Reading Speed and Accuracy are Affected by Light Level and Lamp Spectrum.*

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Introduction:

This study examines the hypothesis that light with relatively higher bluish color content constricts the pupil, which in turn improves acuity and reading performance. In particular, the study examines this hypothesis at light levels and print sizes that are found in modern offices (200 to 500 lux horizontal, 6 point to 12 point type) using high and low CCT lamps (865 and 830 respectively) and two different fixture types (pendant hung indirect and recessed parabolic fixtures). Subjects ages range from 18 to 49, divided into 3 separate groups, each of which included roughly equal numbers of males and females. For each subject, a visual task with constant size and a range of contrasts (possible values from 0.1 to 0.4) were selected with a procedure that was designed to produce a significant difference in reading performance between the highest contrast at the highest light level and the lowest contrast at the lowest light level, while requiring the maintaining of an accuracy percentage of at least 50% under the most difficult lighting condition. During the analysis phase it was found that this procedure did not work as planned for the oldest age group, and this age group is currently being retested. The results for the two younger groups are presented here.

Background:

Many past studies have shown that word reading speed is affected by the illumination level (Sheedy et-al 1984, Legge et-al 1985, Bailey et-al 1993, Whitaker et-al 1993, Lovie-Kitchen et-al 1994). These studies show, consistent with intuition, that as illumination levels diminish reading speed decreases, while at the high end of illumination levels reading speed tends toward saturation becoming almost independent of level at high light levels. The slowdown in reading speed is a measure of visual function in the intermediate region of lighting and task parameters occurring between the highly sensitive threshold conditions and the essentially stable supra threshold conditions, conditions typical of commercial building work environments (Bailey et-al 1993).

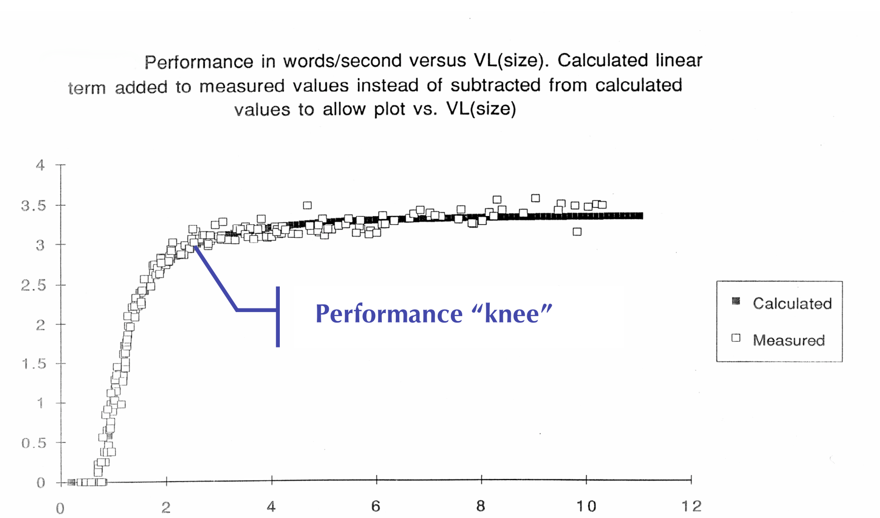

Figure 1 illustrates the typical slowdown in word reading from supra threshold to threshold quantitatively as a function of size. The ordinate is word-reading speed in words per second and the abscissa is the ratio of test size to the threshold size. A very similar graph is observed when the abscissa is replaced by the ratio of test contrast to threshold contrast.

The performance "knee" is the region where visual performance is high, but sensitive to changes in task difficulty (due to task itself or lighting conditions affecting the task).

It has been generally accepted for most of the 20th century that spectral variations in the illumination do not affect the threshold conditions of acuity or contrast sensitivity and therefore have no effect on reading speed. However in the 1990's it was shown at light levels typical of interior environments that both acuity and contrast sensitivity could be affected by spectrum at constant luminance levels (Berman et-al 1993,1994,1996). Spectra with more short wavelength content i.e. more bluish content, were shown to produce better acuity and contrast sensitivity when compared to lighting of less bluish content both evaluated at the same luminance level.

