U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

SOLID-STATE LIGHTING PROGRAM

Discussions about possible health implications of exposure to light at night run the gamut, but given the available research, should any changes be made to currently recommended lighting practices?

Light at Night: The Latest Science

BACKGROUND

Our understanding of the visual and non-visual effects of light on humans remains incomplete. The photopic lumen is currently used in all lighting applications, be they interior or exterior, daytime or nighttime. Investigations into the possible visual performance benefits of "spectrally enhanced" electric lighting for interior and exterior use are ongoing. Similarly, researchers are seeking to establish recommended requirements and restrictions for minimum daytime and maximum nighttime exposures to light. Lighting ordinances reflect longstanding visual sensitivity to errant electric light at night in exterior applications, commonly referred to as obtrusive light or light pollution. Some of these ordinances focus on the protection of particular species of wildlife. Recently, increasing attention has been given to possible health effects of light for night-shift workers in interior environments.

SYNOPSIS

A panel of leading experts was assembled to explore what today's science can tell us about light at night.

While it remains unproven that typical exposures to outdoor lighting have negative health impacts, this cannot be ruled out without more empirical data and a standard metric for quantifying the relevant light exposures.

LED technology holds tremendous potential for energy savings, but it is not yet clear whether its spectral characteristics will offer advantages over other light sources in terms of vision and circadian regulation.

Meanwhile, rapid progress is being made in the field of solid-state lighting (SSL), largely in the form of inorganic light-emitting diodes (LEDs). Recognizing the energy savings potential of this emerging technology for the purposes of general area and task lighting, the U.S. Department of Energy (DOE) has created a number of SSL R&D projects and market-based programs to accelerate development while simultaneously helping to ensure appropriate application of these new products. LEDs are already beginning to outperform incumbent technologies in a number of lighting applications, but this technology is generally not yet in a position to be considered the de facto light source of choice. Indeed, as standards continue to be developed and as new challenges arise, the economic viability of SSL in many applications will likely remain questionable for years to come.

In July 2010, DOE assembled a panel of experts on the topic of nighttime light exposures as part of the agency's fifth annual SSL Market Introduction Workshop in Philadelphia[1], with the intention of providing an update on current research and a forum for discussion. While these issues are not unique to LEDs,

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[1] Please see presentations at www.ssl.energy.gov/philadelphia2010_materials.html.

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dealing with them while the technology is still at a relatively early stage can help us avoid mistakes that may have already been made with other lighting technologies. The goal of the panel was to communicate what we currently know and don't know about the visual and non-visual effects of nighttime light exposures, focusing on differences in spectra between available light source technologies.

Moderator Jason Tuenge of Pacific Northwest National Laboratory opened with a summary of the DOE SSL perspective to provide background and set the stage for the panel of experts. Ronald Gibbons, Ph.D., of Virginia Tech Transportation Institute (VTTI) followed with an overview of recent and ongoing research into the effects of spectrum on visual performance in outdoor environments at night. George Brainard, Ph.D., of the Neurology Department at Jefferson Medical College, discussed his work studying the non-visual circadian, neuroendocrine, and neurobehavioral effects of light spectrum and irradiance on human health. Mariana Figueiro, Ph.D., of the Lighting Research Center at Rensselaer Polytechnic Institute (LRC) closed by explaining the current difficulties in accurately quantifying exposure to nighttime lighting, and provided a preliminary estimate of the potential for typical nighttime light exposures to have an impact on acute melatonin suppression.

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THE DOE SSL PERSPECTIVE

SSL technology offers a number of potential advantages for outdoor lighting applications. LEDs can already light many tasks using less wattage than would be required using a traditional light source, and their efficacy (lumens produced per watt consumed) continues to improve at a remarkable rate. Reductions in connected load can be accomplished by a combination of improved luminaire efficacy and the reduction or elimination of wasted light directed upward or outward beyond the target. LEDs can also distribute light more uniformly, allowing for reduced average light levels in some applications, such as parking lots, and thereby further reducing power draw and reflected uplight. Additionally, LEDs are dimmable and tolerate frequent switching, so they can be combined with motion sensors and/or scheduled control to further reduce energy use during periods when full output is not required. Reduced energy consumption translates to reduced demand for energy production—and reduced CO_2 emissions.

The broad-spectrum light produced by white LEDs can improve color contrast, and there is evidence that such sources improve visibility. If the Illuminating Engineering Society of North America (IES) adopts a model of mesopic photometry, it is likely that additional energy savings could be realized by switching to broad-spectrum sources like LEDs. Specifically, it might then be possible to reduce photopic light levels (and wattage) in outdoor applications for those sources featuring spectra with a substantial short-wavelength (blue) component. However, even if for the time being only photopic light levels are evaluated (as per the IES), spectral content must be considered in selecting an LED source if optimal energy savings are to be realized. This is because unlike other source types, LED efficacy tends to increase with increasing correlated color temperature (CCT) and short-wavelength content. In other words, within any given product line, the LEDs with a "cool" appearance will generally be substantially more efficacious than those having a "warm" appearance. Figure 1 illustrates this phenomenon.

While it is clear that short-wavelength spectral content plays a role in the photopic efficacy of LEDs, it is not clear how to reconcile the *possible* improvements to visual performance with the *possible* health implications of non-visual responses. The DOE will continue to monitor progress being made by subject matter experts such as those on this panel, but actionable guidance on these complicated and controversial matters must ultimately come in the form of IES recommendations.[2]

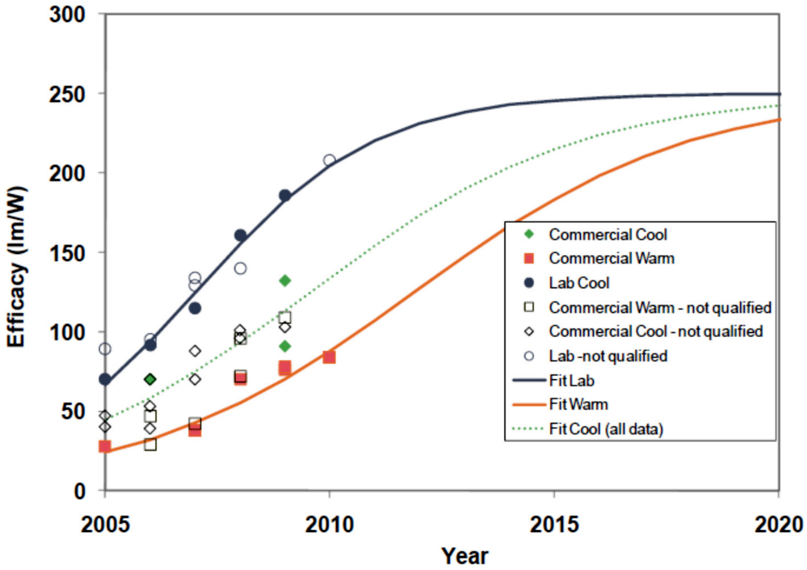

Figure 1. White-light LED package photopic efficacy targets, laboratory and commercial[3]

OUTDOOR LIGHTING AND VISUAL PERFORMANCE

Gibbons's research at VTTI has focused on driver behavior and safety under various roadway lighting conditions. His work with SSL has primarily centered on the use of broad-spectrum sources to reduce photopic lighting levels and power consumption, thereby displacing other sources without compromise to safety.

After moving outside from brighter indoor lighting, or during the transition from daylight to darkness, the human eye adapts to the low light levels produced by outdoor lighting systems. As part of this transition process, the eye gradually shifts from photopic (cone) vision toward scotopic (rod) vision, such that both rods and cones are contributing to vision. This change in spectral sensitivity, known as the Purkinje shift (see Figure 2), can result in underestimation of visual performance under sources featuring a substantial

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[2] See the "Light at Night and Human Health" fact sheet at www.ssl.energy.gov/factsheets.html for additional background.

[3] Multi-Year Program Plan, Solid-State Lighting Research and Development, U.S. Department of Energy, March 2010.

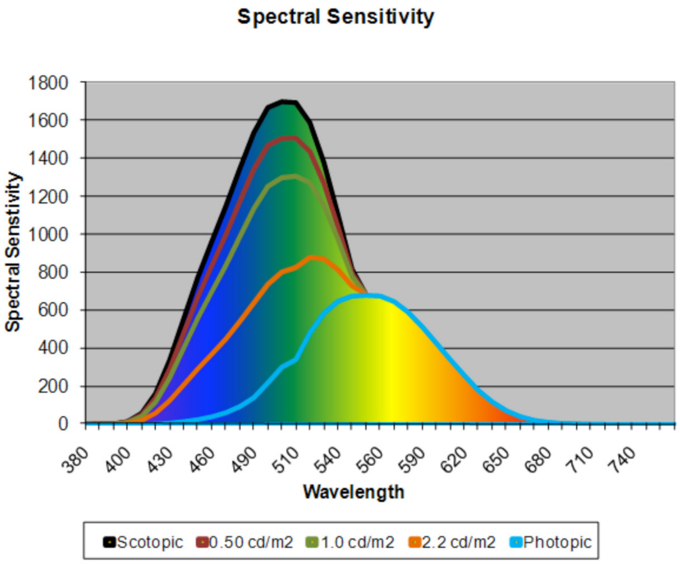

Figure 2. The Purkinje shift[4]

blue component, and possible overestimation of visibility under sources deficient in the short-wavelength portion of the visible spectrum. In outdoor applications with low light levels, where the photopic lumen is not always an adequate predictor of performance, a new "mesopic" lumen appears to be needed.

An additional benefit of broad-spectrum light sources is that they can provide improved color contrast, as illustrated in Figure 3. Vision relies largely on contrast, which takes two forms—luminance contrast and color contrast (or color difference). Light levels and luminance contrast are typically given first priority, and while some attention may be paid to the apparent color or chromaticity of light, color rendition and color contrast are ignored—the world is essentially imagined in shades of gray pavement. But by improving color contrast, we can more quickly distinguish and identify surfaces or objects of differing color.

Figure 3. Color contrast provides visual depth between background and foreground

Gibbons described three field investigations of color contrast, making use of recent projects in Anchorage, Alaska; San Diego, California; and San Jose, California. Each of these cities installed induction luminaires and LED luminaires, both broad-spectrum light sources, for comparison with typical high-pressure sodium (HPS). San Jose also compared LEDs of three different CCTs against monochromatic low-pressure sodium (LPS), which has been used to reduce sky glow for nearby astronomical observatories. The small target visibility (STV) model was used as a guide for Gibbons's studies, whereby small objects of differing size and color were placed on the roadway, and passengers were asked to describe these objects as soon as they could. The corresponding detection distance was recorded for all luminaire-object

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[4] Diagram courtesy of Ronald Gibbons.

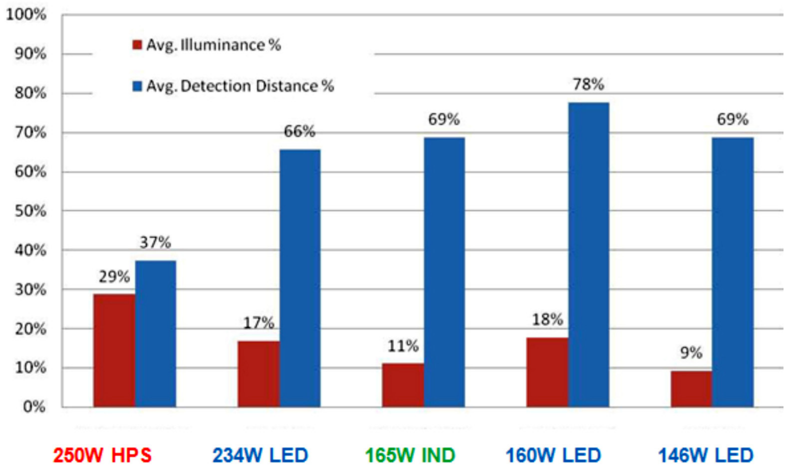

Figure 4. Anchorage: Average illuminance vs. detection distance, relative to 400W HPS

combinations, and it was observed that the broad-spectrum sources required less photopic light (and less wattage) than was required for HPS or LPS. Results in Anchorage, summarized in Figure 4, exemplify this phenomenon.

