Pupillary Size Differences under Incandescent and High Pressure Sodium Lamps

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Introduction

In the absence of a color-discrimination requirement, it is common in the fields of illuminating engineering and lighting design to consider that two lighting systems with an equal photopic illuminance level and equal spatial distribution are essentially equivalent (Office Lighting Committee, 1982). Differences in spectral power distribution associated with different lighting technologies are presumed not to affect visual performances when the task is achromatic (Bullet and Fairbanks, 1980). Thus, lighting systems with different spectral power distributions are often considered equally valid for general and task lighting, as shown by the common usage of incandescent, fluorescent, and high-pressure sodium lighting for similar applications. The decision of choosing one lighting system over another is then determined by criteria other than spectral power distribution. This practice is based on the assumption that the CIE luminous efficiency function adequately describes visual function under common lighting conditions.

As part of a continuing joint program between Lawrence Berkeley Laboratory and University of California, San Francisco to study human responses to electric lighting, we report here that significant differences in pupil size occur when subjects are exposed to indirect high-pressure sodium (HPS) as compared with indirect incandescent lighting when the light intensities are photopically matched. The spatial luminance distributions of the two lighting systems were approximately the same and the HPS lamps were driven at high frequency (approximately 30 kHz) in order to eliminate modulation of light intensity as a possible confounding variable. We attribute the observed differences in pupil size to be most likely due to the differences in spectral power distribution of the two lighting systems. Since pupil size can affect visual performance and other aspects of visual system function, the findings here indicate that spectral power distribution should be considered in lighting design and application.

Methods

Eight young, healthy, adult, Caucasian, paid volunteers—five males and three females—between 17 and 20 years of age participated in this study. All were tested to have 20/20 vision and were reported to be free of drugs.

All testing took place in a sound-attenuating, RF-shielded chamber (Erik A. Lindgren & Associates, Chicago, Illinois) measuring 2.3 m high and 2 m by 2 m. The subject sat in a chair and faced a metal wall coated with Kodak Reflective Paint (spectrally flat reflectance) which had few visual features. That wall was about 1.1 m distant and was bathed by lighting fixtures mounted above the subject's head, shielded from direct view. The rest of the chamber was lit only by reflected light.

The electrical lights used in this study were incandescent and HPS, both manufactured by General Electric. Different levels of illumination were achieved by using incandescent lamps of different wattage, operated at or near 120 V. The 35-W HPS "Lucalox" lamp was activated by a G.E. high frequency fluorescent ballast which operated the lamp at about 30 kHz. Hence, we refer to this lighting as "high-frequency high-pressure sodium" (HF-HPS). Different luminance levels were achieved by varying the voltage to the HF-HPS ballast. Continuous monitoring of the illuminance of the lamps was accomplished with a Tektronix J-16 digital photometer mounted on the directly illuminated front wall at approximately eye level of the subject. A Spectra Pritchard photometer (model 1980A-PL) was mounted over the left shoulder of the subject and measured the luminance of a small area of the wall (6-minute field) directly in front of the subject, using the built-in photopic and "scotopic" filters. We have compared these measured values of the photopic luminances to a calculation performed by folding the measured spectral power distribution of the lamps with the CIE photopic response (Wyszecki and Stiles, 1982) of the eye and have found agreement between measured values and calculated values within 1 percent . Unfortunately, the scotopic filter is not a completely faithful reproduction of the scotopic response function; it has small decrements in the region from 550 nm to 650 nm. Although these are small and produce only a 3- to 4-percent increase between actual and filter responses when folded against

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an incandescent spectral power distribution, the effect is much greater for the HPS spectrum because the filter decrement occurs in the wavelength region where the HPS spectral power distribution is falling rapidly. Thus, an incandescent lamp and an HPS lamp that are "matched" for scotopic luminances by the Pritchard filter are actually as much as 35 percent different. The correct values of scotopic luminance were obtained by folding the measured values of the HPS spectral power distribution at the various input voltages against the published values of the scotopic response function (Wyszecki and Stiles, 1982). We have performed these measurements and calculations and have determined the correction factors for each of the scotopic luminance measurements recorded by the Pritchard Spectrophotometer with its erroneous filter.

Infrared pupillometry (Stark, 1968) was carried out using a MicroMeasurements, Inc., pupillometer which measured pupil area with built-in corrections for angle of gaze and the distortions produced by reflecting the pupil image through a front-surfaced mirror mounted slightly below the direct line of vision (thus permitting the subject to view the wall rather than either the mirror or the video camera). The pupillometer output was digitally read by a PDP-8 computer which controlled data acquisition and then transmitted the data files to a PDP-11/44 computer for further analysis and statistical tests.

The subject practiced coming up to the chin rest of the pupillometer and centering his/her gaze so that the pupil image was centered on the pupil monitor, then sitting back to relax between recording periods. Subjects were instructed to maintain their visual direction towards the front wall, fixating upon a small visual point during recordings, and to not look into shadows between recordings. To confirm the following of these instructions, the eye position was observed during recordings via the pupillometer monitor and between recordings via a second video monitor showing the subject's face. In addition, a continuous recording of the pupillary response was accomplished with a video tape recorder (Hitachi VT-9700A) and a FOR VT-300 Video Timer. For each 5-second recording, when the subject was positioned so that the pupil was properly recorded, he/she was instructed, via an intercom, to prepare for a recording by blinking, swallowing, or moving, and then when fully ready, to press a button upon which their finger rested. Having the subject start the recording period resulted in significantly less blink artifacts. Pupil area was recorded at 20 Hz for 5 seconds, a total of 100 data points per recording.

Each subject was acclimatized inside the exposure chamber for 30 minutes prior to testing under the lowest intensity of light. Twenty consecutive recordings of 5-second duration were made under each light condition with an interrecording interval of approximately 30 seconds. The average pupil area over the first 16 artifact-free 5-second recordings was taken as the average pupillary response per light condition.

Three intensities, photopically determined with the Pritchard photometer, of 30, 60, and 90 cd/m$_2$ were used for a photopically matched comparison between incandescent and HPS. A second set of tests at three other intensities was also done in each subject. This set of intensities had been intended to provide intensities matched scotopically. However, as mentioned above for technical reasons associated with errors in the scotopic filter in the Pritchard photometer, the intensities were not matched. Within the testing of each lamp the intensities were always tested in ascending order of luminance. Each subject was tested with at least three intensities of each of two lamps within one day. The full testing of each subject required approximately eight hours. The order of testing a given lamp was random across subjects to counterbalance any diurnal effects.

Results

Data were gathered under a number of lighting intensities, a subset of which included photopically matched lighting conditions at three intensities. Taking only this data, pupil area was larger for HF-HPS than for photopically matched incandescent (Inc) illumination (**Figure** 1 and **Table** 1). (Note that in this and all figures, error bars indicate the standard deviation of the observations around the means.) When analyzed with a two- way repeated measures analysis of variance (ANOVA) with lighting condition and intensity as the two within-subjects effects and average pupil area as the dependent variable, there was a highly statistically significant effect of lighting condition. The analysis showed that the probability of the observed pupil size difference under the two lights being due to a sampling error (*i.e.*, due to chance) was less than 0.006 ($p < 0.006$, $F = 15$, $df = 1,7$). Thus, by this direct approach it is clear that pupil area is not uniquely a function of photopic intensity alone.

Examination of the responses of individual subjects showed the same trends as in **Figure** 1. Out of 24 pairs of individual measurements that make up the averages shown in **Figure** 1, only 1 pair had the HPS pupil area slightly smaller than the incandescent, and 1 pair had measurements that were identical. For the other 22 pairs of observations, the HPS pupil area was larger than the incandescent in that subject at the same photopic intensity.

We had obtained additional data at intensities that were unmatched photopically, and this additional data, along with the photopically matched data is shown in **Figure** 2. Note that HPS photopic intensity must be about 2–3 times greater than that of incandescent in order to provide the same pupil area. Since the data are not matched photopically at all points, a similar ANOVA cannot be used to test the statistical difference between the two curves in **Figure 2**. Because of this, and because we wished to determine if a spectral distribution other than photopic luminous efficiency could account for the pupil areas measured, we analyzed all of our data using the general linear models (GLM) procedure of the Statistical Analysis System (SAS Institute, Inc.). The details of this method and the findings are presented in the Appendix. The overall findings are reported here.

Table 1—Photopic match pupil area in mm²

	HPS (cd/m²)			Inc (cd/m²)		
	30	60	90	30	60	90
Ronald	30	29	21	22	16	14
Jenny	30	29	22	12	13	8.3
Jon	37	19	15	24	15	14
Lenny	26	22	18	29	15	14
Max	13	12	9.2	13	9.6	7.1
Michelle	34	30	29	30	24	17
Sandra	36	27	24	33	27	22
Sherif	27	19	18	14	9.2	7.2
N	8	8	8	8	8	8
M	29	23	19	22	16	13
std	7.8	6.5	5.8	8.2	6.3	5.1

Since the photopic luminance alone did not distinguish the pupil area effects of Inc and HPS, we plotted our observed pupil area measurements as a function of the corrected scotopic luminance, as shown in **Figure 3**. It is clear visually that the two curves are closer together than in **Figure 2**, and that the curves lie within a single standard deviation of the between-subject variability.

