and existing electrical generating plants could be devoted to genuine growth. The overall societal benefits are two-fold because the consumer saves costs for electricity, and is burdened with less environmental pollution because there is less electricity generation.

A fluorescent lamp with an even higher ratio of scotopic to photopic lumens and with good photopic lumen output should be achievable by augmenting the high color temperature narrow band lamp with the addition of a phosphor having a reasonably sharp maximum in emission at the scotopic peak (508 nm). Such a lamp could achieve a ratio of scotopic to photopic lumens (S/P ratio) of 2.5, with a photopic output of 3000 lm. This proposed scotopically rich lamp is referred to as SR-NB in **Table 1**. It would require 31 percent less energy than cool-white lamps to produce the same pupil luminance. This means that the common four-lamp fixture using four 34-W cool-white lamps could be replaced with two 47-W lamps of the proposed scotopically rich narrow band type. In many cases the two-lamp fixture will operate in a more thermally efficient environment than the four-lamp fixture, in which case the wattage of the proposed SR-NB lamp for operational visually effective lumen equality could be reduced by about 15 percent (Siminovitch et al,[25]), from 47 to 40 W. For this replacement, there would be additional economic benefits resulting from the cost reduction by the substitution of a two-lamp fixture and a single ballast compared to a four-lamp fixture with two ballasts. The potential national benefits in terms of electricity savings would also be increased by between 40–50 percent over the $4.23 billion value mentioned above.

Conclusion

The potential highly cost-effective lighting energy benefits that could accrue from a national transition to the use of scotopically richer lighting have been illustrated here. Because this large potential is conceivable, the lighting community should place a high priority on gathering further information that would allow these concepts to become part of lighting practice.

Acknowledgements

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Discussions

This paper continues the intriguing work of Dr. Berman and his group into the possible advantages of using a lumen other than the unit defined by the CIE in 1924. In this contribution, a case is made for reductions in energy usage if scotopically [V′(λ)] weighted spectral sensitivity functions are used and "pupil lumens" are used to compute the effectiveness of lighting.

I have several questions and comments on the paper:

The V (λ) function is specified for 2 degree fields. It is well known that it incorrectly predicts brightness for larger fields; indeed, the CIE itself offers a large field standard observer (the 1964 CIE 10 degree observer) which provides greater sensitivity at short wavelengths. Even the Judd correction of the 2 degree field data increases short wavelength sensitivity. It is clearly inappropriate (albeit commonly done) to use the 1924 observer for large field conditions and its use has largely been abandoned in the vision community. What is the effect of using the photopic large field sensitivity function [$V_{10}(\lambda)$] instead of the 2 degree function?

Visual performance studies have looked at the luminance or illuminance necessary to provide criterion levels of performance. Since these are empirically, rather than theoretically, determined, it isn't clear why changing the definition of the lumen alters the relationship; however the subjects perceived the stimulus, or however their pupils were affected, as along as there is a constant relationship between the units, the functions remain valid. Even if brightness perception is increased by inclusion of a rod contribution, it isn't clear that the cone-driven resolution-dependent tasks used in most visual performance studies would be affected.

Dr. Berman points out that the order (but not the magnitude?) of the results of visual clarity experiments correlate well with the S/P ratios of various light sources. While such a co-variation may suggest that the two are related, it is highly speculative to conclude that one is caused by the other. In addition, the notion that depth of field may be solely responsible for the effect discounts the powerful influence of binocular factors in depth perception. He may well be correct, but, in the absence of control studies, it seems premature to state that "visual clarity probably combines. . . increased brightness perception. . . and scotopically richer lights."

