SCOTOPIC vs. PHOTOPIC

Research on vision suggests that we have more to learn about the eye and energy efficiency

Many engineering and architectural texts contain an incorrect view of how the eye deals with light. In these texts one encounters the correct statement that our eyes have two types of photoreceptors, namely cones and rods, along with the erroneous statement that the cones are responsible for day vision and the rods responsible for night vision.
Vision scientists have long known that this segregation of day and night vision is overly simplistic. Nevertheless, until some recent efforts by two pragmatic scientists, the significance of a better understanding of the workings of the eye for lighting practice and lighting energy efficiency had been entirely overlooked.

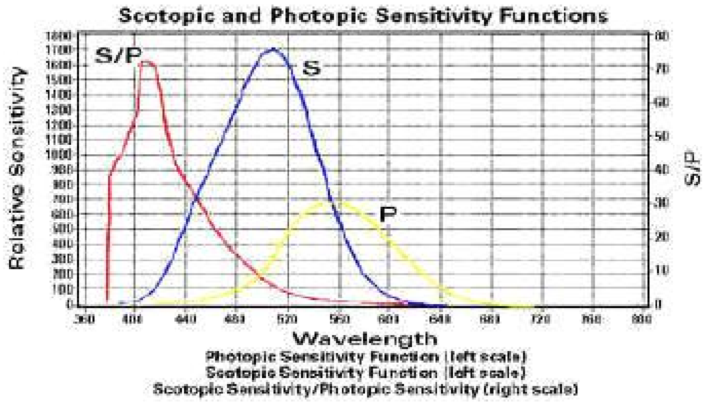

Fig. 1. At a different light levels, people exhibit different relative sensitivities to light. The figure compares photopic and scotopic sensitivity and charts their ratio.

Over the last decade, a series of experiments sponsored by the U.S. Department of Energy showed that rods play a role in vision in lighting conditions typical of the workplace. The tests took place in realistic environments with typical interior lighting and task conditions. The tests showed that both vision and lighting energy efficiency would be improved if lighting practice accounted for the role of the rods in performing tasks in the workplace.

The two scientists, Dr. Sam Berman and Dr. Don Jewett, combined their disparate scientific backgrounds to demonstrate unequivocally the active role of rods in vision at typical interior light levels. Berman is a physicist and senior scientist emeritus, former head of the lighting group at the Lawrence Berkeley Laboratory. Jewett is a neurophysiologist and professor Emeritus at the University of California Medical Center.

Together they used infrared technology to show that rods primarily controlled the opening and closing of the pupil of the eye. Subsequently, in separate studies, they demonstrated that the perception of room brightness was significantly influenced by rod contributions. They also showed that pupil size, as controlled by the spectrum of the room lighting, was a factor in visual performance under workplace lighting conditions.

The benefits of these conclusions are easy to capture with lighting already in catalogs of the major lamp manufacturers. Nevertheless, mainstream lighting practice has essentially ignored the new findings. In fact, the same simplistic segregation of rod and cone vision is explicitly repeated in the latest edition of the IES Lighting Handbook. In spite of this, some forward-thinking practitioners are applying the new principles to provide better and more efficient lighting in major facilities (see sidebar).

The Seminal Studies

Separate series of studies were required to demonstrate the two major effects of rods in daytime lighting conditions. Most of these studies have been printed in full in the Journal of the Illuminating Engineering Society in the 1990s. These studies establish the principle of pupil size and brightness perception
.

The most convincing of the demonstrations establishing rod control of the pupil at typical interior light levels was completed during the mid-1990s. In that study, the pupil sizes of 17 adult subjects were determined as they sat in a chair in a 9- by 12-foot room watching a small television.

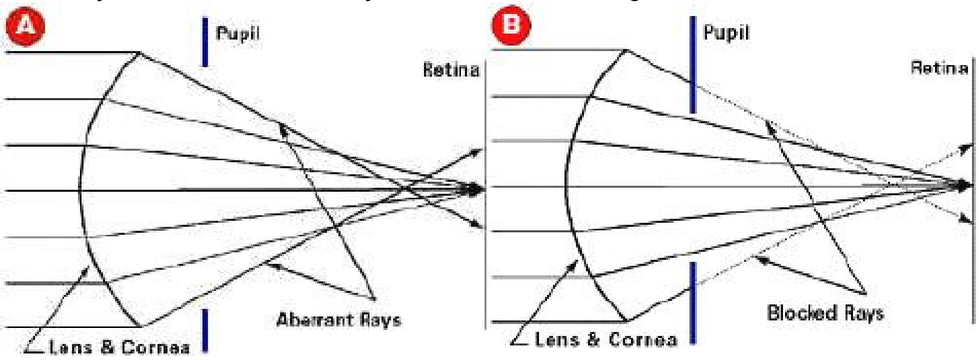

Fig 2. The pupil plays an important role in visual acuity.

