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DEPT OF TRANSPORTATION
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August 8, 2001

136070

Chris Flanigan
NPS-21, Room 5307
NHSTA
Department of Transportation
400 7th Street, SW
Washington, D. C. 20590

Dear Chris:

NHTSA-01-6885-7

As I spoke to you, please find enclosed a two page driving impressions for the Neodymium Oxide doped headlight lamps, as well as the June 6, 2001 letter to Richard VanIderstine with its attachments.

Yours truly,

Daniel Karpen

DRIVING IMPRESSIONS - NEODYMIUM OXIDE HEADLIGHTS

Daniel Karpen
Professional Engineer

3 Harbor Hill Drive
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Tel: 631 427-0723

In "The Road Less Traveled" which appeared in the July, 1998 issue of LD+A, I described a novel solution to the problem of headlight glare. My solution was to add Neodymium Oxide, a rare earth compound, to the glass of the bulb, to filter out a portion of the yellow with wavelengths between 565 and 595 nanometers.

In June, 2000, I signed a licensing agreement with Federal-Mogul Corporation, which will market the lamps under the Wagner Lighting trade name.

In mid-March, Wagner Lighting announced that they had made up sealed beam lamp types H4651BK, H4656BK, H6024BK, H6054BK, and H6545BK. The Neodymium Oxide is added to the tungsten halogen burner, and the burner capsule appears bluish. Unlike the blue coated lamps, the Neodymium Oxide is incorporated into the glass during the melt.

I have a 1987 Dodge Aries, which uses a sealed headlight lamp. Wagner Lighting supplied me with a set of H6054BK lamps for my vehicle. I had them installed on the vehicle, and I gave the lamps a test drive.

The performance of the lamps was better than I expected they would perform. Due to the reduced yellow content of the light, the lamps appear whitish, rather than yellow, or bluish which is characteristic of the xenon high intensity discharge lamps.

There was excellent contrast of road markings, even those that were worn down. Black and white road signs were of excellent contrast, and could be seen hundreds of feet away, even during use of the low beam.

Red and green reflectors on mail box posts and other places could be seen as far as 800 to 1,200 feet away, allowing time to think about driving, instead of reacting to objects that just became visible. Green street signs "jumped out" at you, especially hard to see street signs for side streets. Stop signs appeared "redder" than one would see in normal daylight.

Light could be easily reflected off the green Interstate signs in high beam from 1,200 feet away. Where there was a long straight section of road, a high beam could be bounced off such signs from as far as 2,640 feet away, or a half a mile.

I found it almost impossible to "overdrive your headlights" whether in high beam or low beam. I was much less tired, in fact, never tired at all, which driving at night with the Neodymium Oxide doped headlight lamps.

I believe that the use of Neodymium Oxide doped headlight lamps will significantly reduce night time accidents.

I also found it easier to see with Neodymium Oxide doped headlight lamps on roads without any street lighting than on roads that had street lights. For the first time in my life, I was able to see pedestrians on the sides of the streets and on sidewalks hundreds of feet away. The colors on the clothing could be recognized easily. The grass appeared as bright green instead of a non-distinguishable color. The outlines of a road, particularly on curves, was excellent.

Where were the lamps ineffective? I found that in downtown areas, the high pressure sodium lighting overwhelmed the color rendering properties of the Neodymium Oxide doped headlight lamps.

I was reading through some correspondence to Bill Jones that I sent him between 1990 and 1992. I had some notes abut about the visual effectiveness of Neodymium Oxide lighting. I took a 150 watt standard A type incandescent lamp outdoors on a cloudy moonless night, and I found that I could discern the color red 175 feet away from this lamp, and the light level, as measured by a photopic light meter, was .001 Foot-Candle.

You can't see colors very well under high pressure sodium lighting, and you can't see colors at all under low pressure sodium lighting. Perhaps we should consider the use of Neodymium Oxide street lights.

There would be significant energy savings. My calculations, based on Sam Berman's work on spectral sensitivity, show that one can replace a 250 watt HPS lamp with a 150 watt Neodymium Oxide doped incandescent lamp, and one would be able to see better.

Isn't it about time that we take a really hard look at how we do street and highway lighting?

Wagner lighting is working on development of other headlight lamp types, and is showing 9004 and 9007 lamps to the automobile manufacturers. In the near future, Neodymium Oxide doped lamps will appear as original equipment.

DANIEL KARPEN
PROFESSIONAL ENGINEER & CONSULTANT, P.C.
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(631) 427-0723

June 6, 2001

Richard VanIderstine
NPS-21, Room 5307
NHSTA
Department of Transportation
400 7th Street, SW
Washington, D. C. 20590

Dear Richard:

RE: LIGHTING ILLUMINATION UNITS

As I spoke to you today, you can't use photopic (daytime) lighting units to predict the visual performance for scotopic (night time) illumination.

It just doesn't work. The net result is the underprediction of the performance of blue rich light sources, and overprediction of the performance of yellow rich light sources.

Sam Berman spent ten years of time researching this problem. His research was prompted by a paper of Blackwell, which is cited and analysed in a paper of Bill Jones that I am including in this package.

What Sam Berman found was that a good blue rich light source, such as a 7500 K full-spectrum fluorescent lamp, was ten times more visually effective than yellow rich light sources such as low pressure and high pressure sodium lamps.

I am sending you copies of two of Sam's many papers. The first paper is the "Energy Efficiency Consequences of Scotopic Sensitivity" paper. It summarizes the work, and provides data on various lamp types.

The second paper is the "Wall Color Effects" paper which refines his formulas and provides an extremely sharp data set.

Sam's work was followed up by a paper of Navvab. Navvab's paper looked at the surround lighting. This paper explains why light sources that illuminate a wider field of view are more visually efficient.'

EFFECT ON NHSTA REGULATIONS

What does this research mean in terms of NHSTA's headlight standards?

At one time, all headlight lamps on vehicles were basically the same in terms of their spectral energy distribution. They were sealed beam incandescent lamps, and basically all of them had approximately the same color temperature (plus or minus a little bit) and the same spectral energy distribution of a filament lamp.

But today's headlight lamps are not the same. There are different light sources. You still have the incandescent sealed beam, but you also have tungsten halogen which has a higher color temperature. You have blue coated tungsten halogen lamps, which have been around for several years, and you have high intensity discharge lamps with a much higher color temperature. Federal Mogul has the Neodymium Oxide doped tungsten halogen lamps, and eventually we are going to have Neodymium Oxide doped high intensity discharge lamps, if anyone gets around to developing them.

You also have different beam patterns as you discussed on the phone with me. The HID lamps seem to have a wider light distribution pattern, which makes them better for the driver, but produces glare for everyone else.

For your information, I have taken a sample of a Neodymium Oxide doped glass filter to filter out the yellow portion of the HID lamp, while I was standing on the side of the road, and I found that I could get rid of the glare from an HID source in this manner.

WHAT DOES ALL THIS MEAN?

What this means is that you can't take a photopic unit of measurement, and apply it to scotopic illumination.

For the first time, we have S/P ratios of a number of headlight lamp sources, as shown by Table 6 on page 21 of UMTRI report 2001-9, dated April, 2001, and prepared by John Sullivan and Michael Flannagan. Their research showed that the Neodymium Oxide doped tungsten halogen lamp, with an S/P ratio of 1.72 compared with an S/P ratio of 1.55 for a standard tungsten halogen lamp. That means that the Neodymium Oxide doped lamp is 11 percent more visually effective, foot-candle for foot-candle, than a standard tungsten halogen lamp. I am attaching this paper directly to this letter.

The present standards, which gives allowable minimum and maximum candlepowers, do not take into account the changes in the lamps now being used for motor vehicles.

I would suspect that the S/P ratio for an HID lamp is somewhere between 2.0 and 2.3. We have computer programs that can calculate these numbers based on a spectral energy distribution of the lamp. These lamps were not evaluated in the UMTRI report.

In order to correctly predict visual performance, based on what we currently know of the physiology of the eye, we must immediately change DOT regulations to base all minimum and maximum performance standards of the lamps on the scotopic candlepower, not the photopic candlepower.

I am petitioning NHSTA to start a rule-making proceeding to accomplish this goal.

Yours truly,

Daniel Karpen

cc: (of letter and attached table only)
Michael Perel NHSTA
Keith Bucher (Federal Mogul Corporation)
Bill Jones, Lighting Research Laboratory, Orange, California
Secretary of Transportation Norman Y. Mineta

Table 6. Threshold difference factors between centrally viewed (C) and eccentrically viewed (E) light sources, and the calculated scotopic/photopic ratios.