Since Alpern and Campbell (1962) had measured spectral responses of the pupil to varying monochromatic wavelengths which were neither purely photopic nor scotopic, we plotted our observed pupil area measurements as a function of a measure of intensity calculated from their published spectrum (folded against our measurements of the spectral power distribution of the lamps used). The results are shown in **Figure 4**, where it can be seen that the curves lie in intermediate positions, compared with their positions in **Figures 2** and **3**. (It should be noted that the Alpern-Campbell spectral response curve is peaked approximately midway between the scotopic and photopic peak wavelengths.)

The question is which of the spectra of **Figures 2, 3,** and **4** best allows prediction of the pupil area *independent of the lamp type*. The GLM (as described in the Appendix) provides an answer to this question by first normalizing the individual subject data to the mean value for a given subject across all conditions, and then determining the amount of the within-subject variance of pupil area across the lighting trials that can be accounted for by the different spectra associated with each trial. The results in the Appendix are quite clear: without specifying the lamp type, scotopic luminance accounts for 97 percent of the lighting related variance in pupil area while the photopic luminance accounts for only 65 percent of such variance, and the Alpern-Campbell luminance accounts for 79 percent. Both photopic and Alpern-Campbell spectra can account for 100 percent of the observed variance only if the lamp type is also specified—said in another way, in **Figures 2** and **4** the two curves are statistically different from one another. On the other hand, the scotopic luminance accounts for 97 percent of the variance, *independent of lamp type*. It is likely that the 3 percent of the variance not accounted for by the scotopic luminance is due to chance. This interpretation is supported by the GLM analysis (see Appendix). On the basis of this result and others presented in the Appendix, we conclude that the scotopic spectrum is the major determinant of the pupil size under the experimental conditions described here.

Two principal factors that determine the amount of light that reaches the retina are the luminance of the overall visual field and the pupil area. The product of these two numbers is a measure of light passing into the eye through the pupil and is measured in trolands (candelas per square meter of luminance times square millimeters of pupil area). We call these *"entrance-*trolands" since we have not included the spectral absorption within the eye. We replotted our data to show entrance-trolands as predicted by the three spectra (photopic, scotopic, and Alpern-Campbell), as shown in **Figures 5, 6,** and **7**. The results are similar to that seen in **Figures 2, 3** and **4**, namely that the photopic luminance can predict the entrance-trolands only if the lamp is specified, whereas the curves from the two lamps are very similar when the scotopic luminance is the primary measure (**Figure 6**). The Alpern-Campbell luminance (**Figure 7**) provides curves intermediate between the photopic (**Figure 5**) and scotopic (**Figure 6**) graphs. (Since the troland computation involves the product of the luminance and the pupil area, the statistical analysis of the primary pupil area data provides the same results when entrance-trolands are the dependent measure.)

If net retinal illumination is the prime requisite of a lighting design, **Figure 5** clearly shows that the spectrum of the source should be considered as relevant. Note that **Figure 5** predicts that within the range that we measured, for photopic entrance-trolands to be equal to Inc values, HPS luminance must be *reduced* by a factor of about 2. On this basis, there could be additional energy savings in the use of HPS lamps *provided* that the tasks performed under the lighting are not adversely affected by a larger pupil.

Our results clearly suggest that the pupil size mechanism functions to control the amount of scotopic light that enters the eye. The size of the pupil in turn affects the amount of *photopic* light that enters the eye. If the ratio of scotopic luminance to photopic luminance is constant from one light source to another, then the pupil would control equally well both scotopic and photopic luminance entering the eye. However, the scotopic/photopic ratio does differ between the two light sources we studied. Thus, the pupil does *not* control the photopic luminance entering the eye under all conditions. To show this we plotted the photopic entrance-trolands in our experimental results as a function of scotopic luminance (**Figure 8**). It is clear that while scotopic luminance determines scotopic entrance-trolands (**Figure 6**), scotopic luminance is a *very poor* predictor of the amount of light that will be available for photopic visual functioning under conditions of indoor electrical illumination (**Figure 8**). The GLM statistical analysis confirms this conclusion by showing that only 24 percent of the lighting-related variance of photopic entrance-trolands is accounted for is accounted for by the scotopic luminance, whereas the difference in the two lighting conditions accounts for 76 percent of such variance (see Appendix).

Discussion

The results here can be understood if it is assumed that the spectral response of the pupillary system differs from the canonical spectral visual efficacy of the eye. This latter function, referred to as the λ function, is the spectral shape that, when folded against the various lamp spectral power distributions, defines the photopic illumination value of a given light source. If the spectral response of the pupillary system is not λ then two lamps with different spectral power distributions would provide different puppillary responses even though they provide equal photopic illumination. These considerations are discussed below.

The spectral response of pupil size has been studied by several investigators but there is no consensus within the vision literature. One commonly held view is that the spectral response of pupil size is the same as the usual photopic luminous efficacy function [λ], e.g. see Laurens (1923) and Alexandridis (1985, page 22). Our results appear inconsistent with that view and are also inconsistent with the results of Alpern and Campbell (1962) and ten Doesschate and Alpern (1965) who claim that pupil size is affected by both rods and cones at daytime light levels and that the spectral response function of the pupil is maximum approximately half way between the scotopic and photopic peak wavelengths. At the other extreme, the work of Bouma (1962, 1965) (reiterated in a review of the field by Hedin, 1978) concludes that the rods are the predominant receptor controlling pupil size over a wide range of luminances, with a maximum in the monochromatic spectral response curve at a wavelength slightly less than the scotopic peak. Our results are probably consistent with the conclusions of these latter authors. However, there is a small amount of variance (3 percent) that is not accounted for by our use of the scotopic spectrum, which might be accounted for by the slight difference from the scotopic curve in their results. Note that these small differences are in a region of their results in which there are relatively few data points. It is clear that further research in the field of vision on a larger number of subjects can be used to determine the effective pupillary action spectrum.

Consequences for Illuminating Engineering and Lighting Design

Pupil size is known to have important effects on depth of field and on the ability of the visual system to resolve fine detail as reflected by visual acuity (Liebowitz, 1962) and the spatial contrast sensitivity function (Campbell and Green, 1965). For example, depth of field increases approximately inversely as the pupil diameter decreases (Campbell, 1957). However, for a given ambient luminance a larger pupil results in more retinal luminance (trolands) (Luckiesh and Moss, 1934, and Ferguson, 1956). Thus depending on the specific nature of the visual task, improvements in visual performance could result by spectrum control of pupil size independent of luminance (Eastman and McNelis, 1963). *If* retinal illumination is a *limiting* factor in the visual environment, then a scotopically deficient lamp resulting in a larger pupil may be more appropriate than another lamp richer in scotopic lumens when both produce equal photopic luminances. (See **Figure 8** to see how such scotopic illumination determines photopic trolands between Inc and HPS.)

On the other hand, studies of contrast sensitivity (Campbell and Green, 1965, and Campbell and Gubisch, 1966) show a steady reduction in this quantity with increasing pupil size. Should further studies show that there are preferred pupil sizes in the everyday world of visual tasks, the results here should lead to a new dimension for improving the quality of our lighting environment, since spectral distribution in lamp design can be varied over large ranges.

It should be noted that it is not an *a priori* requirement that the results of multichromatic stimuli be predictable on the basis of monochromatic results, unless the degree of interaction between wavelengths is known. Thus, though our results might have been anticipated on the basis of Bouma's work, such a prediction could not have been verified without experimentation such as we have done. However, in as much as our results are similar to that of Bouma, it can be concluded that there is relatively little spectral interaction in the pupillary spectral response, provided it is indeed the scotopic function. But given the controversies within vision science, and the importance of pupillary response to vision and lighting design, futher testing on other lights will be necessary to seen how much other lamps affect pupil function, and whether measures of scotopic illuminance will be adequate measures of retinal illuminance under different spectral distributions. When such additional information is available, the general principles governing this aspect of visual efficiency will have a more certain base.

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Appendix

We repeated the same GLM analysis using each of three different measures of the luminance: the photopic measurement, a corrected scotopic measurement, and the pupillary action spectrum observed by Alpern-Campbell (1962). For each of the three spectra, analyses of log transformed independent and dependent variables enabled our statistical model to account for a higher percentage of variance in the dependent variable (either pupil area or entrance-trolands) than if either dependent or independent variables were not log-transformed. For this reason, all of the analyses below pertain to log-transformed data, and **Figures 9-15** show the data on log-log plots. **Figures 9-15** should be compared with the corresponding **Figures 2-8**, to note how well the data fit a log-log plot. Note that since the data is log-transformed in these figures before computations are made, the error bars here differ from those in earlier figures. The best fit line of the means are shown, along with the 95 percent confidence limits of the line position.

The GLM procedure is used to partition variance of the dependent variable among various effects. Since each subject acted as his own control, by entering a subject effect into the GLM procedure, we were able to measure between-subject variation and remove that source of variation from the analysis. All experimental effects were then assessed with respect to the pooled within-subject variance.

The pooled within-subject variance was then partitioned in analyses using various combinations of the three spectral intensities, a dichotomous categorical variable indicating the light source, and interaction effects. In all cases, the variance accounted for by any set of these variables was never greater than 72 percent.

The data under the two different lamp types was then individually fit with the best linear least-squares fit, and these regression lines were then used to determine the residual variance not accounted for by the various conditions. All combinations of the three light spectra as well as lamp type were computed. In all cases the variance accounted for by these factors was never greater than 72 percent.