These results for acuity were extended to near vision at normal reading distance and standard whitish illumination at typical interior light levels as provided by commonly used fluorescent lamps, again demonstrating that lamp spectrum has a similar effect on near acuity for both young adults (Navaab 2000,2001) and school children (approximately 10 years of age) (Berman et-al 2006). It is thus reasonable to conjecture that in view of the spectral effects on acuity and contrast sensitivity that there should be a concomitant affect of spectrum on reading speed and/or accuracy. This would provide an opportunity to save energy because a light source with a relatively lower Correlated Color Temperature (CCT) could be replaced with an light source having more bluish spectral content, i.e., higher CCT but operating at a lower light level, thereby producing the same vision conditions as its predecessor. This augmentation of bluish content in light sources as a trade-off for illuminance is referred to as Spectrally Enhanced Lighting (SEL). Estimates of the lighting energy savings from SEL have been determined to be about 20% (Berman 1992, AfterImage & Space 2004).

To date, there has been one published study that has attempted to determine the extent to which spectrum might affect reading performance (Boyce et-al, 2003), which used the speed and accuracy of detecting orientation of a variable size gap in a Landolt C as it's method for assessing visual performance. This study found that lamp spectrum had no effect on subject performance; however the study was also unable to show any performance change with a 30% reduction in light level for normally-sighted subjects. This insensitivity to the lighting conditions may in part have been due to the failure to control the distance between the subject and task, and the failure to use a within-subject analysis, both protocols of which have been corrected in the study reported here. In any case, the insensitivity of the Boyce study to lighting conditions makes it inappropriate for evaluating spectral effects on reading performance, and thus the potential for saving energy.

Because of the potential for major lighting energy savings on a national basis, the US DOE has sponsored some investigations in operating buildings to examine building occupants' acceptance of SEL (AfterImage & Space 2004, 2006). Although these investigations showed acceptability of a 5000K CCT light source by the building occupants under the conditions of reduced illuminance, the use of spectrum as a guide to illuminance levels has not yet been made part of the Illuminating Engineering Society (IESNA) illuminance selection criteria thus hampering the implementation of this method on a national level. A major obstacle to IESNA acceptance of SEL has been the lack of evidence regarding the overall effect of spectrum on visual performance.

Methods:

A simulated office was constructed with 9' ceilings and 2 different commonly used luminaire types (pendant-hung indirect and recessed parabolic). Each luminaire type had computer controlled dimming ballasts. Subjects were tested under each luminaire type twice, once with an 830 lamp and once with an 865 lamp, and at three different light levels for each luminaire/spectrum combination. Thus, the testing consisted of a 2x2x3 design (2 luminaire types x 2 spectrums x 3 light levels), for a total of 12 different lighting conditions. The High, Medium, and Low light levels produced luminances on the visual tasks of 65, 49.5 and 37.8 cd/m^2 respectively for all four luminaire/ spectrum combinations. The lamps in the parabolic luminaires were T8 lamps, while the lamps in the indirects were T5HO lamps; the resultant Scotopic/Photopc (S/P) values were 1.29 and 1.32 for the 830 lamps in the indirect and parabolic fixtures, respectively, and 2.04 and 1.87 for the 865 lamps in the indirect and parabolic fixtures. An ASL infrared eye-tracker/pupilometer with a 60 Hz data acquisition rate was employed to obtain pupil sizes and fixation frequency and duration and light level readings were constantly monitored to ensure stable luminance values.

Forty-nine naïve subjects both male and female ranging in age from 20 to 50 years were selected through public advertising. They were divided in to 3 age groups: group 1 (18-29), group 2 (30-39) and group 3 (40-49). Visual acuity was obtained onsite for all subjects by a licensed optometrist; measured acuities ranged from 20/12 to 20/25.

A special visual task with a minimum of cognition and language proficiency was developed specifically for this study. In preliminary tests, we administered Bailey-Lovie type tests where subjects read a list of unconnected words out loud (Bailey,Lovie 1976) (we note that the reading of the task out loud is a necessary requirement in order to establish both speed and accuracy). Bailey-Lovie charts are a standard for the determination of word acuity, however we found that even for simple words of relatively small number of letters, that vocabulary and enunciation proficiency, cognition and prior word familiarity affected reading speed and thus could introduce undesired confounds in performance. We could not find any standard protocols that were sufficiently focused on the visual aspects of reading speed to avoid the above confounds. We therefore developed, by trial and error, a test consisting of two-digit, three syllable numbers, such as "86" (pronounced "eighty-six"). These 2-digit numbers proved to be both easily reproducible and excellent for reducing the above confounds.