Similarly, the results in San Diego showed no relationship between photopic illuminance and detection distance. After switching to broad-spectrum sources, visibility improved even though photopic light levels were reduced. This indicates that something else is needed to explain differences between the three light source technologies, and spectral content appears to be the missing variable. A surprising finding in San Jose was that blue objects were rendered so poorly by LPS that they appeared black, and were thus readily distinguishable from the other colors by a process of elimination (no black or white objects were used in the study).

While the findings of these studies and others do not seem to justify outright rejection of the photopic lumen for use in outdoor lighting applications, it appears we may be missing an opportunity for energy savings and improved safety. For this reason, the Federal Highway Administration (FHWA) is sponsoring a project to attempt to better characterize the relationship between spectrum and light levels in terms of visual performance.[5]

Related research is being performed at VTTI to better characterize driver behavior. The hope is to answer fundamental questions, including where a driver is actually looking while driving, and whether hazards are typically detected using peripheral vision or primarily with eyes directed at the object. It's possible some objects are actually detected not peripherally but rather by the fovea as the eye follows a glance pattern or visual search. The study is also examining the role of object motion in determining the mechanism of visual detection. Due to the differing distribution of cones and rods, mesopic effects likely don't apply evenly across the retina. Eye-tracking instruments are being used to track driver behavior, and the findings are expected to help determine whether accident avoidance is primarily attributable to on-axis (chromatic) or off-axis (achromatic) vision.

Gibbons also noted that the controllability of SSL could prove very useful in roadway lighting applications. Dimming controls could produce energy savings during periods of reduced roadway activity, reducing light levels so that they are more appropriate for current environmental conditions. While this practice is already consistent with IES RP-8, which classifies roadways partly on the basis of pedestrian activity, the next revision of that standard will provide more explicit guidance to encourage municipalities to adopt dimming control systems as they upgrade to SSL. Gibbons also discussed recent work by others predict-

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[5] FHWA DTFH61-10-R-00027, "Evaluation on the Impact of Spectral Power Distribution on Driver Performance."

ing greater atmospheric scattering (sky glow) for short-wavelength light than for longer wavelengths, and noted that this issue may merit consideration when selecting a light source.

CIRCADIAN, NEUROENDOCRINE, AND NEUROBEHAVIORAL RESPONSES TO LIGHT EXPOSURE

Brainard has been studying biological and behavioral effects of light on humans. The main theme is trying to understand how the human eye detects light and transduces it, not for vision, but for physiological regulation. The human eye actually contains two discrete sensory systems, as illustrated in Figure 5. One supports the familiar sensory functions of vision and visual reflexes by supplying input to the lateral geniculate nucleus (LGN) for use by the visual cortex. The other provides input to the suprachiasmatic nucleus (SCN), a non-visual part of the brain, which relays signals throughout the nervous system, providing information regarding time of day and ambient levels of light and darkness. A secondary pathway to the intergeniculate leaflet (IGL) also supplies information about environmental light to the SCN. One part of the brain, the pineal gland, receives signals from the SCN and, in turn, regulates its production and secretion of its hormone melatonin. Melatonin production is greatest at night and lowest during the day. This holds true not just for humans but across all diurnal and nocturnal species that have been studied.

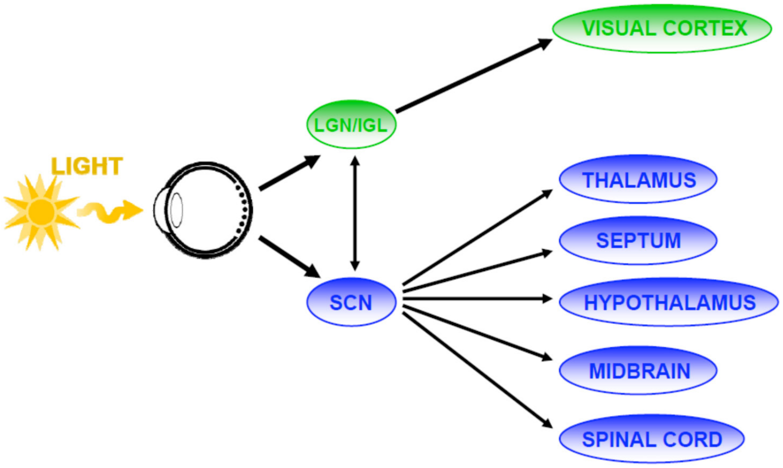

Figure 5. Processing light for visual and circadian functions[6]

In 1980, researchers at the National Institute of Mental Health (NIMH) demonstrated that exposure to 2500 lux of bright white light at night strongly suppressed production of melatonin.[7] This study opened the door to studying how light drives biology and behavior in humans, but note that this laboratory light level was far higher than would typically be encountered at night. Levels of 500 lux, realistic for portions of a home or office but unlikely to be found outdoors, appeared to have a very slight reduction of melatonin production in that study.

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[6] Copyright Warfield, Brainard, Thomas Jefferson University, 2010.

[7] Lewy AJ, Wehr TA, Goodwin FK, Newsome DA, Markey SP. Light suppresses melatonin secretion in humans. *Science*. 1980 Dec 12;210(4475):1267-9.

Brainard's team took the subject another step forward by examining how different parts of the spectrum affect melatonin production. For example, are blue and red wavelengths equally potent? What was desired was an action spectrum similar to those that serve as the basis of the photopic lumen and the scotopic lumen (see Figure 2). Volunteers would arrive at the laboratory at midnight, have their pupils dilated, be blindfolded, and then sit in darkness from midnight until 2:00 a.m. On a control night they would continue in darkness until 3:30 a.m. On an exposure night they would be exposed to 90 minutes of monochromatic light and be monitored by a camera to ensure that their eyes remained open. Plasma (blood) samples were drawn at 2:00 a.m. and 3:30 a.m. The laboratory light sources used, having all energy focused into 10–14 nm half-peak bandwidths, were very difficult to produce and are not commercially available (or even viable) for outdoor lighting applications. In total, 72 healthy men and women participated in over 700 nighttime studies. The wavelength exposures were 420, 440, 460, 480, 505, 530, 555, 575, and 600 nm, and the resulting action spectrum is shown in Figure 6.

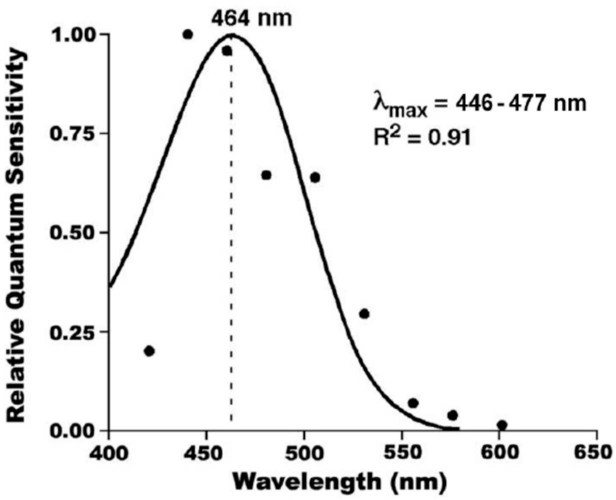

Figure 6. Action spectrum for melatonin production in healthy humans[8,9]

This opsin curve, published in 2001, has the familiar mathematical shape of the curves for the cone and rod opsins (rods contain rhodopsin), but the unique and remote location of the peak wavelength led to the conclusion that the human eye must have an as-yet unidentified sensory system. The peak is somewhere between approximately 446 nm and 477 nm—located in the portion of the spectrum that has a blue appearance to the visual system. To date, other laboratories have published 10 similar action spectra studying humans and other animals, including rats and monkeys, and arriving at essentially the same conclusion.

In 2002, a new class of photosensors, the intrinsically photosensitive retinal ganglion cells (ipRGC), were discovered, along with their unique photopigment, melanopsin. These photosensors had escaped detection by earlier investigators partly due to their role in circadian regulation (versus vision), and due to their very small physical presence—accounting for just three percent or less of the total population of photosensors on the retina. Whereas the visual system appears to rely strictly on input from rods and cones, the stimulation of the non-visual photoneural responses (circadian, neuroendocrine, and neurobehavioral regulation) relies primarily on input from the ipRGCs, with some additional input from rods and cones.

The hormone melatonin has a key role in circadian regulation that, in turn, regulates daily physiological rhythms in virtually all tissues of the body and modulates alertness, cognitive performance, and other

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[8] Brainard GC, Hanifin JP, Greeson JM, et al. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. *J Neurosci*. 2001 Aug 15;21(16):6405-12.

[9] Brainard GC, Sliney D, Hanifin JP, et al. Sensitivity of the human circadian system to short-wavelength (420-nm) light. *J Biol Rhythms*. 2008 Oct;23(5):379-86.

behavioral rhythms. With an understanding of these effects, properly applied light exposure can be used therapeutically. Perhaps the best known example is the treatment of winter depression, or seasonal affective disorder (SAD). But just as any medication can be expected to be accompanied by side effects, exposure to light can be expected to have both positive and negative consequences.

In 1987 Stevens first posited a hypothesis that a light-melatonin-cancer link could explain higher cancer rates in industrialized countries.[10] Supporting epidemiology includes a decreased risk among the blind, and increased risk for night shift workers and people enduring frequent jet travel (and jet lag). Additionally, laboratory studies show us that cell cultures and animals respond to melatonin in an oncostatic manner; i.e., melatonin reduces tumor formation and growth. Similarly, human breast cancer tumors have been shown to respond directly to melatonin levels in the blood. In 2007 a branch of the United Nations, the International Agency for Research on Cancer, concluded that shift work, a proxy for circadian disruption (due in part to excessive exposure to light at night), is probably carcinogenic to humans.[11] Since then, the Danish government has awarded damages to 38 of 75 female shift workers in that country who developed breast cancer.

LED luminaires are currently being evaluated for replacing the current fluorescent lighting system aboard the International Space Station. A combination of white phosphor LEDs (CCT of 4800K) and separately controllable red-green-blue (RGB) LEDs in these luminaires can together be tuned to approximate daylight (at around 6500K). While CCT is used widely in lighting specifications, it does not appear to provide an adequate characterization of a light source's spectral content. The goal is to find optimal illuminances and spectral power distributions (SPDs) to support both vision and circadian regulation in astronauts aboard the station. The SPD for a 4800K LED light source is shown in relation to action spectra for melatonin suppression and the photopic lumen in Figure 7. Note that a prominent "spike" in the SPD roughly aligns with the peak sensitivity of the circadian system.