Table 2 presents data on whether the luminance of the lamps associated with the photopic, Alpern-Campbell, or scotopic spectra, either seperately or in combination, can be used to predict pupil area. (Only combinations of luminance for two spectra are presented because adding luminance of the third spectrum to the prediction equation never resulted in any increase in predictive power.)

Table 2—Dependent variable: log (area)

	F	p	% of variance accounted for
Prediction model 1			
First predictor:			
log (photopic lum.)	76	$<10^{-9}$	47
Add'l predictor:			
log (scotopic lum.)	76	$<10^{-9}$	25
			—
			72
Prediction model 2			
First predictor:			
log (scotopic lum.)	202	$<10^{-10}$	70
Add'l predictor:			
log (photopic lum.)	5	<0.022	2
			—
			72
Prediction model 3			
First predictor:			
log (alpern lum.)	114	$<10^{-9}$	57
Add'l predictor:			
log (scotopic lum.)	46	$<10^{-9}$	15
			—
			72
Prediction model 4			
First predictor:			
log (alpern lum.)	114	$<10^{-9}$	57
Add'l predictor:			
log (photopic lum.)	46	$<10^{-9}$	15
			—
			72
Prediction model 5			
First predictor:			
log (photopic lum.)	76	$<10^{-9}$	47
Add'l predictor:			
log (alpern lum.)	76	$<10^{-9}$	25
			—
			72
Prediction model 6			
First predictor:			
log (scotopic lum.)	202	$<10^{-10}$	70
Add'l predictor:			
log (alpern lum.)	5	<0.022	2
			—
			72

Note: In all cases the degrees of freedom for the first predictor are 1,87, and for second predictor 1,86.

Taking first the ability of a single spectrum to predict the observed pupil areas, scotopic luminance accounted for fully 97 percent (70 percent of a total of 72 percent) of the total predictive power of all spectral luminance data to predict pupil area. Photopic luminance did most poorly in predicting pupil area, accounting for only 65 percent (47 percent of the total of 72 percent) of the predictive power of spectral luminance data. Alpern luminance was intermediate between scotopic and photopic luminance, accounting for 79 percent (57 percent of the total of 72 percent) of the predictive power of spectral luminance data.

When the spectra are considered in pairs, any combinations of two spectra intensities can account for all the the luminance-related variance in pupil area (**Table 2**). (The fact that all of the spectral psirs of **Table 2** account for about 72 percent of the variance indicates that the remaining variance is not spectrally related.) When scotopic luminance is the first predictor, adding either photopic or Alpern-Campbell luminance adds only 1.8 percent of variance to the predictive power of scotopic alone. This addition is significant at ($F = 5.4$, df = 1,86, $p < 0.022$). In the context of the multiple analyses of the data which we performed, this result (at the 2 percent confidence level) remains suspect and must be replicated with new data for it to be solidly asserted. In contrast, all the p-values associated with the other analyses are so small ($< 10^{-8}$) that they are not compromised by our multiple analyses of the data. Thus, scotopic luminance accounts for essentially all luminance-related variance in pupil area. Photopic and Alpern-Campbell luminance in combination predict pupil area as well as scotopic luminance, as shown in **Table 2**. This is not surprising since scotopic luminance can be computed as a linear combination of photopic and Alpern-Campbell luminance.

Another way of looking at this data is that we are trying to predict pupil area for two different light sources using only one spectral luminance measure. As noted above, when the scotopic luminance measure is used, this works because the scotopic spectrum is likely to be the major physiological determinant of the pupil area under the conditions of our experiment (daytime light levels) and subjects (young adults with normal vision).

We have verified the importance of the scotopic spectrum in predicting pupil area in another way. Using the GLM procedure to perform a repeated measures analysis of covariance (ANCOVA), where between-subject variance was removed as above, log pupil area was the dependent variable, the dichotomous categorical variable indicating light source was the independent variable, and the log spectral luminance was used as the covariate. **Table 3** presents the results for three such ANCOVAs with photopic, scotopic, and Alpern-Campbell luminance used as the covarites. In all three cases the combination of the lighting source and spectral intensity variable accounts for 72 percent of the variance of the log pupil area. The variance accounted for by the light source variable is highest when photopic luminance is the covariate, intermediate when Alpern-Campbell luminance is the covariate, and smallest when scotopic luminance is the covariate. (Note that even though the effect sizes are the same as those presented in **Table 2**, the F and p values are different because of the different error terms and degrees of freedom in the ANCOVA procedure.) Finally, the interaction of lighting source and the covariate was very small ($p > 0.5$ in all cases), indicating that the curves of spectral luminance vs. pupil area for the two light sources are parallel over the range studied. From this analysis we conclude that when log scotopic luminance is plotted versus log pupil area (**Figure 10**), one curve fits both light sources. In contrast, for either photopic (**Figure 9**) or Alpern-Campbell (**Figure 11**) spectra, each light source was fitted well by a log-log curve and the two curves were parallel but significantly displaced from each other.

Table 3—Dependent variable: log (area)

	F	p	% of variance accounted for
Analysis 1			
Covariate:			
log (photopic lum.)	76	$<10^{-9}$	47
Independent variable:			
light source	13.4	0.008	25
			—
			72
Analysis 2			
Covariate:			
log (scotopic lum.)	202	$<10^{-10}$	70
Independent variable:			
light source	0.92	0.37	2
			—
			72
Analysis 3			
Covariate:			
log (alpern lum.)	114	$<10^{-9}$	57
Independent variable:			
light source	8.1	0.025^{-9}	15
			—
			72
Dependent variable: photopic entrance-trolands			
Analysis 4			
Covariate:			
log (scotopic lum.)	24.7	$<10^{-5}$	22
Independent variable:			
light source	142	$<10^{-5}$	70
			—
			92

Note: In all cases the degrees of freedom for the covariate are 1,87, and for second predictor 1,7.

Spectral prediction of "entrance-trolands"

The statistics applicable to the pupil area data are equally applicable to the troland plots (**Figures 5-8**, replotted log- log in **Figures 12-15**), since the y axis in these figures is a product of the x axis and the pupil area. However, the plot of photopic entrance-trolands as predicted by scotopic luminance (**Figures 8 & 15**) requires futher calculation, since the variance of the two axes is not inter-related, as in the other plots. Therefore , we utilized the GLM with the dependent variable being photopic entrance-trolands, the covariate scotopic intensity, and the independent variable the light source. The results are shown as Analysis 4 in **Table 3**. It is clear that scotopic spectra alone account for only 24 percent (22 percent of 92 percent) of the variance attributable to lighting, whereas the light source (lamp type) accounts for 76 percent (70 percent of 92 percent) of the variance. Thus, the two curves in **Figures 8 & 15** are clearly different. [Note that the total variance (at 92 percent) attributable to the lighting is greater than in **Table 2** or the upper part of **Table 3** because, in the case of Analysis 4, the variable of the x axis covaries with a factor in the y axis.] In contrast, the two curves of **Figures 6 & 13** are probably the same, within the accuracy of our experiments.

Discussion

This paper reports a well conceived, well executed, and imaginatively analysed experiment. The scotopically dominated response of the pupil, while adequately documented in the literature, has languished in the backwaters of vision research for want of a practical application. Now Dr. Berman and his co-workers have given us a reason to take notice. As they point out, the availability of sources with discontinuous spectral power distributions which have large amounts of energy in relatively narrow spectral bands make it necessary to look anew at the effects of such sources on vision and the visual system.

The important question raised by this paper is: "does the fact that HPS and incandescent light of equal photopic luminance give markedly different retinal illuminances have any practical significance for the lighting engineer or designer?" Several studies have looked at the effects of HID sources on visual performance and most have concluded, that, if contrasts are equated, the spectral distribution of the source does not influence visibility for achromatic tasks. That result is not surprising when you consider that the testing was done under conditions of high contrast, moderately high luminances, and free viewing, allowing the subjects to focus for the task distance. As the authors correctly note, large pupils have two primary effects—they increase the retinal illuminance while decreasing the depths of field and focus. While it has been shown that pupil size has little effect on high contrast visual acuity when the task is in focus (reference 1), the gain in retinal illuminance with in-

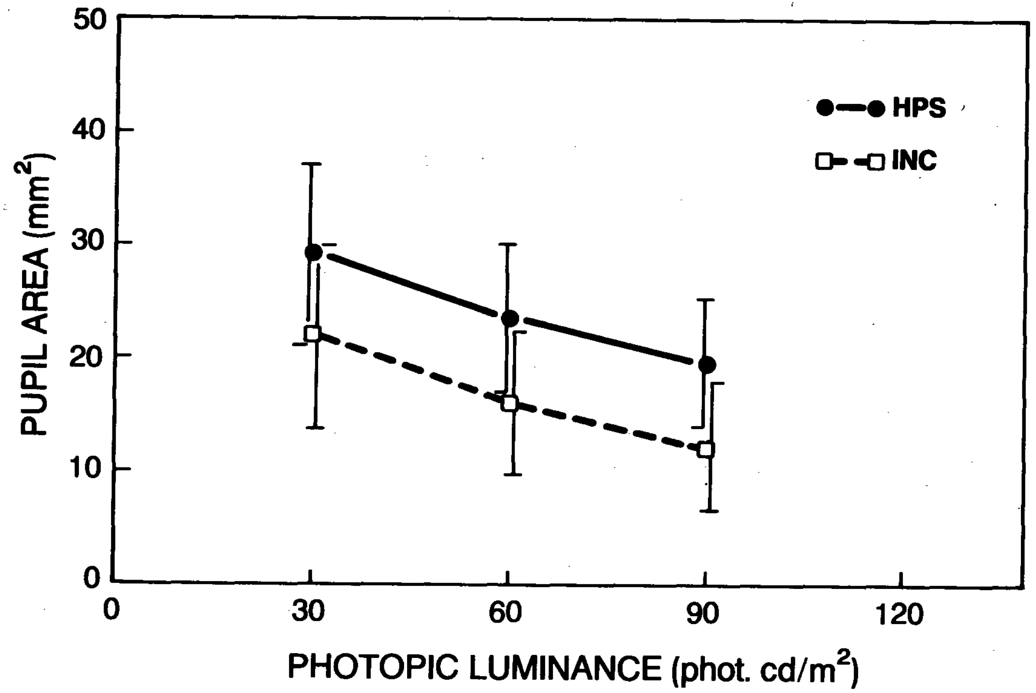

Figure 1—Mean pupil area ± SD for HPS and Inc for photopically matched exposures.