Several studies are cited which support the idea that visual performance of tasks varies with the spectral composition of the illuminant. Several other studies have shown no such effect. The reasons for the different results are the subject of debate, but the fact that the significance of spectral distribution on visual performance (defined as speed and accuracy) remains in dispute weakens secondary analyses of possible origins. The energy savings predicted in the paper require that the model proposed by Dr. Berman is physiologically correct. Because the obvious control procedures such as experiments with a fixed or artificial pupil have not been conducted it seems premature to suggest major economic advantages from an approach whose validity remains to be confirmed. The speculations presented in the paper are indeed tantalizing, but do not, by themselves, provide evidence for the model. Nonetheless, they raise fascinating questions about the use of the 1924 standard observer as the basis for units that are used to define the quantity of light in situations that clearly violate the conditions appropriate to that standard. Right, wrong, or in between, this paper must cause us all to rethink what we have taken for granted for too long. Dr. Berman may be absolutely correct, but even if he isn't, we are in debt to him for making us re-evaluate the very foundations of the bases for our lighting decisions.

A.L. Lewis

This paper requires careful consideration because it ranges from the established to the speculative. What is well established is that in full field conditions, pupil size is influenced primarily by scotopic luminance. Therefore, lamps rich in scotopic wavelengths will produce smaller pupil sizes when they are used to light large, neutral reflectance fields. The optical consequences of the smaller pupil are a greater depth of field and, possibly, an improvement in retinal image quality. Also associated with a smaller pupil size is a perception of greater brightness.

These consequences are used to explain three lighting studies, of which one explanation is believable, one is open to question, and one cannot be judged. Piper's task required the subject to change focus from near to far distance at frequent intervals. Given that a smaller pupil size has a greater depth of field it is reasonable the lamps which produce smaller pupil sizes should give better performance on this task. As for the visual clarity experiments, the doubtful aspect of the pupil size explanation is that the spectrum of light reaching the eyes of the subjects is unknown because the subjects could view both cabinets or rooms simultaneously. As for the Landolt ring search task, given the absence of summary data in the original paper, it is difficult to judge the value of the explanation.

Where this paper becomes speculative is with the suggestion that pupil size can be used as a basis for comparing lamps for all types of applications. A major problem is that there is no evidence that changes in pupil size affect supratheshold performance. The paper does refer to evidence that pupil size affects visual acuity, for low contrast stimuli. Smaller pupil sizes and the associated improvement in image quality at the retina might be expected to improve visual performance for a task requiring resolution close to threshold but whether they would have any effect at supratheshold is open to question. Until this point is clarified it would be unwise to rush into a major reevaluation of what constitutes desirable lamp spectra.

P. Boyce
Lighting Research Center

The author did show a nice overview of the influence of rod receptors to the size of the pupil. Moreover the pupil size does influence the visual performance. In his plea for scotopic enriched light sources, the author sees an opportunity to lower the energy consumption for lighting. Although the pupil size effects are not to be underestimated in selecting the optimal light source for a specific area, more factors such as ambiance, color detection and discrimination, and the appearance of skin tones are also important. To put it more straightforwardly: the color temperature and the color rendition required limit the possibilities to scotopically enrich the spectrum.

In our survey over a number of light sources, the s/p ratio is highly determined by the correlated color-temperature of the light source, reaching almost 2.5 for a D6500 full band fluorescent lamp. Typically, almost all artificial light sources have S/P ratios close or slightly below that of a planckian or daylight radiator of the same color temperature (see **Figure a** and **b**).

The only exception to this general rule is the HPS lamp as quoted in the paper. It must be stressed, however, that this behavior is only observed for standard HPS lamps; white HPS lamps with color temperatures of 2600 K have a s/p ratio of 1.15 which is close to the incandescent data and, because of the inherent efficacy of white "HPS" lamps, will yield pupil lumens/watt up to three times of the incandescent lamps.

Could the author comment on the optimum choice between scotopic enrichment and related lighting criteria (Tc-CRI) and the opportunities of white HPS lamps compared with standard HPS lamps?