The subjects were exposed to various room lighting spectra provided by combinations of differing wall colorings and common fluorescent lamps. Pupil size was measured remotely by a computer-controlled infrared imaging device that took thousands of datum from each subject. Pupil size changed with both light level and the type of spectrum illuminating the subject's eyes. However, when the average pupil size variation was compared with the test illuminance variation at the eye (measured with a conventional light meter) there was no correlation. On the other hand, a near perfect correlation was obtained when the same data were compared to a different type of illuminance based on the relative sensitivity of the rods to different wavelengths of light called the rod spectral sensitivity function or the scotopic response function. The more commonly used photopic function is based on the response of the cones to light. All present light-measuring instruments are calibrated by the photopic function alone as rod response (scotopic sensitivity) has been incorrectly assumed as not relevant for lighting practice. Because pupil size follows the scotopic spectrum, this study demonstrates unequivocally and in an objective manner (subjects cannot voluntarily change pupil size) that rod photoreceptors are active at typical interior light levels.

These findings have immediate practical significance. Pupil size plays an important role in vision; smaller pupils provide better acuity, improve the depth of field, and allow less accommo-dative response of the eye. At typical interior light levels, smaller pupils will permit better vision. Present lighting practice often calls for reducing pupil size by raising light levels, which is not efficient and fails to utilize the response of the rods to control pupil size. Simply ramping up light levels in an attempt to improve vision adds glare and wastes energy.

Perception measures were applied to demonstrate that the sensation of room brightness at typical interior light levels depends on both cone and rod responses. Two different room illuminants providing indirect illumination were compared by subjects, who were asked to choose the brighter one on a repeated basis. The illuminants were constructed to appear equal in color, and thus had the same net cone excitation. However the spectral distribution of the two illuminants were very different. A scotopically enhanced illuminant activated the rods more than a scotopically deficient source.

Subjects chose the scotopically enhanced illuminant condition as brighter, even though the light level was 30% lower as measured by the conventional light meter. This result occurs because the contribution to brightness perception coming from rod activation is not captured by the conventional light meter.

Interestingly, if the two illuminant conditions are viewed through an aperture (the use of the aperture eliminates the excitation of most of the rods because rods are absent from the central portion of the eye), they appear equally bright at the same light meter reading.

The full room study was repeated in the form of a demonstration at the national IES meeting in San Diego, CA, in 1992. Over 100 lighting professionals attending the conference made the same comparison as mentioned above. Only two observers failed to judge the scotopically enhanced but lower level of illumination as brighter, and those two had some color blindness.

For more than a century, various lighting users and practitioners have reported that spaces lighted with higher color temperature lamps appear to be brighter even though the metered light levels were the same or often lower for the higher color temperature lamp. Now we know why-because the higher the color temperature, the more the lighting is scotopically enhanced, thereby achieving more rod activation.

Explaining the Concepts

The most important consequence to lighting practice as a result of these two studies (and others published in the Journal of the IES) is the concept that both cone and rod responses to lighting need to be evaluated. This means knowledge of both photopic and scotopic components of the observed light is necessary to provide optimum lighting for visual performance and brightness perception.

Ideally this would require having light meters with two calibrations, one for determining photopic (conventional) illuminance and a second for determining scotopic illuminance. However, most applications can be managed simply by using the conventional light meter coupled with the knowledge of just the ratio of scotopic to photopic quantities (S/P value) for the light source, as this ratio is independent of light level for fluorescent and HID lamps.

If the surfaces of the lighted space have relatively neutral color, the S/P values of the environmental illumination will be approximately independent of viewing direction and will have the same value as the illuminating source. Conveniently, most sources used in the workplace have a fixed S/P value that is a property of the source just as is the correlated color temperature (CCT) or the color rendering index (CRI). Typical S/P values for most lamps range from 1 to 2.3, except for HPS and LPS lamps which have S/P values of 0.6 and 0.4 respectively. The incorporation of rod effects into lighting practice is then achieved with the conventional light meter coupled with additional factors that depend on the S/P value for the source under consideration.