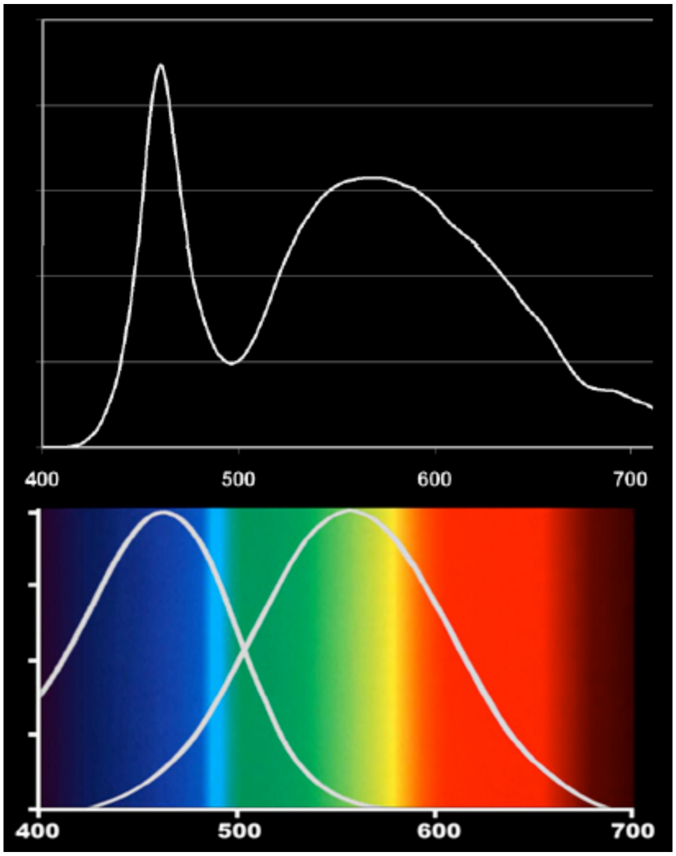

Figure 7. SPD for a 4800K light source (top) and action spectra for melatonin suppression (lower left) and photopic vision (lower right)[6]

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[10] Stevens RG, Blask DE, Brainard GC, et al. Meeting report: The role of environmental lighting and circadian disruption in cancer and other diseases. *Environ Health Perspect*. 2007 Sep;115(9):1357-62.

[11] World Health Organization, International Agency for Research on Cancer. IARC Monographs Programme finds cancer hazards associated with shiftwork, painting and firefighting. Press Release #180: 2007.

NASA lighting criteria for the Constellation Program have been generally based on IES recommendations but modified for the specific needs of astronauts and the constraints of space flight. For example, the "night lighting" criterion was initially 20 lux at crew members' eyes. In light of the published circadian and neuroendocrine data, this lighting criterion was revised as shown in Table 1. Note that restrictions are given for maximum illuminance incident at the eye, whether upright or prostrate.

Recall that in 1980, NIMH found that 2500 lux of white light suppressed melatonin and 500 lux did not.[7] Contrast this with Brainard's finding, where 1.3 lux of monochromatic light at 460 nm suppressed melatonin and 0.6 lux did not.[8,9] Another study, in 1986, found that 12,000 lux was needed to phase-shift the circadian rhythm, but again under monochromatic light and laboratory conditions this value would be reduced to 5 lux.[12,13] It is apparent that while laboratory findings often have limited relevance in practice, we cannot dismiss potential risks due to exposure to nighttime lighting solely on the basis of illuminance levels.

Table 1. Selected NASA requirements and restrictions for astronaut light exposure[14]

Task	Illumination (lux)	Measurement Location
Invasive wound care (cleaning/suturing)	≥ 500	At treatment surface (mucosa or skin)
Reading 6 point font (non self-illuminated text or graphics)		On the surface to be read
General Lighting	≥ 350	On most surfaces in vehicle common areas
Reading 12 point font (non self-illuminated text or graphics)		On the surface to be read
Handwriting/tabulating - ink on white paper	≥ 320	On the paper
Fine maintenance and repair work		On the affected component surface
Dining	≥ 250	On intended dining surfaces
Non-invasive wound care		On the wound
Exercise		On the exercise equipment
Video conferencing		On the face(s)
Gross Maintenance & housekeeping		On surfaces involved
Mechanical assembly		On the components involved
Emergency equipment shutdown	≥ 30	On controls
Night lighting	≤ 1	At crewmember eyes
Emergency egress	≥ 10	On protruding surfaces
Crew sleep in dedicated sleep quarters	≤ 0.02	At crewmember eyes

The IES, the International Commission on Illumination (CIE), and the German Institute for Standardization (DIN) have all produced documents recently offering preliminary guidance on this subject. Brainard contributed to CIE 158:2004, and both Figueiro and Brainard contributed to IES TM-18-08.

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[12] Czeisler CA, Allan JS, Strogatz SH, et al. Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. *Science*. 1986 Aug 8;233(4764):667-71.

[13] Lockley SW, Brainard GC, Czeisler CA. High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light. *J Clin Endocrinol Metab*. 2003 Sep;88(9):4502-5.

[14] NASA Constellation Program Human-Systems Integration Requirements, CxP 70024 Rev D, 2009-12-11.

Brainard closed with a handful of general recommendations. He said that lighting specifications should be based on relevant empirical data. These design criteria also should be sensitive to environmental concerns and optimized for both the visual and biological needs of humans. He stated that daytime exposures should generally be increased and enriched with short-wavelength visible radiation. He also stressed that nighttime levels should generally be reduced and that light sources should be optimized for high efficacy and minimal short-wavelength content.

> A number of fundamental questions must be answered before conclusions about the beneficial or detrimental impact of light on human health and well-being can be responsibly drawn.

QUANTIFYING NIGHTTIME LIGHT EXPOSURES

Figueiro's research at the LRC has focused on modeling the phototransduction mechanisms of the circadian system and has emphasized the importance of light measurements for determining the impact of light on health and well-being. Ultimately, the research at the LRC attempts to reconcile laboratory findings with practical application. Figueiro emphasizes that a number of fundamental questions must be answered before conclusions about the beneficial or detrimental impact of light on human health and well-being can be responsibly drawn. How much light are your eyes actually exposed to over the course of the day, and how does this differ from the exposure experienced by a rotating-shift nurse? What constitutes significant circadian disruption for humans, and how much of this is due to light? How do we interpret cancer research on laboratory animals to improve our understanding of health risks to humans?

It's likely that the overall light/dark pattern is of importance, and sensitivity to typical nighttime exposures may well be overshadowed by the inadequacy of typical daytime exposures. But light/dark patterns and exposures for humans are at present poorly understood, and little naturalistic or ecological field data are available. We also lack formal links between human light/dark patterns and those of laboratory animals. Given that experimental restrictions are stricter for humans, we must look to animal models for much of our understanding of the impact of light in diseases. Ultimately, we need to understand how to adjust exposures for laboratory animals such that they are equivalent to exposures for humans, determine the thresholds at which negative health effects are observed, and then translate it all back to humans to establish restrictions for maximum nighttime exposure and requirements for minimum daytime exposure.

In 2005, Figueiro's team published a model of human circadian phototransduction.[15] The algorithm considers both the neuroanatomy and physiology of the visual and circadian systems, and includes inputs from rods, cones, and the recently discovered ipRGCs. The model also takes into account spectral opponency, which is formed at the level of the bipolar cells in the retina.[16] This paper effectively worked

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[15] Rea MS, Figueiro MG, Bullough JD, Bierman A. A model of phototransduction by the human circadian system. *Brain Res Brain Res Rev*. 2005 Dec 15;50(2):213-28.

[16] Figueiro MG, Bierman A, Rea MS. Retinal mechanisms determine the subadditive response to polychromatic light by the human circadian system. *Neurosci Lett*. 2008 Jun 20;438(2):242-5.

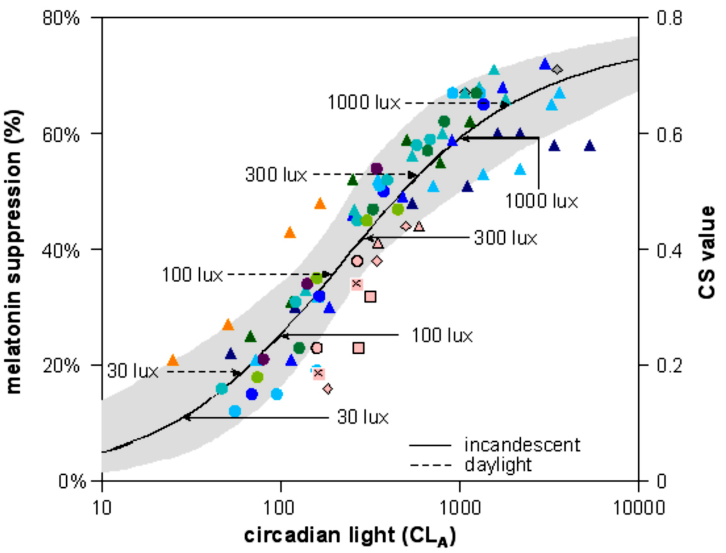

Figure 8. Circadian light transfer function[18]

upstream of the action spectra published by Brainard (2001) and Thapan[17] for melatonin suppression, hypothesizing the mechanism by which the signals controlling melatonin production are generated. The model is also based on melatonin suppression data for polychromatic light sources from a series of published studies. The model is, however, based on a set of experimental conditions (one-hour light exposure at the earlier part of the night, when melatonin levels are rising, and fixed pupil size; it does not account for photic history and regeneration process of the ipRGC), and different experimental conditions may lead to different predictions. Moreover, acute melatonin suppression and phase shifting have been shown to be related when using polychromatic “white” light sources, but a functional relationship between these two outcome measures is yet to be developed using narrow-band light sources. This model was supplemented with a circadian light transfer function, which is shown in Figure 8 plotted against the wide variety of melatonin suppression data gathered from available studies on the impact of light on acute melatonin suppression at the time of the publication.

Table 2. Illuminance and input watts for predicted 50% melatonin suppression, assuming a one-hour exposure during the early part of the night and a pupil diameter of 2.3 mm.

Light source	Illuminance (lx)
Daylight (CIE D65)	270
2856 K incandescent A-lamp	511
2700 K CFL (Greenlite 15WELS-M)	722
3350 K linear fluorescent (GE F32T8 SP35)	501
4100 K linear fluorescent (GE F32T8 SP41)	708
5200 K LED phosphor white (Luxeon Star)	515
8000 K Lumilux Skywhite fluorescent (OSI)	266
Blue LED (Luxeon Rebel, λ_{peak} = 470 nm)	30

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[17] Thapan K, Arendt J, Skene DJ. An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans. *J Physiol*. 2001 Aug 15;535(Pt 1):261-7.

[18] Adapted from Figueiro MG, Rea MS, Bullough JD. Does architectural lighting contribute to breast cancer? *J Carcinog*. 2006 Aug 10;5:20.

This function allows for comparison of various light sources having different SPDs for a range of light levels, as illustrated in Table 2. Note the comparable effect of different source types at 2856K (incandescent), 3350K (fluorescent), and 5200K (LED), assuming specific experimental conditions.

