IMPLICATIONS OF ROD SENSITIVITY TO INTERIOR LIGHTING PRACTICE

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ABSTRACT

Conventional photometry is based on the psychophysical response of observers with the field of view confined to 2°. That region of the human retina contains only cone photoreceptors and does not contain rod photoreceptors. However, the majority of the retina is dominated by rods. Perhaps because the measurement of rod spectral response requires extremely low light levels in order to remain below cone threshold, it has been erroneously assumed that rods are inactive at normal interior light levels. Thus, any effects of rod receptors have not been included in the measurement of light quantity that is applied to lighting practice. Our studies demonstrate that rods are indeed active at typical interior light levels and that under conditions of full field of view they dominate the spectral determinants of pupil size, as well as, contributing significantly to brightness perception. Rod intrusion is well known to vision scientists, but nevertheless many useful past studies of lighting effects have fallen by the wayside because the obvious invoking of rod contributions have not been part of interior lighting science. We present here evidence that indicates that the time has come for the C.I.E. to recognize that lighting practice requires an enhanced photometry which incorporates realistic viewing conditions and the resultant scotopic sensitivity.

1. INTRODUCTION

Rod photoreceptors are absent in the human retinal fovea, the region which occupies the central 2° of the visual field. Conventional photometry which provides a quantitative assessment of visual sensation to light energy is based on stimulation and response of the fovea. Lighting design and application are hardly ever restricted to such small fields of view, but nevertheless lighting practice relies on the values provided by conventional photometry for its measure of light quantity. It is likely that this use of photometry, especially for interior design, is based on the supposition that rods, which are five to six times more prevalent in the retina, are inactive or somehow non-contributing to visual response at typical interior light levels. But light stimulation of rods at these levels and at even much higher levels is often reported in the literature. For example, Stiles and Wycecki[1] reported in their studies of color matching functions that more than 20,000 trolands are needed to suppress rod sensation, while Aguilar and Stiles[2] argue that between 2,000 and 5,000 trolands are required for rod saturation. These retinal illuminances imply more than 1,000 cd/m^2 of viewed luminance for pupil sizes typical building interiors. This means that rod activity is occurring over the entire range of interior light levels.

Our research adds further support to the proposition that a satisfactory assessment of interior lighting must include the effects of rod activity. In particular we have shown that in conditions of full field of view, pupil size is predominantly controlled by scotopic spectrum and that brightness perception receives a major scotopic contribution. The consideration of pupil size is important for lighting practice because at typical interior light levels pupil size controls the ultimate capabilities of visual performance. The principle reason for this is the ubiquitous presence of imperfections of the eyes' optical system. These are generally manifested as optical aberrations and occur throughout the population. A major inference of our studies implies that at typical interior light levels retinal illumination is sufficiently adequate that observed improvements in visual performance are dominated by improving optical quality rather than increased light level. Smaller pupils reduce the effects of optical aberrations and visual performance is improved with smaller pupils. Our results show that this behavior occurs for adults from ages 20 to 70 years and most likely would also occur for children. Smaller pupils will yield better depth of field, visual acuity for both high and low contrast tasks while also providing the additional benefits of reduced disability glare effect and accommodation demand. Some discussion of the details of those visual performance studies is presented in a separate paper for this symposium.

2. BRIGHTNESS PERCEPTION

As mentioned above, we have also determined in full field of view that scotopic spectrum contributes significantly to brightness perception[3]. In that study, subjects compared two illuminants that provided different spectral power distributions but with equal chromaticity (10° observer). The comparison was made in full field of view in a 2 m^3 room with subjects switching between the illuminants. These were composed of standard fluorescent lamps that were situated in the room to provide indirect light. By maintaining the same chromaticity, possible chromatic channel contributions to brightness perception are held constant during the comparison. The illuminants provided a whitish yellow light whose chromaticity coordinates for the 10° observer are x=0.4824 and y=0.4086. Twelve naive observers generally chose the illuminant as brighter when it was produced by a scotopically enhanced spectrum (S/P=2.2 compared to S/P=0.85) even though it was controlled to produce 25% lower luminance on the viewed surfaces as measured by a conventional photometer.* Further details and statistical analysis is provided in reference 3.