Applying the Concepts

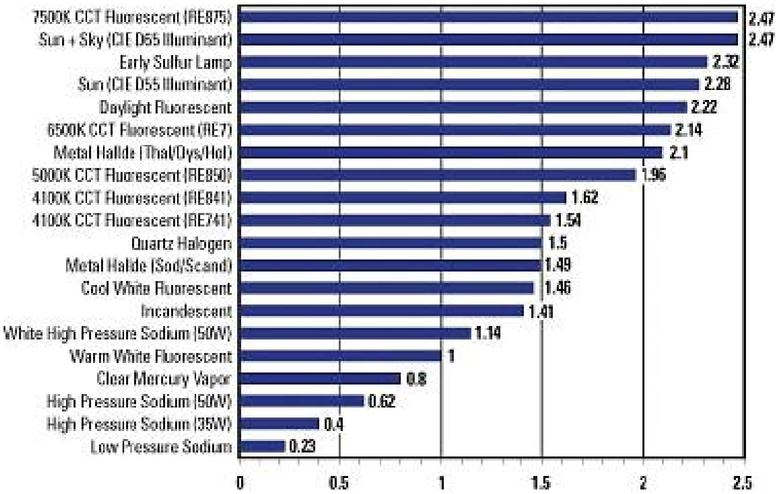

Figure 3. Commercially available light sources are available in a range of S/P ratios, but these are often not published by manufacturers, making it difficult for engineers and designers to make use of this performance parameter.

To illustrate how ambient lighting applications depend on the S/P value, the following situations are considered.

Application 1.

Ambient lighting also provides task lighting, and Visual performance is important.

In this case, the lighting should be judged on the basis of achieving the clearest vision. Research has determined that the relevant photometric factor is the equivalent pupil luminance or illuminance which is given by the quantity P[(S/P)0.78], where P is the photopic amount and the exponent (0.78) of the S/P value has been determined empirically in laboratory studies.

Consider the comparison of two T8, 32-watt (W) readily available fluorescent lamps costing about the same and with the same color rendering index (CRI) of 85. For this example, lamp A would have a correlated color temperature (CCT) of 3500 Kelvin (K), and 2950 initial rated (photopic) lumens. Lamp B would have CCT of 5000K and 2800 initial rated (photopic) lumens. The choice of lamp is generally made on grounds of luminous efficacy, which favors lamp A. On the basis of the new findings it is the visually effective lumens that should be compared, which means multiplying the photopic lumens by the factor (S/P)0.78.
The S/P value for the lamp A is S/P = 1.4; for lamp B, S/P = 1.9. As a result, lamp B produces more visually effective lumens than lamp A (4619 for lamp B, 3835 for lamp A). In other words, lamp B is 20% more visually effective per watt than lamp A, just the opposite of current wisdom.

Application 2.

Task lighting is provided independently as in a computer environment; visual performance is important.

This application shows how the research findings provide an entirely novel approach to the lighting of the computer environment. At the same time, the example demonstrates the severe inadequacy of a lighting practice that fails to include scotopic effects.
Any ambient lighting will produce some glare effects on a computer screen as well as desaturation of screen colors. Unfortunately, computer work without any surround illumination will cause pupils to become dilated, resulting in poorer vision and possibly visual fatigue due to the additional accommodative response needed to focus when pupils are larger, so working in a dark room is not a good option. Thus the best compromise for the ambient lighting is to provide the smallest pupils with the least amount of glare. This means that the ambient lighting needs to be judged purely on the basis of its scotopic content, i.e., the relevant lighting quantity is S = P(S/P).

Example: Since a high value of CRI is less important in the computer environment, the comparison here is made between two T8, 32-W fluorescent lamps costing about the same and having the same CRI value of 75. Lamp A has a CCT of 3500K, 2850 initial (photopic) lumens, S/P =1.3 Lamp B has a CCT of 6500K, 2700 initial (photopic) lumens, S/P = 2.15.
Conventional practice would lead to the selection of lamp A because of its higher efficacy. However, in the computer environment it is the scotopic lumens that should be considered, which for lamp A is 3705 and for lamp B is 5805. Lamp B operating at 64% of the power density of lamp A will provide the same amount of scotopic lumens. But because lamp B produces these scotopic lumens with fewer photopic lumens, lamp B will cause considerably less glare and desaturation.

Barriers to Application?

It has been more than 13 years since the first studies demonstrating significant rod activity at typical interior light levels along with arguments for major consequences in lighting practice, were published in the Journal of the IES Since then over a dozen papers have been published and many presentations have been made at national and international venues. Except for a few lighting retrofit companies that have adopted the new findings, there is a noticeable lack of mention of these results by the mainstream lighting community. Even a basic property of lamps, namely their S/P value, is absent from the lamp industry catalogues.

