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Abstract

Subjects judged the orientation of a 2 min. gap Landolt C located at a distance of 2.4 m. The stimuli were presented in central vision on a CRT, at low to medium contrast. The effects of varying the spectrum and luminance of surround lighting were assessed on both pupil size (measured using infrared pupillometry during task performance) and task accuracy. The task display was protected from the surround lighting, so that its luminance and contrast could be varied independently of the changes in the surround lighting. Indirect surround illumination was provided by either two illuminants of very different scotopic spectral content but with the same photopic luminance (Experiment 1 and 3 each), or by using the same illuminant at two different luminance levels (Experiment 2). In experiment 3, the effect of changing surround spectrum was compared to the effect of varying task background luminance between 12 cd/m^2 and 73 cd/m^2. In all experiments, scotopically enhanced surround lighting produced pupil areas which were reduced by almost 50% in comparison with surround lighting with relatively less scotopic luminance. Concomitantly there was improvement in Landolt C task performance with the scotopically enhanced surround lighting at all contrast and luminance levels. In these experiments, smaller pupil sizes were associated with significantly better visual-task performance in spite of lower task retinal illuminance when compared to the condition with larger pupils. These results suggest that changes in surround spectrum can compensate for the effect on task performance of a reduction in task luminance and supports the possibility that lighting energy savings can accrue in the workplace by shifting lamp spectra to obtain greater scotopic efficacy.

Introduction

In prior studies we have shown that the rod photoreceptors of the retina have significant effects on pupil size and perceived brightness at light levels typical of building interiors[1,2]. In these studies of adults 20-40 years of age, for conditions of almost full field of view, scotopic spectral content of the ambient illumination was the predominant determinant of pupil size, and was a major determinant of perceived brightness of whitish light. We showed that for two illuminants providing the same level of photopic luminance of indirect whitish light, the illuminant with the greater scotopic luminance yielded smaller pupils and was perceived as brighter.

Past studies of the effect of lighting variables on visual performance have accentuated the role of luminance and contrast as the primary determinants of visual performance, while the spectral distribution of the lighting was considered important mainly for chromatic tasks. To the extent that lighting spectral distribution can affect pupil size, and that pupil size can affect visual performance, it is possible that light spectrum could also be a significant determinant of visual performance for achromatic tasks. In the studies presented below, we demonstrate for pupil sizes typical of interior lighting conditions, that Landolt C recognition is significantly improved with smaller pupil sizes, and that this performance effect is much larger than the opposing effect in these conditions of either reduced task luminance or reduced retinal illuminance.

There are two opposing task performance effects which may occur when pupil size is decreased. On the one hand, decreased pupil size may increase task performance by mitigating the effects of optical aberrations. On the other hand, the reduction in task retinal illuminance (Trolands), due to decreased pupil size, could have a negative effect on task performance. Given two opposing effects, it is an open question whether pupil decreasing size provides any visual benefits (or burdens) within the range of pupil sizes that can occur under typical indoor lighting conditions.

The literature does not provide definitive evidence for the direction of change in visual performance with decreasing pupil size under such conditions. Studies have shown that either pupil size or retinal illuminance affect aspects of acuity but none address quantitatively the visual performance tradeoff between task retinal illuminance and pupil size for a specific task. Shlaer[3] showed that for a fixed artificial pupil of 2 mm diameter, high contrast Landolt C acuity (resolving the gap orientation) increases with increasing retinal illuminance (up to approximately 10,000 Trolands). Woodhouse[4] varied the size of artificial pupils using the resolution of a vertical grating task with low to moderate contrast levels and found that with fixed retinal illuminance, grating acuity decreased with increasing pupil size. Liebowitz[5] examined the question of whether there is an optimal pupil size when the task is a grating of high contrast. Because of the influence of the Stiles-Crawford[6] effect, he used a constant subjective brightness criterion for retinal illuminance and found that grating acuity had a rather broad maximum occurring at intermediate pupil sizes with the optimal pupil size depending on the criterion illuminance. It is quite possible that pupillary related visual effects could be idiosyncratic, depending on the optical status of individuals tested. The studies of

Atchison et al[7] showed that for subjects provided with slight added positive lens power beyond their best refractive condition, Snellen acuity generally decreased with artificial pupil sizes over most of the range of pupil sizes occurring in building interiors, even though retinal illuminance increased.

Our present studies address the question of whether pupil size differences induced by changes in surround luminance affect the recognition of Landolt C orientation, first under conditions of constant task luminance and subsequently with task luminance varying. The task Landolt C was displayed on a CRT where its luminance and contrast were independently controlled such that the surround illuminance affected neither task luminance nor its contrast. This allowed us to dissociate pupil size effects from task luminance effects. There are no prior studies where task luminance was controlled but task retinal illuminance was varied as a consequence of changing the size of the natural pupil through changes in the surround illumination. The experimental conditions most closely mimic the lighting conditions which can occur when viewing self-illuminating tasks such as video display terminals.

Our hypothesis is that smaller pupils can yield improved performance, even though there is a resulting decrease in task retinal illuminance (which is proportional to the product of task luminance and pupil area, expressed in Trolands). In the first of three experiments, we tested this proposition by keeping the task luminance the same and varying pupil size by providing surround lighting of the same photopic luminance but with very different scotopic luminances. The result was that Landolt C accuracy was better with smaller pupils. However, the surround illuminants differed in color, and observed Landolt C accuracy effects might have been the result of either pupil size differences or of differences in the neurally induced color of the foveal task. Hence, a second experiment was carried out to reduce such a color effect by comparing the effect of differing pupil sizes on Landolt C performance using the same illuminant at two different levels of surround luminance, again with task luminance fixed. In the third experiment, task luminance was varied to examine to what extent decreases in pupil size could offset the effects of decreases in task luminance. In all experiments, our hypothesis was confirmed in that Landolt C task performance is affected by pupil size at all contrast levels and task luminance values studied.

Methods

Subjects: Separate samples of twelve subjects each (all Caucasian) were recruited via advertisement, for each of the three experiments. Subjects were recruited and were screened during a telephone interview to exclude potential subjects who reported that they could not drive an automobile without glasses at night. Upon arrival in the laboratory, subjects' distance acuity without glasses was tested for each eye separately using the Snellen chart at 20 feet. All subjects had at least 20/20 vision as per the Snellen chart. In prior studies, we developed procedures to exclude all subjects who could not produce an operational pupil image for pupillometry (see below) due to excessive blinking or cosmetics. None of the potential subjects for this study needed to be excluded.

The subjects for experiment 1 were 21 to 37 years of age and included 7 females and 5 males. For experiment 2, subjects were 21 to 45 years of age and included 4 females and 8 males. For experiment 3, subjects were 18 to 45 years of age and included 5 males and 7 females.

<u>General Experimental Procedures:</u> The experimental situation was designed in such a way that surround lighting and task lighting could be manipulated separately, with minimal effects of surround lighting on task illumination. The experimental room had dimensions 2.5 m x 2 m x 2 m, with walls and ceiling painted with a spectrally flat white paint (Kodak). Task stimuli were presented on a video display terminal, with surround lighting generated via indirect illumination of the room using 40 watt fluorescent lamps. Because at times we changed the spectrum, it is necessary to specify the filter used when making the photometric measure: if photopic, the units are in photopic candelas (pcd); if scotopic, in scotopic candelas (scd). Lamp spectral power distributions as a function of wave length were determined by direct measurement using a Pritchard Spectraphotmeter (model 1980 A) in the wave length scanning mode. A similar method was used to determine that the reflectance for the white paint in the chamber was spectrally neutral. (For more details see ref. 1)

The face of the video display was shielded from the surround lighting. It was covered with a matte black surface except for a rectangular tube of length 46 cm with an opening 5 times higher and 6 times wider than the C. In addition, the central 30° on the wall directly in front of the subject was covered with a matte black curtain in order to decrease any confounding effects of glare. Thus, surround luminance was present primarily on surfaces beyond the 30° central field. Figures 1 and 2 are photographs of the experimental arrangement.

The task was at a visual distance of 2.4 m, accomplished by placing the display terminal behind the subject, who viewed it on a front surface mirror situated in the middle of the black curtain in such a manner that no direct light rays from the lamps or wall behind the subject was seen in the mirror. In both experiments, a variable contrast "Landolt C" of approximately 14 min. angular subtense of outer dimension and approximately a 2 min. gap in the "C" was presented for a period of 200 ms on a white CRT screen. Figure 3a shows the precise dimensions of the Landolt C and Fig. 3b shows the orientations as viewed by the subjects. The "C" was oriented 45° from the horizontal so as to distribute across all orientations any possible effect of horizontal astigmatism that the subjects might have. In experiments 1 and 2, the immediate background of Landolt C on the CRT screen had a constant and fixed luminance of 13.2 pcd/m^2 with the surround lighting off and increased about 12% to 14.7 pcd/m^2 due to the small amount of light that found its way on the CRT surface when the surround lighting was on. For experiments 1 and 2, the entire CRT screen (both the part inside and outside of the area covered by the viewing tube) was set to the background intensity. For experiment 3, in order to achieve higher levels of background luminance, a smaller area of the CRT screen (which entirely included the area within the viewing tube) was set to the background luminance. In experiment 3, the small amount of surround lighting that protruded into the tube was reduced to about 0.3 cd/m^2.

The task was presented on a Mitsubishi VGA monitor using a Matrox graphics board. A specific Landolt C contrast was generated by separately setting the intensity of the CRT background pixels and Landolt C pixels, with the Landolt C contrast achieved by setting the "C" luminance <u>lower</u> than its immediate background, where contrast is defined as the difference luminance divided by the task background luminance. The experiments were designed to use the same contrasts over surround lighting and task background conditions. For simplicity the initial procedures for setting task luminance used a split screen with one half set to the desired task background luminance and the other half set to the desired "C" luminance. Subsequent to all the data collection, we determined that each CRT pixel's measured luminance is a function of the total number of pixels which are set to a particular CRT control value. If half the pixels are set to a certain CRT control value with the rest of the pixels off, the on pixels are brighter than if all the screen pixels had been set to that same control value. Thus, the actual CRT luminance values for the specific experimental conditions determined from the initial half-screen calibration procedure were incorrect, with actual luminances being a function of the area and intensity of the illuminated areas of the screen.

This effect necessitated a redetermination of the task background and "C" luminances used during data collection. Luminances were measured using a Pritchard Spectrophotometer (Model 1980A). For each experimental condition, we measured the actual "C" and background luminances directly. The "C" luminance was measured using a 6' aperture on the Pritchard. This aperture allowed sighting within the strokes of the "C", but included only 6 pixels such that slight differences in sighting resulted in variability of the measured luminances. Measurements were taken at twelve different locations on the "C", and averaged. The task background luminance was measured and averaged over 4 different locations using a 20' aperture. The contrasts were adjusted for the leakage of the surround lighting onto the CRT screen.