Our findings on brightness perception and pupil spectral response argue that conventional photometry based on the V(λ) function as the sole means of quantifying light levels provides an inadequate measure of visual response when the field of view is representative of interior lighting applications.

3. PAST STUDIES THAT SUPPORT SCOTOPIC SENSITIVITY

Because of the lack of recognition by lighting practitioners of scotopic sensitivity, a number of interesting studies that produced surprising results have disappeared from the world of lighting applications. Their disappearance was primarily due to a lack of explanation of these results by conventional knowledge based on traditional photometry. Perhaps one of the more infamous cases were the studies done by Bellchambers and coworkers in the UK in the late 1960's and early 1970's. A return to these studies armed with knowledge of scotopic sensitivity gives them revived credibility. Another very interesting study done by Piper in the USA showing poorer visual performance under HPS lighting compared to CW fluorescent can now also be readily explained, as well as, a study by Blackwell in the USA on spectral effects of threshold visibility. These 3 past studies are discussed in more detail below. The reader should also be aware of the large number of anecdotal reports by many lighting professionals who have suffered doubts about photometry when they perceived HPS lighting as obviously dimmer when compared to mercury, fluorescent, metal halide and incandescent lighting, but were denied their truth because of the values shown on the omnipotent light meter.

3.1 Visual clarity

In 1969, Aston and Bellchambers[4] 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 lit 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 to 60 years 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 resultant ratios obtained are in good agreement with the values given by Lynes[5] 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.

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* A portable version of this same study was taken to San Diego, California for the 1992 annual meeting of the Illumination Engineering Society of North America. Over 100 attendees composed of lighting engineers, designers, researchers and manufacturers participated in a quasi study with the same illuminants and conditions as described above. The choice of the illuminant which provided the brighter scene was overwhelmingly given as the scotopically enhanced one even though it provided about 25% less photopic luminance on the viewed wall.

A second visual clarity study[6] comparing nearly full-size rooms confirmed Aston and Bellchambers findings. In addition, they reported the results of 7 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 7 observers and the 3 WW levels (200, 400, 600 lux)] of 25.8% when equal visual clarity was required and 18.7% 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% for equal visual clarity, while our very rough estimate of the scotopic contribution to brightness perception[3] predicts a 17% reduction.

The authors of these studies on visual clarity and others,[7] have provided perplexing and dubious explanations of these results such as more efficient retinal responses to lamps with narrow band wave 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[8]) has claimed several factors which increase visual clarity such as increased color temperature, 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[7] 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 spectrum affect visual function at typical interior light levels.

3.2 The Piper study

Piper[9] presented a study which purported to demonstrate that a group of subjects (24) 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 causing a different contrast 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 5 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 footcandles 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%.

Our explanation of this result is that HPS lighting has a substantially lower (S/P) ratio than CW fluorescent (0.6 compared to 1.45), leading to larger pupil size and causing smaller depth of fields and poorer performance. Piper offers an explanation of his results which he states is due to the HPS spectrum providing 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 wave length best focused on the retina shifts from red to blue as accommodation increases (Ivanoff[10]; Millodot and Sivak[11]). 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[12] found that contrast sensitivity increased by about 30% 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 improved depth of field 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% between fluorescent and HPS lamps. Such small differences in contrast at the high contrast levels (about 93%) of the Piper experiment are highly unlikely to be the cause of effects of the magnitude of 4% in performance. A rough estimate of how much contrast difference would be needed to achieve a 4% 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.[13] Since Piper adjusted the conditions at the task far point to be just at the limit of "high accuracy" performance we will assume here that it has the value 99%. Using the ogival fit shows that this value would be achieved at a level of VL=3. A decrement of performance of 4% in accuracy would shift the ogive from 99% to 95%. This corresponds to a level of VL=2.7 or a 10% reduction in contrast. This amount is an order of magnitude larger than the results of our contrast measurements due to possible fluorescence. In addition, since Piper measured task performance and not just visual performance, we would expect a significant non-visual component in the measured task times. To find a 4% 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% 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% temporal modulation compared to the 30% to 40% 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% 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.