Source	C vs. E Threshold Difference	Scotopic/Photopic Ratio
Blue	0.83	1.63
ND	0.84	1.72
TH	0.74	1.55
Deep Red	0.37	0.19
Deep Blue	0.99	3.90

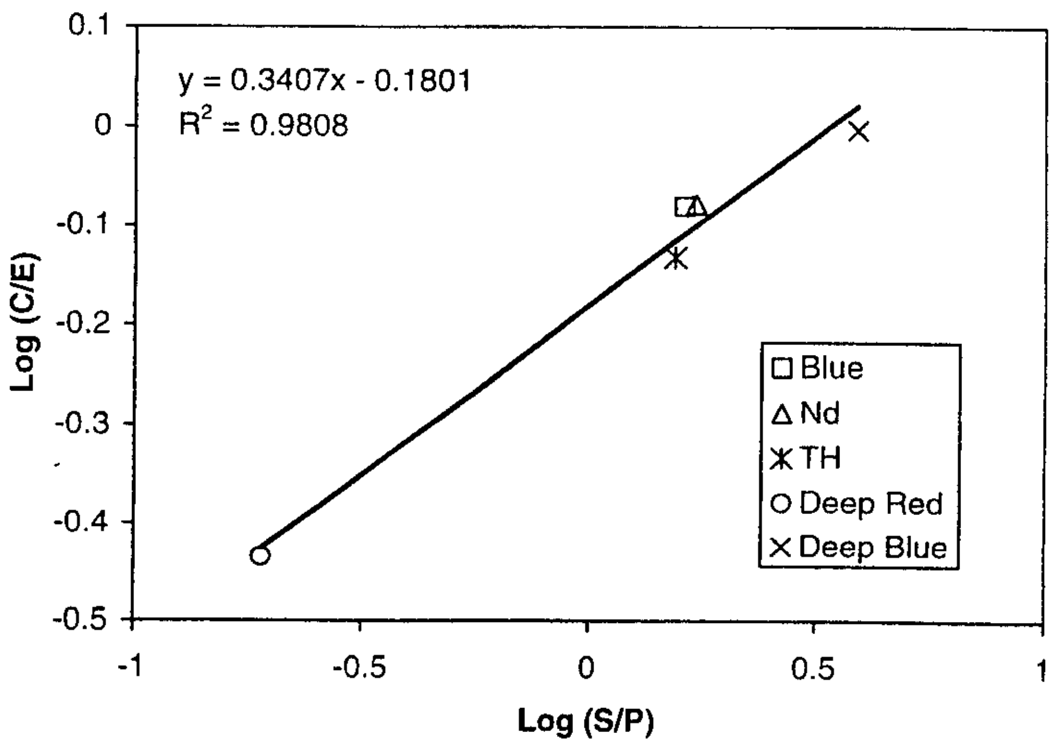

Figure 10. The relationship between log of the threshold ratios (central threshold divided by eccentric threshold) and log of the scotopic/photopic ratios.

A Comparison of Visual Performance Under High and Low Color Temperature Fluorescent Lamps.

Mojtaba Navvab, Ph.D.

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Abstract: Over a two year period, two sets of 101 subjects each were tested for word reading and letter acuity under two different fluorescent lighting systems. Subjects' word reading acuities were evaluated in a test room while they were seated at a desk in normal reading posture and read unrelated words of progressively diminishing size with the words placed in a horizontal or nearly vertical position. The lighting in the room was provided by either an equal number of low color temperatures or high color temperature fluorescent lamps in the conditions of fully lit surround or dark surround. Because of the equal number of lamps, task luminance was always at least 50% higher under the low color temperature lamps. In spite of this large bias favoring the low color temperature lighting, word reading acuity was highly significantly better under the high color temperature lamps for the fully lit surround condition. No significant differences in acuity occurred in the dark surround condition. Spectrally driven pupil size changes are conjectured as the mechanism responsible for the observed effects.

Introduction and Background: Recently a pilot study of the effects of lighting spectrum on psychological and vision factors of elementary school children was undertaken in Bay City Michigan. In that study, full spectrum (FS) lamps of high color temperature of 6300K and CRI of 85 were compared with low color temperature lamps, 3500K and CRI of 70 ('735') at approximately equal levels of illumination. Very brief vision testing was performed on a selected sample of the participating children yielding results that showed some factors were better under FS lighting than under the '735' lighting. In that study only monocular acuity of the students was measured and the lighting comparisons were separated by a period of at least 6 weeks in order to allow for a sufficient period to elapse for the possible psychological effects to occur.

Because of prior claims for the vision benefits of scotopically enhanced lighting **[1,2,3]** which is provided by the FS lamp, and the conditions of measurement used in the Bay City elementary school study, a separate investigation of the effects of different lamp spectrum on normal binocular visual acuity was undertaken at the lighting laboratory of the University of Michigan, College of Architecture and Urban Planning.

At this site there is a 10x10x10 ft. room where the lighting conditions can be readily changed and where subjects can sit at a desk and be easily tested for near visual acuity. **Figure -1** shows the view of the actual workstation in the room used for testing the subjects' visual performance. In the absence of a dimming ballast we decided to compare the FS lamps and the '735' lamps on the basis of an equal number of lamps. Because of the difference in photopic lumen output of these two lamps there will be substantial differences in both the task luminance and the illuminance at the subjects' eyes. Measurements showed that this difference was always greater than 50% with the '735' lamp always producing the higher levels. Nevertheless, because of the higher S/P value of the FS lamp (S/P=2.3) its scotopic illumination levels were always higher than the '735' lighting (S/P=1.3). Thus; in spite of the very large bias in task photopic luminance favoring the '735' lighting, we decided to test the acuity of a large number of subjects with good eyesight. The populations gender ratio for both studies was approximately 50% female and 50% male between 22-25 years of age.

Study Concept: Two different lamp spectra lighting a room are to be compared for their effects on visual acuity. The lighting conditions are such that the illuminated acuity task can be viewed with either a fully lit surround, i.e.; the walls are basked by the lighting or with a dark surround where the walls are dark. If pupil size is primarily controlled by the surround lighting then for the FS lighting (high S/P) pupil sizes will be smaller than for the '735' lighting (low S/P). According to previous research findings, a smaller pupil will elicit better acuity and therefore the acuity should be better under the FS lighting **[4,5,6]**. On the other hand, if the test is carried out with the dark surround, then just changing the spectrum of the task lighting should not change pupil size and there should be no difference in the measured acuities.

Protocols: The visual task was a series of unrelated words on a chart presented at high contrast (black letters on white background) that continually diminished in size as the lines proceed from top to bottom of the chart. Lines can have several words. (Bailey-Lovie charts from the University of California School of Optometry)**[7,8,9]**. Subjects were scored on the number of correct words read. The charts were placed on a desk in both a horizontal position and a tilted position, 30 degrees away from the vertical (somewhat simulating computer geometry) with the subjects seated in a chair placed 5 inches from the desk. The distance from the subjects' eyes to the mid-point of the charts was in the range of 14 to 19 inches. Subjects were told not to bend when reading the words and were told to read the words out loud. **Figure-2** shows the schematic cross section view of the workstation.

The study was carried out in two phases because of time and labor constraints. One phase tested only the dark surround for the two lamps and the other fully lit surround condition. These phases were separated by approximately one year and hence used a different set of subjects. Thus the two lamps were compared under the dark surround condition by one subject group and again compared in the fully lit surround condition with a different subject group. In both phases 101 subjects were evaluated. The illumination or lighting conditions are described by using indices such as average task luminance, illuminance at the eye and illuminance on the vertical wall surface. The summary of the data is shown in **Table-1.**

In this viewing geometry the test lighting included about 40 degrees of viewing angle as compared to the 180 degrees in the full field of view when the subjects were completely seated inside the room as in the first study. Under the restricted lighting conditions of this second study we would expect the pupil size differences between the FS and '735' lighting to be diminished and this should cause less of an effect on differences of acuity.

Table 3 below shows the lighting level conditions for this second study (subjects standing at 20 feet distance from the letter chart) and Table 4 shows the results for the two sets of 101 subjects (phased as in the first study). In **Table 4** the white wall and dark wall conditions refer to the walls of the test room. Note that, as was the case in the first study, the luminance on the letter chart is about 50% greater for the '735' lighting as compared to the FS lighting.

Table 3. Lighting conditions for second study for acuity test at 20 feet distance from letter chart.

Lighting conditions.	Average task luminance.	Vertical illuminance at the eye.
White walls and FS lighting (fully lit surround of first study)	70 Nits (cd/m^2)	6.0 Lux (lm/m^2)
White walls and '735' lighting	99	7.6
Dark walls FS lighting	60	1.1
Dark walls '735' lighting	87	1.3

Table 4. Results of the second study for acuity test at 20 feet distance from letter chart.

Lighting Conditions	Mean number and standard error of correctly identified letters (high contrast letters)	Mean number and standard error of correctly identified letters (low contrast letters)
White walls and FS lighting	48.3± 0.5	42.1 ± 0.6
White walls and '735' lighting	47.0 ± o.5	40.2 ± 0.6
P value for the difference between FS and '735'	0.038	0.018
Dark walls and FS lighting	46.3 ± 0.6	39.1 ± 0.6
Dark walls and '735' lighting	45.4 ± 0.5	39.8 ± 0.6
P value for the difference between FS and '735'	0.26	0.39

The results shown in **Table 4** demonstrate that the differences in acuity scores between the FS and '735' lighting in the white wall condition are much smaller in the second study as compared to the first study. This diminished difference is consistent with the smaller change in pupil size that is expected when a smaller portion of the visual field is receiving light. Nevertheless, some statistically significant results are present (white wall condition) with better acuity for the FS lighting even in the presence of the strong luminance bias favoring the '735' lighting. Again in the dark wall condition there is further reduction in the field of view receiving light and there are no significant differences between the two lighting systems. Pupil sizes were not measured in the second study but variation in pupil size is the most parsimonious explanation of the results of both studies. **Figure 4** show the luminance distribution within the actual workstation (white wall

Table 1- Average task luminance on the task and illuminance at the eye.