Data were collected in blocks which included twenty "C" presentations for each level of task contrast (three levels for experiment one, four levels for experiment two, and four levels of contrast for each level of task background luminance in experiment three), with orientation of the "C" and task contrast randomly varying over presentations, while surround illumination and task background luminance was held fixed through the block. The sequence of luminances and surrounds was randomly varied across subjects. The subjects' task was to press one of the four buttons on a keypad indicating the orientation of the Landolt C just presented. Each 200 msec "C" presentation was preceded by a 2.5 sec pupil size measurement. The pupil size measurement prior to the next presentation was initiated one second after the subject responded to the previous presentation. For each experiment, eight blocks of data were collected for each of the two respective surround lighting conditions (described below) in either an ABBAABBA or BAABBAAB format, where A and B refer to the two surround lighting conditions.

Pupillometry: Figures 1 and 2 show the placement of the pupilometer. The source of the infrared radiation for the pupilometer was a 12V incandescent lamp with a Hoya RM90 infra-red filter (passing a negligible amount of radiation in the visible spectrum) which directly illuminated the eye. An infra-red sensitive video camera (RCA) fitted with an identical filter was trained on the eye via the mirror. The output from the camera was displayed on two monitors. The first monitor showed the unprocessed video camera output, while the second showed the image of the eye as processed by the computer. The unprocessed image was monitored by the experimenter to ensure that subjects remained in the camera's plane of focus (ensuring stable image calibration) and that eye position did not change. Pupil area was measured by the pupillometer, by methods previously described by summing the lengths of raster lines in the pupil area[10]. The pupillometer was calibrated using artificial pupils of various sizes, and the relationship between pupil area and the output of the pupillometer was confirmed to be linear up to about 15° of gaze deviation.

Statistical Analysis: Data for experiments 1 and 2 were analyzed using the multivariate solution for a repeated measures Analysis of Variance via the General Linear Models Procedure within the SAS (Statistical Analysis System) data analysis system. Since all subjects went through every condition within an experiment, all experimental effects were evaluated as within-subject effects; there was no analysis of between subject effects.

For experiment 3, since our initial calibration method was incorrect, the actual task background and "C" luminances were not balanced with respect to contrast. That is, for each level of task background luminance, a slightly different set of "C" contrasts was actually used. Given this unbalanced design, contrast and background luminances could not be analyzed as repeated measures effects, but rather were analyzed as covariates using the BMDP2V program (BMDP Software Inc.).

Results

Experiment 1

Experiment 1 was designed to test whether changing pupil size (by a change in surround spectrum) affected Landolt C recognition when the task and surround photopic luminances were fixed.

Two different illuminants were studied. One was a combination of 3 red and 1 pink hue fluorescent lamps and the other used a single greenish-blue hue lamp (all F40T12). The phosphor coating in this latter lamp is Sylvania phosphor #213 which has its peak output at the maximum of scotopic sensitivity and is referred to here as the F213 lamp. The ratio of scotopic to photopic luminance (S/P) for the red/pink combination was 0.24 while for the F213 lamp, the S/P was 4.31. For this experiment, the intensity of these illuminants was set so that the front wall luminance was 63 pcd/m^2 as measured on the viewed walls, while the scotopic luminance of necessity varied from 15 scd/m^2 for the red/pink combination and 272 scd for the F213. According to our previous studies, this choice of illuminants having a large difference (a factor of 18 fold) in scotopic luminance should produce significant differences in pupil size. For this experiment, the three actual contrast levels for the Landolt C were 15, 23, and 32%. In pilot studies, these contrast levels yielded task performance ranging from chance to about 90% accuracy.

<u>Pupil Area:</u> Even though the conditions were photopically equivalent, there was a significant lamp effect on pupil area, with an average 43% (s.e. = 3%) reduction in pupil area under scotopically enhanced F213 lighting compared to scotopically deficient red/pink lighting ($F_{1,11}$=39.0, p<.0001). Mean pupil area (standard error) for the 12 subject sample was reduced from 18.1 (± 1.9) mm^2 under the red/pink illuminant to 9.8 (± 0.7) mm^2 under the F213 lamp. All twelve subjects demonstrated a reduction (from 24% to 57%) in pupil size with F213 lighting, with pupil size unaffected by either the contrast of the Landolt C stimulus ($F_{2,10}$=1.31, p=.31) or the orientation of the Landolt C gap ($F_{1,11}$=0.06, p=.81).

<u>Landolt C Performance:</u> There was a large and consistent effect of task contrast on task performance ($F_{2,10}$=80.9, p<.0001) with performance increasing monotonically with increasing contrast. Moreover, every subject showed this monotonic increase in performance accuracy with increasing task contrast. Figure 4 illustrates both the effect of contrast and the significant main effect of lamp spectrum on task performance ($F_{1,11}$=13.1, p=.004), namely, orientation detection improved under the scotopically enhanced surround lighting compared to the scotopically deficient lighting when both were photopically equal. On the average, there was a 4.5% (s.e. = 1.3%) increase in task accuracy with F213 lighting compared to red/pink lighting at the same surround photopic intensity, with ten of the twelve subjects evidencing an increase in accuracy under F213 across contrast levels (Fig. 5). There was a significant interaction of lamp by percent contrast ($F_{2,10}$=5.3, p=.027) such that with F213 there was less of a linear increase in performance with increasing contrast in comparison to red/pink. There was relatively more of an increase in performance accuracy between the two illuminants as contrast went from 15 to 23% and less of an increase as contrast went from 23 to 32%. This trend is consistent with an asymptote at higher task contrasts for the F213 illuminant. The orientation of the Landolt C stimulus did not have a significant main effect on task performance ($F_{1,11}$=2.62, p=.14), nor did it have a significant interaction effect with lamp ($F_{1,11}$=2.0, p=.19).

Within the General Linear Model procedure, we produced normal equations showing the performance accuracy as a function of both surround lighting and task contrast. This analysis showed that, on average, a 1.3% increase in performance occurred for each 1% increase in task contrast. Thus, the resultant 4.5% improvement in performance that occurred when surround lighting was shifted from red/pink to F213 illuminants was equivalent to the amount of performance increase which would have resulted from a 3.5% increase in task contrast.

Experiment 2

Experiment 2 was designed to see if Landolt C recognition with fixed task luminance was affected by changes in pupil size caused by varying only the luminance of the same surround illuminant (no spectral change).

In this experiment, only the F213 illuminant was used. Its intensity was set so that surround illumination was either 3.5 or 53 pcd/m^2, as measured on the viewed front walls, resulting in a 15 fold difference in luminances. For this experiment, the actual four Landolt C contrasts used were: 12, 16, 24, and 33%.

Pupil Area: Increasing surround F213 luminance from 3.5 to 53 pcd/m^2 resulted in a very large, consistent, and reliable reduction of pupil area averaging 68.6% ($F_{1,11}$=110.8, p<.0001). Mean pupil area (standard error) for this 12 subject sample was reduced from 20.1 (± 1.7) mm^2 at 3.5 cd/m^2 to 6.1 (± 0.5) mm^2 at 53 cd/m^2. All twelve subjects demonstrated a reduction in pupil size, with the size of reduction in pupil area ranging from 42% to 80% (mean 68.5%, s.e. ± 2.94).

Landolt C Performance: The effects of surround luminance and task contrast on task performance are displayed in Figure 6. There was a highly significant effect of contrast on task performance, such that greater contrast was associated with increased Landolt C accuracy ($F_{3,9}$=62.0, p<0.0001). There was also an effect of surround luminance on performance, such that increased surround luminance was associated with an average 9.8% (s.e. = 2.8%) increase in percent correct on the Landolt C task ($F_{1,11}$=11.9, p<0.0055). Nine of the twelve subjects evidenced an increase in accuracy with increasing surround luminance (see Figure 7), with the change in performance over all 12 subjects ranging from a 6.25% reduction in percent correct to a 22.5% increase in percent correct. The luminance by contrast interaction was not statistically significant ($F_{3,9}$= 0.67, p=.59), indicating that the contrast vs. accuracy curves were parallel for the two surround luminance levels.

Experiment 3

Experiment 3 was designed to determine if the effects of experiment 1 could also be found when the task background luminance was varied. In addition, the trade-off between decreasing pupil size and decreasing task background luminance could be examined.

In this experiment, surround lighting was provided by the same two illuminants as in experiment 1, with both providing a surround luminance level of 53 pcd/m^2 (13 scd/m^2 for the red/pink and 228 scd/m^2 for the F213) on the front chamber wall. Four levels of task background luminance and four levels of task contrast were chosen for each value of task background luminance. These are shown in Table 1 where contrast ranges from 16 to 50% and background luminance ranges from 12 cd/m^2 to 73 cd/m^2.

As noted above, because of problems in the intial calibration, the task contrasts were different from those originally planned and resulted in non identical sets of contrasts for each of the task background luminance conditions. This required additional procedures for removing the effects of a confounding of task background luminance and task contrast. To remove this confounding, we used an Analysis of Convariance (ANCOVA) procedure, which is equivalent to holding task background luminance fixed (at one of its four levels), generating regression lines as a function of task contrast to predict either pupil size or task accuracy and then comparing the generated regression lines at the various levels of task background luminance. The ANCOVA with task contrast as the covariate is similar conceptually, except that task contrast is held fixed only in a statistical sense. This procedure permits the analysis that takes into account the condition of a group of differing levels of task contrast that does not have the same set of values for each of the task background luminance conditions.

Pupil Area: Except for slightly larger pupil sizes (consistent with slightly lower surround luminance), the pupil size results for experiment 3 were almost identical to those of experiment 1. There was an average 40% (s.e. = 3%) reduction in pupil area under F213 compared to red/pink lighting ($F_{1,11} = 66.2$, $p < 0.0001$). Mean (±s.e.) pupil area for the 12 subject sample was reduced from 18.2 (±1.3) mm^2 under the red/pink illuminant to 11.1 (±0.6) mm^2 under the F213 lamp. All twelve subjects demonstrated a reduction (ranging from 26% to 51%) in pupil size with F213 lighting, with pupil size unaffected by the contrast of the Landolt C stimulus ($F_{3,33} < 0.01$, $p = 0.99$) or the task background luminance ($F_{3,33} = 0.02$, $p = 0.98$). Nor were there any significant interactions among lighting condition, task contrast and task background luminance.