A subsequent study by Figueiro's team involved monitoring light/dark patterns and activity/rest patterns over the course of seven days for day-shift and rotating-shift nurses from the Nurses Health Study, a cohort established at the Harvard School of Public Health.[19] This study was funded by the Centers for Disease Control and Prevention (CDC) and the National Institutes of Health (NIH). Nurses wore a specially designed instrument called the Daysimeter, mounted at eye level, to separately measure photopic illuminance and energy in the short-wavelength portion of the visible spectrum.[20] This device also monitored activity. Post-processing of recorded measurements allowed for estimation of "circadian light." Activity levels were correlated with light/dark patterns to generate the circadian entrainment diagrams in Figure 9.[21]

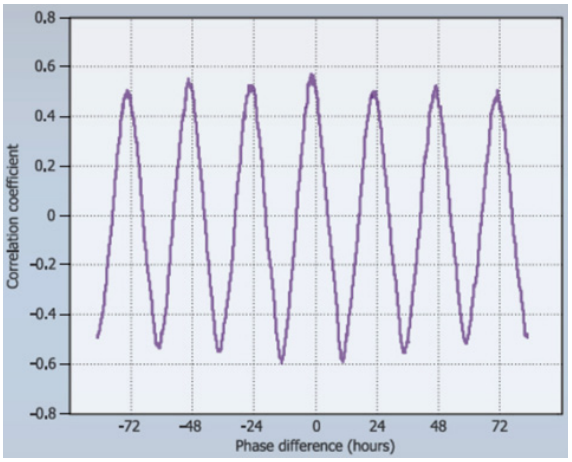

Figure 9a. Circadian entrainment of day-shift nurses

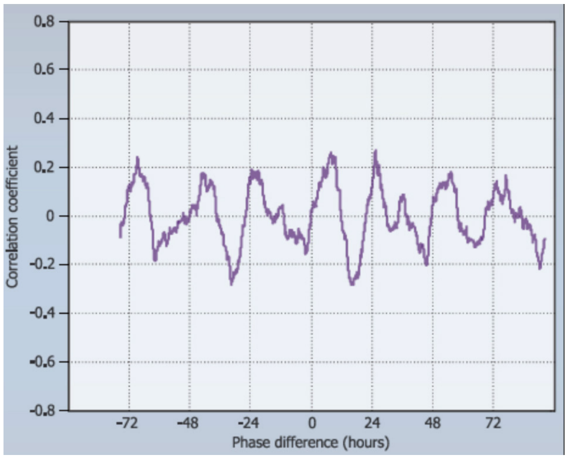

Figure 9b. Circadian entrainment of rotating-shift nurses

Circadian disruption has been associated with a series of maladies in animal studies, including increased risk for cancer, diabetes and obesity, and cardiovascular disease. Assuming circadian disruption is a result of lack of synchrony between light/dark and activity/rest patterns, a "healthy" light/dark pattern generally features regular and extended periods of inactivity (sleep) coinciding with darkness. As shown in Figure 9b, the rotating-shift nurses are poorly entrained, meaning their activity/rest patterns are poorly aligned with light/dark patterns, much as would be expected of a frequent flyer experiencing chronic jet lag. This may well be a source of some of the health issues associated with shift work and circadian disruption.

Another LRC project, sponsored by the National Electric Manufacturers Association (NEMA) and currently underway, follows a study published in Israel, which showed increased breast cancer rates in areas

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[19] Miller et al., in press

[20] Bierman A, Klein TR, Rea MS. The Daysimeter: a device for measuring optical radiation as a stimulus for the human circadian system. *Meas Sci Technol*. 2005;16:2292-9.

[21] Rea MS, Bierman A, Figueiro MG, Bullough JD. A new approach to understanding the impact of circadian disruption on human health. *J Circadian Rhythms*. 2008 May 29;6:7.

having more sky glow.[22] The Daysimeter is being used to compare exposure in teachers working a regular day shift and living in urban and rural areas in upstate New York, selected on the basis of sky brightness.[23] Activity levels, light/dark patterns, and circadian light levels are being evaluated to determine the actual indoor and outdoor light exposures experienced. Daysimeter units are being placed outside bedroom windows to measure how much street light reaches residential windows, and the same type of device is also being placed next to the participants' bedside tables to determine how much street light reaches their bedrooms. There are clearly other risk factors in urban environments, and this field study will provide a quantitative measure of nighttime light exposures experienced by people in their homes.

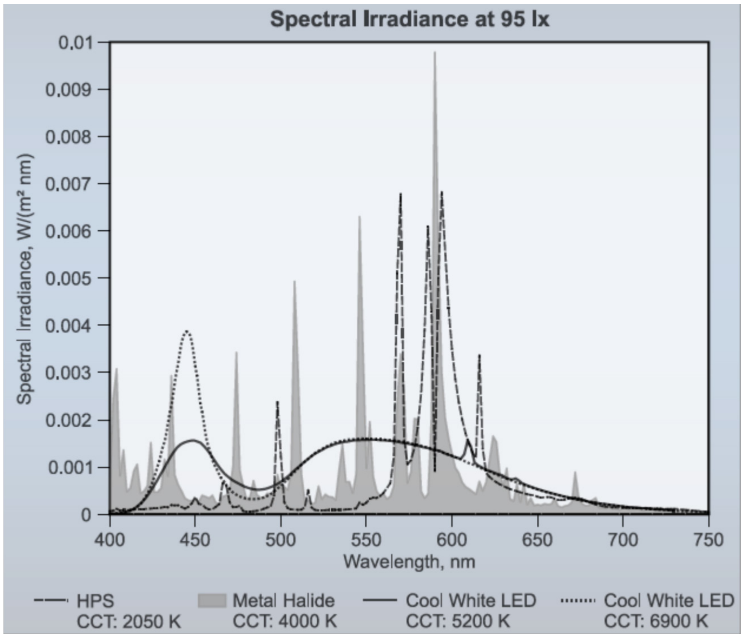

Figure 10. SPDs for different light sources, normalized for equal photopic light levels

Figueiro's team recently completed an analysis for their Alliance for Solid-State Illumination Systems and Technologies (ASSIST) program, in which calculations were performed to estimate melatonin suppression for nighttime light exposures for pedestrians in typical outdoor environments.[24] Four luminaires using three light source types applied in three scenarios were evaluated to provide a range of values in a typical street lighting application with pole height of 27 feet and 150W nominal luminaires. SPDs for each luminaire are illustrated in Figure 10, normalized for equal photopic illuminance to provide a meaningful representation of the relative amplitude of peaks in each spectrum.

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[22] Kloog I, Haim A, Stevens RG, Portnov BA. Global co-distribution of light at night (LAN) and cancers of prostate, colon, and lung in men. *Chronobiol Int*. 2009 Jan;26(1):108-25.

[23] Cinzano P, Falchi F, Elvidge CD. The first world atlas of the artificial night sky brightness. *Mon. Not. R. Astron. Soc*. 2001;328:689-707.

[24] Rea MS, Smith A, Bierman A, Figueiro MG. The potential of outdoor lighting for stimulating the human circadian system. Alliance for Solid-State Illumination Systems and Technologies, 2010.

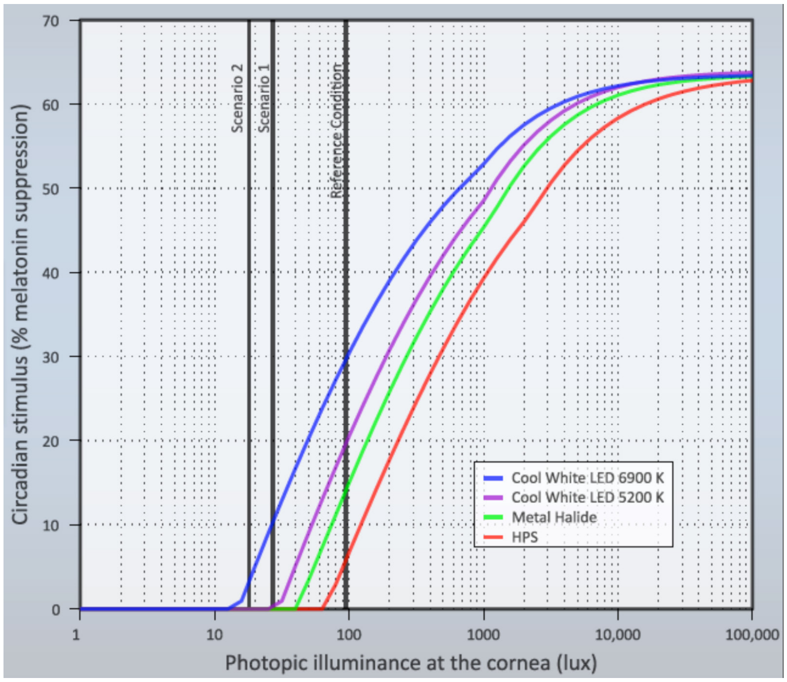

Figure 11. Predicted melatonin suppression after one hour of exposure with freely reactive pupils

One scenario was considered a "reference condition," with a pedestrian located five feet from the pole and looking directly at the luminaire. The other two scenarios were for eyes directed horizontally toward the pole, with a pedestrian either 10 or 30 feet from the pole. Results of predicted melatonin suppression are illustrated in Figure 11.

In the "reference condition" scenario, all four sources would be predicted to suppress melatonin, ranging from five percent suppression for HPS to 30 percent for the 6900K LED. Note that the reference condition, with 95 lux of exposure at the cornea for a duration of one hour, would be more representative of a laboratory environment than typical exposures outdoors. Scenario 1, producing 27 lux at the cornea for a duration of one hour, is somewhat more realistic, and no melatonin suppression would be expected for the HPS, metal halide (MH), and 5200K LED sources. The 6900K LED would be expected to suppress melatonin by 10 percent in Scenario 1, and this value would be expected to drop to three percent for Scenario 2, where corneal illuminance is held at 17 lux for one full hour.

These preliminary estimates provide a sense of the predicted magnitude of the effect of typical exposures to exterior lighting systems on acute melatonin suppression. It is important to note, however, that different exposure durations and pupil areas will result in different predictions. Moreover, the impacts of photic history and melanopsin regeneration are not being considered in these calculations. Additional research is needed before potential risks associated with light exposures at night can be managed or dismissed. We must first establish and validate a metric to adequately characterize and quantify nighttime light exposures as a stimulus, and items such as daytime exposure (photic history) may play a major role.

DISCUSSION

The first question fielded during the Q&A session regarded spectral dependence of scatter, specifically as it pertains to fog. Gibbons indicated that scatter in fog is actually wavelength-independent, much like white clouds. A broad-spectrum source like MH or LED, compared to a yellowish source like HPS, will appear (visually) to create more scatter, but measurements show no difference. This is analogous to the brighter appearance of pavement illuminated by broad-spectrum sources, relative to pavement illuminated to the same photopic light levels by HPS or LPS. In terms of visibility in fog, spectrum doesn't appear to be an issue.

The second question was whether any studies have compared groups exposed to differing levels of daytime illumination, to determine the effect on sensitivity to exposures to light during the night. Brainard indicated that adaptation can indeed confound interpretation of experimental results for nighttime exposures. His group, for example, showed that as little as 18 lux of incandescent light exposures at night does not suppress melatonin directly, but does "reset" the sensitivity of the melatonin-generating system.[25] He then deferred to Figueiro, since her group and other laboratories also have been investigating these issues. Figueiro said this daytime adaptation is a part of photic history and indicated that we may ultimately determine that the real problem is not excessive exposure to light at night, but rather inadequate exposure to light during the day. The full 24-hour light/dark pattern should be evaluated. Preliminary findings by her group indicate that daytime exposure does appear to affect alertness at night, but further research is clearly needed.