Lighting Conditions	Horizontal Task Luminance	Tilted Task Luminance	Illuminance at the eye looking at the H. Task	Illuminance at the eye looking at the Tilted Task	Illuminance on the Side walls surface
Fully lit surround with FS lamp.	74 Nits (cd/m^2)	42 Nits (cd/m^2)	69 Lux (lm/m^2)	75 Lux (lm/m^2) .	40 Lux (lm/m^2)
Fully lit surround with '735' lamp.	109	58	105	122	64
Dark surround FS	50	31	16	23	1.1
Dark surround '735' lamp.	63	39	24	27	2.0

Results: The principle results of the study are a set of values for word reading acuity expressed as the mean number of correct words read for the various lighting conditions. These are listed in **Table-2.** For the fully lit surround condition the differences in mean score between the 2 lamp types (same subject group) are some 5 to 9 standard error units. Thus the very high statistical significance indicated by the p values, i.e., for the horizontal task, the probability that the FS lighting provides better acuity is 99.999%. **Note** that this result occurs even in the presence of the very strong luminance bias favoring the '735' lighting. This bias is strongly evident because, for a fixed lamp type, it is likely that increasing task luminance causes better performance. Support for this argument is suggested by comparing mean acuities for the horizontal and tilted positions for either the fully lit surround or the dark surround. The luminance is 50% to 70% higher in the horizontal position (due to the fixture geometry) and the differences in acuity favor the higher luminance condition by more than 10 standard error units. This argument would be stronger if we had direct evidence on the effect of changes in task luminance with the task kept constant. In the dark surround condition but with the other subject group, there were no significant differences between the two lamp types for either of the task positions.

Table 2. - Mean number and standard error of words read correctly for the various lighting and task conditions.

Lighting Conditions	Task horizontal	Task tilted
Fully lit surround and FS lighting.	67.6 ± 0.5	61.9 ±0.4
Fully lit surround and '735' lighting.	64.9 ± 0.4	58.3 ± 0.4
P value for the difference between FS and '735' lamps.	7 E-06	5 E-09
Dark surround and FS lighting on task area.	66.6 ± 0.8	60.0 ± 0.7
Dark surround and '735' lighting on task area.	66.2 ± 0.8	59.8 ± 0.7
P value for difference between FS and '735' lamps.	0.7	0.8

Discussion: In the previous studies of the relationship between spectrally induced pupil size changes and acuity, the visual task was always located at a distance of 39.37 inches **(1 meter)** or greater from the subject [5,6,7]. This positioning protocol was utilized in order to diminish the light independent effect of accommodation on pupil size. (Generally there is a reduction of pupil size accompanying the eyes' accommodation response to near tasks). The luminance measurements were made in the direction of gaze for both the horizontal and vertical word charts. The angle of tilt from the vertical for the 'vertical' charts was zero and 30 degree for the tilted word charts. The illuminance at the eye changes for the horizontal and vertical positions due to the viewing direction and the background walls' luminance. There is no veiling glare in the vertical position. Both word charts surfaces were lambertian surfaces. Both lighting systems were powered by 60 Hz and 120 volts ballast. There was no possibility that the lens used to cover the low CCT lamp could have changed its spectral output. The lens showed no signs of yellowing and If that were the case some of the blue end of the low CCT spectrum would be absorbed out and its S/P value would have be even lower than 1.3. There were no changes in the chromaticity of the measured values with and without a lens therefore there was not much of a spectral effect. The luminance distributions compare for the two lamps in the word reading mode did not show any an appreciable difference in light distribution on the task. This could have been a concern as a possible cause for the performance difference.

The study reported here did not measure subjects' pupil sizes. Nevertheless, we hypothesize that spectral effects on pupil size is the likely mechanism responsible for our word reading accuracy results in the comparison of the FS and '735' lighting. Given the strong light level bias favoring the '735' lighting, the results presented here overwhelmingly demonstrate the visual superiority of FS lighting over conventional warmer color temperature lighting. The current methods and design guideline practiced by lighting designers cannot reach such a conclusion. Furthermore, in view of our findings and in addition, to some highly successful applications by other forward thinking lighting practitioners, there is a compelling reason to study and question the comprehensiveness of the current IES recommendations for interior lighting **[10]**.

Second study: Some support for pupil size changes as the mechanism responsible for the results of the word reading study is provided by a second study conducted in the same laboratory comparing FS lighting and '735' lighting but with viewing conditions somewhat different than in the first study. **Figure-3** shows the schematic view of the experimental set-up for the second study reading the letter charts and the extent of binocular (vision by both eyes) and monocular (vision by one eye.) visual fields. The binocular visual field extends vertically 130 and horizontally 120 when both eyes are focused on the fixed object.

In this second study acuity is again evaluated with subjects viewing a standard acuity letter chart of both high and low contrast (10%) but in a lighting geometry where much less of the surround is illuminated. This was accomplished by first removing the back wall of the test lighting room and then having the subjects standing in the non-illuminated larger hall that housed the test lighting room while looking into the that room through the open wall. Subjects stood a distance of 20-ft. (10 ft. back from the removed wall) from the chart that was placed on the front wall of the lighted test room. Lighting by the FS lamps and the '735' lamps was provided only in the 10x10x10-test room. Under these viewing conditions, where only a small portion of the surround visual field is exposed to light, prior research has shown that changing the spectrum of the surround light is less effective in eliciting corresponding pupil size changes **[1,2,3]**.

room and the full spectrum lighting system) measured using the digital scanning system. (8mm, lens, 180 degrees, equal-distance).

Brightness Judgments: Subjects responses were obtained to the question posed of differences in perceived brightness between the two lamp types. The question of brightness comparison was asked of the subjects at the beginning of the second study. In the condition of white walls the illuminance at the eye or the mean luminance of the back wall was about 25% higher for the "735" lighting as compared to the FS lighting. Nevertheless, 76% of subjects said that the two lighting systems were equal in perceived brightness, 17% said the FS was brighter and 8% said that the FS was dimmer. In the condition of the black walls study more than 50% claimed that the lighting systems were perceived as equally bright.

Conclusion: A previous study of brightness judgments comparing different lamp spectra seen in full viewing field conditions claimed that equality in brightness is achieved when the ratio of the viewed luminance is the inverse of the square root of the ratio of S/P values [4,5]. For the lamps used here this factor is $\sqrt{(2.3/1.3)} = 1.33$. Given the smaller field of view in our study, that value is quite consistent with the brightness judgments reported here. We conclude that all our results are most easily understood as a consequence of scotopic sensitivity at these interior light levels.

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ACKNOWLEDGMENTS: Special thanks to: Dr. Sam M. Berman, Dr. Clear, R. in association with Lawrence Berkeley National Laboratory and Dr. Bailey, IL, from the University of California School of Optometry for their assistance and contribution in application of the various photometry concept to this work in lighting applications.

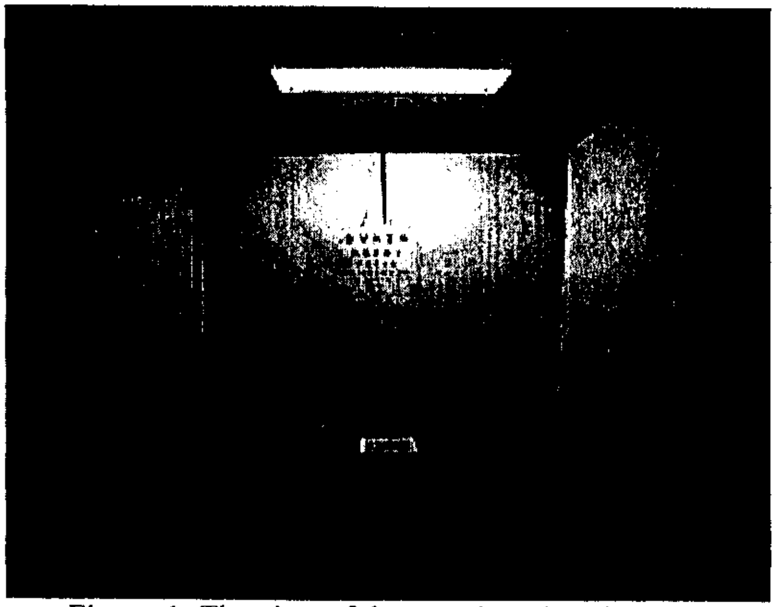

Figure 1- The view of the actual workstation used for testing the subjects' visual performance

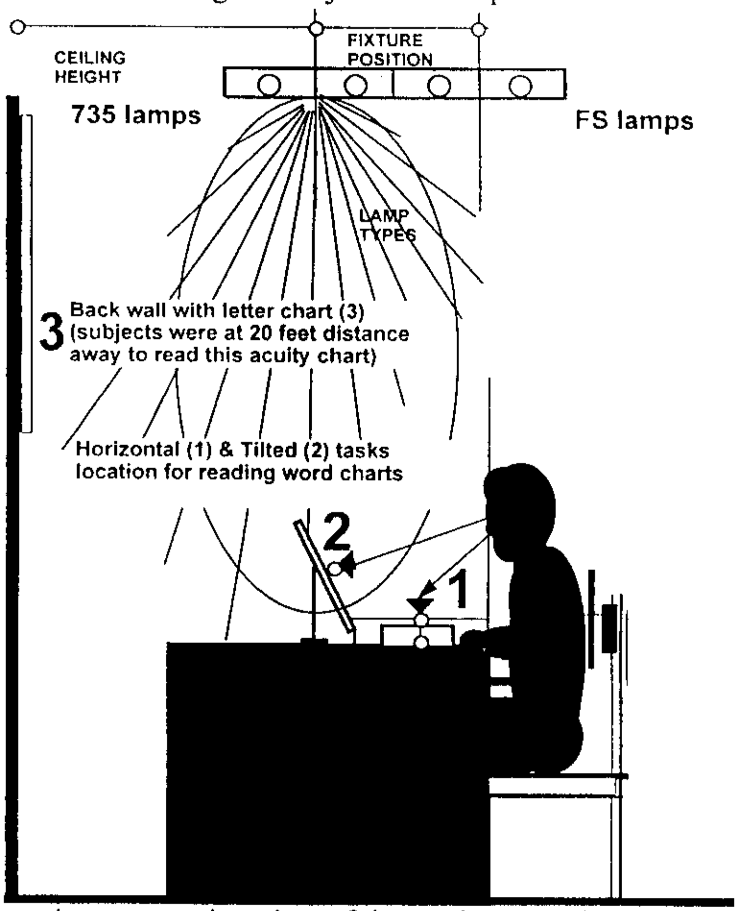

Figure 2- Schematic cross section view of the workstation showing the task and source relationships used for testing the subjects' visual performance