Why? Perhaps there is great difficulty in accepting a substantial and sometimes nearly radical change from what has been the standard practice for the entire past century, even though this change is supported by solid scientific evidence. Witness the dramatic example of the computer environment where the relevant photometric quantity needs to shift from photopic to scotopic illuminance.

What is even more surprising is the total absence of any attempts by the small lighting research community to replicate and independently confirm or deny the findings. In other scientific areas there is usually a mad rush to replicate, disprove, or confirm a new and revolutionary result. The only response from this lighting research community has been to either ignore the new results or to claim they are irrelevant. Something is amiss in this community.

The lack of interest and the marginalization by the mainstream lighting community has exacted its effect on the DOE, which eventually ceased to fund the research. Although they recognized the large potential societal benefits, they were overwhelmed by the complexity of dealing with the implementation in the absence of any substantial constituency.
However, as more lighting practitioners begin to apply the new findings making lighting better and more efficient, the IES and other lighting organizations will need to rethink their position lest they instead become marginalized.

The Intel Experience

Over the past decade major improvements in workplace lighting energy efficiency have occurred based on the retrofit strategy of replacing existing fluorescent lamps and their ballasts with the combination of F32T8 fluorescent lamps and electronic ballasts.
Is there a next step ready to garner further cost-effective savings? Intel answers with a definite "Yes." Surprisingly this next step does not call for any new technology. Instead the improvement in lighting energy efficiency at Intel facilities combines the new understanding of our vision with selecting lamps whose properties take advantage of this new knowledge.

History

In 1995, in response to the local utility energy conservation program, the Intel Corporation, the world's largest manufacturer of computer chips, decided to examine the possibility of retrofitting their large multi-building campus located in Hillsboro, OR, with more energy-efficient lighting. The generally accepted mantra at that time called for replacing existing lighting systems with F32T8 lamps and electronic ballasts. However, after viewing a demonstration setup in the lighting laboratory of the local utility (Portland General Electric), the Intel facilities engineers realized that it would be possible to go a considerable step further than just the standard retrofit.

Laboratory Demonstration

The demonstration at the PGE laboratory was set up for the purpose of showing how the new findings on rod (scotopic) sensitivity affected vision and brightness. The demonstration used conventional fluorescent lamps to compare the vision effects of a high color temperature lamp (scotopically enhanced), and therefore higher bluish output, with a low color temperature lamp (lower bluish output, scotopically deficient).

Intel facilities staff observed that under the scotopically rich lighting one could see better and that this lighting would be perceived as brighter even though a traditional light meter would indicate the opposite, which is exactly what PGE had set out to show. Intel realized that with scotopically rich lamps, they would achieve larger energy savings by reducing the number of lamps and at the same time maintain or improve the prior vision and brightness conditions.

Pilot Strategy

The luminary chosen for a pilot retrofit housed four 34-W T12 lamps of color temperature 3500K and CRI of 70, driven by energy-saving electromagnetic ballasts. Intel replaced these lamps with two 32-W T8 lamps of color temperature 5000K and 80 CRI driven by a single high lumen output (HLO) electronic ballast with a 126% ballast factor. The HLO ballast was chosen because there was a concern that use of a standard electronic ballast would result in an unacceptable drop in illumination.
After applying this retrofit to a large area, the average horizontal illuminance levels at work height dropped from the pre-retrofit value of about 65 footcandles (fc) to about 55 fc.

Occupant and Facility's Response

Occupants universally and bitterly claimed that the new light levels were much too high! Subsequently the HLO ballasts were replaced by standard electronic ballasts. Average illuminance levels then dropped to about 45 fc. Still occupants reported that the light level was better but still too high. After a short time the complaints ceased and the program proceeded to retrofit about 1400 luminaries in the pilot building and was considered successful.

Pilot Energy Savings

This strategy clearly produced significant energy savings. The measured lighting power per luminaire went from the original value of 144 W to a final value of 62 W, for an overall reduction of 57%. As a result of the success of this strategy, four other major strategies were introduced, depending on the luminaire. Each of these took advantage of the energy savings potential of the effects of scotopic enhancement. These strategies involved replacing three T12 lamps with two T8 lamps, and in some cases installing reduced output ballasts.

Full Campus Implementation

These strategies were applied to all nine buildings of the Hillsboro campus and when combined, yielded annual lighting energy savings slightly larger than 8 million kilowatt hours. These scotopically enhanced lamps have been in consistent use since their initial installation.

About the author

Sam Berman is presently senior scientist emeritus at the Lawrence Berkeley National Laboratory (LBNL). He was the originator and the first leader of the lighting research program. Before joining LBNL, he was professor of physics at Stanford University, where he was a member of the team that founded the Stanford Linear Accelerator.