Landolt C Performance: As in the other experiments, there was a very large and consistent effect of contrast on task performance. Contrast effects were highly significant with the F statistic having 3 and 11 degrees of freedom and values ranging from 31.2 to 65.1, (all $p << 0.0001$) over the values of task background luminance. The effect was primarily linear, with a significant quadratic component wherein the effect became smaller at higher contrasts. The linear component of the contrast effect was more than an order of magnitude larger than the quadratic component. There was also a significant, although much smaller, effect wherein increased task background luminance yielded increased task accuracy ($F_{3,33} = 6.20$, $p = 0.0018$) see figures 8a-8d. This effect also was quadratic, with the linear component being more than twice as large as the quadratic component. There was a highly consistent and statistically significant improvement in task accuracy with F213 compared to red/pink surround lighting ($F_{1,11} = 69.7$, $p < .0001$) with this effect becoming smaller (asymptoting) with increasing task contrast. All subjects showed this overall surround lighting effect, though in some cases one or at most two subjects showed smaller opposite effects at different background luminances(Fig. 9). There was no significant interaction between surround illuminant and task background luminance ($F_{3,33} = 0.02, p=0.98$).

Within the General Linear Model, we produced a normal equation, predicting Landolt C performance as a function of surround lighting, task background luminance and task contrast. This enabled us to compare the size of the effects on performance of varying task contrast, task background luminance and surround light spectrum. After statically controlling for task background luminances, the improvement in performance accuracy (caused by the change in surround lighting) was equivalent to the performance increase achieved by increasing task contrast by 13%. Again after statically controlling for task contrast, the improvement in performance accuracy, which resulted from changing the surround lighting spectrum from red/pink to F213, was equivalent to the performance increase that would be achieved by increasing the task background luminance by 29 pcd/m^2. This effect was determined after statistically removing the confound of task background luminance and contrast which resulted from the unbalanced experimental design.

This comparison between the effects of surround illuminant and task background luminance is illustrated in Figure 10. In this figure the estimated performance accuracy by linear regression analysis at 30% contrast under the two lamps is plotted against task background luminance. The seperation between the two curves, <u>on average</u>, was equal to the change in performance that would result from an increase in task background luminance of about 30 cd/m^2 for the scotopically deficient lighting.

Discussion

In the first experiment, we showed that performance improves for most subjects under the scotopically-enhanced greenish-blue lighting as compared to the scotopically-deficient red/pink lighting when both provide the same surround photopic luminance of 63 pcd/m^2. Since the CRT on which the Landolt C was displayed was self-illuminated and reasonably well protected from any room light, the luminance and spectral distribution of the task lighting was for the most part unaffected by the surround lighting. A reasonable interpretation is that the visual performance effects were a consequence of the smaller pupil size which occurred under the greenish-blue illuminant compared to the red/pink illuminant. However, there was also the possibility that changes in the surround color induced apparent color changes in the task that might have affected visual performance in experiment 1. A neurally induced color was perceived by the subjects, with the CRT target area appearing to the subjects to have a faint pinkish hue when the surround lighting was provided by the greenish blue lamp and to have a faint blue-green hue when the surround lighting was provided by the red/pink illuminant. This effect was neural in nature as the physical spectrum of the CRT target was only very weakly affected by the presence of the surround lighting (to the extent that the small 12% infiltration of the surround light occurred) and was also observed in experiment 3, where there was less than a 2% change in the task luminance due to the surround lighting. This same effect was present also in experimental 3 when the light leakage was negligible.

The second experiment demonstrated that similar visual performance effects are present when pupil size is changed only by surround luminance level, but without any change in surround spectrum. Our contention that the performance effects in the two experiments were a consequence of pupil size differences is supported further by the almost doubling of the pupil area reduction in the second experiment as compared to the first experiment resulting in a concomitant doubling of the task accuracy differences. Note that Landolt C recognition in the second experiment improved under the higher surround luminance even though "effective" task retinal illuminance was reduced in that experiment nearly threefold by the reduction in pupil area. We determined the "effective" task retinal illumination by taking into account the directional sensitivity of the fovea by means of the Stiles-Crawford[6] correction. Using their directional sensitivity parameter, we calculated the effective pupil area, A_{eff}, in terms of the measured pupil area, A, as:

$$A_{eff} = a\left[1-e^{(-A/a)}\right],$$

where the parameter a = 27.322 mm^2. Applying this factor to our results yields ratios of average effective task retinal illumination of 1.60 (rather than 1.85 without the Stiles-Crawford correction) for experiment 1, and of 2.60 (rather than 3.29) for experiment 2, and 1.45 (rather than 1.640) for experiment 3.

In all three experiments, the within-subjects design allowed each subject to act as his or her own control, eliminating between subject variability in performance on the Landolt C task from the evaluation of the lighting effects on task performance, resulting in increased statistical power of the experiment to detect lighting effects. A potential problem of a within-subject design occurs when subjects can pick up cues as to the experimenter's hypothesis and skew their performance accordingly. We were highly diligent in insuring that no cues were available to subjects regarding our experimental hypothesis (that F213 lighting would result in better performance). Subjects were given instructions to perform as accurately as possible on the task, and were given brief rest intervals between trials under the different lighting conditions. During testing, communication occurred only when the task was about to be resumed, and when the lighting was to be changed. No mention was made of any hypotheses on our part, nor was the subject given any feedback on how well he or she was actually doing as the experiment progressed, all subjects were told that they were doing very well. In fact, it wasn't until days later that the recorded data was decoded such that we could examine the experimental effects.

Regarding possible motivational differences induced by the lighting conditions, no such phenomena were reported on debriefing of subjects. Moreover, task lighting was unchanged during both experiments, even though surround lighting was manipulated, and subjects did not report noticeable subjective difference in task comfort. This was true in experiment 1 and 3 for changes in surround spectrum, and in experiment 2 for changes in surround light intensity.

The results shown in Figures 4 and 6 are consistent with those of Adams[8] who measured Landolt C acuity as a function of contrast at a task luminance of 54 pcd/m^2. They showed the onset of the drop in acuity to occur between 30% and 40% contrast. This is in reasonable agreement with our measurements which have the mixed condition of surround luminance varying between 3.5 and 63 pcd/m^2, with constant target area luminance of about 14 pcd/m^2.

We note that two subjects in experiment 1 and three subjects in experiment 2 (Figures 5 and 7) showed an opposite effect, with improved performance associated with larger pupils. Retesting one of these subjects at a later date showed that his results were replicable. We hypothesize that a possible cause of this effect is the presence of a minimum of lens aberration in this subject; however, we did not conduct any ocular examinations to verify this hypothesis.

In the second experiment, the two different surround luminance levels also presented two different conditions of disability glare (i.e., a veiling luminance produced on the retina by scatter in the optical media, reducing the retinal contrast slightly below that determined directly by the photometer measurements). The equivalent veiling luminance, which is proportional to the surround luminance can be calculated from the expressions given by Vos[9]. For the high surround luminance condition, this veil is about 1 cd/m^2, which means that in this case the retinal contrasts were reduced by about 6.5% from the measured values. For the low surround luminance condition, the veil is a factor of 15 smaller and has a negligible effect on task contrast. Thus, not only is the effective task retinal illuminance smaller for the high surround luminance condition, but there is additional glare in that condition. We interpret the improved performance under higher surround luminance as showing that the pupil size benefit is greater than the retinal task illuminance and glare effects combined.

In experiment 3, at all four task background luminances, performance was always better on average when the surround lighting produced smaller pupils. More importantly, on average, the change in surround spectrum was roughly equivalent in its effect on performance to a 29 pcd/m^2 change in task background luminance (figure 10). This value, which results from our GLM procedure, is an underestimate of the affect of surround spectrum at the lower contract values because of the a symtotic behavior of performance with increasing task background luminance. We note that the ratio of average pupil areas provided by the two surround illuminants was a factor of 1.64 which is well within the range of sizes attainable by the spectral differences among general use fluorescent lamps. Since the surround field of view excluded the 30° central portion, the spectral effect on pupil size is less in this study than in our previous studies where changes in spectrum of a nearly full field of view affected pupil size.[1]

In our studies, task background luminance and surround luminance have been separated with the task luminance conditions provided by a self illuminated display. In a lighting environment where both task and surround luminances are a consequence of the same light source, a scotopically deficient illuminant would have to be maintained at a higher photopic level to achieve the same performance as obtained by a scotopically enhanced illuminant. For the conditions of our study, raising the task background luminance by 200% to 300% (see Fig. 8) could not compensate for the performance decrement caused by the larger pupil size, which demonstrates both the sensitivity and importance of pupil size as a determinant of performance. For the scotopically-enhanced surround lighting condition which produces the smaller pupil, there was almost no variation in performance as the task background luminance varied from 30 cd/m^2 to 70 cd/m^2 at all four task contrast levels. This result is consistent with Shlaers[3] finding which showed the change in visual acuity over the same Troland range to be less than 0.5% and supports our proposition that performance changes are predominantly due to pupil size variation at these illumination levels.

In a study of performance of reaction time, Rea et. al.[11] showed significant changes in task performance as task background luminance levels varied. They also showed significant changes in pupil size for the same variations in task background luminance. An alternative explanation of the Rea results based on the studies presented here and those of Shlaer is that pupil size variation is the principle reason for the effect they observed rather than just task luminance alone. Rea et al have argued against the pupil size hypothesis because they did not find a performance variation for a condition where average pupil size had a small (~4% in diameter) but significant difference. However, the pupil size differences they obtained over the range of background luminance variation were of order 40%. It is not correct to argue that if a small change does not cause an effect, that a large change will also not cause an effect.

Because our results show that retinal illuminance is not as important a factor in visual performance as pupil size, the reasons offered for increasing illumination levels for older workers may need to be re-examined. These arguments[12] state that to overcome meiosis in the aging eye, increased illumination is required. Although the aging eye may not see as well, and more illumination may be necessary, our results raise the question of whether smaller pupil size is the mechanism underlying this phenomenon. In experiment two, effective retinal task illuminance increased by nearly a factor of three when the surround luminance was the lower value, and yet performance was poorer for all three values of task contrast. For the conditions of our study task, retinal illuminance alone cannot predict performance, and performance is only a monotonic function of retinal illuminance when pupil size is fixed.

We note that our results might be hypothesized to be based on an unusual rod-cone interaction by which increased scotopic illumination (more rod excitation) would act to enhance cone function. Although this explanation is contrary to the traditional concept of rod-cone suppression effects[13], our present study cannot rule out such an alternative proposition.

We have demonstrated that for a range of task luminance and for a task situated at 2.4 m distance, smaller pupils yield an increase in visual task accuracy, even though effective task retinal illuminance is significantly decreased. Thus, in a range of retinal illuminances where increases are thought to lead to improvements in visibility, we find the opposite result, with pupil size being a dominant factor in determining task performance. These results were obtained for subjects with 20/20 or better uncorrected vision, but might be of more importance to presbyopic individuals wearing spectacles. Spectacles are usually prescribed for viewing at particular distances, and thus presbyopic users tend to suffer some refractive error at most other distances. Based on Atchison's study[7] of pupil size effects on defocus (discussed above), we speculate that vision for presbyopic spectacle users should be generally improved under conditions which yield smaller pupils.