We also found that the quality of reproducibility of the task parameter for spanning the intermediate region between threshold and supra threshold was much better controlled if contrast variation was the chosen method (as opposed to size). Finally, the size of the reading area had to be limited to ensure constant task background luminance and to fit within the eye-tracking equipment range of view. Thus, for each lighting condition, subjects read four sets of five lines (total 20 lines) consisting of 2-digit, 3-syllable numbers of constant size placed at a fixed distance from the subjects' eyes. For each of the four sheets, the contrasts gradually decreased as the subject read down the page. Within these 20 lines, there are seven different contrast steps that nominally changed by 17 percent (measurements showed slight variations between luminaire and lamp types). These contrasts were divided among the 20 lines such that all contrasts were repeated 3 times, with the exception of the second highest level contrast was repeated twice, under each lighting condition. Subjects were instructed to read these numbers as rapidly and accurately as possible, and to slow down to ensure accuracy as the task became more difficult.

We developed a protocol that assigned a specific size and contrast range to each subject with the goal as having each subject operating in the "knee" region of figure 1. In order to accomplish this, 16 sets of tests were printed (4 VA levels x 4 contrast variation levels) and subjects were tested to ensure that they could achieve at least 50% accuracy under the dimmest light level and lowest contrast level for the specific test they were given. The size of the numbers were generally 3x the subject's near VA, consistent with studies by Bailey in which reading speed was shown to begin slowing down when the size of the letters became 3x the near VA. If the 3x the near VA at the lowest contrast was too easy for a subject, the size was reduced to 2.4x the subject near VA. This protocol worked fairly well for age groups 1 and 2, but we found that it resulted in age group 3 operating above the knee of figure 1, and the data for this age group has therefore been removed from the analysis. One other subject was removed when the analysis showed the error count being at a chance level over the subject's more difficult conditions.

Subject performance was recorded with a video camera that allowed both speed and accuracy to be obtained for all conditions. The eye-tracker/pupilometer measured pupil size, fixture duration and number of fixations while the subjects performed the reading task.

Results:

The scoring of reading performance required a procedure for capturing both speed and accuracy for each subject. In the performance literature errors are often disregarded and performance is based on speed alone. However, subjects can trade speed against accuracy, and we found that subjects varied significantly as to whether speed or accuracy varied the most over the range of visibilities presented. We therefore used a scoring function based on z-scores, which are dimensionless parameters where speed and accuracy are normalized by their associated means and standard deviations. In particular the z-scores for a given subject for the time (z_t) and for the number of errors (z_e) associated with reading a complete single line on a chart and for a particular instance (i) of lighting condition (luminance level, spectrum, fixture) is defined as

$$z_t(i) = \frac{\text{[average time for all conditions} - \text{time(i)]}}{\text{[standard deviation of times calculated for all conditions]}}$$

$$z_e(i) = \frac{\text{[average of errors for all conditions} - \text{errors(i)]}}{\text{[standard deviation of errors calculated for all conditions]}}$$

Thus when a subject has a faster time or fewer errors than the average for their combined times or averages, respectively, the z-score will be positive, and conversely when performance is less than average the z-score will be negative. These two z-scores are then combined in the minimum biased manner by simply adding them together. Analysis showed that this RP score is relatively insensitive to the effects of different strategies for trading off time versus errors and is defined as:

$$RP\ score = z_t(i) + z_e(i).$$

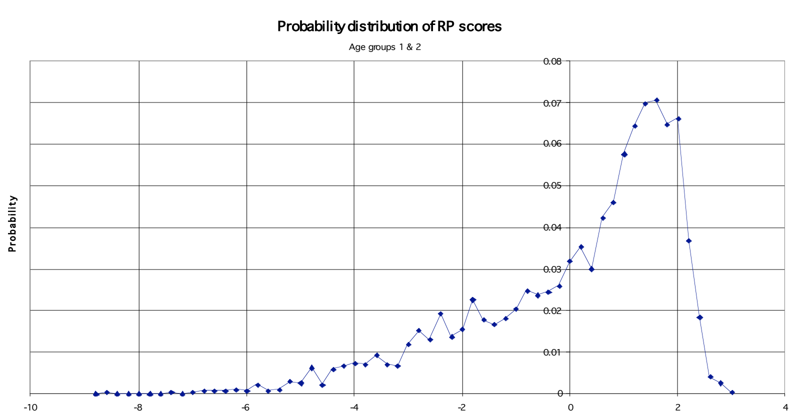

Figure 2 shows the probability distribution of Reading Performance (RP) scores for the 32 subjects comprising age groups 1 &2. Higher RP scores show improved task performance. Note that the distribution shows a longer negative tail and more scores that are relatively high. These results mimic the visual performance characteristics of the illuminance curve in Figure 1 in the demonstration of a drop-off as tasks become difficult.