J.T.C. van Kemenade
Philips Lighting

Author's response

To A.L. Lewis

The choice of any single V(λ) is totally irrelevant as our description requires both a photopic response and in addition a scotopic or rod sensitivity. In our study of brightness perception, the 10 degree observer was used and subsequent further individual subject color adjustments for the full-field condition were made in order to achieve the best color match for the full field of view. The results showed a large scotopic sensitivity, and hence that rods were contributing to brightness judgements. The principal reason for introducing the S/P ratio with the photopic component given by the 2 degree observer is that this function (2 degree observer) is used in most photometric measuring devices. Since, to our knowledge, the availability of good quality reliable scotopic filters is questionable, it is functional to just measure P and get S by multiplication by tabulated values of S/P. This is useful for lamps and surfaces with broad spectral responses as these surfaces will preserve the S/P ratios of the illuminants. For surfaces with narrow and selective spectral responses, the best procedure is to fold their measured spectral response per unit wave length with the published values of V(λ) and V′(λ).

Most previous studies did not consider the spectrum of illumination in studying visual performance. When spectrum was included as in the recent Blackwell study discussed in the paper, the results were most easily explained in terms of the spectral effect on pupil size.

The paper clearly states magnitude effects of both pupil size and brightness perception as applied to the original Visual Clarity studies. To mention again our results predict a 26.3 percent reduction in the test illumination when compared for clarity based on equal pupil size compared to the measured average value of 25.8 percent reduction and for brightness perception a predicted value of 17 percent reduction compared to the measured 18.7 percent reduction. While the Visual Clarity studies were not controlled for individual color equality, and pupil size was not measured, the significant results of those studies follow reasonably and simply as a consequence of visual scotopic sensitivity.

I agree completely that binocular factors are important in depth perception, but since we are considering depth of field in relation to visual clarity and not depth discrimination, I fail to understand the relevance of his comment.

Dr. Lewis is correct to point out that there are studies that do not show effects of illumination spectrum on visual performance. Studies by Smith and Rea[a] and Rea, Oullette, and Tiller[b] looked for effects of lamp type and hence spectrum on their performance measure. The principle reason these studies failed to show the spectral effect relates to the method of analysis. In the Smith and Rea paper they averaged over all contrasts studied which included both high and low contrasts. If they had separated out the low contrast data or examined a contrast interaction term in their ANOVA, I believe they would have found the effect. Similar considerations apply to the later study of Rea, et al. Perhaps a more interesting case is the work of Boyce[c] in the late 1970s on visual clarity employing his elegant testing concept of miniature attic-like office scenes viewed by the subjects with their heads protruding through the attic floor. There are aspects of the Boyce study which might be explained by pupil size effects, but because his tasks employed both near and distant vision there is the potential for a significant confounding condition, namely, that of the effect of accommodation for near vision tasks which is inevitably associated with pupil contraction. Thus, the Boyce study has a known nonphotic input to pupil size which was not controlled and hence, makes the interpretation of his study ambiguous when based on the pupil spectral effect alone. The aspects of his study dealing with achromatic environments is reasonably explained in terms of scotopic effect on brightness perception which might not be affected by the accommodation pupil synkinesis.

I would agree whole heartedly with Lewis's closing comment. There is clearly new and significant evidence that denies the adequacy of a single metric of photometry based on the CIE 1932 2 degree observer or any single replacement.

References

a. Smith, S.W. and Rea, M.S. 1979. Relationships between office task performance and ratings of feelings and task evaluations under different light sources and levels. *Proc CIE 19th Session*:207–211.

b. Rea, M.S.; Ouellette, M.J.; and Tiller, D.K. 1989. The effects of luminous surroundings on visual performance, pupil size and human preference. *J of the IES* 19(no.2).

c. Boyce, P.R. 1977. Investigation of the subjective balance between illuminance and lamp color properties. *Lighting Research and Technology* 9:11-24.