We have also shown that by shifting the spectrum of fluorescent lamps to be more scotopically-enhanced, while leaving the photopic output luminance of the lamps unchanged, pupil size is reduced with a concomitant improvement in Landolt C task performance. This suggests that it might be possible to maintain present standards of visual performance by substituting scotopically enhanced surround lighting while operating at reduced photopic luminance levels. Depending on the overall efficacy of such lighting, there could be energy savings.

Acknowledgment

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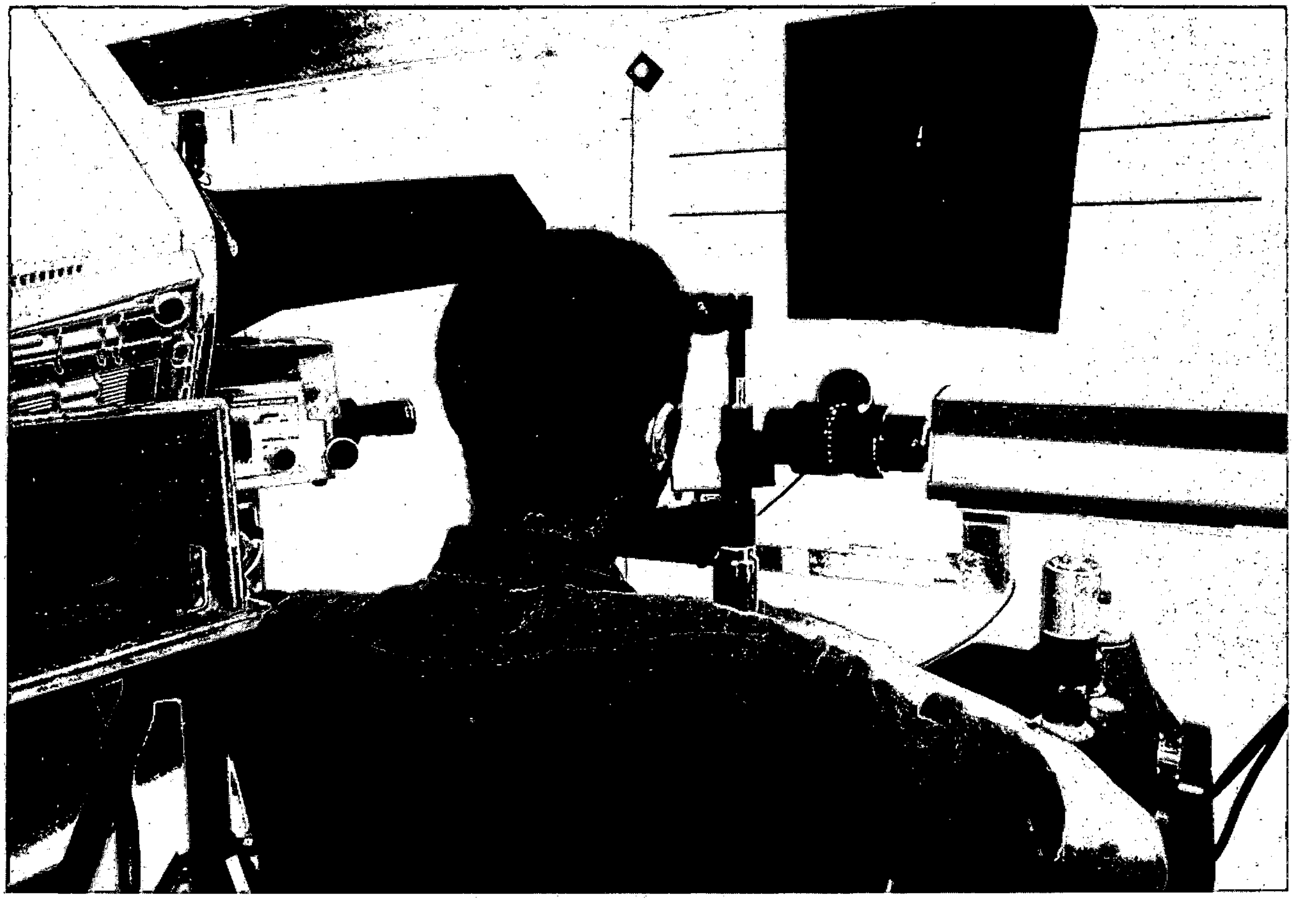


Figure 1. Rear view photo of subject in the test room with head on pupilometer chin rest viewing the task. The task is viewed via a front surface mirror situated in the middle of the black curtain. The CRT surface is covered with matt black except for the viewing tube. (ZBB-916-4500)

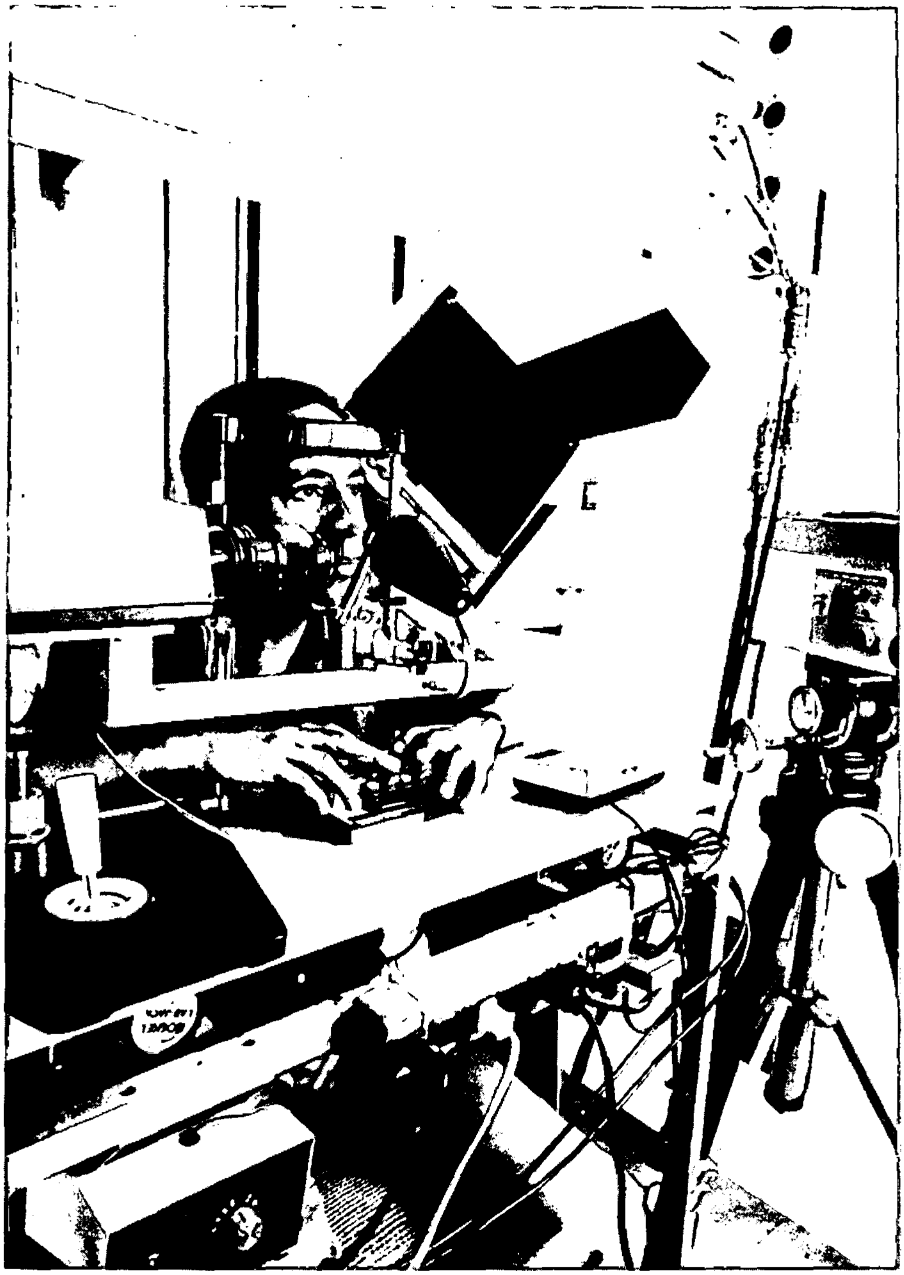
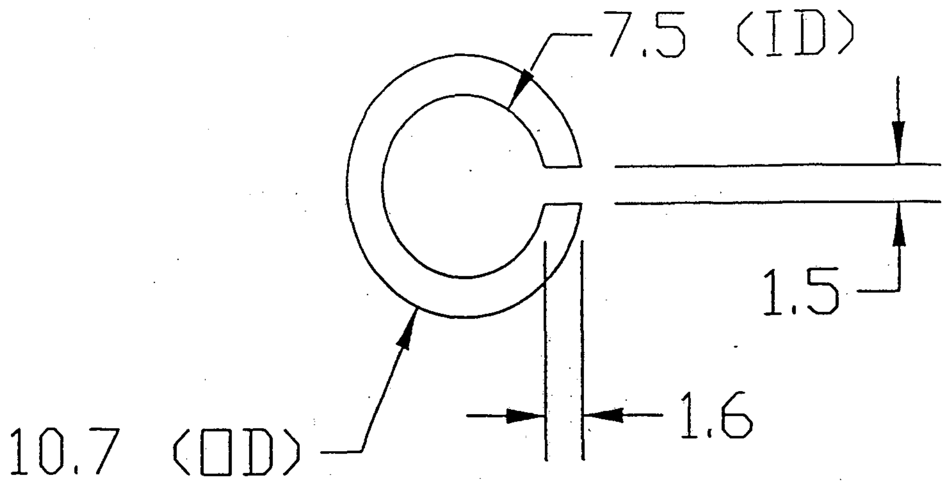
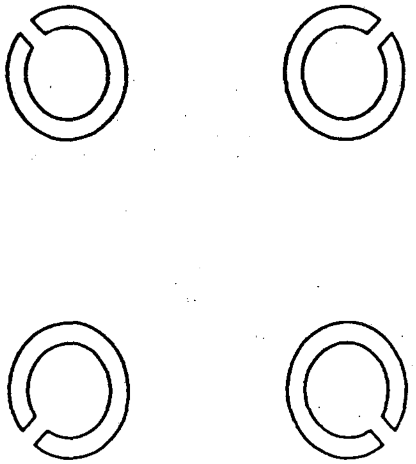


Figure 2. Frontal view of subject viewing the task in the test room with hands on the button press used to indicate orientation of Landolt C. Pritchard spectrophotometer is resting on the tripod to the right of subject. (ZBB-916-4499)



(A) LANDOLT C DIMENSIONS IN MM (DIAMETERS AND GAP)



(B) THE FOUR POSSIBLE LANDOLT C ORIENTATIONS

Figure 3. (a-b) Dimensions of the "Landolt C" in millimeters used in this study and the four orientations of presentation. The C dimensions are slightly different from the canonical size ratio of 5 to 1 between height and gap of a true Landolt C. For this study the various contrast levels are obtained by dimming the Landolt C compared to its immediate background (task background) on the CRT. The task background luminance is fixed and continuously "on" during the "C" presentations.