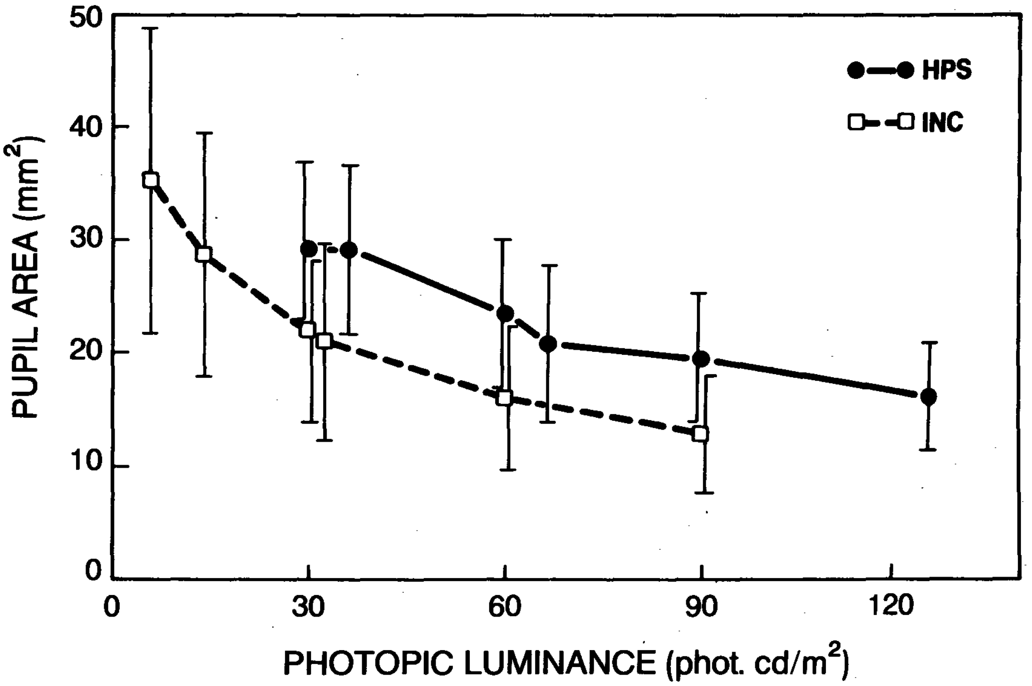

Figure 2—Mean pupil area ± SD for all exposures of HPS and Inc, some photopically matched and some not, as a function of photopic luminance of the exposure.

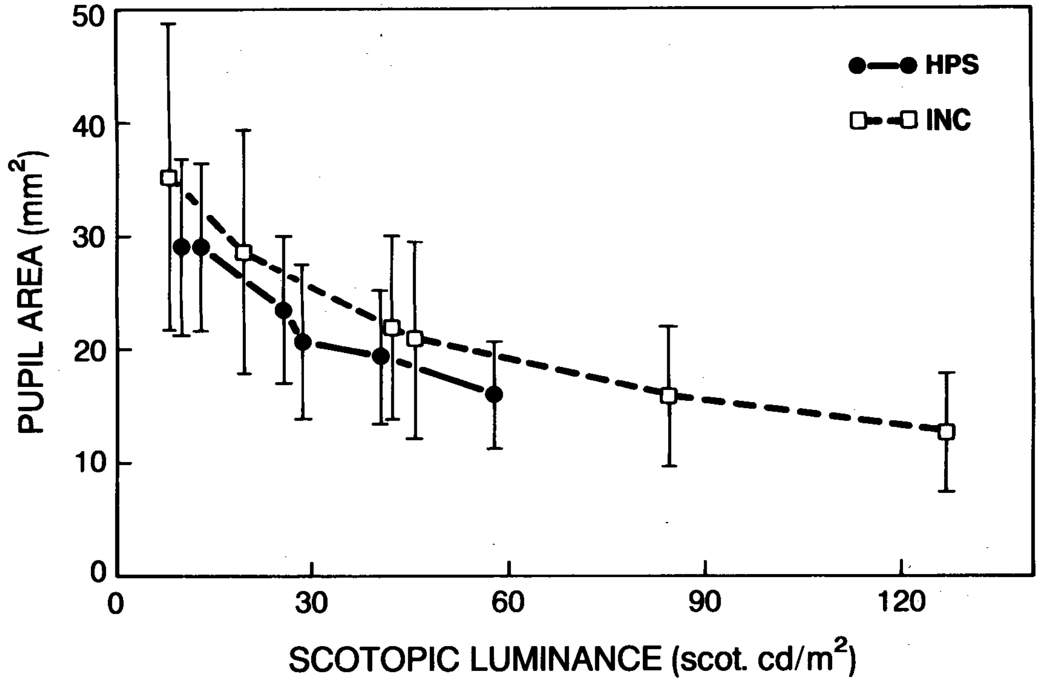

Figure 3—Mean pupil area ± SD of Figure 2, replotted against the corrected scotopic measurement of the exposure luminance.

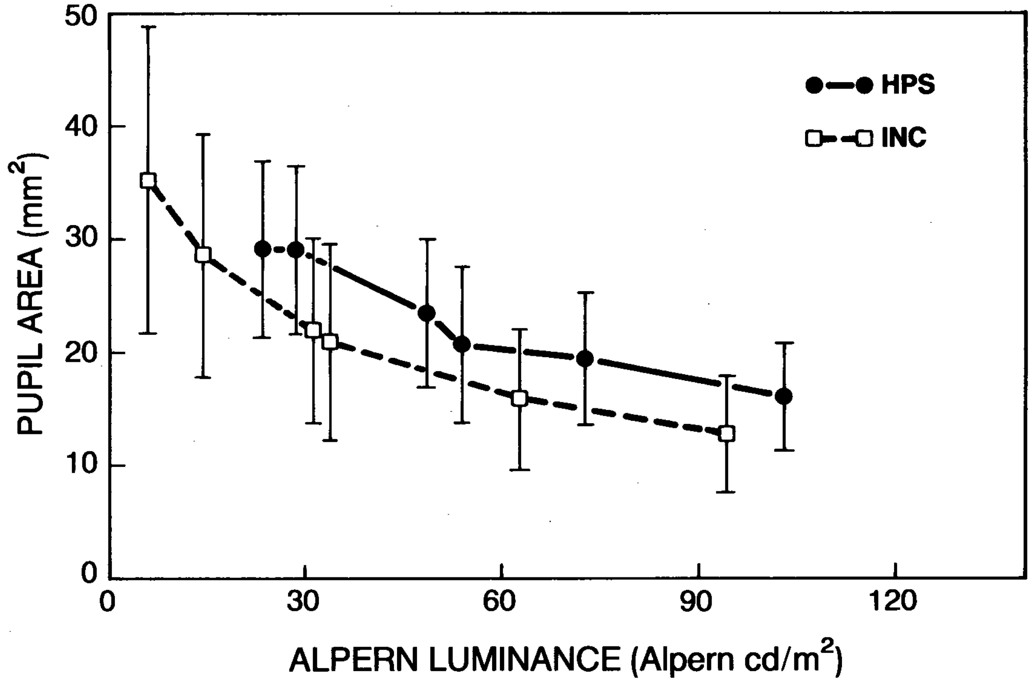

Figure 4—Mean pupil area ± SD of Figure 2, replotted against the exposure luminance computed from the pupillary response action spectrum of Alpern-Campbell (see text).