To P. Boyce

I take Boyce's comments to mean that he is in reasonable agreement on the findings that there is a significant scotopic sensitivity of the human visual system at typical interior light levels, but with a concern over whether there are consequences for lighting applications, especially for conditions considered normal for working indoor environments. These conitions are presumed to be the suprathreshold case as referred to by Boyce. In response to these concerns, I mention again our study of brightness perception carried out at wall luminances of order 50 cd/m^2 which is certainly not a threshold condition and is a reasonable interior light level. If one of the end points of a particular lighting design is to provide a level of brightness appearance in a neutral color environment, then scotopically richer lighting will generally be more visually efficacious per watt of electric power when compared to scotopically deficient lighting. Thus, from the point of view of brightness perception, there is definitely a benefit at suprathreshold conditions. From the more precise quantitative view, at the present time, we can only provide a rough estimate of the brightness lumen. A more exacting determination is presently underway in our laboratory.

A second consideration of suprathreshold condition is the effect of pupil size on depth of field as exemplified by our interpretation of the Piper study with which Boyce states his agreement. If depth of field is improved with smaller pupils—is it not true that the lit and viewed environment will appear clearer or crisper with scotopically richer lighting? To the extent that clearer three-dimensional scenes are a desired endpoint of a lighting design, scotopically richer lighting is again preferred. Furthermore, the quantitative comparison between light spectrum and depth of field is given by the pupil lumen with the energy benefits associated with this application expressly provided by **Tables 1** and **2** of our paper.

However, as Boyce states, if the end point of the environmental lighting is to provide a level of visual performance for reading tasks, then there appears to be insufficient evidence among vision studies to confirm or deny the concept of the pupil lumen as the unique metric of visual performance. In that sense, our contention of the universality of the pupil lumen could be speculative depending on the outcome of studies still to be carried out. The most significant of these being a separation of pupil size and luminance effects on acuity with luminances being typical of building interior conditions and with target distances employing both near and far vision.

In this regard, we have recently completed a study of twelve subjects which demonstrated the effect of pupil size on the recognition of orientation of a Landolt-C (reported at the July 1991 Quadrennial of the CIE). The C was presented on a CRT screen placed at the end of a short black tunnel but viewed at a distance of 2.5 m. By varying the spectrum of the surround lighting at fixed luminance (63 cd/m^2), pupil size is controlled while the tunnel condition allows the target luminance to remain unchanged during the manipulations on pupil size. One might expect that for the condition of small pupil size, performance might be poorer because retinal illumination would be reduced. However, subjects had smaller pupils with the scotopically richer surround lighting and performed better on the task. Presently we are studying performance on this task when the surround lightings are adjusted so that subjects have the same pupil size for the two different spectral illuminants. In our study, this means that there is a factor of 18 between the photopic luminance of the two surround lighting conditions to be compared. Since pupil size will be equal under both conditions, oûr hypothesis is that performance will also be the same.

Concerning the studies on visual clarity, Boyce has mentioned that the interpretation proposed here, and based on the spectral content of the room illuminants under view, is open to question because the subjects could have viewed the rooms simultaneously. It is true that the manner in which those studies were carried out precluded knowing where the subjects fixated. However, subjects were instructed to compare the scenes—and were not instructed to view the scenes simultaneously, especially dichoptically or with one eye on each of the scenes. Since the lighting of the two scenes compared was not grossly different, it is just as likely that subjects viewed on scene and then the other each binocularly. The results of the visual clarity viewers when compared quantitatively with our determination of the pupil lumen and the approximate brightness lumen are in excellent agreement with our numerical predictions. Perhaps this result is fortuitous, but taken together with our other findings it certainly cannot be dismissed.

The statement made by Dr. Boyce on the Blackwell study appears somewhat biased. It is true that the raw data are not included in Blackwell's report, however, he states explicitly the algorithms that were applied to the data. It is straightforward but possibly tedious to conclude that the relative ordering of the performance is not affected by Blackwell's calculational procedures as is indicated in our paper. The value of our post hoc explanation is that it follows in an elementary manner from the effects of the different lamp spectra on pupil size.