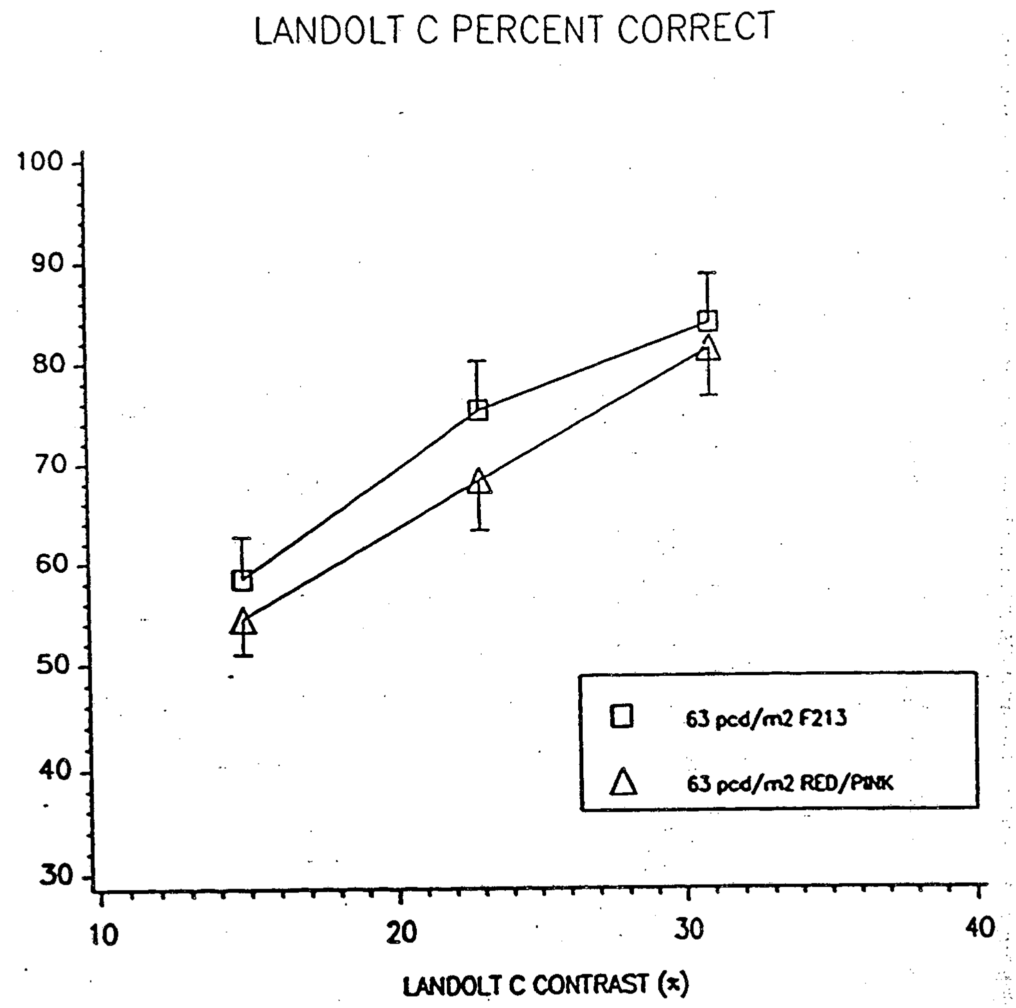


Figure 4. Mean and standard error of task accuracy scores versus percent contrast of the Landolt C. The squares are the results for the F213 lamp while the triangles are for the red/pink illuminant. For purpose of visual clarity, only the upper/lower half of the s.e. are shown for the two illuminants. Contrast is defined as the ratio (expressed as a percentage) of the difference luminance between the C and the background luminance divided by the background luminance.

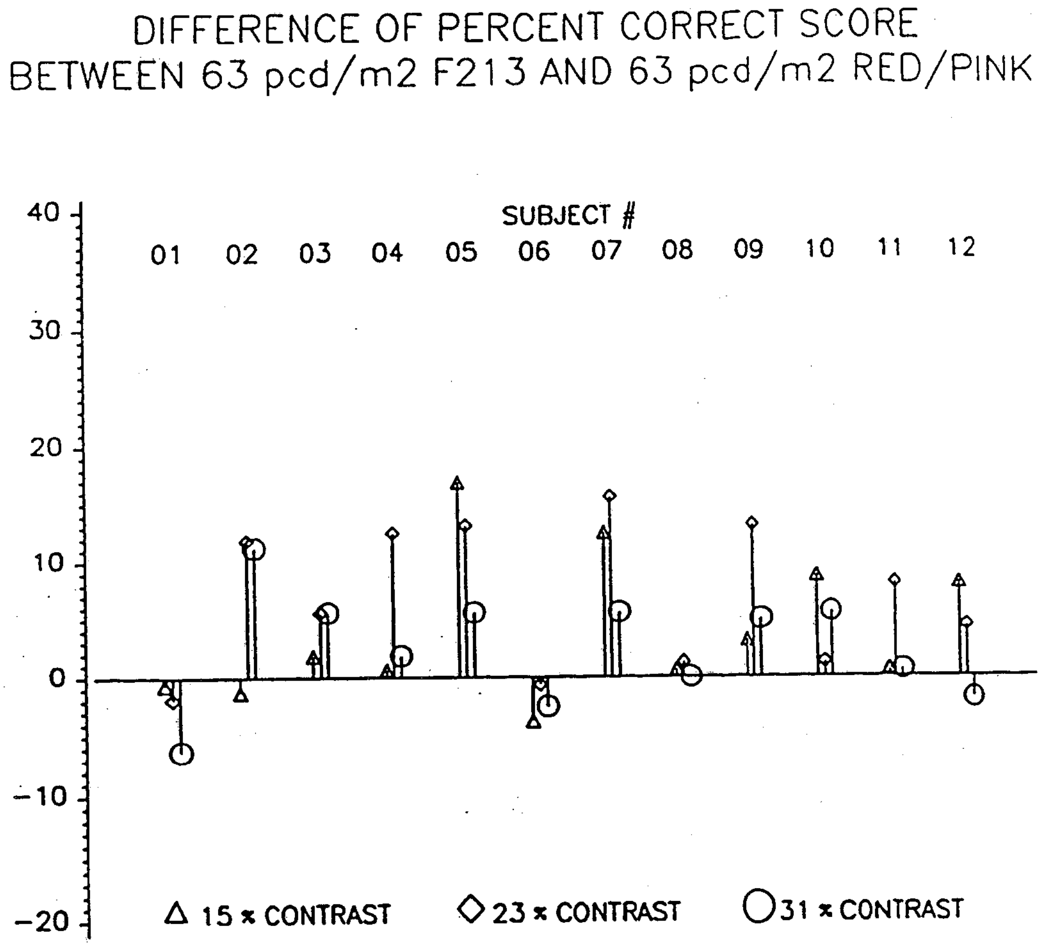


Figure 5. The difference in task accuracy between the two illuminants (F213 - red/pink) for each of 12 subjects at the three values of contrast of the Landolt C. Subjects are ordered according to amount of difference in pupil area caused by the surround illuminants. The vertical lines are for visual purpose only with triangle, diamond, and circle showing the values for the three contrasts respectively. No association between size of pupil area differences and size of task accuracy differences was apparent. Ten of the twelve subjects demonstrated better performance under F213 surround lighting (i.e., smaller pupils), while two subjects showed effects in the opposite direction indicating better performance with larger pupils, under red/pink lighting.

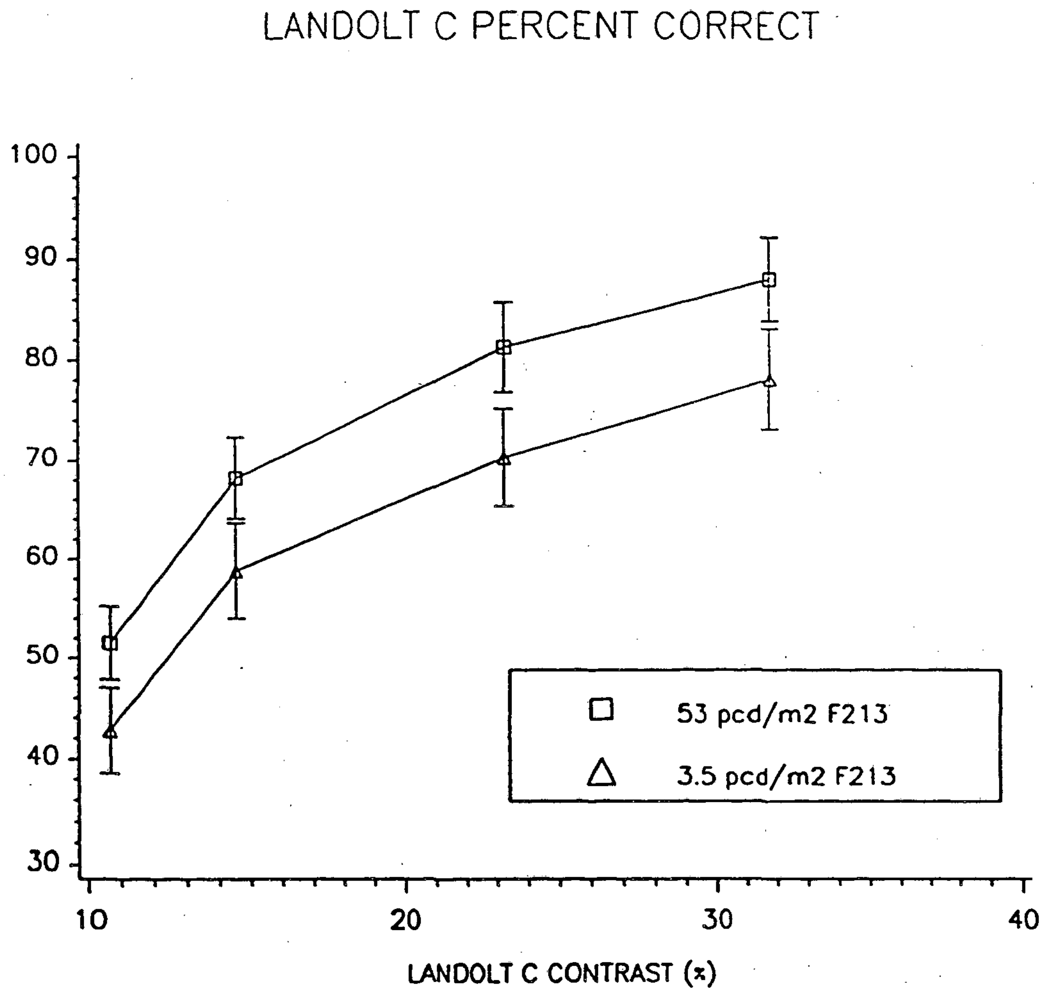


Figure 6. Mean and standard error of task accuracy scores versus percent contrast of the Landolt C. The squares are the results for the F213 lamp at 3.5 cd/m^2, while the triangles are for the F213 lamp at 53 cd/m^2.