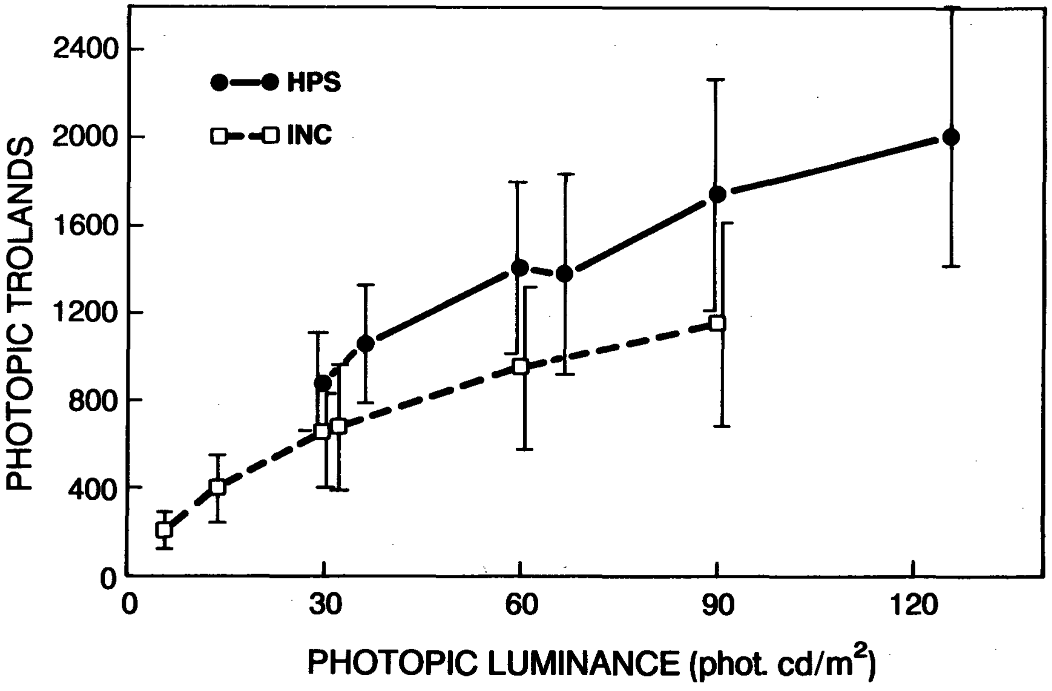

Figure 5—Mean photopic entrance-trolands ± SD as a function of photopic luminance.

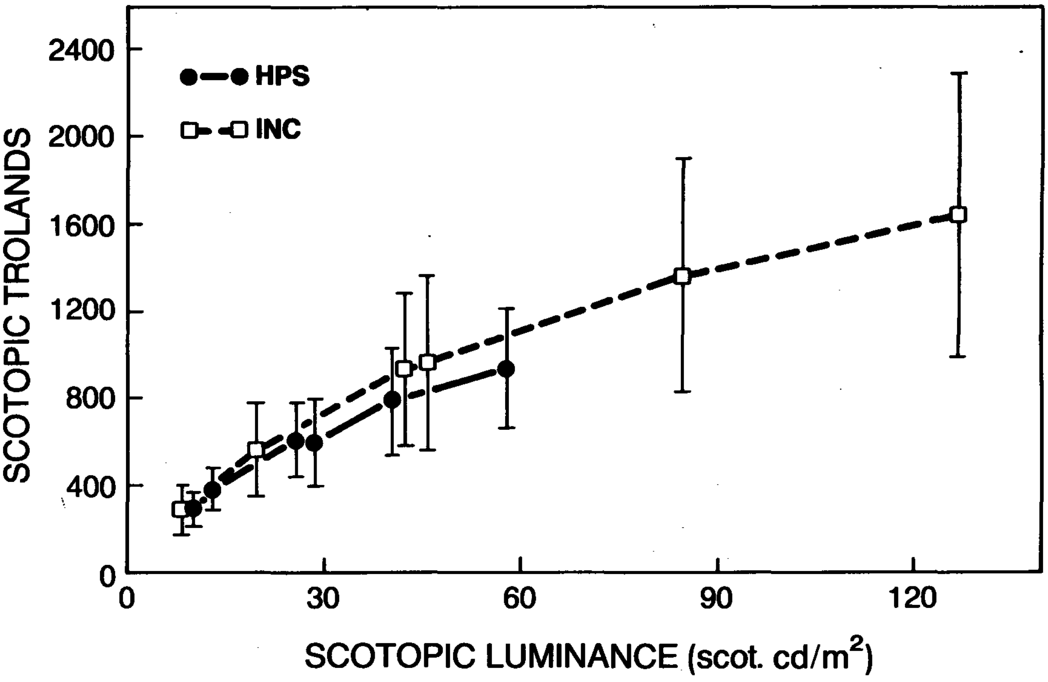

Figure 6—Mean scotopic entrance-trolands ± SD as a function of scotopic luminance.

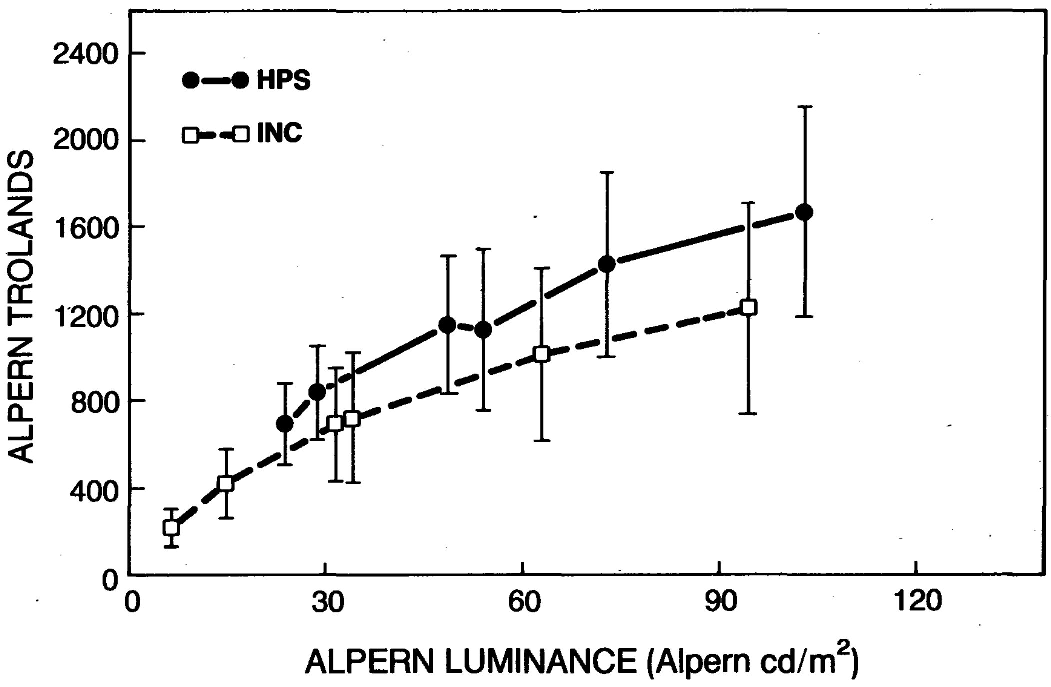

Figure 7—Mean Alpern-Campbell entrance-trolands ± SD as a function of Alpern-Campbell luminance, as in Figure 4.

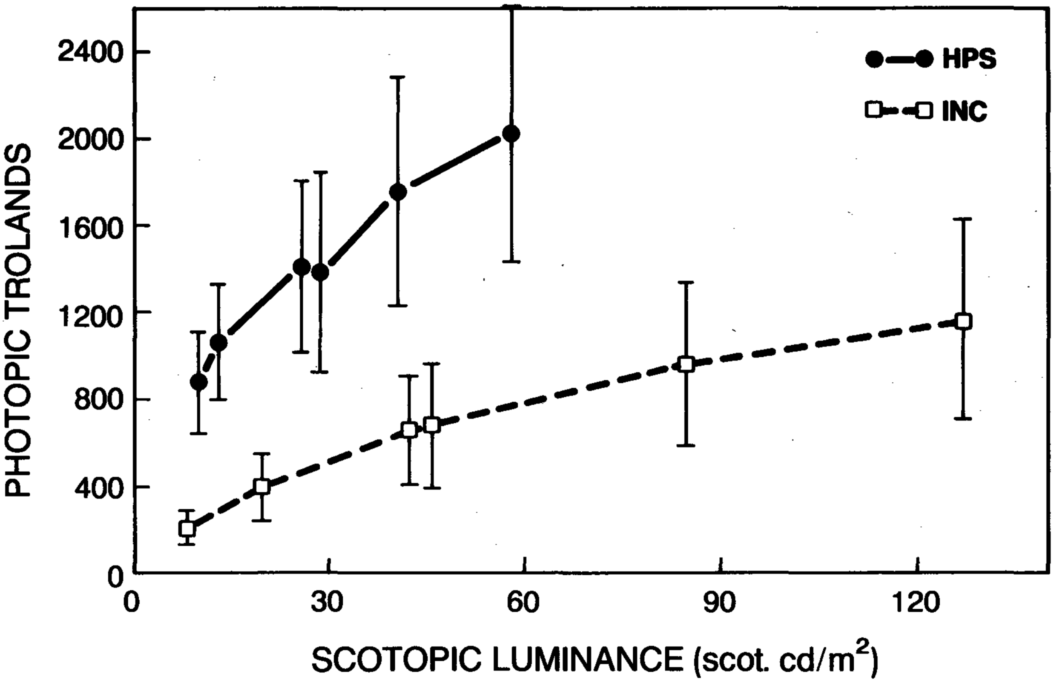

Figure 8—Mean photopic entrance-trolands ± SD as a function of scotopic luminance. Compare with Figures 6 and 5.

