NEW DISCOVERIES IN VISION AFFECT LIGHTING PRACTICE

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For about the last 100 years lighting practitioners have operated under the impression that there are two photoreceptors in the retina of the eye, namely cones and rods. Furthermore the calibration of our standard light meters is accomplished by employing the collective cone spectral response known as the V(λ) function. The V(λ) function provides for the conversion of physical radiant power in watts to photometric light quantity in lumens as the unique and standard measure of human visual response to light.

However this paradigm is now ready for re-examination in view of some new and significant findings coming from the world of vision science.

The New Findings:

At the end of year 2002 the prestigious journal 'Science' announced that the discovery of a new retinal photo-sensing receptor located in the non-central (non-foveal) regions of the eye and functioning at interior and higher light levels was among the 10 most important scientific breakthroughs of the year (1). More support for such an additional human photoreceptor came from studies of the light driven spectral response of melatonin, the hormone regulating circadian rhythms (2). Because of the position of the spectral peak melatonin regulation was claimed neither a rod nor cone spectral response function but also related to a new retinal receptor. Further advances in vision science were made during the next 5 years and especially this year (3) with new and direct evidence from studies in humans confirming directly the existence of a new non-central retinal photoreceptor.

The new photoreceptive pigment has the name 'melanopsin' and its peak wavelength sensitivity occurs at about 482 nm based on the most recent vision science studies (3). Melanopsin lies on a class of large retinal ganglion cells situated outside the central fovea (4). These cells have been given the name 'intrinsically photosensitive retinal ganglion cells' (ipRGC's). The principle role for these ipRGC's (even though they are some 1000 times less numerous than retinal cones) is that they directly innervate the brain regions responsible for non-imaging vision functions such as circadian regulation and pupil size variation (3).

The Importance of the New Findings for Lighting Practice:

Besides circadian regulation, these discoveries are important because they offer explanation for many observations encountered in lighting practice but often dismissed as unsupportable by previous conventional wisdom.
For example, there is compelling evidence that these receptors can explain the well known brightness perception, that when viewed in natural conditions and at typical interior levels, lighting relatively richer in bluish tint (higher correlated color temperature) is perceived as brighter compared to lighting with less bluish tint (lower CCT), both viewed at the same standard meter illuminance. Such an explanation is highly credible because in calibrating our conventional light meters, the bluish favored light responses of the new receptor have not been included. Thus for the last 100 years we have been making an accounting error in fully evaluating the quantity of light. Holy Mackerel! How could this be? Where did we go wrong? Here is the story.

Foveal Faith:

First step down the primrose path was that illumination engineering became an unconditional supplicant of foveal faith and accepted the $V(\lambda)$ function as the unique means for converting optical radiation to visual light quantity and thus to calibrate light meters. The $V(\lambda)$ calibrating function is determined in vision laboratories from brightness responses to light of varying wavelengths restricted to fall only on the fovea, a very central region of the eye populated by cone receptors alone. But since there are no ipRGC's in the fovea and indeed if these receptors are contributing to the perception of light when viewed in natural circumstances, (i.e. full field of view) then their light driven input to our senses, especially in terms of perceived brightness, has been left out of the calibration. Since before year 2002 there was supposed to be no other photosensitive cells in the retina operating at photopic levels (interior and daytime exterior levels) other than the cones, the illumination community accepted that the cone $V(\lambda)$ function was the operative calibration to be applied for natural viewing conditions.

Early Warnings:

The first harbinger that something might be awry with such an indiscriminant faith was the work of Herman Bouma a Dutch vision scientist who in 1962 (5) measured the spectral response of his own pupil size at photopic levels when light was presented in full field of view. He found that pupil size changes had a peak spectral response much more in the bluish region peaking around 490nm and not at 555nm as it would be if $V(\lambda)$ was the only operative sensitivity. The lighting community did not appreciate his work perhaps because he claimed the measured response, that mimicked a scotopic spectral response, was a consequence of the rod receptors. This claim was counter to the generally accepted dogma that rods were well saturated and not capable of light responses at the photopic levels of his study.

Re-examining Bouma:

For 25 years Bouma's work lay in the archives of questionable science until in the late 1980's the articles of foveal faith were re-examined from a lighting practitioner's perspective by Berman and his coworkers. They had a technical advantage over Bouma because advances in infrared (IR) technology allowed remote IR pupilometry for the measurement of pupil response under conditions where tested subjects were sitting comfortably in a simulated office environment. (The eye does not respond to IR light allowing IR photography of the pupil without concern about interactions with the ambient test light.) With the more modern IR technology they found that in the natural condition of full field of view and at light levels typical of building interiors, the spectral response of pupil size was well explained with the two traditional spectral responses of the eye, namely the photopic and scotopic sensitivities, but was dominated by the scotopic sensitivity by a factor of 3.4 to 1 (6). This result appeared to vindicate Bouma's earlier work. [Recently Gamlin et al also found a similar result (3).]

Why is pupil size variation relevant to lighting practice?

As any camera buff knows a smaller lens aperture (higher f-stop) allows greater depth of field and images appear sharper. The same is true for the eye. But more intriguing is that our pupils contract when the overall scene appears brighter. Thus there is a strong correlation between spatial brightness perception and pupil size. (Spatial brightness perception, in contrast to the central vision or foveally dominated specific object brightness, is the sense of overall brightness associated with viewing a room or a large space.)