3.3 The Blackwell study

H.R. Blackwell (1985)[14] 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° 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 CIE model[13] 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 resultant 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 incandescent lamp 1.4, clear mercury 0.8 and HPS 0.6. The relative ordering given by Blackwell is the same as the relative ordering in the S/P values for the four lamps. Because the 3 gas discharge lamps all have flicker modulations close to 100% while the incandescent lamp modulations are on the order of 5%, there is the possibility that flicker was not properly controlled. Nevertheless, the relative performance ordering for the 3 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: (1) the often claimed deficiency in the CIE V(λ) weighting function in the far blue (400-450 nm); (2) chromatic aberration effects; and (3) 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 studies are now underway to determine the pupil spectral response under conditions of luminance variation in the field of view, as well as, brightness perception determined by a full field flicker balance protocol. In addition, specific field studies with realistic environments and tasks should be undertaken to test the generalizability of the scotopic sensitivity hypothesis proposed here.

4. POTENTIAL ECONOMIC BENEFITS OF SCOTOPICALLY RICH LIGHTING

Because scotopically enhanced 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 allow the pupil lumen[15] as the measure of visual effectiveness, we see from Table I 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% less power. The interpretation of this result is that the same visual effectiveness is obtained with 24% less power, and is therefore an excellent strategy to achieve cost-effective lighting energy efficiency. Thus, in North America the common 4-lamp fixture containing four 40 watt cool white lamps could be replaced by a new fixture with 3 narrow band 40 watt lamps and achieve the same visual effectiveness. The difference in cost between 4 CW lamps and 3 NB lamps is about $10.00. At typical operating conditions of 3000 hours and $0.08 per kilowatt hour, the payback is about 1 year. For a lamp with a 5-year lifetime this should be a good return on investment.

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 while maintaining good CRI, with a photopic output of 3,000 lumens. This proposed scotopically rich lamp is referred to as SR-NB in Table I. It would require 31% less energy than cool white lamps to produce the same pupil luminance. This means that the new 4-lamp fixture using four 32 watt cool white lamps could be replaced with two 40 watt lamps of the proposed scotopically rich narrow band type. The two SR-NB lamps at 40 watt each will output about 8% less pupil lumens than the four 32 watt CW lamps, but because the two lamp fixture will have less of a thermal effect in practice it would more than compensate for this difference.[16] This strategy would provide the additional economic benefit resulting from the cost reduction by the substitution of a 2-lamp fixture and a single ballast compared to a 4-lamp fixture with 2 ballasts.

TABLE 1: Visual Efficiency of 40W Fluorescent Lamps

Lamp	Photopic Lumens	S/P Value	Pupil Lumen $[P(S/P)^{.78}]$	Brightness Lumen* $[P(S/P)^{.5}]$	Pupil Lumens Per Watt	Brightness Lumens Per Watt
Warm White	3200	0.97	3125	3152	78	79
Cool White	3150	1.47	4254	3819	106	95
Narrow Band Phosphor CCT 5000°K	3300	1.96	5578	4620	139	116
Scotopically Rich Narrow Band	3000	2.5	6130	4743	153	119

* See reference 3.

5. CONCLUSION

The potential highly cost-effective lighting energy benefits that could accrue from an international transition utilizing scotopically enhanced lighting have been illustrated here. Because this large potential is conceivable, the lighting community should place a high priority on the consideration of an enhanced photometry and take the steps that would integrate these concepts into lighting practice.

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