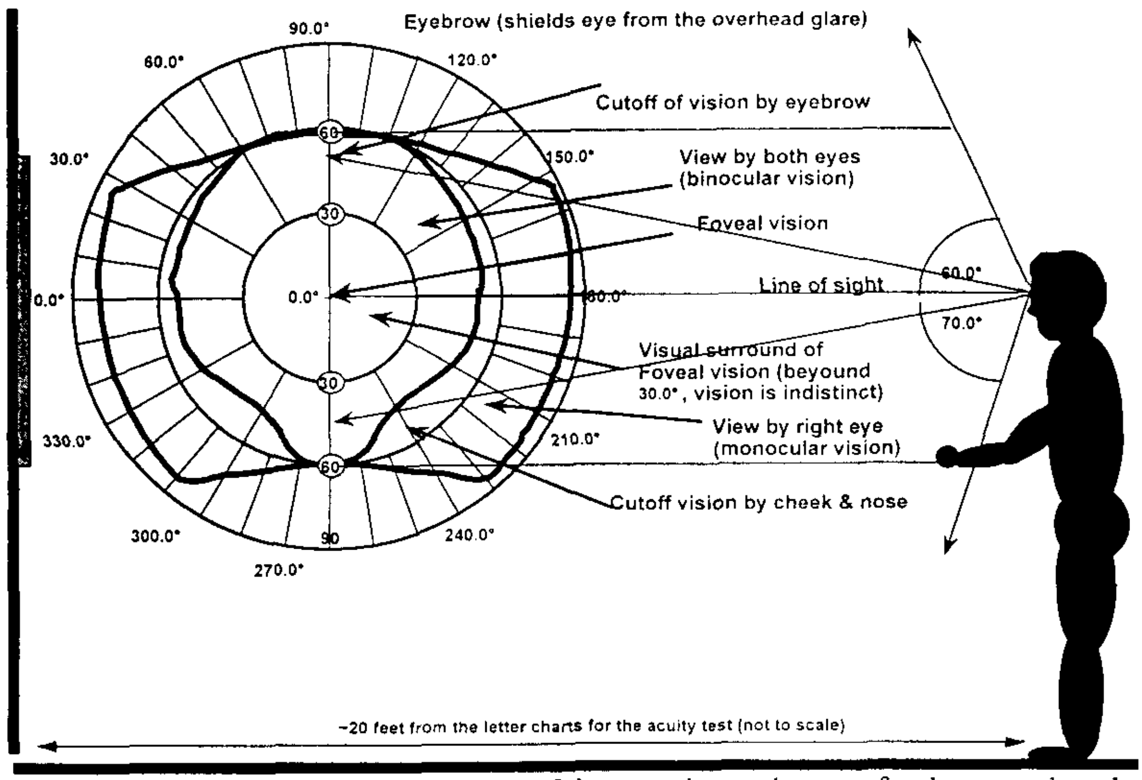

Figure 3. The schematic view of the experimental set-up for the second study (reading the letter charts) and the extent of the binocular and monocular visual fields.

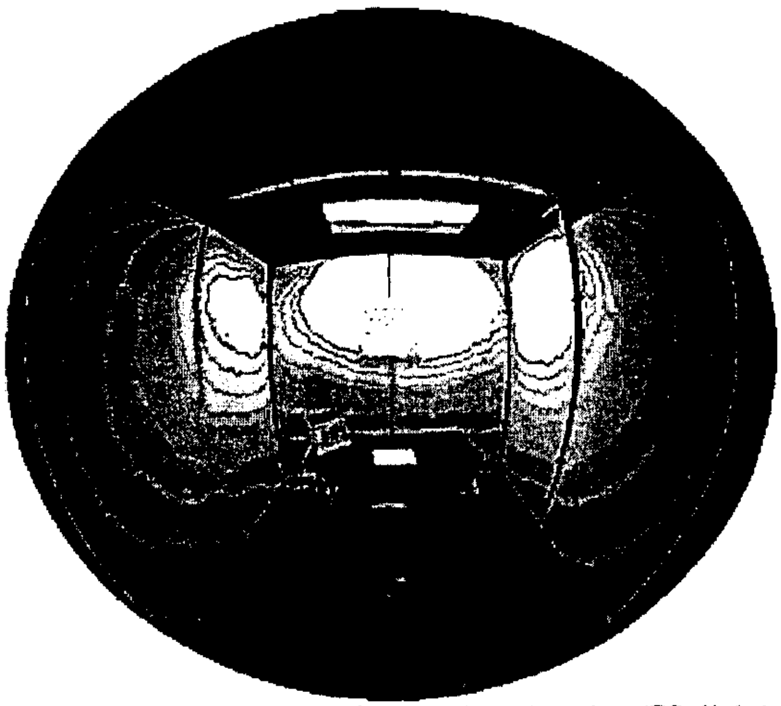

Figure 4- The luminance distribution within the actual workstation (FS. lighting system & white walls) measured using the digital scanning system. (8mm, lens, 180 degrees, equal-distance).

Energy Efficiency Consequences of Scotopic Sensitivity

S.M. Berman

THIS PAPER WAS PRESENTED AT THE 1991 IESNA ANNUAL CONFERENCE.

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 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

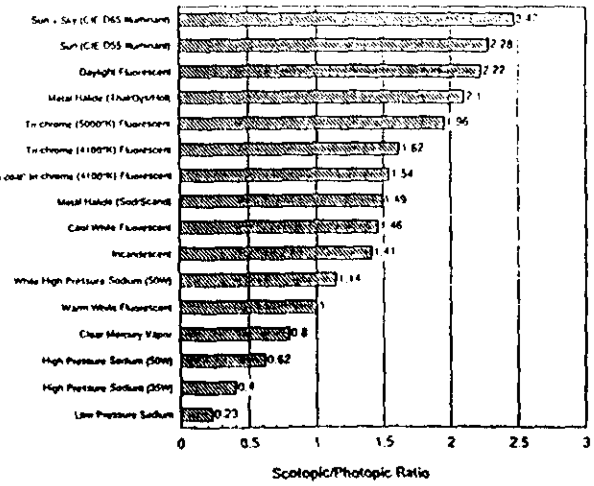

Figure 1—Scotopic/photopic ratios for various light sources

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.[5] 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

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 U.S. Department of Energy under Contract No. DE AC03-76SF00098.

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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 reevaluate 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.

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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, our 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.

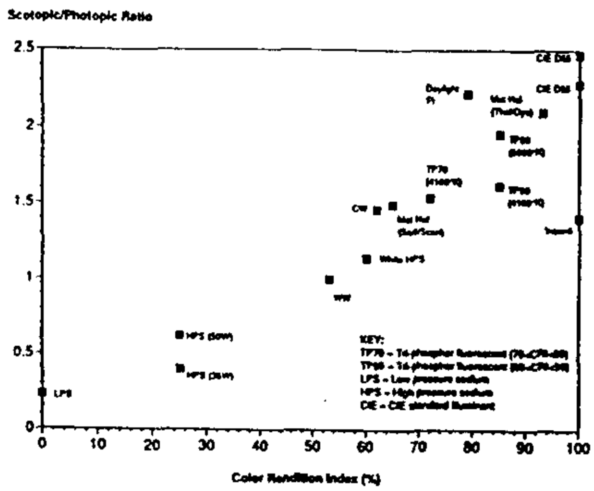

Figure a—SP ratios for black body radiators at varying color temperature

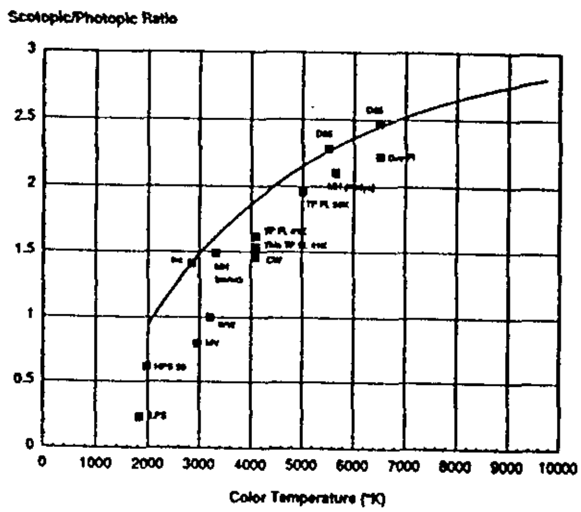

Figure b—Scotopic/photopic ratio vs. color rendition index for various light sources

Despite Different Wall Colors, Vertical Scotopic Illuminance Predicts Pupil Size

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THE 1996 IESNA ANNUAL CONFERENCE

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Introduction

Illumination recommendations for building interiors[1] are often based on criteria such as visual performance, brightness perception, and visual comfort, but not upon spectral power distribution (except as related to the color rendition index).[2] However, because of the visual consequences of scotopic sensitivity, illumination specifications that neglect spectral effects may be less than optimum in terms of vision and/or brightness perception.[3] We have previously shown that the spectral response of pupil size is predominantly a scotopic sensitivity.[4] We have also demonstrated that brightness perception, although not dominated by scotopic spectrum, has a prominent contribution dependent on the scotopic content of the illumination.[5] These effects are manifested when the lit environment is viewed in full visual field, the typical viewing conditions for occupants of building interiors. Conversely these effects are not observed if the visual field is confined to small angles, which is the procedure used in the determination of the photopic V(λ) function. Since the V(λ) function is the basis of calibration of photometers and light meters, scotopic sensitivity is not a part of a general lighting practice which relies on illuminance measures.