To demonstrate that the spectral effects driving pupil size contraction were also driving spatial brightness perception, the Berman team tested subjects in a featureless white room (7). They showed that people experiencing white lighting with more bluish content, perceived such lighting as considerably brighter than white lighting of the same color but with less bluish content even though the standard light meter reading recorded the inequality in just the opposite way. In this way they clearly demonstrated the accounting error caused by using a meter calibrated solely on foveal input.
Many lighting practitioners were relieved that their brightness perceptions of spaces so long delegated to the realm of subjective partiality might, at last, have some validity. The Berman crew even brought a portable room demonstration to the 1992 IESNA conference in San Diego where more than 100 conferees perceived the same spatial brightness perception effect. However, to explain their results the Berman crew reiterated Bouma's refrain and suggested that the mechanism had to be rod mediated and thus for the most part were delegated to the Bouma closet.

Vision Science Starts Catching Up:

However, lo and behold the year 2002 arrived and vision science began catching up with lighting science. It just so happens that there is another retinal photoreceptor functioning at photopic light levels with a pigment of peak wavelength sensitivity determined to occur at 482 nm (3). When the spectral transmission of the eye is included, the peak shifts upward to 491 nm, a value very close to the 507 nm peak of the scotopic spectrum (8). In fact when the Berman et al pupil size measurements of 1997 (9) are re-examined in light of the new receptor, the data with its error bars is about as equally explained by the 491nm spectrum as the scotopic spectrum (8).

And what of the brightness perception?

Vision science has yet to completely catch up and confirm directly that the new receptor also plays a role in full field or spatial brightness perception.

However, way back in 1971, David Newsome working at the National Eye Institute showed that successive large pupillary contractions were associated with simultaneous perceptions of brightness enhancements, thus demonstrating that pupil reaction and brightness perception are indeed correlated (10). Therefore we can be assured that when vision scientists accomplish their version of brightness studies those results will likely confirm what we already know.

A new age for lighting:

The finding of a new non-central light sensitive receptor in the eye operating at typical interior light levels means that we should rethink exclusive foveal faith even in photopia. Thus for a complete lighting practice in the photopic region, there will not be one but instead two spectral sensitivity functions and further, that for all of lighting practice (interior and night-time exterior) instead of traditional two, there will be a family of 3 spectral sensitivity functions, namely photopic, scotopic and cirtopic. These functions are generally characterized by their peak wavelengths occurring at 555nm, 507 nm and 491 nm respectfully. When taken together as the photometric family these sensitivity functions are all normalized to the defining value of the lumen, namely the value of 683 lumens per watt at 555 nm. The new or third function so normalized is named here as ‘cirtopic’ in deference to its relevance for circadian regulation. A graph of the 3 functions is displayed in the Figure below. Note that the different peak values of the functions (3616, 1700, 683) as shown in the graph is a consequence of the normalization at 555nm and is not related to any fundamental differences in absolute sensitivity.

The Cirtopic Proxy:

At the time the spectral studies of Berman et al were carried out, the new photoreceptor had not yet been discovered. However, they found their data on pupil size, brightness perception and visual performance could be accurately fit by employing the two traditional retinal photo sensitivities with the scotopic spectral sensitivity now appreciated as the empirical proxy for the required additional bluish sensitivity. Since the peak wavelength of the scotopic spectrum of 507 nm is close to the peak wavelength of the new retinal photoreceptor of 491 nm, the proxy allows consistent interpretation of the data with the empirically determined spectral modifiers remaining applicable, although not fundamental (11).

Incorporating Cirtopia:

Because the photopic and cirtopic spectral sensitivities are different, incorporating the new receptor into lighting practice becomes an issue only when the lighting application involves consideration of multiple spectra. If there is only one spectrum of concern, then brightness perception and visual performance will follow the relative readings of the standard light meter (12). However, when comparing sources of different spectra for spatial brightness perception or visual acuity, the relative weightings between the photopic and cirtopic contributions will shift. Since the conventional light meter is based solely on V(λ), relying on those values alone will fail to give an accurate account of the visual system response. Furthermore, correcting the accounting error allows a means for improving the energy efficiency of lighting because blue rich lighting will include a relatively higher input from the new receptor.

Conclusion:

The discovery of a new non-central photoreceptor affirms the need for a more accurate accounting of how light affects the visual system under the full field viewing conditions encountered in most lighting practice. Incorporating the related new knowledge will provide that practice with a valuable upgrade thereby allowing the attainment of both a more visually efficient and energy efficient lighting economy.

References and Notes:

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11. The closeness of the two peak wavelengths allows an algebraic relationship between the previous empirical guiding application factor for interior lighting, the scotopic/photopic ratio (S/P value) and what we now consider its more fundamental replacement, the cirtopic/photopic ratio (C/P value).
For example, based on the spectral function provided by Gamlin et al (3), the following relationship between S/P and C/P can be determined for a wide range of broad band light sources, namely that,
$S/P = (0.66C/P)^{0.74}$ or $C/P = (1.37S/P)^{1.35}$
(For narrow band sources such as LPS or LED's the above relationship would not be accurate.)
Thus the empirically determined result (6) showing pupil size depending on the factor $P(S/P)^{0.78}$ remains valid. However if that data had been analyzed instead in terms of cirtopic and photopic sensitivities, the exponent of the alternate quantity (C/P) would have turned out to be different. But because of the strong correlation between S/P and C/P, either procedure offers a satisfactory explanation of the data.

12. In addition, if the task is purely foveal such as local supra-threshold contrast or small object brightness then including the response of the new receptor should not be necessary.

Figure showing the 3 spectral sensitivity functions.