Both performance and pupil size data was analyzed with an ANOVA procedure. All subjects (including group 3) showed highly significant pupil size differences for the 2 different lamp spectra at all light levels with the higher CCT or S/P lamp always producing relatively smaller pupils as compared to the lower CCT / S/P value lamp.

The graphs in figures 3 and 4 show the mean pupil diameter in millimeters for the subject pool as a function of contrast level for the parabolic and indirect fixtures. These results clearly demonstrate that light level, spectrum, contrast, and to a lesser extent, light distribution, affect pupil size. The standard error in the diameter for this sample is always less than 0.0084 mm.

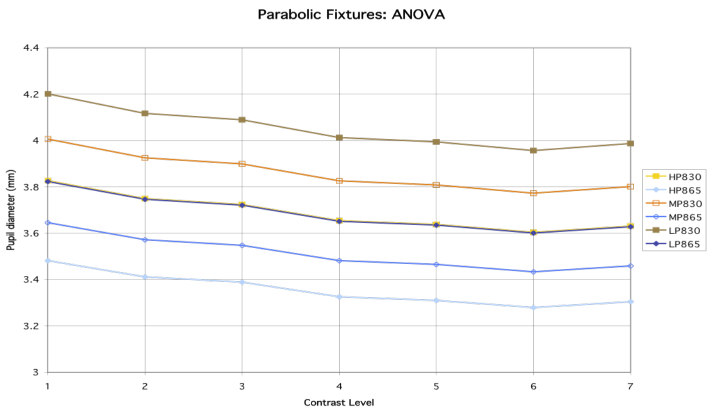

Figure 3

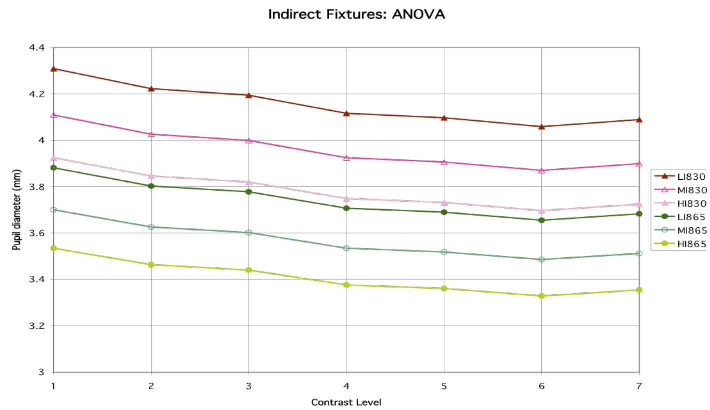

Figure 4

The difference in mean pupil size with spectrum fits well against a recently published spectral sensitivity of the photoreceptive Retinal Ganglion Cells (pRGC)'s as modified by the spectral absorbtivity of the combined lens and cornea. Light level also produced significant but smaller pupil size differences. There was also a small but significant luminaire effect on pupil size indicating the possibility of an interaction effect between light distribution and spectrum on pupil size. Pupil size was also affected by task difficulty with pupils decreasing in size as the task became more visually difficult with a slight trend towards dilation for the last and most difficult contrast level. The decrease in pupil size with task difficulty is most likely a result of the interaction between accommodation and pupil size as the task becomes more visually demanding.

As mentioned above, reading performance as determined by applying the z-scores also showed a significant spectral and light level effect as well as an unanticipated luminaire effect. The spectrally related performance effect was significant for the group as a whole with about 2/3 of the subject sample showing better performance with the higher S/P lamp. There was also significant correlation between pupil size and performance as well as a clear trade-off between light level and spectrum. Performances are compared for each of the fixtures at the 3 different light levels and shown in Figures 5 &6. These results clearly demonstrate that under the high light level (65 cd/m^2) of the lower CCT lamp subjects perform poorer than under the higher CCT lamp at the medium light level (49 cd/m^2). This same feature does not prevail when comparing the medium light level with the low light level because as the light level dips into the lower regime, pupil size is less important than light level.

