1991 IESNA ANNUAL CONFERENCE *by S.M. Berman*
as published in the JOURNAL of the Illuminating Engineering Society Winter 1992

Energy Efficiency Consequences of Scotopic Sensitivity

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( ) 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( ) 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( ), 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( ) 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 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 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, 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 3-4mm 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 lumens for several 40-W (F40, T12)

Table 1 - Forty watt fluorescent lamps

Lamp	Photopic lumens	Scotopic lumens	Effective pupil lumens [P(S/P).78]	Relative Power, level for equal pupil size	Pupil lumen, 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	

*(1O W for ballast is included)

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'( ) 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 function differences of importance to lighting engineers and designers.

*Pupil lumens are determined by the factor $P(S/P)^{0.78}$, where P and S are photopic and scotopic output of the lamp. 7'he 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 ( ) and V'( ). 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 predominately 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]

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[8] 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 a 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 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 (Ivanaff,[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 supports 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(T) 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 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 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 a 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 an three NB lamps is about $10. At typical operating conditions of 3000 hrs and $0.08/kWh, the pavback 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 saving 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 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.

Author's affiliation Lighting Systems Research Group, Lawrence Berkley Laboratory, Energy and Environment Division, Berkley, CA.

Acknowledgments

I would like to express my appreciation to my colleagues in the pupil size and brightness perception studies, Dr. Don Jewett and Dr. George Fein, for their invaluable scientific and technical advice and support. In addition, I wish to thank Robert Clear for his critical remarks, to Francis Rubinstein for calculations and for contributions to Figure 1, and Mike Gilford for his careful reading of the manuscript. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Equipment Division of the US. Department of Energy under Contract No. DE AC03-76SFOOO98.

1. Berman, S.M.; Jewett, DJ.; Bingham, L.R. Nahass, R.M.; Perry, F.; and Fein, G. 1987. Pupillary size differences under incandescent and high pressure sodium lamps. J of the IES, 16(no. 1):3-20.

2. Berman, S.M.; Jewett, DJ.; Fein, G.; Saika, C.; and Ashford, F. 1990. Photopic luminance does not always predict perceived room brightness. Lighting Research and Technology, 22(no.1):37-41.

3. CIE 1981. Technical Report No. 19/2, An analytic model for describing the influence of lighting parameters upon visual performance. Vol. 1, Technical Foundations International Commission on 1luminatian.

4. Rea, M. and Ouellette, M. 1988. Visual performance using reaction times. Lighting Research and Technology. 20(no. 4):139-153.

5. Clear, R. and Berman, S. 1990. Speed, accuracy and VL. J of the IES, 19(no. 2):124-131.

6. Atchison, D.A.; Smith, G.; and Efron, N. 1979. The effect of pupil size on visual acuity in uncorrected and corrected myopia. American J. Opt. & Physiol, Optics, 56(no. 5): 315-323.

7. Woodhouse, J.M. 1976. The effect of pupil size on grating detection at various contrast levels. Vision Research, 15: 645-648.

8. Campbell, FW. 1957. The depth of field of the human eye. Acta Optica, 4(no. 4):157-164.

9. Ogle, K.N. and Schwartz, T.N. 1959. Depth of focus of the human eye. J. Opt Soc. Amer., 49:273-280.

10. Tucker, J. and Charman, W.N. 1965. Depth of focus of the human eye for Snellen letters. American J. Optom. Physiol, Optics, 52:3-21.

11. Sheedy, J.E.; Bailey, I.L; and Raasch, T.W. Visual acuity and chart luminance. American J. of Opt. and Physiol. Optics, 61(no. 9):595-600.

12. Shlaer, S. 1937. The relation between visual acuity and illuminations. J. of Gen. Physiol, 21(no. 2):165-188.

13. Berman, S.M.; Fein, G.; Jewett, D.J.; Saika, G.; and Ashford, F. A visual performance task with spectrally controlled pupil size. Presented at the 22nd Conference of Commission Internationale De L'Eclairage(C.I.E.), Melbourne, Australia, July 1991.

14. Wyszecki, G. and Stiles, W.S. 1982. Color Science. 2nd ed. New York: Wiley (105).

15. Aston, S.,M. and Bellchambers, H.E. 1969. Illumination, color rendering and visual clarity. Lighting Research and Technology, l(no. 4):259-261.

16. Lynes, J.A. 1988. Lighting and the pupil. Lighting in Australia. 26-31.

17. Bellchambers, H.E. and Godby, A.C. 1972. Illumination, color rendering and visual clarity. Lighting Research and Technology, 4:104-106