The third question regarded recommended CCT for LED outdoor lighting. Gibbons offered no recommendation but indicated that, at least based on the three installations he studied, CCT preference could actually be somewhat regionally based. Anchorage settled on 6000K, possibly due to the presence of snow. Moving southward you first reach Los Angeles, which chose 4100K, approximately the color of moonlight. Still further south, in San Diego, warmer-appearing 3000K was selected, primarily due to familiarity with LPS that had been used for years to the benefit of the Palomar Observatory. Gibbons reiterated that CCT is by itself inadequate for the characterization of a source's spectral content.

> Given the available research, it is unclear what changes, if any, should be made to current best-practice lighting design.

The fourth question was whether Brainard would dispute the findings of the LRC, specifically pertaining to health risks and sleep disruption from exposure to low light levels. Brainard indicated that it is best to work from direct empirical measurements, and when these data are unavailable, a robust data-driven model is the next best thing. The data, however, must be relevant and appropriately interpreted. Brainard noted that, for example, co-modulation between rods, cones, and ipRGCs cannot be ignored, but in these

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[25] Jasser SA, Hanifin JP, Rollag MD, Brainard GC. Dim light adaptation attenuates acute melatonin suppression in humans. *J Biol Rhythms*. 2006 Oct;21(5):394-404.

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early days of research, different groups have reported differing interactions including opponency, additivity, synergism, and time-dependent effects.[26] Results of studies on rodents by Johns Hopkins University showed such co-modulation, and these results were incorporated into the models by Figueiro and others at the LRC. Figueiro added that melatonin suppression is usually preceded by the term "acute" in her group's publications, because acute melatonin suppression still hasn't been clearly linked to health effects. This is partly due to the greater difficulty of data collection for phase shifting versus melatonin suppression. Figueiro reiterated that data should take precedence over personal interpretations, and that more research is clearly needed. In fact, the ASSIST publication clearly states that it is not known whether acute melatonin suppression is indeed related to health and well-being. Brainard concluded by reminding the audience that melatonin is just one indicator, so a lack of suppression does not necessarily mean there are no negative health impacts.

The fifth question concerned the relative importance of indoor and outdoor nighttime light exposures. Figueiro reiterated that whereas typical indoor light levels are probably too low during the day, these same levels are probably too high at night in many cases. She noted that a recently completed study by the LRC showed that the switch to daylight saving time, extending daylight later into the evening, resulted in a measurable delay in dim light melatonin onset.[27] She also reiterated that if you are exposed to inadequate light levels during the day, you might then be more sensitive to light exposures at night, and noted that evidence for this was found in the same study. The circadian system appears to want clear input signals—contrast between day and night. Brainard agreed that the full 24-hour cycle must be evaluated.

The sixth question regarded the status of the draft Model Lighting Ordinance (MLO), a collaborative effort of the IES and the International Dark-Sky Association. The second draft of the MLO has been through public review and is in the process of being developed for release. Gibbons estimated that the guide would be finalized before the end of the year, and noted that the MLO must be implemented by a given municipality before it can be enforced.

The seventh question regarded the significance of red light, such as that produced by sunsets and fire, in terms of timing of exposure and onset of sleep. Brainard indicated that although long-wavelength light (orange- and red-appearing light) is relatively weak, if the irradiance is sufficiently high, these wavelengths can stimulate circadian, neuroendocrine, and neurobehavioral responses.[28] Outdoor irradiances of skylight around sunset are quite likely to influence the human circadian system. In contrast, the light from an oil lantern or a few candles indoors would probably be inert in terms of photoneural responses, while still supporting visual activities that don't require higher acuity or color discrimination during evening hours.

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[26] Gooley JJ, Rajaratnam SM, Brainard GC, Kronauer RE, Czeisler CA, Lockley SW. Spectral responses of the human circadian system depend on the irradiance and duration of exposure to light. *Sci Transl Med*. 2010 May 12;2(31):31ra33.

[27] Figueiro MG, Rea MS. Evening daylight may cause adolescents to sleep less in spring than in winter. *Chronobiol Int*. 2010 Jul;27(6):1242-58.

[28] Hanifin JP, Stewart KT, Smith P, Tanner R, Rollag M, Brainard GC. High-intensity red light suppresses melatonin. *Chronobiol Int*. 2006;23(1-2):251-68.

CONCLUSIONS

Given the available research, it is unclear what changes, if any, should be made to current best-practice lighting design. So what do we know, and what remains murky? It is clear that additional peer-reviewed research and validation are required to determine the relative significance of the visual and the photoneural effects of typical light exposures on circadian, neuroendocrine, and neurobehavioral regulation. It is also apparent that additional guidance is needed from the IES to inform the quantitative selection of appropriate spectra for particular visual tasks and environments. Nighttime lighting systems are most likely to be safe and efficient if these consensus recommendations are followed, and LEDs remain a viable option for a growing number of applications. Basic panel recommendations, following from the presentations and discussion, are outlined in the following tables. Note that these tables are arranged in logical sequence; e.g., items in Table 4 may be contingent on progress for items in Table 3.

Table 3. Needed research

Area	Task	Comments
Human vision	Characterize mesopic effects	Probably no single action spectrum
	Characterize color contrast	Significance vs. luminous contrast?
Human health	Bridge the research gap between humans and laboratory animals	Biology varies between species
	Gather more naturalistic/ecological data for full 24-hour cycles	What constitutes a “typical” exposure and a “typical” response?
	Better characterize the relationship between variables	E.g., timing, duration, spectrum, intensity, photic history
Basic biological studies	Detail of report must be adequate for translation and applicability to humans	Elaborate on lighting equipment and measurement methods used
Wildlife impacts	Detail of report must be adequate for use by lighting researchers	A daunting task, given the great diversity of species
Sky glow	Develop a complete algorithm proven to accurately calculate scatter as a function of light intensity, angle, wavelength, local atmospheric conditions, etc.	Would ideally consider both direct and reflected uplight (to credit reduced average illuminance and to account for spectral reflectance)

Table 4. Needed guidance from IES

Area	Task	Comments
Minimum day-time exposure for humans	Develop a metric to characterize adequate exposure	
	Consider increasing recommended light levels where appropriate	Likely accomplished using daylighting, not electric
	Consider increasing short-wavelength content where appropriate	
Maximum night-time exposure for humans	Develop a metric to characterize excessive exposure	Likely a function of "typical" daytime exposure, etc.
	Consider reducing recommended light levels where appropriate	
	Consider reducing short-wavelength content where appropriate	This must be weighed against compromises to luminous efficacy
Circadian lumens	Adopt an action spectrum (or set of action spectra) for circadian sensitivity	
Mesopic lumens	Adopt an action spectrum (or set of action spectra) for mesopic sensitivity	
Color contrast	Consider establishing recommended minimum color rendering/quality criteria for outdoor applications	To supplement other criteria driven by luminance contrast
Ecological conservation	Develop criteria for protection of those species that have been adequately characterized and shown to be at risk	Age can be a factor, so may for example only apply to hatchlings Criteria should only be applied where the particular species is present
Sky glow	Incorporate an unambiguous algorithm for estimation of relative sky glow (see Table 3)	IES TM-10 would be the likely medium The latest draft MLO doesn't characterize atmospheric scatter

Table 5. Needed changes to lighting practice

Area	Task	Comments
Specifications	Design based on relevant empirical data	Well-intentioned interpretations may not produce the desired results
	Design for visual and biological needs of humans	CCT does not appear to adequately characterize the SPD of a light source
	Design with sensitivity to environmental concerns	Produce no more or less light than is needed
	Consider incorporating controls to reduce levels during periods of low activity	

International Dark-Sky Association

Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting

May 4, 2010

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Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting

International Dark-Sky Association

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Abstract

Outdoor lighting is undergoing a substantial change toward increased use of white lighting sources, accelerated most recently by developments in solid-state lighting. Though the perceived advantages of this shift (better color rendition, increased “visual effectiveness” and efficiency, decreased overall costs, better market acceptance) are commonly touted, there has been little discussion of documented or potential environmental impacts arising from the change in spectral energy distribution of such light sources as compared to the high-pressure sodium technology currently used for most area lighting. This paper summarizes atmospheric, visual, health, and environmental research into spectral effects of lighting at night. The physics describing the interaction of light with the atmosphere is long-established science and shows that the increased blue light emission from white lighting sources will increase visible sky glow and detrimental effects on astronomical research through increased scotopic sensitivity and scattering. Though other fields of study are less mature, there is nonetheless strong evidence for additional potential negative impacts. Vision science, much of it the same research being used to promote the switch to white light sources, shows that such lighting also increases the likelihood of glare and interferes with the ability of the eye to adapt to low light levels a particular concern for older people. Most of the research evidence concerning adverse effects of lighting on human health concerns circadian rhythm disruptions and breast cancer. The blue portion of the spectrum is known to interfere most strongly with the human endocrine system mediated by photoperiod, leading to reduction in the production of melatonin, a hormone shown to suppress breast cancer growth and development. A direct connection has not yet been made to outdoor lighting, nor particularly to incidental exposure (such as through bedroom windows) or the blue component of outdoor lighting, but the potential link is clearly delineated. Concerning effects on other living species, little research has examined spectral issues; yet where spectral issues have been examined, the blue component is more commonly indicated to have particular impacts than other colors (e.g., on sea turtles and insects). Much more research is needed before firm conclusions can be drawn in many areas, but the evidence is strong enough to suggest a cautious approach and further research before a widespread change to white lighting gets underway.

Introduction

A recent trend in outdoor lighting has been the shift toward widespread use of white light sources. While there has been a series of different and sometimes opposing trends in outdoor lighting, this one is driven by a synergy of aesthetics, improvements in lamp efficiency, reduced operating costs, and emerging developments in visibility science. It is, however, important to recognize that all white light sources are not the same: some radiate much more energy than others in the blue portions of the spectrum. Concurrent with the developments in human vision research, there is growing evidence for adverse impacts associated with wavelengths shorter than about 500 nm. While the bulk of research demonstrating the visibility advantages of white light has been generated within the lighting profession, a body of research literature showing some distinct adverse consequences is accumulating in other disciplines. This paper presents a brief synopsis of current science from the fields of epidemiology, astronomy, land conservation, and biology, as well as vision and lighting.

The spectral output of white light sources stands in contrast to the most common high-intensity discharge (HID) source used for area and roadway lighting for the last several decades, high-pressure sodium (HPS). Thus these sources represent a substantial change in outdoor lighting practice because they produce a larger amount of radiation in the bluer portions of the spectrum than HPS. Most HPS emission falls between 550 nm and 650 nm; the ratio of radiant output shorter than 500 nm to the total output in the visible spectrum (here defined as 400 nm to 650 nm) is 7%; for fluorescent (including induction fluorescent) and metal halide (MH) sources the ratio is about 20% to 30%; and for white LED sources this ratio is in the range of 20% to 50% (see Figure 1). LED manufacturers have indicated that the ratio is expected to be less as LED technology develops and, indeed, some manufacturers have already announced "reduced-blue" LED products for outdoor lighting. But if more white light, regardless of light source type, is used for outdoor lighting, the amount of blue-rich light emitted into the environment will also rise substantially.

Correlated Color Temperature (CCT) is commonly used to describe the perceived color of white light sources, but it is an inadequate metric to describe how much energy is emitted in the blue portion of the spectrum. For example, MH and LED sources of equal CCT can have significantly different amounts of emission below 500 nm. Furthermore, lamp spectra that can have sharp emission peaks, such as MH and LEDs, have the potential to concentrate their energy in a spectral region that is environmentally sensitive, causing a disproportionate impact. Thus, a discussion of the broader impacts of outdoor lighting must be attuned to the spectral power distribution of lamps and the spectral responses of biological systems.