The question of meaning and significance of suprathreshold effects is a complicated issue deserving a separate paper. However, the following illustrates the vacuousness of the suprathreshold crowd. Consider a person at the optometrist's office for an eye examination to test the need for spectacles. The patient is asked to read the letters on the eye chart. He or she sees the large E at the top and states, "I can see the big E clearly, spectacles are unnecessary." The optometrist asks the patient if he or she can see the other rows on the chart and the patient replies, "I never have to look at anything but big Es." The optometrist asks, "But wouldn't you like to see all your Es very crisply with nice sharp edges and corners?" The suprathreshold crowd answers "no" but most of the rest of the world answers "yes."

Perhaps a goal of good lighting design is that it should be beneficial to a large majority of users. If there are many individuals in our interior environments who are working with less than optimal refractive states such as not wearing spectacles even though they should, then even a small decrease in pupil size could be beneficial. If this could be provided at less or comparable cost—is it not worthwhile to further evaluate the lighting benefits of scotopic sensitivity?

To J.T.C. van Kemenade

If a task has a specific chromatic demand, it is possible that the scotopic quality of the lighting may not be of relevance. However, there is a strong positive correlation between S/P ratio for a lamp with whitish light and both TC and CRI. The figures below show this for some commonly used lamps.

The white HPS lamp is definitely an improvement when compared to the earlier versions of HPS lamps on all accounts, i.e., S/P ratio, TC, and CRI. However, in terms of spectral quality, the white HPS is not as high as the Thaleum-dysproseum MH.

When compared to incandescent, the white HPS is much better in terms of equivalent pupil lumens than the older HPS lamps. The exact amount can be determined from the photopic lumen per watt ratio, including the ballast for the HPS and then factoring in their relative pupil lumens.

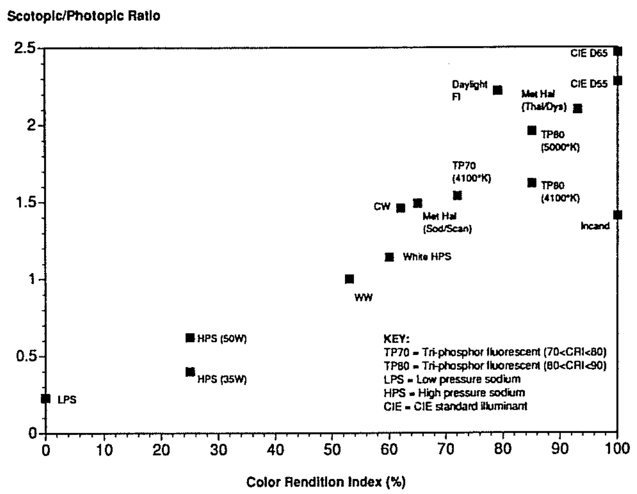

Figure a—SP ratios for black body radiators at varying color temperature

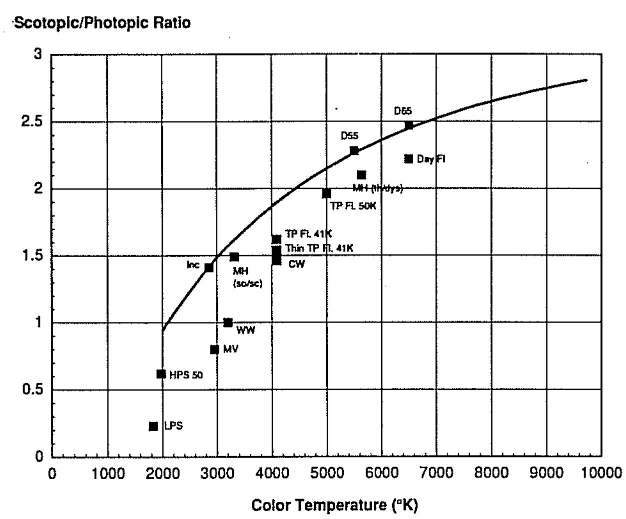

Figure b—Scotopic/photopic ratio vs. color rendition index for various light sources