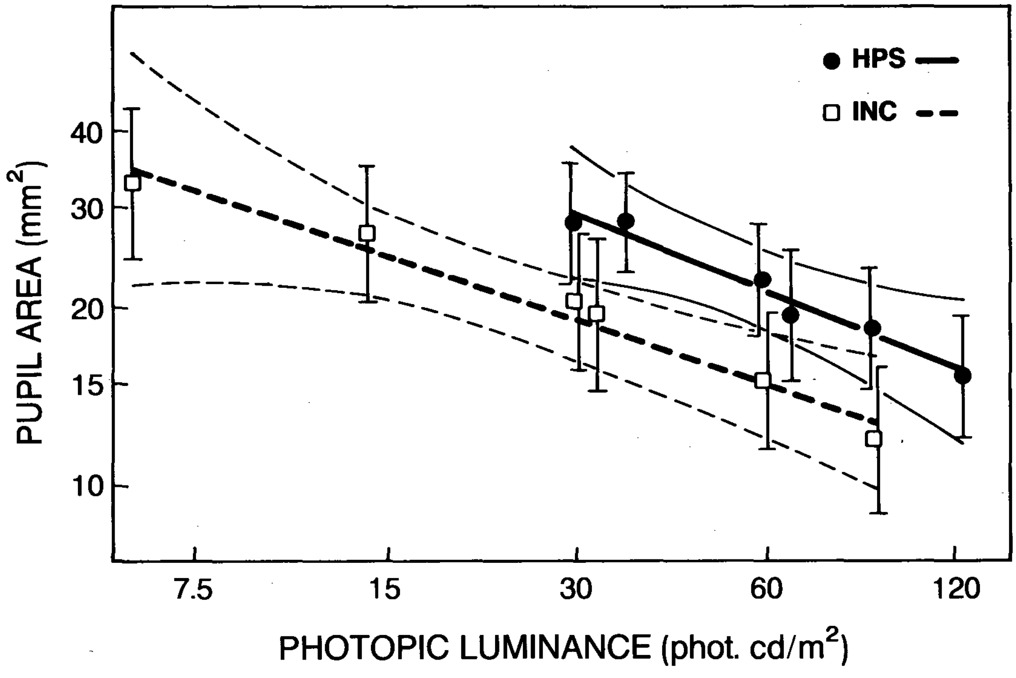

Figure 9—Mean pupil area ± SD as a function of photopic luminance. This is from the same data as in Figure 2.

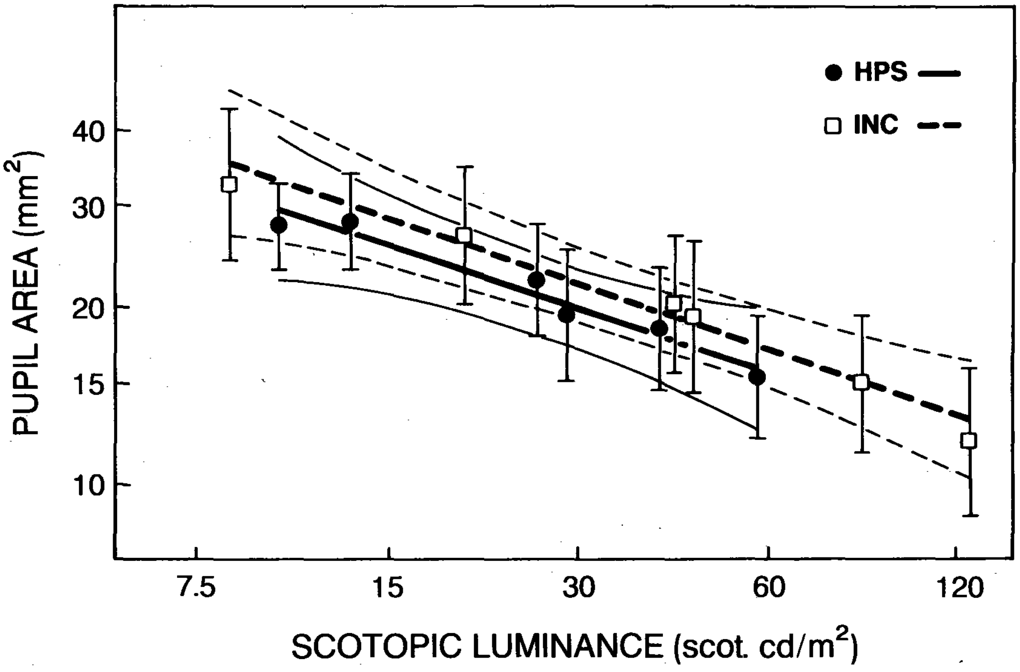

Figure 10—Logarithmic graphing of mean pupil area ± SD as a function of scotopic luminance. This is from the same data as in Figure 3. Compare with Figure 9.

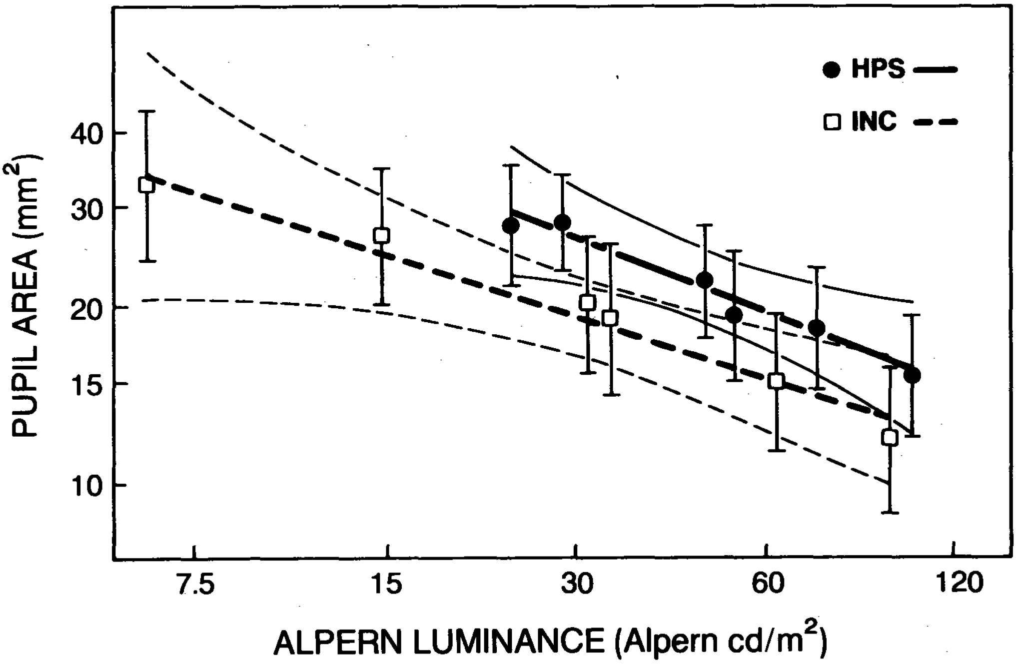

Figure 11—Logarithmic graphing of mean pupil area ± SD as a function of Alpern-Campbell luminance. This is from the same data as in Figure 4.

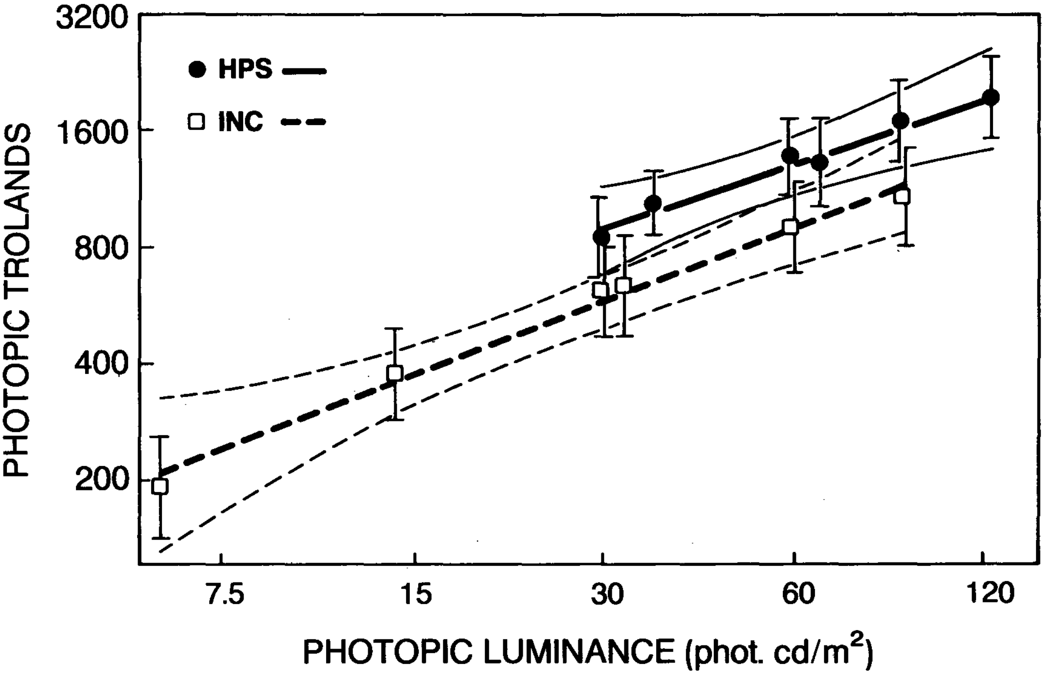

Figure 12—Logarithmic graphing of mean photopic entrance-trolands ± SD as a function of photopic luminance. This is from the same data as in Figure 5.