In our previous study on pupil size,[4] we measured the effect of light spectrum for young adult subjects (ages 20–40 years) in conditions of almost full field of view and luminances typical of interior lighting conditions. The previous study differed from the study reported here in several ways, so we describe the conditions of the previous study. The room had spectrally flat white walls and an unpainted natural wooden floor. The infrared pupilometer partially obstructed about 1 steradian of the total full field of view (2π sr). Either a small fixation spot located on the front wall or a small low luminance TV was viewed by the seated subjects, who leaned slightly forward while placing their heads on a chin rest.

Employing a wide variety of fluorescent lamps of different spectra, we established that photopic and scotopic spectrum combined in a particular manner to provide the pupillary spectral response when the luminance range was restricted to lie between 20 cd/m^2 and 300 cd/m^2. The spectral response was determined by expressing the data for the average pupil area (A) in the form

$$\log A = c - a(\log S) - b(\log P) = c - (a+b) \log [P (S/P)^{a/a+b}]$$

where S and P were the scotopic and photopic luminances of a control area on the front viewed wall and a,b,c are constants fitted to the data. The quantity P (S/P)a/a+b we refer to as pupil luminance. The exponent (a/a+b) was empirically determined from our data to have the value 0.78 when viewing the fixation spot and approximately 1.0 for TV viewing.

We have previously demonstrated in several studies[6-8] that visual acuity and contrast sensitivity of normally sighted subjects at typical interior light levels are determined by pupil size and not by retinal photopic illuminance. Thus, the efficacy of lighting to influence visual performance is best evaluated by pupillary illuminance rather than by strictly photopic quantities.

We now extend our findings to a more realistic, colored environment, using standard commercially available lamps, measuring pupil size remotely, keeping equal the photopic vertical illuminance at the subject's eye. In addition, we have also measured the power consumed by the ballasts for the various conditions of lamp type and wall color, thereby determining the effective pupillary efficiency for a lamp combined with a wall color.

Methods

Subjects

All procedures were approved by the Human Use Committee at the University of California, Berkeley. Twelve female and five male subjects who responded to local newspaper advertisements and college postings were studied. They ranged in age from 23 to 47 years, with a median age of 34. Fourteen of the subjects did not use spectacles or contact lenses, while three wore contact lenses or glasses and were tested while wearing them. All subjects were determined to have Snellen acuity of better than 20/30, as tested. Prior to testing, subjects were screened by questionnaire regarding unusual sensitivity to light, and for pupils unresponsive to added peripheral light. No subjects were excluded from the study.

Pupil size recording an ASL Model 4250R remote Eyetracker/Pupilometer[9] was used to measure subjects' pupil size under the conditions of the experiment. The instrument measures pupil diameter (horizontally across the pupil) at a sampling rate of 60 Hz. The ASL E4000(V. 4.8620B) software package was used to control the pupilometer and send pupil diameter and point of gaze infor-

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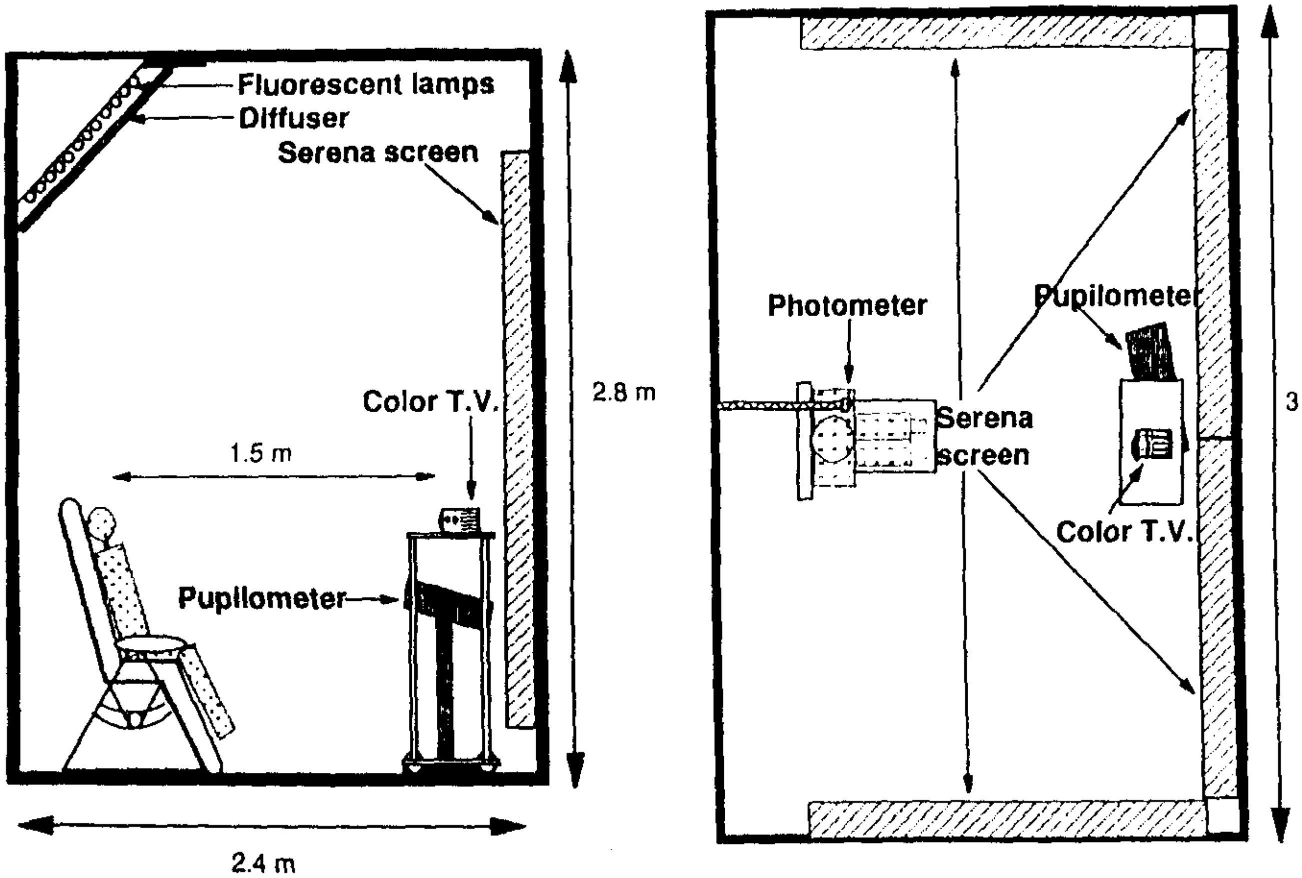

Figure 1— **Drawing of the simulated office showing subject position, fluorescent lamps, diffuser, serena screens, small screen color television, ASL pupilometer, and LMT photometer head (not to scale).**

mation to a master computer. The master computer used software written by Abratech Corporation to remove blinks from the raw data. Both the raw data and processed data were saved in data files.

Surround lighting

The study took place in a rectangular room with a 2.4 by 3.6 m (8 by 12 ft) floor area, and a ceiling height of 2.8 m (9 ft, 3 inches). A specially designed lamp fixture containing 24 fluorescent lamps (F40T12) controlled in pairs by 12 high-frequency, solid-state dimmable ballasts provided lighting for the room. The lamps were mounted horizontally at a 45 degree angle from the wall, above and behind the subject (**Figure 1**). The subject was seated such that illumination on the viewing surface came directly from the lamps, with no direct light rays from the lamp fixture being seen. The intensity of the lamps was controlled by computer.

The lamps were chosen because of commercial availability and significant scotopic differences in spectra: a scotopically rich daylight lamp and a scotopically deficient lamp. The correlated color temperatures (CCT) were 7500 ° and 3000 °K respectively. The scotopic-to-photopic ratio of the lamp spectra was S/P = 2.40 for the scotopically-rich daylight lamp and S/P = 0.97 for the scotopically-deficient lamp.

The vertical photopic illuminance and scotopic illuminance at the level of the subject's eye directly under the bank of fluorescent lamps was measured with an LMT B510 photometer. The study was conducted at two nominal vertical illuminances of 64 and 108 photopic lx (6.0 and 10.0 fc) for each of the two lamp types. Because of lamp thermal effects, the actual vertical illuminances differed slightly; actual values were used in the data analysis and in the figures. Each of the illuminant conditions were studied with each of the four different colored walls.

Visual field

The color of the vertical walls surrounding the subject were controlled by motor driven Lutron "Serena" screens,[10] allowing for changes from one wall presentation to another in about 15 sec. Three meters of the front wall as viewed by the subjects were covered by two 1.5 by 2.1 m high screens, while the side walls each had a 1.5 by 1.8 m unit (**Figure 1**). Three colors and an open setting (exposing the white walls behind the screens) were chosen to give markedly different spectral

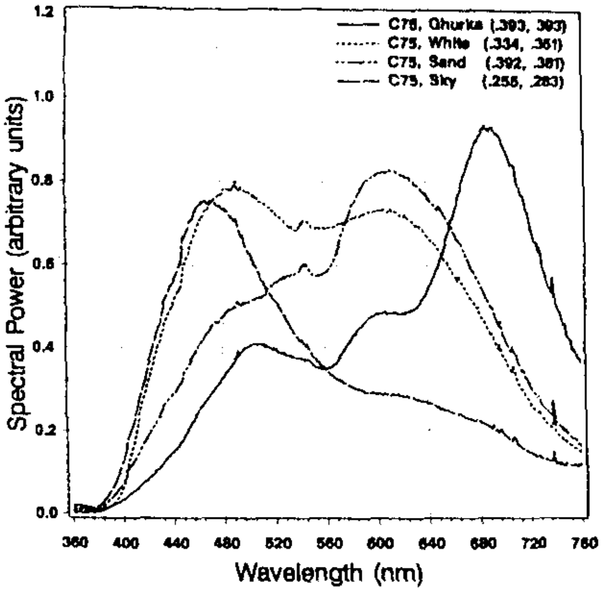

Figure 2—Wall spectral power distribution for the scotopically-rich daylight lamp and four wall surfaces. The chromaticity coordinates for a ten degree standard observer are also given.