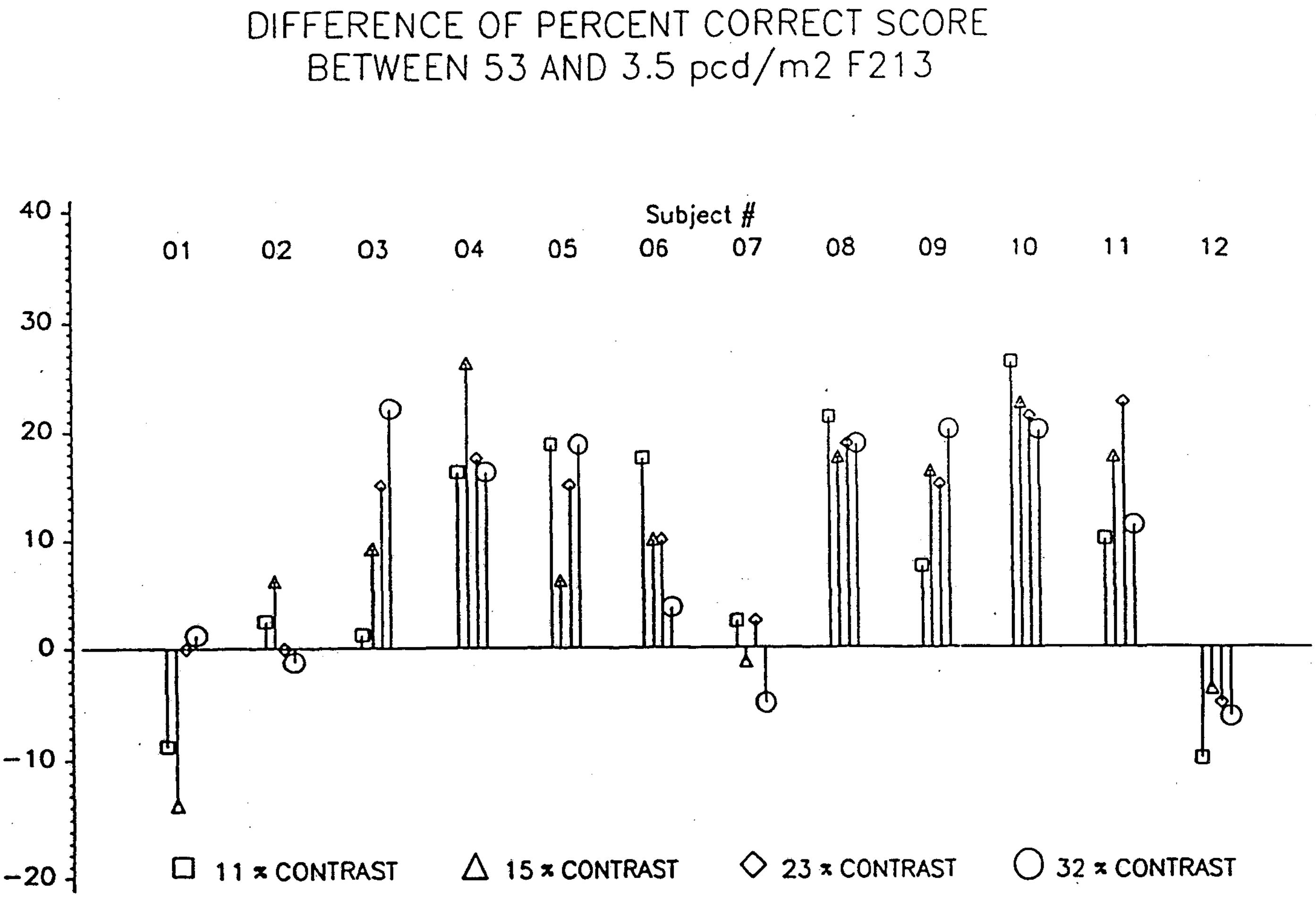


Figure 7. The difference in task accuracy between the two F213 luminance levels (3.5 cd/m^2 - 53 cd/m^2) for each of 12 subjects at the 4 values of contrast of the Landolt C. Subjects are ordered according to surround luminance percentage difference in pupil area, as displayed in Fig. 5. No association between size of pupil area differences and size of task accuracy differences was apparent. Nine of the twelve subjects demonstrated better performance under higher luminance F213 surround (i.e., smaller pupils), while three subjects showed effects in the opposite direction indicating better performance with larger pupils, under lower luminance surround lighting.

Fig. 8A. SCORE vs CONTRAST
12 pcd/m2 TASK BACKGROUND

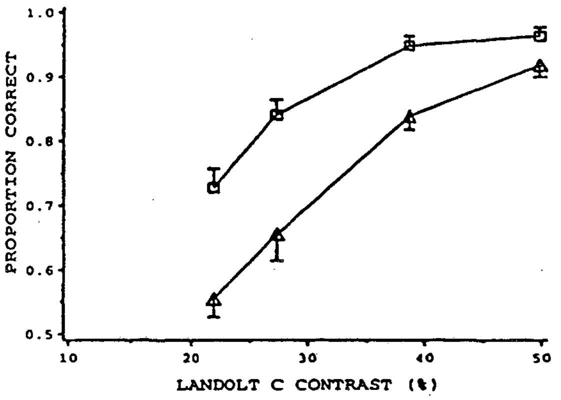


Fig. 8B. SCORE vs CONTRAST
28 pcd/m2 TASK BACKGROUND

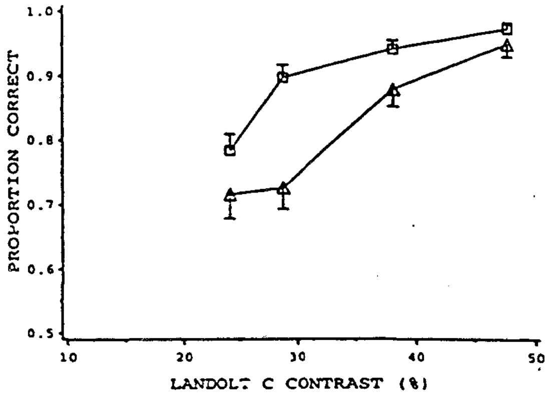


Fig. 8C. SCORE vs CONTRAST
47 pcd/m2 TASK BACKGROUND

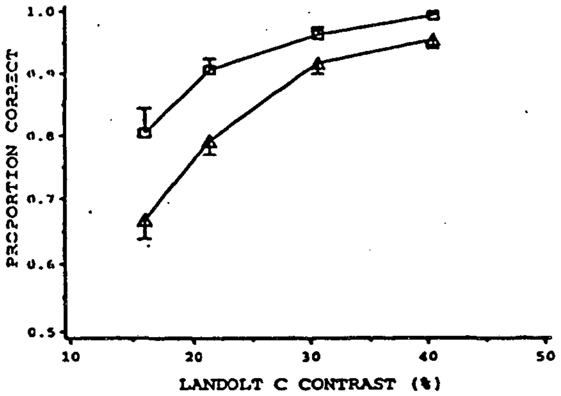
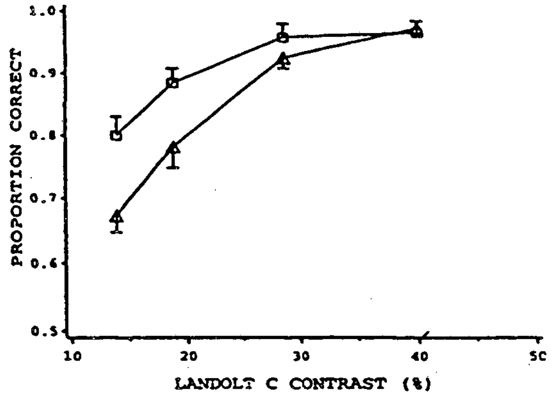
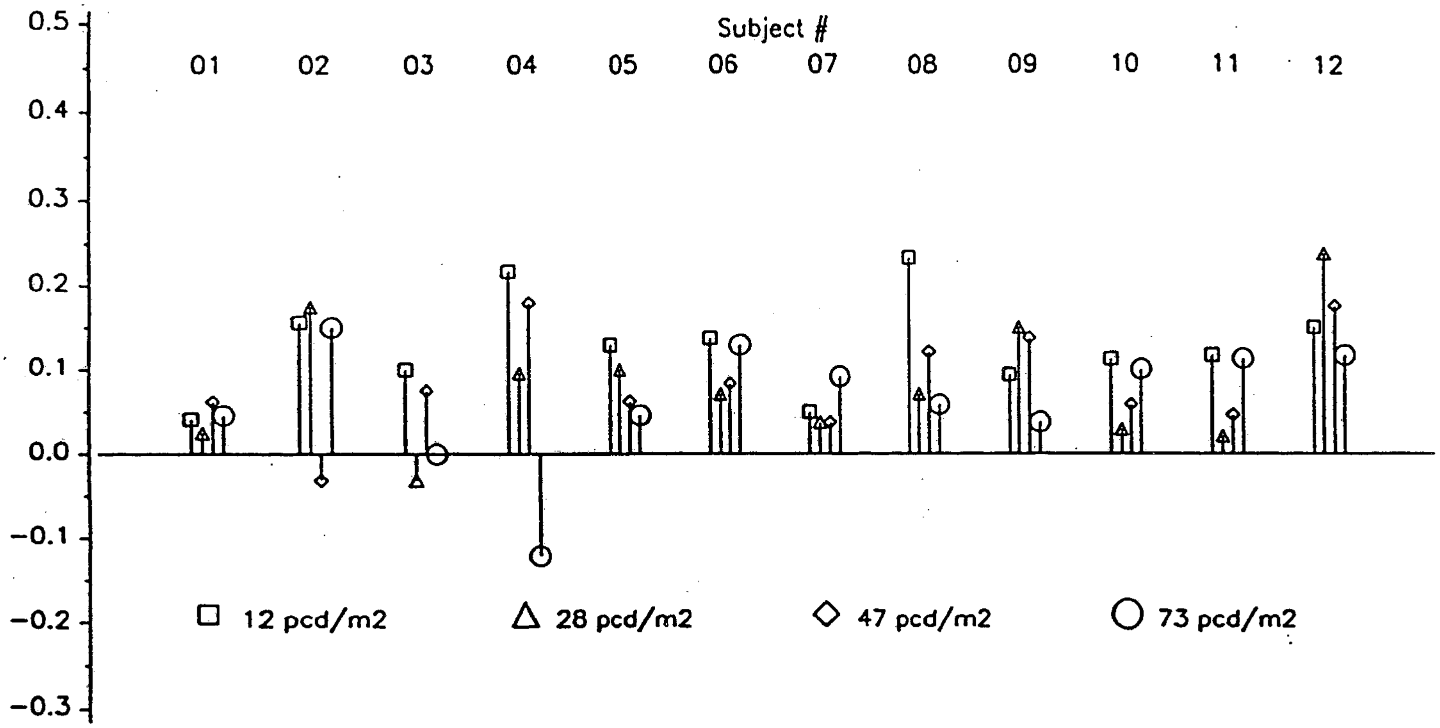