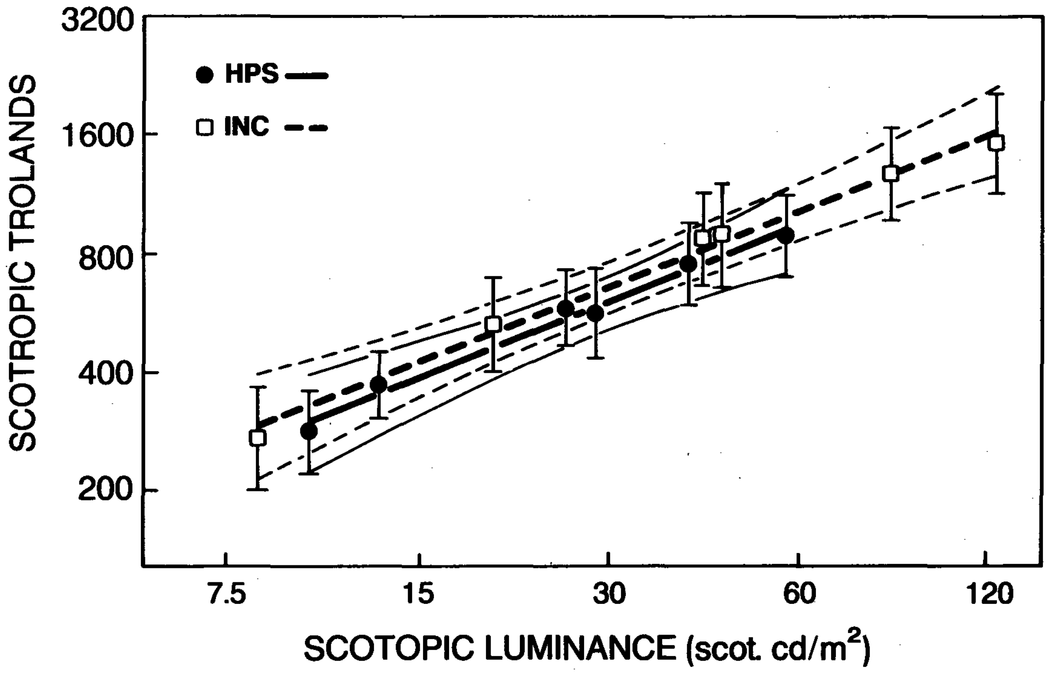

Figure 13—Logarithmic graphing of mean scotopic entrance-trolands ± SD as a function of scotopic luminance. This is from the same data as in Figure 6. Compare with Figure 12.

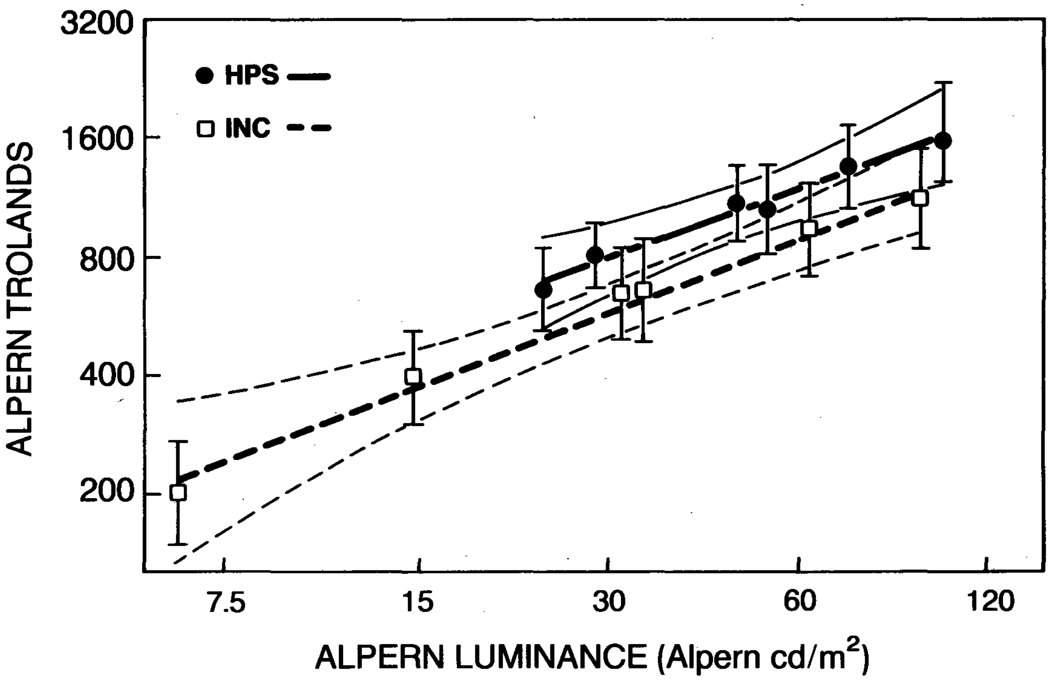

Figure 14—Logarithmic graphing of mean Alpern-Campbell entrance-trolands ± SD as a function of Alpern-Campbell luminance. This is from the same data as in Figure 7.

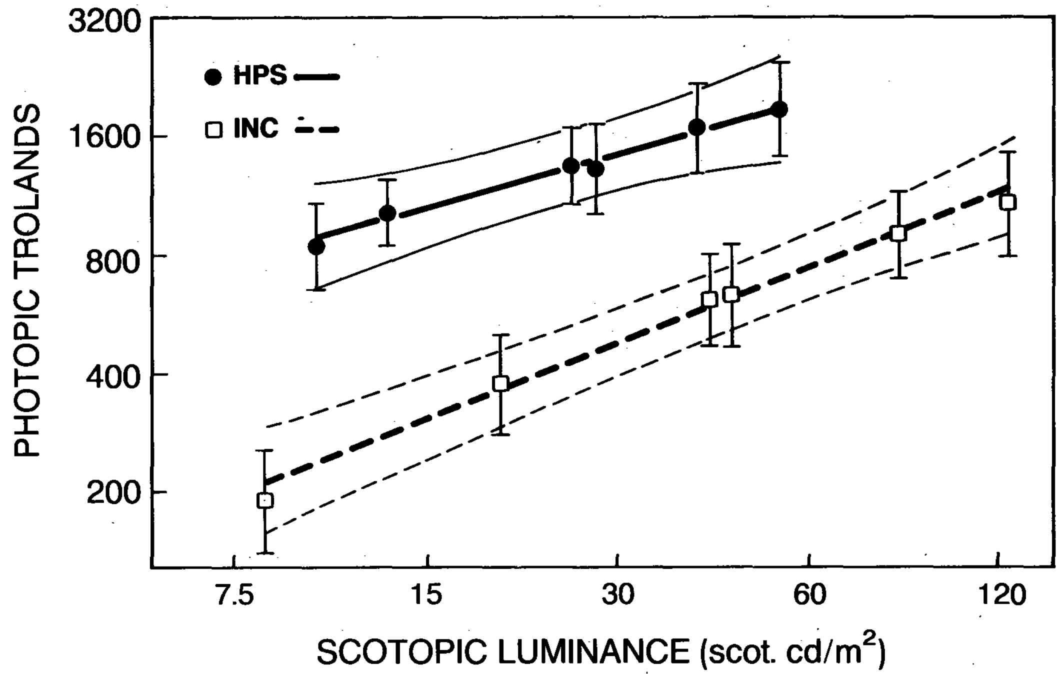

Figure 15—Logarithmic graphing of mean photopic entrance-trolands ± SD as a function of scotopic luminance. This is from the same data as in Figure 8. Compare with Figures 12 and 13.

creased pupil size may be of significant benefit under conditions of low task illuminance, low contrast, or to the aged.

On a strictly technical note, the scotopic dominance found by the authors may be due to the large visual field used in the study. Both Alpern and Campbell (reference 2) and ten Doesschate and Alpern (reference 3) have shown that cones do contribute to the pupillary response, but that the cone-mediated response is small compared to that of rods except for very small fields or very high retinal illuminances (*e.g.* 10,000 trolands). One would also expect the effect to be diminshed under conditions where the field of view contains surfaces with different spectral reflectances so that the retinal illumination is not determined solely by the spectral power distribution of the source as was the case in this study. None-the-less, for any task which has a reasonably neutral background, the effect may well be significant and may tilt the efficacy advantage even further in favor of HPS illuminants.

Alan L. Lewis

References

Atchison, D.A., G. Smith, and N. Efron. 1979. The effect of pupil size on visual acuity in uncorrected and corrected myopia, *Am J Optom & Physiol Optics* 56:315-323.

Alpern, M. and F.W. Cambell. 1962. The spectral sensitivity of the consensual light reflex, *J Physiol* 164:478-507.

ten Doesschate, J and M. Alpern. 1965. Response of the pupil to steady state retinal illumination, *Science* 149:989-991.

This is certainly a very interesting paper to the lighting public in general and the roadway lighting professionals in particular. There has been diverse opinions concerning the question of whether the human sees better under high pressure sodium versus other types of artificial sources. Many subjective evaluations have been offered, some saying they see better under HPS and others saying that seeing is not as good. Even though the results are not correlated to visual performance they show there is a difference in the eye response between HPS and incandescent light. It is hoped that this work will be carried further to the point of determining if there is a correlation between these results and visual performance.

There are some questions relating to the methodology in the work. Even though it is not stated exactly the implication is that the incandescent lamps were operated at 60 Hz. Is this correct? What was the waveform of the high frequency driving the HPS lamp? Was this a pure sinewave or some other waveform? If not a pure sinewave could the waveform have effected a difference in the response of the Pritchard relative to the eye response? As the input voltage to the HF HPS ballast was increased did the driving frequency to the lamp or its waveform change? If so, what effect, if any, did it have on the readings?