Solid-state LED lighting deserves careful examination due to the commonly higher proportion of energy emitted below 500 nm, the strong emission spike at 450–460 nm, and the emphasis on blue-rich "cool white" LEDs in the marketplace. LED have many potential advantages, including both improvements to human utility and reduced energy use. The technology is not inherently dangerous. But the information described below indicates the complexity of the issue and care that should be exercised when applying blue-rich white light sources outdoors.

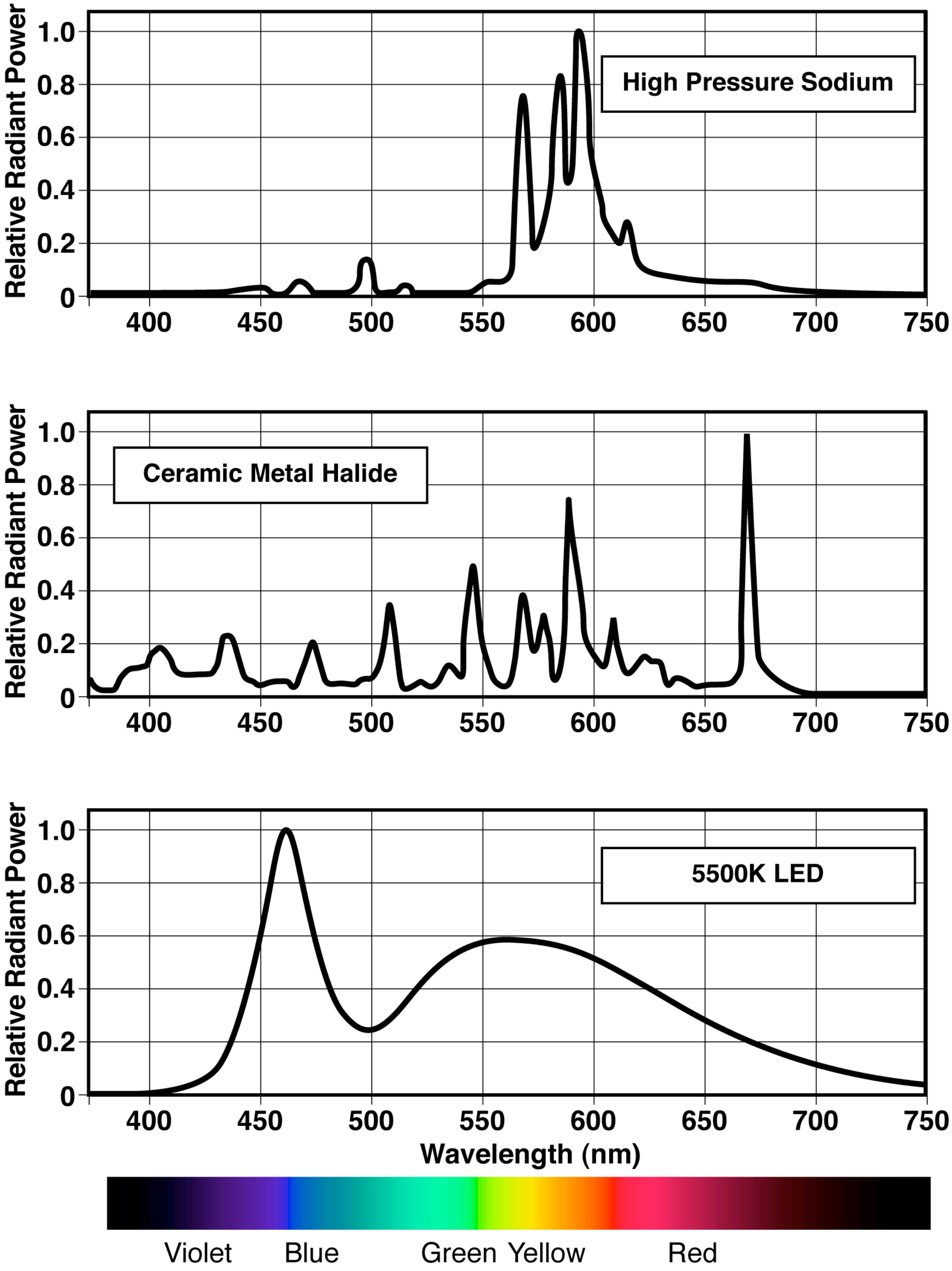

Figure 1. Typical spectral power distributions of HPS (orange); ceramic metal halide (cyan); white LED (blue).

This report presents a brief description of the physical processes related to the propagation of light through the atmosphere for background, then a discussion of the ramifications for human visibility and lighting, followed by a brief synopsis of human health effects, environmental effects, and finally, astronomical and scenic considerations.

Terminology

In the discussion that follows, the term "blue-rich light" will often be used to refer to all types of white light. The term is used in contrast to yellow-rich sources (principally HPS) and includes sources with varying proportions of blue light, generally defined as light with wavelengths shorter than 500nm. The term is not meant to imply that the light would actually appear blue, though some of the sources discussed do have a blue hue. Examples of such blue-rich light sources include fluorescent, white LED (all CCT), induction, and metal halide.

Physical Processes

The basic physics describing the interaction of light with molecules and aerosols was described in the 19th and early 20th centuries. Scattering by molecules was described first by John William Strutt, Baron Rayleigh (Strutt, 1871) and has since been referred to as Rayleigh scattering. Rayleigh scattering has a very strong dependence on wavelength with the molecule cross-section σ_R, and thus the resultant scattering, proportional to the inverse fourth power of the wavelength:

$$(1) \qquad \sigma_R \propto \lambda^{-4}.$$

In everyday experience, the consequence of this increased scattering for shorter wavelengths is revealed in the blue color of the clear daytime sky. The consequence for artificial light sources with high blue-light emissions is greater scattering by molecules compared to scattering by longer-wavelength sources. Garstang (1986, 1989) used the following values to represent the scattering cross-section per molecule of broad regions of the spectrum representing the astronomical V and B bandpasses centered at 550 nm and 440 nm:

$$\sigma_R(550nm) = 4.6e10^{-27}\,cm^2$$
$$\sigma_R(440nm) = 1.136e10^{-26}\,cm^2.$$

The ratio between these two cross-sections (11.36/4.6 ≈ 2.5) shows that light at 440 nm scatters from molecules 2.5 times as much as light at 550 nm. As most light sources emit a range of wavelengths, the amount of Rayleigh scattering experienced by light from a given source is determined by weighting the spectral power distribution of the source using relation (1). The effective relative scattering of different light sources, called the Rayleigh Scattering Index, RSI (Knox and Keith, 2003), can be determined. These values for a selection of lamp spectra, divided by the RSI for HPS, are shown in Figure 2.

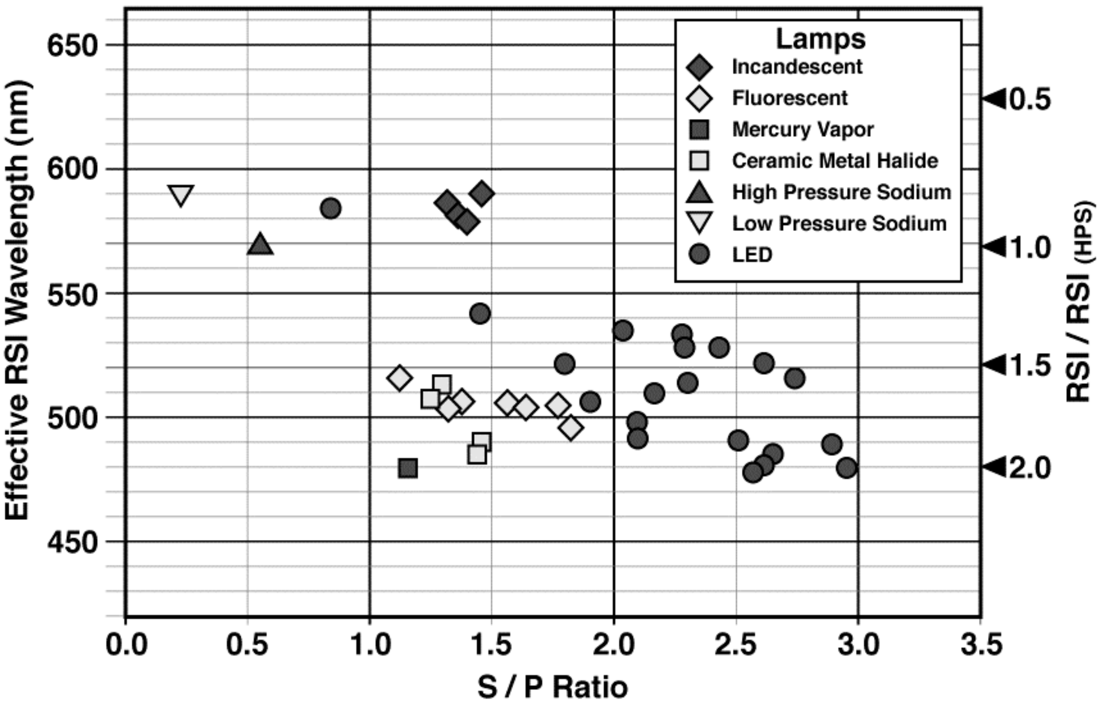

Figure 2. Rayleigh Scattering Index relative to HPS, and effective RSI wavelength for a selection of lamp types vs. their scotopic/photopic ratios S/P.

These results show that the light from white LEDs scatters from molecules 1.2 to 2 times as much as light emitted by an HPS lamp, light from fluorescents is scattered about 1.5 to 1.7 times as much, and that from a sample of ceramic metal halide from 1.5 to 1.8 times as much.

The atmosphere is not composed entirely of gaseous molecules: chiefly in the lower atmosphere, aerosols or particulate matter are an important component. The theory describing the interaction of light with aerosols was developed by Mie and others (see Mie, 1908). Though the theory is complex and depends upon particle size and composition, for the particles of most importance in the lower atmosphere, aerosol scattering still exhibits a tendency for greater scattering by shorter wavelengths, with particle cross-section σ_a proportional to the inverse of the wavelength (Garstang, 1986):

$$\sigma_a \propto \lambda^{-1}.$$

In most situations the total scattering from aerosols is greater than that from molecules (Garstang, 1986), but the angular dependencies are different: aerosol scattering is very strongly weighted in the forward direction; that is, light scattered from particles is mostly only slightly deviated from its original direction. Scattering from gaseous molecules is more evenly distributed in all directions. The easily observed consequence of the angular dependence for aerosol scattering is that the blue daytime sky tends to become both brighter and whiter when observed closer to the sun. The consequence for sky glow caused by artificial lighting is that, despite greater overall scattering from aerosols in most situations, the increases in sky glow in the overhead sky tends to be dominated by Rayleigh scattering, with its much stronger dependence on wavelength.

In a real atmosphere including both molecules and aerosols, the strong dependence of Rayleigh scattering on wavelength is diluted though not removed. This means in hazier atmospheres, such as in polluted urban areas, the sky tends to be less blue and more white. Under such situations the impacts of the blue-rich light sources relative to yellow sources such as HPS are still greater, but diminished relative to the situation where the atmosphere has low aerosol content.