Fig. 8D. SCORE vs CONTRAST
73 pcd/m2 TASK BACKGROUND



□ 53 pcd/m2 F213
△ 53 pcd/m2 RED/PINK

Figure 8 (a-d). Mean and standard error of task accuracy scores versus task background luminance for each of the four task background luminances (11.9, 27.7, 47.0, and 73.4 cd/m^2). In all cases, the upper curve is for the scotopically enhanced surround illuminant (F213) while the lower curve is for the scotopically deficient illuminant (red/pink). Both illuminants are adjusted for equal photopic luminance of 53 pcd/m^2.



MEAN DIFFERENCES (ACROSS CONTRASTS) OF PERCENT CORRECT SCORE BETWEEN 53 pcd/m2 F213 AND 53 pcd/m2 RED/PINK

Figure 9. The mean differences in task accuracy (across all contrasts) for each of the twelve subjects for the conditions of experiment 3. (53 pcd/m^2 for both surround illuminants and averaging overtask contrasts. Subjects are ordered as in figures 5 and 7.

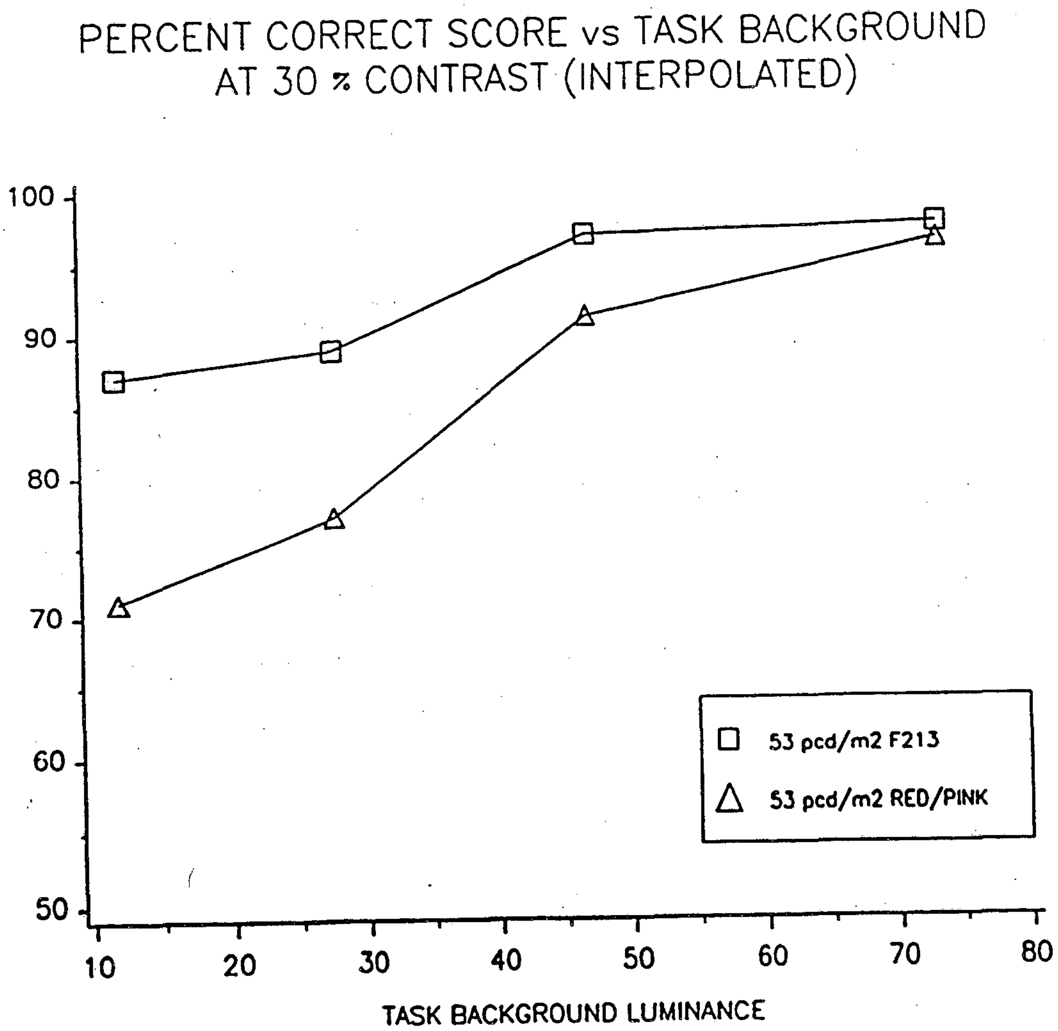


Figure 10. Estimated task accuracy at 30% contrast is displayed vs task background luminance separately for the two surround illuminants. Each plotted symbol was estimated using linear regression analysis restricted to all 12 subjects data for that surround illuminant and task background luminance (4 data points recorded at four task contrast).

TABLE I

Task Background Luminance (cd/m^2)	Contrast of Landolt "C" (%)			
12	22	27	39	50
28	24	29	38	48
47	16	21	31	41
73	14	19	29	40

Discussion:

The three experiments reported here add to our understanding of the effects of scotopically-enriched light sources by establishing that lamp spectral content can effect visual performance, and in the predicted direction. However, this series of investigations does not eliminate alternatives to the pupil size explanation.

Berman and his colleagues propose a model that they have not directly tested: Lamp spectral distribution affects pupil size, and pupil size effects performance. There is nothing in this paper that demonstrates that pupil size mediates visual performance. It is possible that both effects are caused by some third variable.

The performance effect in Expt. 1 may have occurred because the comparison was between lamps that were unusual or odd to the subjects (a motivational effect). No details were provided describing the CIE coordinates, colour temperature, or CRI of the lamps. However, if the red-pink lamps were unpleasant or strange, or if the F213 lamp was more similar to the usual conditions under which these subjects worked, visual performance might have been affected for reasons other than changes in pupil size.

Psychophysiologists use pupillary diameter as a measure of the cognitive difficulty of a task; the more difficult the task, the larger the pupil and the lower the performance (e.g., Mathews, Middleton, Gilmartin, & Bullimore, 1991), and this is believed to relate to the allocation of attention to the task. The results of these three experiments might indicate that it was easier for the subjects to focus their attention on the task under F213 than under the red-pink alternative. No evidence yet exists to say that a similar effect exists when the comparison is between a scotopically-enriched source and any lamp commonly used in workplaces.

Performance of real work in real settings is not indexed by visual performance alone; and lamp spectral distribution may affect other variables in addition to visual performance. Until we know how users evaluate rooms lit with scotopically-enriched lighting, in comparison to more common light sources, and until we know how complex tasks are affected by light source spectral distribution, it is premature to plan to apply this new technology.

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Institute for Research in Construction
National Research Council of Canada

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Response to Dr. Veitch:

We thank Dr. Veitch for taking the time to read our paper and for her discussion. The comments provided illustrate a different view of psychophysical research, but for lighting users it ends up with the same conclusion, namely that performance is better with bright scotopically enhanced, i.e. rich in blue green, lighting. We argue that this effect is mediated through pupil size changes while Dr. Veitch would argue this effect is mediated through subjective experience. Perhaps we offer comfort to those who believe that behind every crooked smile there is a crooked molecule.

The remarks about cognitive difficulty are interesting, but we do not believe they are applicable to our study. Our task conditions are identical under the two surround lightings and the cognitive load is extremely light with no memory nor computational demands. Subjects were concentrating on the task and not looking at the peripheral areas lit by the surround lighting. Pupil size measurements occurred for 2.5 secs. before the 'C' was flashed. The time interval between pupil measurement and the onset of the 'C' was less than 1 millisecond and the duration of 'C' (200 msec.) is about the refractory period for pupillary response. The pupil video monitor, which continued to operate during the 'C' flash, showed no indication of any significant pupillary response during the flash period.

The reference to the paper of Matthews - et al is puzzling as the purpose of their study was to use pharmaceuticals to affect either sympathetic or parasympathetic pathways to the pupil response in order to examine which of the autonomic channels was relevant to the cognitive stimulus. Their task was difficult, involving recognition of letters, remembering them and then performing mathematical manipulations based on a code. The pupil dilations they measured were in response to the task and its increasing cognitive loading. This is quite different than our study where identical tasks are compared under the two surround conditions.

We agree that field studies involving scotopically enhanced lighting could add valuable information to lighting practice. However, we also note that natural light and daylight lamps, both of which are quite rich in scotopic content, already have a large user constituency.

Discussion:

There is no question that pupil size is affected by spectral composition; this has been known for many years (Alpern and Campbell, 1962; Alpen and Ohba, 1972). Further, there is no question that pupil size affects the optical quality of the retinal image. Aberrations, both chromatic and spherical, increase with pupil size (Kaufman and Christensen, 1984). Stiles and Crawford (1933) also showed many years ago that light entering the eye is most effective along the optical axis and less so than light entering the eye from the margins of the pupil. The surprising fact, reported by a variety of researchers including J.M. Woodhouse (1975) and others (Ogle, 1951; Graham, 1965; Borish, 1970; Rea, Ouellette and Tiller, 1990; Nakayama and Shimizu, 1991; Saito and Hosokawa, 1991), is that pupil size has a small effect on performance. it take very sensitive psychophysical techniques to measure any differential effects on performance due to pupil size over the range of naturally occurring pupil sizes typically encountered in electrically illuminated environments (pupil diameters between 2.5 and 5 mm for luminance levels between 350,000 and 0.5 cd/m^2, respectively).