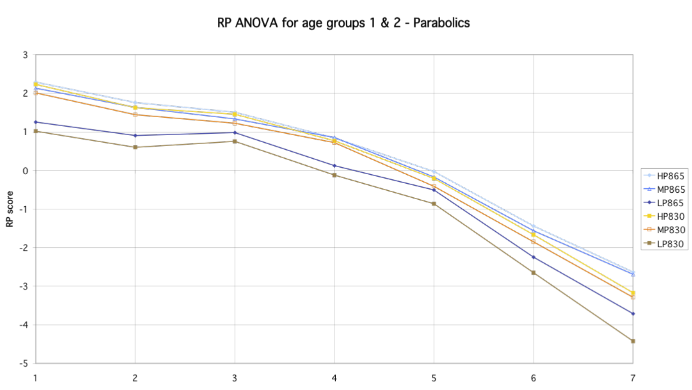

Figure 5

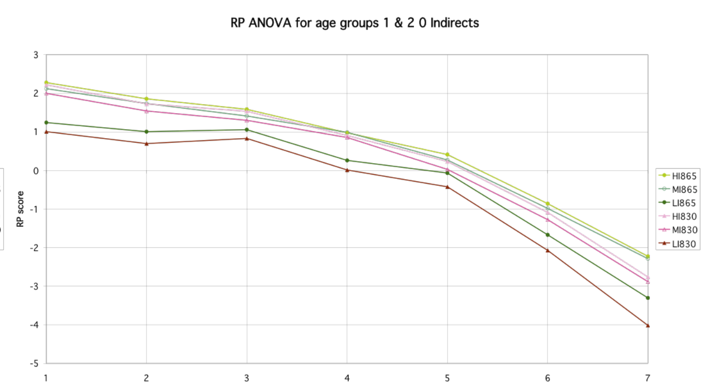

Figure 6

Figure 7 shows the overall RP scores in rank order. These results shows: 1) for a fixed luminaire/spectrum combination, illuminance plays a role in Reading Performance (High has higher RP than Medium, Medium has higher RP than Low); 2) where the luminaire type is fixed, spectrum plays a role in reading performance (high CCT yields higher RP than low CCT); and 3) where the spectrum is fixed, the lighting distribution has a role in reading performance (indirect lighting has higher RP than parabolics). The light distribution effect findings are specific to the room geometry and the placement of the luminaires relative to the room, the subject and the task.

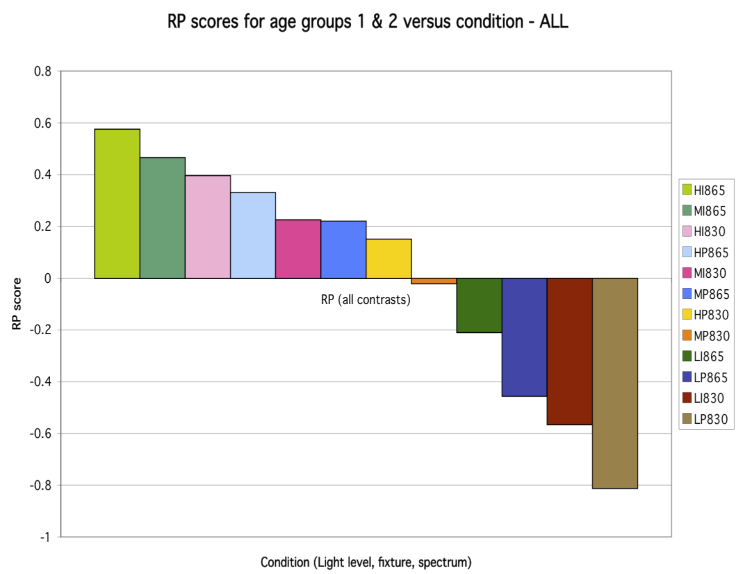

Figure 7: The Reading performance is affected by three factors – light level, spectrum and light distribution. The best reading performance is at the high and medium light levels with the 865 lamp/indirect luminaire combination while the worst reading performance is under the 830 lamp in the indirect and parabolic luminaire.

Legend Code:

The first letter represents light level (H=High, M= Medium, L=Low);

The second letter represents Luminaire: (I = Indirect, P= Parabolic)

The number represents lamp spectrum: (830, 865)

Finally, calculations were performed to assess the correlation between pupil size and Reading Performance. In this case, we isolate the performance to the condition of each luminaire type at a specific light level, as the confound of distribution from the luminaires does not allow for a comparison between pupil size and Reading Performance. These results are shown in Figure 8.