Finally, scattering of all types leads to an important consequence. When light travels through the atmosphere for large distances, more and more light is removed from any light beam, with the consequence of the above described wavelength dependencies being that bluer light is removed more than yellow or red light. This effect is stronger in hazier atmospheres. The everyday consequence of this effect is the red color of the sunset clouds or the sun near the horizon. For artificial lighting the consequence is that the impacts of the increased scattering suffered by blue light will be greatest when near the light sources, such as within or near cities, but diminish as distance from the sources increases (Luginbuhl et al., 2010). The close coupling of the increased scattering and absorption must be carefully interpreted. Though the impact of blue-rich light decreases with distance more rapidly than that of yellow-rich sources, this decreased impact arises from the scattering of short-wavelength light out of the light beam in the areas nearer to the cities. In other words, the decreased impact at greater distances is at the expense of increased impacts nearby. For clear atmospheres, less light is scattered overall, but the impacts are spread over a larger area; for hazier atmospheres more light is scattered, so the overall impacts to sky glow are larger and more strongly concentrated near the light sources.

Human Vision

Several studies have concluded that blue-rich light is advantageous to human vision in some circumstances. Though his study dealt with bright indoor lighting, Berman (1992) pointed out that “photopic illuminance alone does not adequately characterize the visual system spectral response,” and that there are other potentially pertinent attributes of spectral response undescribed by the CIE photopic curve. As ambient lighting levels decrease and the human eye becomes adapted to lower illumination levels, visual performance becomes more complex. Human vision outdoors at night in the presence of artificial lighting involves both the rod cells and cone cells in the retina, and a complex, task-dependent blending of the scotopic (rod) and photopic (cone) responses. That rods are more sensitive to blue wavelengths has given rise to the idea that blue light is more visually effective at lower luminances, and that artificial outdoor light should increase utilization of blue-rich lamps.

The dynamics of the change in visual spectral response (the Purkinje shift) at mesopic luminance levels (between the very low luminances used to define scotopic response and the higher luminances used to define photopic response) has been investigated by a series of researchers using foveal brightness matching (e.g., Ikeda and Shimozono, 1981; Sagawa and Takeichi, 1986; Trezona, 1991) and others using reaction time for stimuli in the foveal, parafoveal, and peripheral fields (e.g., He et al., 1998; Lewis, 1999). Such literature has served as a basis for proposed mesopic response functions where rods and cones both contribute to vision. However, uncertainty remains about how critical visual characteristics in the mesopic range can be translated into real-world lighting practices.

In particular, different visual performance measures produce different mesopic curves. Measures of peripheral target reaction time indicate the Purkinje shift begins as high as 1.0 cd/m^2, while the brightness matching metric points to a 10x lower adaptation level, or about 0.1 cd/m^2, with a couple of studies as low as 0.01 cd/m2 (Rea et al., 2004). Other studies have modeled the mesopic function through chromatic pathways, with the S-cones playing a key role rather than the rods (Walkey et al., 2006). Because typical target outdoor lighting levels overlap only the brighter portion of the mesopic range, the exact behavior and onset of the eye's spectral sensitivity is a critical question. Depending on which studies and performance metrics are emphasized, the relevance to outdoor lighting design can be either quite significant, or hardly more than an academic point.

Remaining uncertainties concerning which visual stimuli are critical, the shape of the mesopic spectral response, what visual performance metrics are most appropriate to design for, the feedback between scotopic and photopic responses, the weighting of foveal, parafoveal and peripheral stimuli, and how all of these are related to adaptation luminance level over time make this an interesting field of study that may or may not result in a successful unified photometric system. Clearly, there is more to low luminance visual performance than solely scotopic response, and there is no unique mesopic response.

Despite the complexity and uncertainty of vision at mesopic light levels, and despite the official position of the Illuminating Engineering Society of North America (IESNA, see below), some commentators and manufacturers are nonetheless recommending the application of or actually applying correction factors to the luminous output of blue-rich lighting products (see, e.g., Lewin, 1999; U.S. Dept. of Defense, 2006; Berman and Josefowicz, 2009). While the correction factors are often presented tentatively, many are interpreting the suggestions more concretely than the authors may have intended: web searches on the terms “lumen effectiveness multipliers” and “pupil lumens” yield thousands of references, many on manufacturers' websites. The application of such corrections has achieved official recognition in Britain (see, for example, BS 5489-2:2003 “Code of practice for the design of road lighting”). In the case of blue-rich light, such weighting functions increase the apparent efficacy of the associated lighting and fundamentally alter the economics of those systems.

On November 15, 2009, the IESNA issued a Position Statement pointing out that all IESNA recommendations are to be used with the photopic luminous efficiency function as defined in the IESNA Lighting Handbook unless there are specific exceptions stated in IESNA documents (IESNA, 2009). The use of spectral weighting functions such as those used to determine S/P ratios, “pupil lumens,” or “lumen effectiveness multipliers” (Lewin, 2001) are not approved.

On April 1, 2009, the Commission Internationale de l’Eclairage (CIE) released the Visual Performance in the Mesopic Range Technical Committee report detailing a recommended system for mesopic photometry (CIE 2009). Their conclusions are that a log-linear transition between photopic and scotopic modes, blending the eye’s luminance and chromatic systems, and choosing an upper threshold between the USP system proposed by Rea et al. (2004) and the MOVE system proposed by Goodman et al. (2007) gave satisfactory agreement with laboratory experiments. CIE’s resultant mesopic luminance adjustments are not as dramatic as Lumen Effective Multipliers for blue-rich light. While this proposed mesopic photometric system draws from a large number of studies to develop a practical system for lighting engineering, it does not address the following issues that complicate or confound the advantages of blue-rich light at mesopic levels.

Pupillary Response

Several studies have shown that pupil size is more strongly correlated to blue light intensity (e.g., Barbur et al., 1992) than to photopic luminance, with the effect becoming more prominent at lower luminance levels. Blue-rich light causes incrementally smaller pupil sizes than yellower light. Although it is sometimes assumed to be mediated by rod cell (scotopic) response, research indicates that pupil size may be dependent on blue-sensitive S-cones (Kimura and Young, 1999), a combination of rod and cone cell response with peak sensitivity at 490 nm (Bouma, 1962), or a L-cone minus M-cone mechanism (Tsujimura et al., 2001).

At lower luminances, a smaller pupil size and the resultant lower retinal illumination may reduce visual performance for tasks more closely related to foveal vision or photopic luminance. Pupil size is an important covariable that should be examined using a range of performance tasks, not just reaction time, and the ramifications of a lower retinal illumination on foveal vision tasks have not been adequately addressed.

Adaptation

The scotopic vision process has a much lower light-detection threshold than photopic vision (Blackwell, 1946; Rose, 1948). However, the scotopic and photopic systems are not independent visual channels that are additively combined. Scotopic activity appears to suppress color (photopic) function (Sugita et al., 1989), photopic activity will suppress low light scotopic function (Stockman and Sharpe, 2006), and scotopic sensitivity declines as the rods become saturated in the upper mesopic range (Stockman and Sharpe, 2006). The timing and duration of the eye’s adaptation between photopic and scotopic modes is also critically important (e.g. Stockman and Sharpe, 2006). In particular, exposure to blue light increases the adaptation time required for maximum scotopic sensitivity (Bartlett, 1965; Brown et al., 1969). This relationship of dark adaptation to lighting color is commonly utilized by military personnel and astronomers who use red lighting to preserve scotopic vision.

Thus, while scotopic response is most sensitive to blue light at low intensities, higher intensities of blue light, including intensities in the mesopic range, inhibit dark adaptation and appear to suppress scotopic response. The implications in a real world setting with glare sources, poor uniformities, harsh transitions, wide-ranging illumination levels and adaptation time scales are important to consider and remain poorly understood. The vision advantages of blue light shown in laboratory experimental settings with dark adapted subjects or in simplified roadway designs does not translate well for some applications.

Glare

Glare in illuminated outdoor settings is seldom quantified but plays an important role in the human vision process. It can produce either a feeling of discomfort, which may manifest in averting gaze, blinking, or squinting, or it may reduce visual performance directly—disability glare (e.g., De Boer, 1967). The earliest studies found that blue light causes more glare (de Boer and van Heemskerck Veeckens, 1955). Later studies have confirmed this and show the S-cone response (peak 420 nm) to be more closely correlated with discomfort glare than the rod (peak 505 nm) (Bullough et al., 2003; Kooi and Alferdinck, 2004).

Blue light in the 350–430 nm range has also been shown to cause the lens of the eye to fluoresce (Zuclich et al., 2005), resulting in intraocular veiling luminance. Complaints about glaring “blue headlights” on automobiles indicate that the blue-rich headlamps are perceived as more glaring than conventional halogen headlights (Mace et al., 2001). Flannagan et al. (1992) found that higher levels of light from halogen lamps produced no more discomfort than lower levels from blue-rich HID headlamps.

The Aging Eye

As the eye ages, it requires more light and greater contrast for the same visual acuity and becomes more sensitive to glare. Ocular transparency is reduced, particularly at bluer wavelengths, which combined with the age related reduction in pupil size yields lower retinal illuminance (Boyce, 2003). Older eyes also are more subject to diseases such as cataracts, macular degeneration, presbyopia, and glaucoma, though studies are inconclusive about whether there are spectral affects. However, since blue-rich sources produce relatively more discomfort glare and older people are more sensitive to glare, blue-rich outdoor lighting is presumed to impact the elderly more than other groups. Elderly people over 65 are a growing percentage of the population in the United States; their numbers increased by a factor of 11 during the 20th century and are expected to more than double from now to 2030 (U.S. Census Bureau, 2008).

Health Effects

The human circadian rhythm is mediated by non-visual photoreceptors in the retina, with a response function peaking near 460 nm in the blue portion of the spectrum (see Figure 3); exposure to light at night, particularly blue-rich light, suppresses the production of melatonin (Brainard et al., 2001). Melatonin is found in animals and humans, and even some plants. In humans this hormone mediates the sleep-wake cycle, and plays a role in the immune system. Light can be effectively used indoors to shape circadian rhythm, and can have several health and lifestyle benefits. While indoor light is generally under complete control of the occupant, outdoor lighting is less so. Dusk-to-dawn lighting such as roadway and area lighting or lighting on neighbors' property can penetrate into homes where people are sleeping. Some studies indicate that the illumination threshold for disruption is quite low. The role of stray artificial light at night has been the subject of special workshops by the National Institute of Environmental Health Sciences in 2006 (Stevens, 2007), and a resolution by the American Medical Association (2009). Surprisingly, the discovery of this circadian photosensory system is quite recent (Provencio et al. 2000), indicating that our understanding of the unintended effects of stray light at night, and in particular blue-rich lighting, lags the development and implementation of lighting technologies.

In a recent comprehensive review, Stevens (2009) summarizes over 100 publications on research into the effect of light at night (LAN) on the disruption of the human circadian rhythm, melatonin production, and breast cancer.. Many laboratory and epidemiological studies show that suppressed melatonin production can lead to increased incidence of or growth rates for breast cancer. Further, evidence indicates that people living in illuminated urban environments suffer increased breast cancer rates while suffering no more than average rates of lung cancer, which is not linked to melatonin levels. All potential compounding factors have not been ruled out, and crucial research concerning realistic incidental exposure to outdoor lighting, as well as the spectral characteristics of such lighting, has not been published. However, the effects of blue-rich light on melatonin production, and the effects of melatonin on human cancer growth in certain laboratory experiments, are uncontroversial. Stevens concludes:

> *"The level of impact [of lighting] on life on the planet… is only now beginning to be appreciated. Of the many potential adverse effects from LAN and circadian disruption on human health, the most evidence to date is on breast cancer. No single study can prove cause and effect, as neither can a group of studies of only one of the factors cited above. However, taken together, the epidemiologic and basic science evidence may lead to a 'proof' of causality (i.e. a consensus of experts). If so, then there would be an opportunity for the architectural and lighting communities, working with the scientific community, to develop new lighting technologies that better accommodate the circadian system both at night and during the day inside buildings."*

While a firm connection between outdoor lighting and cancer has not yet been established, if true it is clear that the blue component of such light would be a greater risk factor.