Although the effects reported in this paper are probably true under the specific experimental conditions used (i.e., smaller pupil sizes do improve visual function at this particular test), there are several methodological points that the authors need to clarify before a complete assessment or an endorsement of these results are possible. More importantly, however, the very sensitive experimental conditions reported by the authors, which were needed to demonstrate an effect of pupil size on visual performance, are extremely different than anything encountered in the real world. Therefore, the impact of these results, true or false, on lighting practice are seemingly inconsequential.

Clarifications in methodology

The uncertainty in photometric measurements of narrow band light sources can be very high, over 100% for certain wavelengths, according to the manual for the Pritchard 1980A spectrophotometer, which was used for the measurements in their experiment. Because both the CRT and the special light sources used in these experiments likely have narrow band, nearly discrete, spectra, it is unclear whether the reported photometric values correctly characterize the psychophysical conditions. This measurement uncertainty is very important for this experiment because small differences in performance due to different light sources are of interest. The uncertain luminance and contrast of the Landolt rings coupled with the uncertain measurements of the two, spectrally different types of veiling luminances might explain the small differences in performance observed when the different surround lights were used. In other words, the imprecise assessments of the two veiling lights incident on the CRT could create different contrasts for the two light sources and, therefore, pupil changes may be confounded with task contrast changes. It appears, but is not clear, that the background luminances in Experiment 3 were flashed as well as the targets. Earlier in the text the authors say that the "task luminance was randomly varying over presentations." Performance can be deleteriously affected by flashed background luminances due to the changes in the threshold over time which do not exactly correspond to luminance (Crawford, 1974). The magnitude of the observed effects would be affected by this procedure and the resultant effect would be expected to be larger for low contrast targets, as shown in Figure 8. This may explain the difference in magnitude between the results of Experiments 1 and 3.

The angular size of the background in Experiment 3 was not included in this paper. This information is important because performance is affected by surround luminance (Lythgoe, 1932; McCann and Hall, 1980; Rea, Ouellette and Tiller, 1990). This phenomenon may contribute further to enhancing the magnitude of the observed effects and the differences between Experiments 1 and 3.

Applicability to lighting practice

The authors use very sensitive psychophysical procedures in an attempt to show that pupil size affects visual performance. They use contrast, small targets that are flashed very briefly (200 ms) at low background levels in the presence of peripheral illumination that can produce disability glare. Even the orientation of the Landolt rings (45°) is known to minimize sensitivity relative to vertical or horizontal orientations; this is known as the oblique effect (Appelle, 1972). What is more, special light sources were created to produce large differences in the respective scotopic content of the surround light sources for the same photopic luminance and, thus, enhance the effects of pupil size on performance. Under these extremely sensitive, but highly unrealistic, experimental conditions, the authors show a marginal improvement in performance in Experiment 1; on average only 4.5%. The magnitude of these results is not replicated in Experiment 3; at the same background luminance the observed effects on performance due to different surround light sources are larger in Experiment 3 than in Experiment 1. (The effects are also smaller in Experiment 3 at higher background luminances). No explanation is provided by the authors for these discrepancies. Given (a) the uncertainty in the specification of the experimental conditions, (b) the inability to replicate their own results, and (c) the literature which shows little or no effect of pupil size on performance, it seems unlikely that the results of these experiments have much significance for lighting practice or energy savings as the authors conclude.

Within the framework of their experiment, another conclusion from the authors is important to discuss. The authors conclude that the observed effects of higher light level on better visual performance are caused by smaller pupils and not, as other researchers have concluded, to neural and photochemical changes in the eye or by presenting targets in Maxwellian view (Westheimer, 1966), which avoids pupil size altogether. Other researchers have, including Shlaer, whom they cite. Such studies of visual performance for fixed pupil sizes show that visual performance improves with higher light levels (e.g., Rea and Ouellette, 1988). In fact, the data reported by the authors in Figure 8 contradict, indirectly at least, their own conclusions. they show in the four panels of Figure 8 that the relative influence of pupil size becomes systematically less important as background luminances increases. Since pupil size cannot respond fast enough to influence performance because changes in pupil size occur after the 200 ms target display (Graham, 1965), this effect must be due to neurological changes in the retina and the brain. Therefore, the well-documented effect of improved performance with higher background luminance is due to neurological changes. These neurological changes are influenced by, but not solely by, pupil size.

Prepared by Mark S. Rea, Ph.D. FIES
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Response to Dr. Rea:

We are appreciative of Dr. Rea's detailed reading of our paper and for the comments in his review. However, we disagree with his conclusion and feel there are strong arguments for the importance of our results for lighting design.

Dr. Rea's main argument is, that pupil size only has a small effect on visual performance, and that the effects demonstrated in our study are... "extremely different from anything encountered in the real world. Therefore, the impact of these results, true or false, on lighting practice are seemingly inconsequential." Contrary to Dr. Rea's claim, the results obtained in our study can have important implications for lighting practice. The issue simply put is the possibility of offsetting illumination level with spectral alteration. We showed that the effect on task performance of changing the surround lighting to a more scotopically rich spectrum was greater than the effect of a 100% increase in task luminance. This large trade-off is clearly not "inconsequential," and it follows that the reasoning based upon some absolute effect of pupil size on performance is inapporiate. We must, as do all other studies of performance, study effects where the visual system is particularly sensitive, i.e. at the threshold of difference limens; however a study near threshold for contrast (to be sufficiently sensitive) does not imply that the effect on lighting design is also small. Furthermore, Rea himself (Rea et al, ref. 11) acknowledges the importance of the 5-10% performance improvements that can result from increases in task luminance and we have found similar percentage changes in performance due to pupil size changes.

As for effects "different from...the real world," the surround lighting under conditions of equal photopic surround luminances yielded pupil diameter differences of about 35%, due to spectral differences, well within the variations that occur under typical interior light level conditions.

In addition, Dr. Rea also raised a number of specific issues and questions regarding our research design. We are very appreciative of his comments, which have afforded us the opportunity to better explain our experimental procedures, as follows:

1. In experiment 3, as in experiments 1 and 2, only the Lendolt C is flashed for the 1/5 sec. period. The task background luminance is held at a steady fixed value during a run of randomly mixed contrasts of Landolt C's. The remarks of Dr. Rea referring to the consequences of flashing the background, such as changes in threshold over time or phasic responses of the pupil to flashing backgrounds, do not apply to the conditions used in our studies. We apologize for the inaccurate descriptions that led to this confusion.

2. As for the Pritchard spectrophotometer, the particular model we used is equipped with attachments allowing it to function in the wave length scanning mode and hence, a complete measurement of the spectral power distribution of the lamps in question was made. These spectral power distributions were folded against the tabulated V (l) function and the computed photopic luminances were compared directly with the photopic luminances measured using the photopic

channel of the instrument. These values agreed to within one percent. This procedure has been reported in several of our published papers, and we revised the manuscript to make this point clearer.

3. The task background area in experiment 3 was slightly larger than the area exposed by the tube protruding from the CRT surface, so that all the CRT area exposed to the subjects' view was illuminated at the task background luminance. We appreciate the opportunity to be more explicit.

4. The remarks questioning the replication of our results are based on an earlier version of the manuscript and presumably refer to the differences in the magnitude of the scores measured in experiments 1 and 2 when compared to experiment 3. The actual contrasts in experiments 1 and 2 are lower than most of those in experiment 3. With the contrasts correctly specified, the scores are consistent as reported in the final manuscript. In the earlier version , we presented results based upon contrasts in experiments 1 and 2 that were incorrectly measured. We notified the chair by correspondence of this discrepancy, pointing out that the contrasts had been recalibrated and requested that reviewers be so notified. The conclusions of the earlier version of the paper were unaffected by the corrected contrasts, but the statistical analysis used for the results in the revised manuscript required a slightly different approach in order to be valid under conditions of unmatched contrasts.

Having clarified these points, we wish to respond to some of Dr. Rea's more general comments about our study by further explaining the design of our experiments.

The purpose of varying the surround lighting in our experiment (which is a study of foveal function) is to control pupil size. This avoids the use of artificial pupils which can require unnatural conditions such as (i) only small pupil sizes (ii) misalignments of the optic axes with the artificial pupil center, (iii) or the use of pupil-dilating drugs which may affect accommodation. Thus, we have avoided possible confounding conditions which might affect visual performance.

The accuracy of photometric measurements were discussed above. Even if there were errors of the type suggested by Dr. Rea, our conclusions would be the same. For example, in experiment 2, the surround lighting was provided at two intensities and we measured two different pupil sizes with corresponding large differences in performance. Since the task background conditions were unchanged for the two different surround illuminants, task performance is compared for two different pupil sizes under identical task conditions. The effect is present even if the absolute measurement of task or surround luminance is in error. Similar arguments can be constructed for experiments 1 and 3.

As stated in our manuscript, there was some surround light leakage (about 10%) coming under the CRT cover in experiments 1 and 2, with this almost entirely eliminated in experiment 3. If the measured values of the surround light leakage were faulty, then the corrections applied to achieve the contrasts under viewing conditions might be in error. If anything, this would have lead to an underestimation of our experimental effect. However, in experiment 2, subjects scored on average 10% better at the higher surround luminance when pupils were smaller. The higher surround luminance condition would produce more leakage light, a larger veil, and negative rather than positive effects on performance. In experiment 3, the leakage was negligible and the screen appeared dark when the CRT was off. We conclude that the purported photometric uncertainties, even if they did exist, cannot be even partly responsible for our conclusions.

In our study (experiment 3), we have shown, with pupil size fixed, that performance improves with increasing task luminance. This supports Shlaer as well as Dowling and Brindlay (see Dr. Rea's references). However, we have shown that the optical effects of pupil size are also very powerful determinants of performance and that large increases in task luminance are required to offset the degradation of optical quality caused by a larger pupil. Furthermore, our study shows the pupil size effect on performance is much larger than the effect of increased retinal illuminance permitted by a larger pupil. We know of no prior examinations of this question.

Discussion:

Given that scotopically enriched light will enhance perception (resolution) at low level tasks, how can we reconcile the probable improvement in museum visibility with increased risk of object degradation due to the shorter wave length light?

Edwin Robinson
Smithsonian Institution

Response to Edwin Robinson:

Our studies of pupil size and related visual performance have not considered light levels below about 15 cd/m2. However, it should be possible to provide scotopically enhanced museum lighting if desired without object degradation by careful choice of spectral content because the scotopic peak of 508 nm is above the objectionable blue wave lengths. Other lighting design techniques could also be helpful such as applying different spectral contents for greater illumination and object illumination or using blue absorbing filters.

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