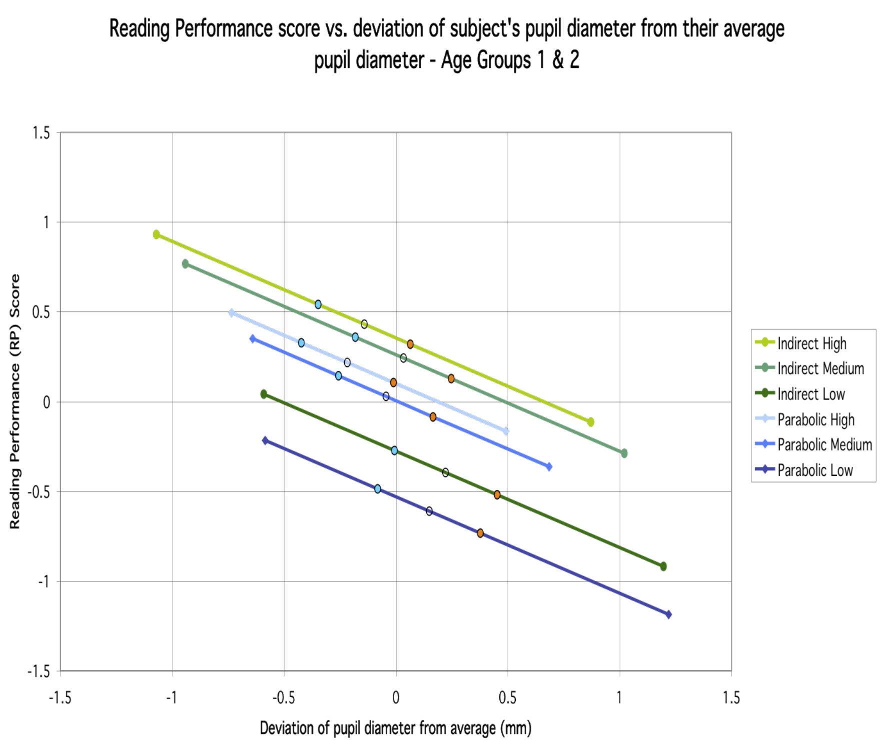

Figure 8: Reading performance is highly correlated with pupil size and pupil size is largely controlled by spectrum. This chart shows that for a given fixture type and light level, the reading performance increases as pupil sizes get smaller. Pupil sizes vary significantly between subjects (3.8 ± 0.6 mm), so the curves are given as a deviation from the average pupil size for the subjects. Pupil size varied with light level, spectrum, age, gender, and fixture

The blue circles represent the average value achieved under the 865 lamp; orange circles represent the average value achieved under the 830 lamps. The center point is the average for all values given the luminaire/light level combination.

There is a clear, statistically significant effect of increasing RP as pupil size decreases.

Conclusions:

Under the conditions of full field of view and fixed near-distance reading of a paper task, we find that for normally-sighted persons:

1. Pupil size is affected by both spectrum and light level; under the conditions of a fixed spectrum, increases in light levels yield smaller pupils, and under the conditions of fixed luminances, higher CCT light sources yield smaller pupils.
2. Reading Performance, (combined speed and accuracy) is affected by both spectrum and light level. There is a trade-off between light level and spectrum; a higher CCT lamp can provide the same Reading Performance at a lower light level than a lower CCT lamp, at moderate light levels typical of interior lighting. We find this effect under the conditions of both pendant indirect and recessed parabolic lighting.
3. Given a specific lighting distribution, as defined in this study by two particular fixture types, there is a significant correlation between pupil size and Reading Performance. This relationship is largely driven by spectrum.
4. The spectrum effect can be explained by a dominant influence of the pRGC's combined with a small contribution from either the cones or rods.
5. Reading Performance is also affected by light distribution. In this study, pendant indirect luminaires consistently yielded better Reading Performance than recessed parabolic luminaires even though the pupil sizes are slightly smaller under the parabolic fixtures. We conjecture that it is due to some artifact of glare from the parabolic fixture or the high value of the luminance on the wall above the task caused by the placement of the parabolic fixture within the room. The artifact of improved performance under the indirect fixtures may therefore not be a function of the fixture alone, but a combination of factors including the specific fixture comparisons used in the study, their placement within the room, and their position relative to the subject and the reading task, all within this specific room.

The analyses performed here use within-subject differences as a means to determine changes in pupil size and Reading Performance.

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