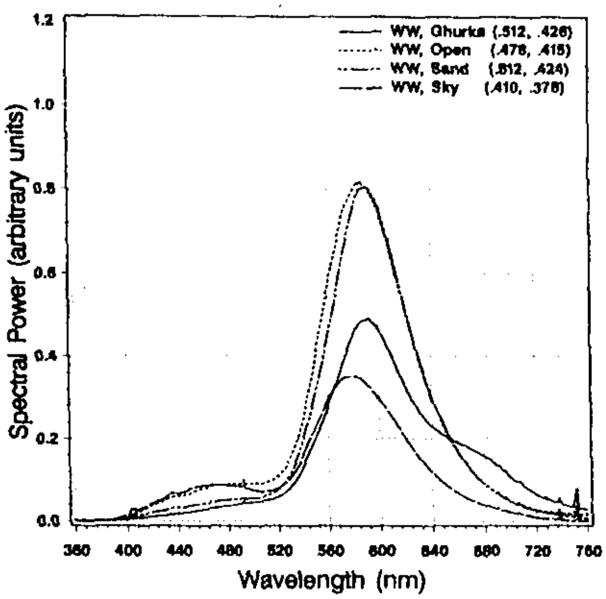

Figure 3— Wall spectral power distribution for the scotopically-deficient lamp and four wall surfaces. The chromaticity coordinates for a ten degree standard observer are also given.

reflectances. The colors were sky blue, sand, and a reddish brown referred to as ghurka. The wall spectrum (measured directly above the TV) under the different illuminants, for the condition of equal photopic vertical illuminance at the subject's eye, are shown in **Figures 2** and **3**. **Table 1** lists the values of the S/P ratio obtained by measuring the illuminances at the eye with the LMT illuminance meter for the two lamp types and the four walls.

The subject faced the long wall of the chamber and viewed a color television with a 11.4 by 7.6 cm screen. The screen subtended a horizontal angle of four degrees and a vertical angle of three degrees. With the room lights off, the TV produced a vertical photopic illuminance at the eye ranging from 0.22 lx to 0.32 lx. The luminance of the TV as viewed from the eye position with the movie showing and the room lights on ranged from 35 cd/m^2 to 220 cd/m^2 while the luminance of the wall to the right of the TV ranged from 15 cd/m^2 to 56 cd/m^2 with the lower values associated with ghurka and sky walls when the vertical illuminance at the eye was set at 64 lx and the higher values with the white and sand walls when the vertical illuminance was set at 108 lx.

Testing procedure

The subject had a variety of bland (nonemotional) movies to choose from. Subjects were seated in a comfortable chair in the experimental chamber and familiarized with the equipment. The remote pupillometer focus and eyetrack positioning were then adjusted and calibrated. A head-mounted earphone/microphone intercom system was used between the subject inside the chamber and the researcher outside.

During each condition, the lighting levels were adjusted and then the subject was given a minimum of 2 min to adapt to changes in the surround lighting and Serena screens. After the adaption time, pupil diameter data were recorded for 30 sec.

Presentation sequence

Sixteen conditions were tested, with each condition consisting of a lamp type (scotopically-deficient or scotopically-rich lamp), a light level (64 or 108 photopic lx of vertical illuminance at the eye), and a wall color (white, sky, sand, or ghurka). A subject was presented with three sets of conditions, each set being a random order of the 16 conditions (a grand total of 48 conditions for each subject). Because of fluctuation in light output with lamp temperature, the light level was adjusted within a tolerance of a few lux at the start of each condition.

Subjects were permitted rest periods on request to minimize subject fatigue or boredom. A testing session for a subject lasted about 3 hrs.

Data analysis

Prior to statistical analysis, an average value of log pupil area for each subject was determined for a particular condition by averaging over the 30 sec data gathering period. A repeated measures Analysis of Covariance (ANCOVA) was then applied where the repeated measures were trials (3), lamp type (2), walls (4), and lamp level (high, low). The log photopic and log scotopic values of vertical illuminance were treated as covariates. We used the BMDP-5V statistical analysis program. No attempt was made to include higher order powers of the log vertical illumi-

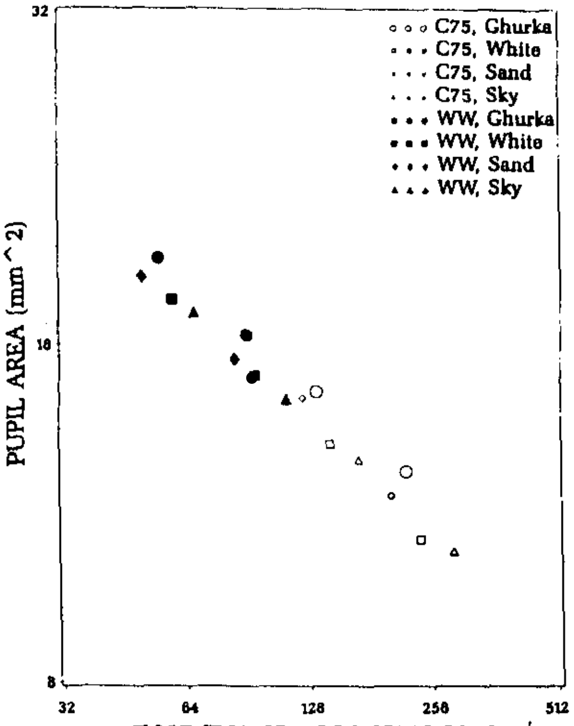

Figure 4—Graph of mean pupil area for the 17 subject vs the mean vertical scotopic illuminance as measured at subject eye level. The 16 data values are the results for the two lamp types, four wall colors, and two levels of vertical photopic illuminance at the subject's eye. The mean pupil area was calculated from the average of the log pupil area.

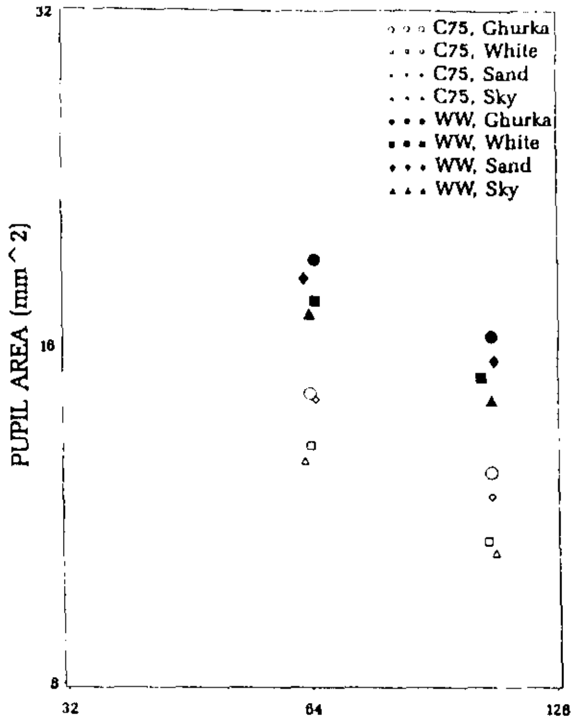

Figure 5— Graph of mean pupil area for the 17 subject samples vs the mean vertical photopic illuminance as measured at subject eye level. The 16 data values are the results for the two lamp types, four wall colors, and two levels of vertical photopic illuminance at the subject's eye. The mean pupil area was derived from the average of the log pupil area. The slightly different values of photopic illuminance at the nominal 64 or 108 lx occurred due to lamp thermal effects (see text).

nances since their range was limited, i.e., from about 64 to 108 photopic lx or 50 to 287 scotopic lx.

Results

Based on our previous study of the spectral response of the pupil where subjects watched a small television, we expected that log pupil area should be linearly related to the log scotopic illuminance. This was confirmed by these experiments, as shown in **Figure 4** which plots the mean pupil area for each of the 16 conditions. The pattern displayed is quite linear and in reasonable agreement with our previous study. The ANCOVA procedure based on the hypothesis that

$$\ln A = a - b(\ln S) - c(\ln P)$$

where A is pupil area and a,b,c are fitted constants, yielded the result a = 4.32 (±0.11 s.e.), p<0.0000; b = 0.33 (±0.01 s.e.), p <0.0000; and c = 0.02 (±0.02 s.e.), (p = 0.38). The Wald test of significance of the covariates yielded for the scotopic covariate (χ^2 [1 DF] = 814, p<0.000) and for the photopic covariate (χ^2 [1 DF] = 0.78, p = 0.38). This analysis shows a trend in the photopic component that is not statistically significant. Establishing the statistical significance of such a small photopic component would require a much larger subject sample. In the model where both log scotopic illuminance and log photopic illuminance were the covariates, the ANCOVA procedure was also used to investigate possible additional interaction terms between scotopic illuminance and lamp type as well as photopic illuminance and lamp type. These possible interaction effects were both evaluated as not significant (p = 0.4 and 0.6, respectively) and hence these covariates were adequate. While the scotopic illuminance explains the pupil areas observed (**Figure 4**), the photopic illuminance alone is a much poorer predictor of pupil size (**Figure 5**). The data plotted in **Figures 4** and **5** are listed in **Table 2**.