When the wattage of an HPS lamp is increased by increasing the in-voltage usually both the lamp voltage and current increase. The net result is not only an increase in lamp lumen output, but also a change in the spectral distribution of the lamp. Was this change observed? If so, how was this change accounted for in the photopic and scotopic response?

The authors state they used a 30 kHz ballast to drive the HPS lamp to avoid a possible confounding variable. But practically all HPS lighting in this country is driven by 60 Hz ballasts. Was the test run using a 50 Hz ballast to see what differences there are? If not, do the authors plan to do any test on the HPS lamp at 50 Hz?

These results naturally lead us to the question of whether other high intensity discharge lamps give the same type results or not. Do the authors plan any further work to determine the effect with other HID sources? If so we assume this would also include low pressure sodium sources?

Billy Lee Shelby
American Electric Division
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This paper presents a thoughtful analysis of the effect of light source spectrum on pupil size. As pointed out, this was first noted in the late eighteen hundreds, and as you might expect, has evoked some spirited unresolved controversy since then. The present paper, because of new instrumentation and well mastered techniques will gain the authors some well deserved recognition in the final resolving of the controversy on "how the light spectrum affects pupil size."

An important larger controversy will remain. That is, "What is the practical effect on human performance of operating with a pupil size reduced by 2 or 3 millimeters?" As a dedicated vision researcher, the following is offered in an effort to assist and encourage necessary further research. Here are comments from past research:

1. Duke-Elder (1942-1972) gives this insight into the subject: "When lights of different colours are used the degree of contraction varies with the luminosity of the light independently of the colour." A small pupil is advantageous in that it lessens the influence of spherical and chromatic aberration and increases the depth of focus; it has the *disadvantage* of increasing the influence of diffraction and reducing the brightness of the retinal image. The visual acuity always improves as the retinal luminance is increased. Even with a pupillary diameter of 5 mm, however, chromatic aberration is negligible. "A small bright area has greater pupillomotor effect than a larger dimly (scotopic) illumin-

ated area."

2. Parry Moon (1961) points out that "Cobb showed that visual acuity is practically unaffected by a change in pupil diameter from 2 to 6 mm. Although pupil diameter does have an effect on retinal illumination, the reason for the marvelous ability of the human eye to adjust itself to a wide range of luminosities must be sought elsewhere than in a change in pupil diameter."

3. Buck, McGowan and McNelis (1975) found no difference in roadway visibility as a function of light source color. Moreover, lighting distribution *did* affect visibility."

4. DeLaney, Hughes and McNelis (1978) found no difference in visibility between 3000 and 5000 Kelvin fluorescents and no difference in human performance between a comparison of cool white fluorescent and high pressure sodium.

5. Judd and Wyszecki (1952) caution that people "become less sensitive to violet and blue light as they get older," suggesting a young population even if drug free may not be a sound body on which to base lighting recommendations. They also caution that "within the scotopic region the rods adjust their sensitivities automatically to the particular luminance level."

6. Luckiesh (1937) points out that the pupil remains practically constant in size for changes in brightness of the visual field as high as 200 to 1 if the increase in brightness is accomplished by gradual and almost imperceptable changes." He also points out that a larger pupil has greater resolving power, although counterbalanced by a decrease in the sharpness of the retinal image.

7. Zoethout (1927) pointed out that by experiment it has been proved that "accomodation of our eye is something far more than pupil constriction, which by itself cannot account for near vision" and "it is only when light is very feeble or very strong that the size of the pupil is greatly altered."

So that it might not appear that I am making much to do about nothing, let me more clearly state that if we are ever to transform this effect which could remain just a laboratory curiosity into a useful and viable force for improving lighting so as to optimize visual efficiency, visibility and human performance, then the dedicated researchers of IES need to pick up the challenge by doing the required research. I hope the authors have the next five years available to dedicate.

John F. McNelis
Lighting Business Group
General Electric Company

Authors' rebuttal

To Prof. Alan Lewis

We appreciate Prof. Lewis' comments that emphasize the implications of our work.

The question of what size of field of view (significantly different in our experiments and those of Alpern & Campbell) is relevant for extrapolating from experiment to lighting applications remains to be evaluated. Our experiments with a large field of view show that field of view, spectrum and rod and cone function must be a concern of rational, realistic lighting design.

We agree with Prof. Lewis that the light reaching the eye is affected not only by spectral difference between lamps, but also by the spectral reflectances of objects in view *and* in the surround. The effects on pupil size should be predictable if all factors are known.

We question whether there is an efficacy advantage of scotopically deficient sources under all conditions. More trolands may not necessarily always translate into better vision, since pupil size (controlled by intensity and spectrum) can affect visual performance. Under some circumstances there may be a visual advantage of smaller pupils brought about by scotopically rich sources. On the other hand, the apparent advantage of extra trolands secondary to illumination with a scotopically-poor HPS lamp may be countered by poor depth of field or visual acuity. Yet trolands may be an over-riding factor under conditions near visual threshold, as in night driving.

To Billy Lee Shelby

Billy Lee Shelby has indicated a number of further studies which are important and relevant to determining what factors should be of concern in practical lighting design. Our present experiment shows that pupil size is important, and suggests that the next questions are: 1) what is the visual consequence of this finding? 2) are there special conditions that affect the result? 3) with what lighting technologies is this result of concern?

Specifically responding to his comments and suggestions: incandescent lamps in this experiment were always operated at 60 Hz.

The wave form of the high frequency HPS driving voltage is irrelevant to the response of human subjects since the frequency is many orders of magnitude beyond any human response. As far as the Pritchard Photometer is concerned, we compared its output to a photo-diode and found no differences between the two instruments when frequency was changed from 60 Hz to 30 kHz.

The spectrum of the HPS lamp does change as its input power is reduced. We were aware of this and at each setting of the input voltage needed to change the light intensity, we made separate measurements with a spectrophotometer to determine the spectral power distribution and then folded that against the standard scotopic response of the eye to determine the scotopic luminance at every voltage setting.

The reason for introducing high frequency ballasts to drive the HPS was to eliminate any confounding influences of flicker since the HPS has a very high (95 percent) modulation as compared to incandescents (5 to 8 percent).

We have performed separate experiments under a grant from the Lighting Research Institute (LRI) of the IES in order to investigate whether frequency modulation affects pupil size. We will be reporting that using a variety of different lamps with large modulations including HPS, LPS, Daylight fluorescent, and a photocopy narrow spectrum fluorescent, the pupil size under each lamp at driving frequencies of 60 Hz and 30 kHz in six subjects shows no statistically significant differences in any of the comparisons.

As to other HID lamps, we predict (and will have to experimentally verify) that the results will depend solely upon the ratio of scotopic to photopic spectral content of lamps, and be unrelated to the light emission mechanism. Continued work with a variety of lamps will be undertaken, especially to examine questions of effects on actual visual performance, so long as funds are available for continuation of this work.

To John McNelis

We whole-heartedly agree with John McNelis that an important next step in this study is to determine if there is any measurable effect on visual function resulting from spectrally induced pupil size differences. It should be noted that researchers in optometry have been aware for a long time that persons with slight uncorrected errors in refraction find significant improvements in acuity with smaller pupils (see e.g., Atchison 1979). A spectacle wearer attempting to read without his or her spectacles will often find it possible when the illumination level is increased with the resultant decrease in pupil size reducing the effects of lens spherical aberration. On the other hand a person with a near perfect lens would probably not have an acuity benefit but might find an improved depth of field with a smaller pupil. Thus, another variable that must be studied is the inherent visual function of subjects with uncorrected refractive errors.

The first quoted statement from Duke-Elder is contradicted by our work and the researches cited in McNelis' first paragraph. The second quotation provides a description of the effect of pupil size on various factors, much of which must be quantitatively evaluated in future research.

Concerning the remarks of Parry Moon, one should note the work of Campbell who showed continued decrement in depth of focus of the normal eye with increasing pupil size. A major future issue is whether uncorrected refractive errors "use up" the "ability to adjust" mentioned by Moon.

We have found it difficult to compare the work of Buck et al. on roadway visibility with different light sources as well as the work by Delaney et al. on an office task under different effective color temperatures of fluorescent lamps, with our own conclusions since in each case, though light source spectrum was varied, spectral reflectance was not known. In addition in Delaney et al. the issue of fluorescence in paper whiteners and unknown target contrast make conclusions concerning the effects of spectral differences on performance uncertain.

The comment made about the use of older subjects is important as senile miosis certainly affects the dynamic range of pupil size and there may be other effects of aging as well. We suggest that extrapolation from our results from young subjects without refractive errors to other groups is not warranted. Each subject group should have a separate evaluation.

As to the remark ascribed to Luckeish, the conditions for which small increments in luminance fail to produce changes in pupil size are primarily under scotopic light levels (Alpern & Campbell, and Bouma) whereas in our experiments light levels were always in visual photopia. The second remark due to Luckeish is supported by the findings that for a very small pupil there is a tradeoff between the limitations caused by diffraction and the improvements in depth of field (see Westheimer (1964) and Green and Campbell (1965).

The reference to accommodation from Zoethout should not apply to the conditions of this experiment since the subject was fixating on a target slightly more than 1 meter away and thus synkinesis is unlikely.

References

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Green and Campbell. 1965. Effect of focus on the visual response to a sinusoidally modulated spatial stimulus. *JOSA* 55(no. 9):1154.