Pupil efficacy

Figure 6 is a plot of the mean pupil area for the 17 subjects as a function of lamp power for the eight conditions. Lamp power for the eight lamp systems was determined by measuring the light output when either the scotopically-deficient or scotopically-rich lamps were operated at full ballast power. To account for possible

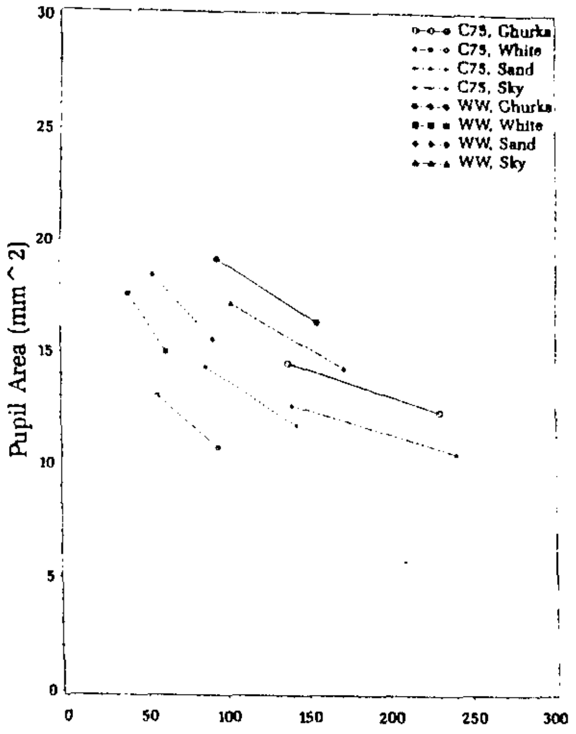

Figure 6— Graph of mean pupil area for the 17 subject sample vs the power consumption. Ballast power and efficiency have been accounted for in the values of lamp power (see text).

ballast losses due to operation at less than 100 percent output from affecting the results, the power for a given condition was determined by prorating the 100 percent power by the ratio of illuminance at the test condition to the illuminance at full power.

From **Figure 6**, where the line joining the data points are for a given wall color, it can be seen that in the regions of overlapping power, the scotopically-rich lamps produce much smaller pupils for all wall colors even though in terms of photopic lumens per watt the scotopically-deficient lamp is 50 percent more efficacious. From the last column of **Table 1**, it can also be seen that the power requirement to achieve a given level of scotopic illuminance is much greater for the scotopically-deficient lamp than for the scotopically-rich lamp, varying between 39 percent more for the sand walls to 108 percent more for the ghurka walls.

The importance of wall color on achieving a given pupil size is also very evident in the data shown in **Figure 6**. White walls are clearly more efficacious in producing smaller pupils for both lamp types. For example, roughly the same average pupil size is achieved with the sand colored wall as the white wall, but the sand colored wall requires at least 25 percent more lamp power.

The data plotted in **Figure 4** show values under the ghurka condition that appear to be systematically shifted by an amount which could be due to an error of 20 percent in the measured scotopic illuminance. We remeasured the ghurka S/P ratios, comparing the LMT photometer with the Pritchard 1980B scanning spectrophotometer and found the difference between the two meters was small and in the opposite direction from that which could account for this effect.

Discussion

In this study the spectrum of light seen by the subjects was mostly a combination of lamp spectral power distribution and wall spectral reflectivity as is typical in building interiors. Although the television alone produced an extremely small level of illuminance (< 0.32 lx), its luminance as viewed by the subject in the presence of the test lighting was comparable to the luminance of points on the front wall just to the side of the television.

The fact that the spectral distribution of light from the television was unspecified meant that there was a confound in the data that we did not control for. However, the vertical illuminance at the subject's eye from the television in the presence of the test lighting was never more than 1 percent of the specified values of 64 or 108 lx. Thus we expect this confound to add noise to the data but not to affect the general trend. Since we did not control for the illuminance of the television, which was the principal contributor to the foveal light, we were unable to determine any possible small contribution of foveal photopic illuminance to pupil size.

Because the four different wall colors range between bluish at one end and reddish brown at the other, a single lamp type set for a particular value of photopic illuminance provided four different scotopic illuminances at the subjects' eyes. The values of vertical illuminances chosen are in the range of photopic illuminances at the plane of the eye in typical office conditions.[12] The size of

Table 1—The S/P ratio for the four walls when illuminated by either scotopically deficient lamp (WW) or scotopically-rich lamp (C75). The S/P for the two lamp types were 0.97 and 2.40, respectively.

Condition Lamp	Wall	Photopic Vertical Iluminance per watt (lx/W)	S/P Ratio	Watts per Scotopic Vertical Lux (W/lx)
C75	White	1.13	2.25	0.394
C75	Sand	0.750	1.90	0.702
C75	Sky	0.449	2.68	0.831
C75	Ghurka	0.579	2.08	0.830
WW	White	1.71	0.91	0.642
WW	Sand	1.18	0.87	0.977
WW	Sky	0.622	1.05	1.53
WW	Ghurka	0.688	0.84	1.73

Table 2—The mean pupil area, scotopic illuminance, and photopic illuminance data for Figures 4 and 5.

Lamp type	Serena screen color	Average pupil area (mm^2)	Scotopic illuminance (lux)	Photopic illuminance (lux)
	white	13.01	144	64
	sky	12.61	169	63
	sand	14.32	123	65
Chroma-75	ghurka	14.50	133	64
	white	10.69	239	106
	sky	10.44	287	108
	sand	11.70	203	107
	ghurka	12.30	221	107
white	17.58	59	65	
sky	17.11	67	64	
sand	18.41	50	63	
Warm-white	ghurka	19.13	55	65
	white	14.99	94	104
	sky	14.29	112	107
	sand	15.52	84	108
	ghurka	16.32	90	107

the viewed televison, subtending visual angles of 3 x 4 degrees, is a lower limit when compared to various self illuminating equipment such as VDTs, computer terminals, portable televisons, etc., which might be providing visual tasks. For these conditions our study clearly demonstrates that pupil size is controlled by the scotopic spectrum present at the viewers' eyes.

In addition, we have determined that log pupil area is linearly dependent on log scotopic illuminance where the illuminance is evaluated in the plane of the viewer's eye. In our previous study where the subject test room had white walls, we found a similar functional behavior of log pupil area but as a function of the log scotopic *luminance* of the wall at a point just beyond the television.

If the room luminance distributions were similar for each of the four wall colors, and if the vertical illuminance at the eye is roughly proportional to the forward luminance, then the relationship found in the present study would be expected from our previous study.[4] However, measurements of luminance at various points on the walls as well as the viewed portion of the ceiling showed large differences depending on the wall color when the vertical illuminance was fixed. For the sky colored wall the forward luminance was about one half that of the white wall while the ceiling luminance was more than twice as much for the sky wall compared to the white wall. Similar variations and differences also occurred for the sand and ghurka walls. Because of these very different luminance distributions and the excellent fit of our present pupil size data, we can conclude that it is the vertical scotopic illuminance at the eye which is the controlling independent variable. The slope obtained here of 0.33 ± 0.01 with illuminance as the independent variable agrees well with the slope of 0.33 ± 0.16 obtained in the previous study with luminance as the independent variable. The similar slopes for two different independent variables is probably due to the fact that in the prior study with nearly uniformly illuminated white walls, the vertical illuminance at the eye was proportional to the forward wall luminance.

Our results measuring lamp power and pupil size indicate that photopic luminous efficacy is an inadequate metric by which to judge the efficacy of indoor illumination. The scotopically-rich lamp has a photopic luminous efficacy only 62 percent that of the scotopically-deficient lamp, so the scotopically-rich lamp requires 1.6 times as much lamp power to achieve equal photopic luminance. Yet, if the metric for indoor lighting is the visual function given by pupil size, the scotopically-rich lamp has equal efficacy to the scotopically-deficient lamp with about two-thirds of the lamp power. With such a large difference (a factor of 2.5), the choice of metric should be based upon a thorough review of the lighting goals of any particular lighting design.

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Discussion

This research appears to be the usual, carefully conducted work that we have come to expect from these authors regarding research into scotopic spectrum effects on pupil size. Our collective understanding of how to influence brightness perception through pupil response has been further enhanced with this work. There are some important implications for future designs and specifications of lighting systems.

The selection of lamp types and wall colors showed the general trend in the influences of lamp color and wall color on pupil size, as well their combined effect on photopic vs scotopic luminous efficacy, a new and important concept. The obvious next step, from a standpoint of making the information applicable in design, is to provide some kind of working reference—perhaps a table—that a specifier could refer to in choosing combinations of lamps and interior surface colors. The scotopically-rich and scotopically-deficient lamps used are at opposite ends of the fluorescent color temperature spectrum and P/S ratios, which made them good for the experiment. But they aren't used much in specifications; they are not often found to be aesthetically acceptable. But what would be the luminous efficacy of the 80CRI/4100 K lamps, for example? The 70CRI/3500K lamps? Are there differences in luminous efficacy between different manufacturers' versions of these commonly used lamps?

What we really need is a scotopically rich lamp that isn't as blue in appearance as are many of those used in the research so far. In my experience, most people find even the C50 lamp to be too blue.

Good solid findings, but designers always want more.

Finally, I am curious as to how scotopic illuminance is measured. Perhaps it was described in an earlier paper; I don't recall.

D. De Grazio
United Electric Co.

The authors are to be commended for their careful research into the lighting parameters that affect pupil size. The present study has assessed the effects of not only lamp spectrum but also wall color—in other words, the entire visible scene on pupil size. The paper clearly demonstrates that warm white light combined with warm wall colors requires the greatest amount of wattage to produce relatively equivalent pupil sizes as a cool white lamp combined with white wall surfaces. The authors indicate that these findings reinforce the need to consider both photopic and scotopic illuminance when specifying desired light output of particular lamps for specific tasks. Have the authors considered ways of correcting the current $V(\lambda)$ function to account for this effect—will the term 'scotopic' lux gain credence? Have they considered use of retinal luminance, rather than illuminance as a more effective metric to account for pupil size and amount of illuminance delivered to the visual receptors—or do they believe that the aberration of the lens is the critical factor responsible for visual performance at these illuminance levels? Would they care to speculate on the role of scotopic illuminance in lighting design particularly at illuminances (albeit photopically specified) above 108 photopic lux? Finally, do they plan more research to assess whether specifying illuminance in scotopic terms results in better, more accurate predictions of task performance as a function of illuminance?

B.L. Collins
NIST

The authors present data which, in addition to their earlier work[a-c] and that of others[d,e] convincingly demonstrate the effects of light spectrum on pupil size. But the practical implications of this research are unclear. The authors assert that "Visual acuity and contrast sensitivity of normally sighted subjects at typical interior light levels are determined by pupil size and not by retinal photopic illuminance." However, the authors have not controlled pupil size in any of their studies, and many researchers have demonstrated that pupil size has an insignificant effect on visual acuity under the conditions the authors describe.[f-h] Furthermore, several of the same authors have acknowledged "no direct correlation between the amount of change in individual subject's pupil size and the amount of contrast threshold change." Such contradictions in the literature, and by the authors themselves lend doubt to their assertion.[i] Even if this assertion were true, its application is limited. The authors have shown visual acuity improvements with scotopically rich light; but visual acuity targets are by definition near the visual threshold, while most visual tasks in workplaces such as offices are well above the visual threshold.[k] The authors present no convincing reason to expect visual performance for such tasks to be significantly improved under scotopically-rich light, even if visual acuity improves. They themselves have previously stated "that differences in contrast sensitivity threshold make no difference on high contrast tasks, such as reading normal-sized text . . ."[j] Are future studies to disprove this statement envisioned?

Still, individual cases of near-threshold visual tasks can be imagined: persons with visual disability or medical examinations and procedures. For such situations, scotopically rich light should present visual performance advantages, but so may other approaches, like magnifying lenses or task lighting. Which solutions are best? Until tested in the proper context, the lighting community will never know.

The authors are encouraged to investigate the benefits of scotopically rich light within the context of "realistic conditions" and other potential solutions, and to test visual performance, not just pupil size. Furthermore, they should review their work which demonstrates enhanced spectral effects with incorrect refraction[l] and use subjects with correct vision. Individuals with refractive errors would be better served with eyeglasses than with scotopically rich light. The results of such research would be put into proper, and much more useful, perspective.

J. Bullough
Rensselaer Polytechnic Institute

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Author's response

To D. De Grazio

The principal reason for choosing two very different lamps, in terms of S/P ratio (or its surrogate CCT), is to demonstrate the effects with a minimum number of subjects. The direction of effects would be as predicted when comparing the 4100 K CCT lamp with the 3500 K CCT lamp, but because the S/P ratios of these lamps are fairly close it would take more subjects to specifically demonstrate a statistically significant effect. However, based on our study the 4100 K CCT lamp would be more efficacious in terms of its ability to affect pupil size.

We agree with the discussor on the issue of optimizing both S/P ratio and preferred CCT. This is a straightforward computer modeling calculation which the major lamp manufacturers could easily perform. We hope they will do it.

Regarding the scotopic illuminance, it is measured by a meter developed by LMT which has an excellent scotopic filter.

To B.L. Collins

A number of specific questions have been posed which we answer in the order presented.

We do not suggest that corrections to the V(λ)function are necessitated by our work. Instead, photometry for lighting practice requires both photopic V(λ) and scotopic V'(λ) sensitivity functions to predict optimal vision. Note that the use of the scotopic sensitivity function V'(λ) provides values in scotopic units, e.g., scotopic lux.

As we have shown in previous studies, retinal illuminance does not predict visual performance, hence its determination for lighting practice would be of limited value. Our studies on visual performance, which show that smaller pupils are associated with better performance, are highly consistent with the proposition that optical system aberrations are the limiting factor on visual function at normal interior light levels.

The study presented here demonstrates that for a VDT environment it is the scotopic illuminance at the eye that fixes pupil size. In terms of lighting practice the most efficient way to achieve a given level of visual performance is to optimize the scotopic vertical illuminance. Although we did not study values above 108 photopic lux, the conclusion should hold for higher light levels, up to the point where pupil size reaches its minimum value. Since we have previously demonstrated that pupil size is the controlling factor in setting the limits on visual performance (acuity and contrast sensitivity), specifying the scotopic illuminance is the preferred performance metric in the VDT environment.

With regard to future activities, our research on these topics has ended due to termination of DOE support, including plans for a rigorous field study of user preferences related to scotopically enhanced lighting.

To J. Bullough

The remarks presented do not address the validity of our study, but are instead directed to theoretical objections to the practical use of scotopically enhanced lighting as related to its effect on pupil size. The discussor has implied that threshold measurements are not applicable to tasks that "are well above visual threshold." We note that the discussor's viewpoint is at odds with experience of most patients at optometric examinations, where patient's spectacle prescription are determined. Even if the patient may not perform "near threshold" tasks, the optometrist does not have the patient judge the prescription on the Snellen Chart's large E alone. To the contrary, the smaller letter sizes are used, down to below-threshold size. This provides a clearly defined, objective endpoint, with the consequences that with the correct refraction, the edges of the large E will be maximally sharp. At his own optometric exam, does the discussor prefer not to read the smallest letters because "it is not relevant to vision of larger letters?" Does the discussor object to taking a reading chart examination when obtaining a driver's license because "it is not relevant to driving tasks?" Indeed, threshold is an objective measure of vision, well established as a valid predictor of vision in psychophysics. The emphasis of the discussor on "visual performance" is misplaced. Few individuals would be willing to have a diopter of added blur to their glasses prescriptions, even if they could still read blurred newspaper headlines.

Our statement that "differences in contrast sensitivity threshold makes no difference on . . . reading normal-sized text" is analogous to "added 1.00 DS blur will not prevent reading headlines." But reading high-contrast normal-sized letters is not the only visual task that occurs under interior lighting. A loss of contrast sensitivity will lead to loss of the subtleties in any visual scene that contains varying shades of contrast.

Given the widespread use of threshold acuity in optometry and psychophysics, we see no reason why lighting research should not also use this useful predictor. We have determined that for typical interior lighting levels, you will see better by substituting scotopically enhanced spectra at the same photopic level.

There are a number of statements made by the discussor that are in error. Contrary to his statement that "the authors have not controlled pupil size in any of their studies," in all our studies on visual performance we have taken great care and designed our test protocols to control pupil size by separating the lighting of the task from the room/surround lighting. We have measured the changes in pupil size, and used each subject as their own control (at a different pupil size). The papers referred to by the discussor cover in detail our methods for accomplishing this, and furthermore show graphs of mean pupil size under the controlled conditions employed. The literature on pupil size effects cited (references f–i) all use monocular artificial pupils, often with paralyzed accommodation, hardly "realistic conditions," that the discussor recommends.

The quotation from our paper on the visual performance of elderly subjects ("no direct correlation between . . . changes in . . . pupil size . . . and contrast threshold change.") is not presented in its proper context. In that study, all subjects (both elderly and young adults) showed significantly better visual performance with smaller pupils, even though there was not a direct correlation between the amount of pupil size change and the amount of performance change. The quote from our papers referred to an attempt to find a direct correlation across subjects between the two amounts. The data for the subject sample size employed showed a trend but, because the correlation under consideration was across subjects, we needed a larger number of subjects to reach significance. The discussor has incorrectly interpreted our discussion; there is no contradiction here, as can be ascertained by reviewing the publication, other than the discussor's summary.

The discussor suggests "magnifying lenses" for those with visual disability. This comment does not recognize that some vision problems cannot be ameliorated by corrective lenses. For example, intra-ocular opacities are common in the elderly. While smaller pupils can improve acuity in such a situation, lenses cannot. Similarly, most people become presbyopic with increasing age, a vision deficiency that can only be partially ameliorated with spectacles. Such eyeglasses provide refractive correction for specific distances. However, it is well known in vision science that as pupil size becomes smaller there is a diminishing need for accommodation; the reader can verify that (pinhole viewing will obviate any need for accommodation). If lighting design can function to reduce the effects of presbyopia, this is surely useful, and also likely to be highly cost effective. The discussor's preoccupation with suprathreshold visual performance as the sole method of judging lighting may be the basis for failing to recognize these benefits of altering spectrum.

The discussor suggests that we "review" our own work (reference l) and then "use subjects with corrected vision." This is easily accomplished, since in reference l our subjects were in fact, refracted by a licensed optometrist. The subjects were tested when both fully corrected and with an added 0.50 DS of blur. A visual performance benefit associated with smaller pupils was obtained for these fully corrected young adult subjects. (The effect was even greater in magnitude in the same subjects with added blur.) Since the data on subjects with correct vision are available in reference l, the results of the research somehow must already be in a "proper, and much more useful, perspective." The discussor states, "Individuals with refractive errors would be better served with eyeglasses than with scotopically rich light." Many individuals tolerate refractive errors of 0.5–1.0 DS before obtaining glasses, and they, as well as fully corrected glasses wearers, as well as those with normal vision, as well as those with intra-ocular opacities, can all benefit from scotopically enhanced lighting. It is unclear from the discussor's comments why anyone must be limited to just one solution or another.