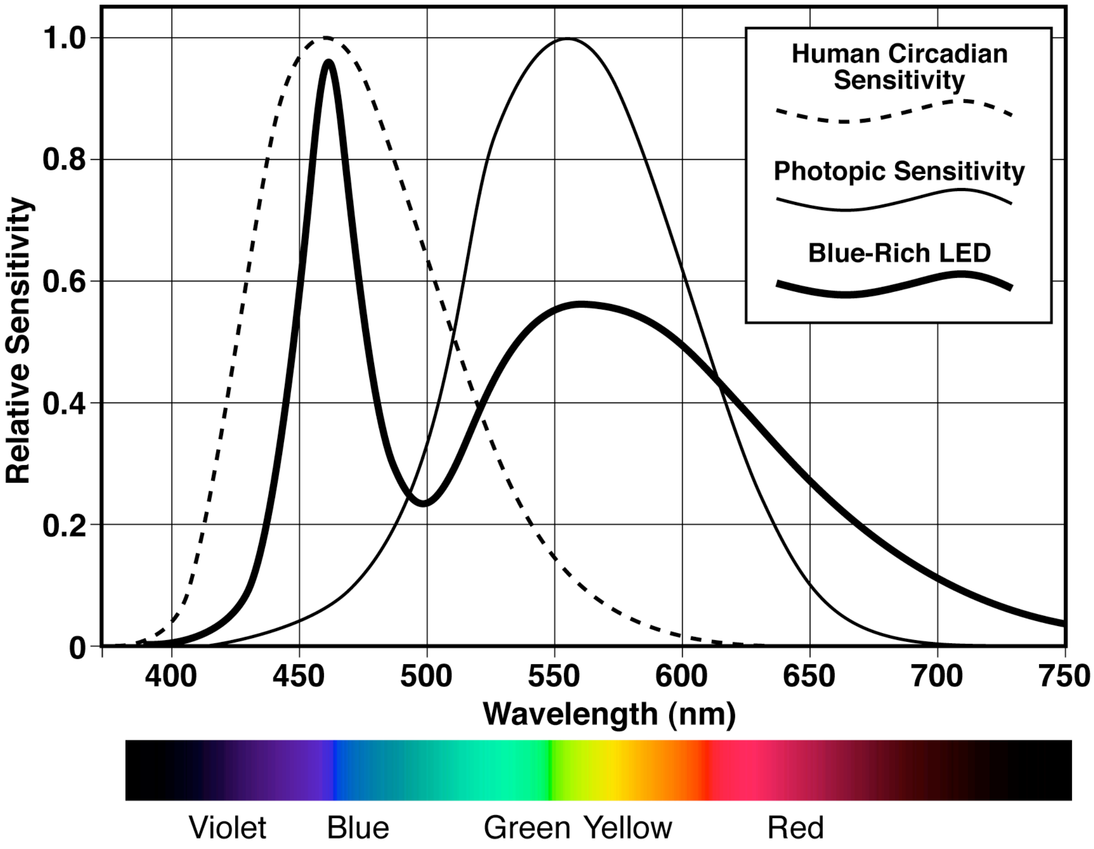

Figure 3. Human photopic and circadian sensitivity curves displayed against a typical blue-rich LED light source spectrum.

Environmental Effects

Artificial lighting is intended to serve only human needs, but once introduced outdoors it radiates freely into the environment where it may have unintended consequences to wildlife (e.g., Longcore and Rich, 2004; IESNA, 2008). It is estimated that the majority of animal life on the planet is nocturnal; this preference for night activity may stem from predator avoidance, heat aversion, foraging advantages, or other factors (e.g., Rydell and Speakman, 1994). The alteration of the ambient light level at night can result in an otherwise suitable habitat being avoided or unusable. Artificial light in the environment may thus be considered a chronic impairment of habitat. “Light pollution has demonstrable effects on the behavioral and population ecology of organisms in natural settings… derived from changes in orientation, disorientation, or misorientation, and attraction or repulsion from the altered light environment, which in turn may affect foraging, reproduction, migration, and communication.” (Longcore and Rich, 2004).

Naturalists noted the impact artificial light can have on wildlife as early as 1883 and the role light color plays as early as 1935 (Rich and Longcore, 2006). The relationship between artificial light and wildlife has rarely received the level of study to yield definitive answers to questions concerning the thresholds of illumination that cause disturbance or what portions of the spectrum affect behaviors of which species. Much of the research concerns only the presence or absence of light and is mute on the relationship between spectral power distribution and biological function.

Nonetheless, evidence does not support a position that the spectral characteristics of outdoor lighting can be shifted without ecological consequence. There are few instances in which increased blue light emission can be construed as being better for wildlife than yellow-rich lighting.. There are several examples where shorter wavelength light has been linked to ecological problems (e.g. Frank, 1988; Witherington and Martin, 2000; Nightingale et al. 2006), though a few studies also point to other portions of the spectrum (e.g., Phillips and Borland, 1992; Wiltschko, 1993; Poot et al., 2008). However, the increased scattering of blue light in the atmosphere, the sensitivity of many biological systems to blue light, and deeper penetration of blue light into aquatic environments (Clarke and Oster, 1967) means that increased use of blue-rich light sources is likely to produce greater environmental consequences.

Examples of Wildlife Disturbance

A robust body of research documents the disorientation of sea turtles by artificial lighting. Hatchlings are routinely drawn to artificial lights instead of cueing on the natural luminance of the ocean and moving from the beach toward the water (e.g., McFarlane, 1963; Witherington, 1992; Salmon, 2006), decreasing survival rates. The photo-orientation response of loggerhead sea turtles shows a 10x difference between light at 450 nm versus 600 nm, with four Atlantic sea turtle species showing a similar spectral misorientation response (Witherington and Martin, 2000). Furthermore, the level of sensitivity is such that distant sky glow, not just a proximal light source, can produce a response (Salmon, 2006). It is worth noting that all six Atlantic species of sea turtles are listed as Threatened or Endangered under the Endangered Species Act and nest throughout the Gulf of Mexico coast and the Atlantic coast as far north as Cape Cod (Plotkin, 1995).

Light sources that have a strong blue and ultraviolet component are particularly attractive to insects (Frank, 1988), though even incandescent sources, broad-spectrum but not commonly thought of as blue-rich, are generally known to attract insects to residential porchlights. There is a dearth of published studies addressing the relative attractiveness of ultraviolet vs. blue light, though a few unpublished ones indicate that while UV has much greater attractiveness than blue light, blue light is more attractive than yellow. Insects in artificially lighted areas are frequently captured by phototactic fixation on lights, but lights also draw insects out of natural habitats into lighted areas, or present a barrier to migrating insects moving through an area (Eisenbeis, 2006). Thus, the distance to which a given light may affect insects can be quite large. Lights without substantial short-wavelength emission, from simple yellow-painted incandescent “bug” lights to low-pressure sodium, substantially reduce or eliminate this phototactic response.

Most bat species are insectivores and have long been observed to feed around lights at night. This results in a complex ecological change that is potentially harmful—the lights concentrate their food source outside of their normal habitat, may result in longer flights to feeding locations, change their diet, and alter the competitive balance between bat species (Rydell, 2006).

Circadian Disruption in Wildlife

Photoperiod is one of the dominant cues in the animal kingdom; an animal's response to it is commonly triggered by length of darkness as opposed to length of daylight. Light is a potent agent and is biologically active (Royal Commission on Environmental Pollution, 2009). As in humans, the circadian clock controls a complex cascade of daily and seasonal endocrine functions. These exert command over migratory, reproductive, and foraging behaviors (Rich and Longcore, 2006, Royal Commission, 2009). The tendency of blue-rich light to synchronize circadian function is common in mammals (Berson et al., 2002), and there is evidence for it in amphibians (Hailman and Jaeger, 1974; Buchanan, 2006) as well as plankton (Moore et al., 2000; Gehring and Rosbash, 2003).

Sky Glow, Astronomy, and the Natural Nightscape

At sites near light sources, such as within and near urban areas, the increased scattering from blue-rich light sources leads to increased sky glow (Luginbuhl et al., 2010; Figure 4). The bluest sources produce 15% to 20% more radiant sky glow than HPS or low-pressure sodium (LPS). This effect is compounded for visual observation, as practiced by casual stargazers and amateur astronomers, by the shift of dark-adapted vision toward increased sensitivity to shorter wavelengths. In a relatively dark suburban or rural area, where the eyes can become completely or nearly completely dark-adapted (scotopic), the brightness of the sky glow produced by artificial lighting can appear 3–5 times brighter for blue-rich light sources as compared to HPS and up to 15 times as bright as compared to LPS.

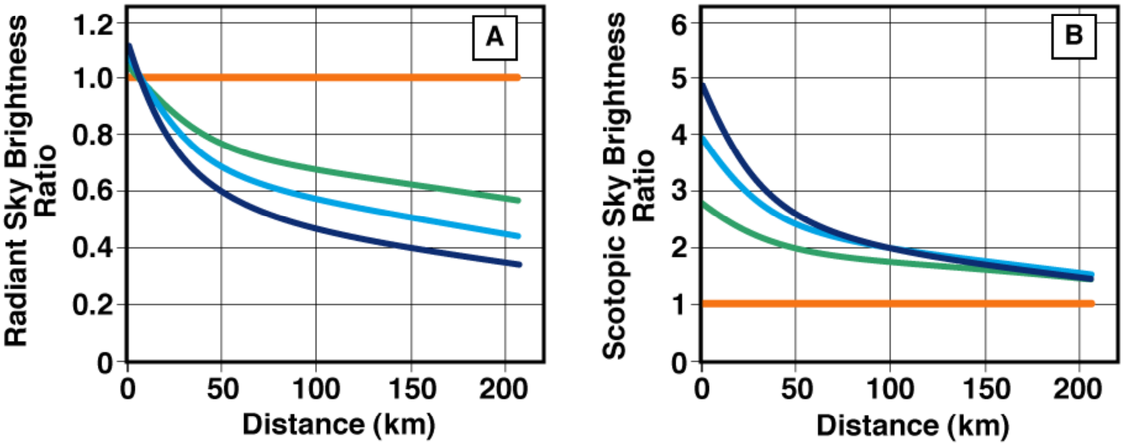

Figure 4. a) Radiant and b) visual (scotopic) sky brightness ratio as a function of distance for equal-radiance light sources with effective wavelengths of 480nm (blue), 500nm (cyan), and 520nm (green), all relative to HPS (yellow) (from Luginbuhl et al., 2010).

At locations far from the light sources, such as at the world's highest-quality observatory sites, increased absorption and scattering of the shorter wavelength emission means that radiant sky glow from blue-rich sources is less than that from HPS (see figure 4a). Nonetheless, to the dark-adapted eye, the brightness produced by blue-rich sources remains greater than that for HPS for long distances, to at least 200 km in typical atmospheres (see figure 4b).

It is important to recognize that, though the radiant sky glow produced by blue-rich light sources falls more rapidly with distance than that produced by HPS, blue-rich light is adding sky glow to a portion of the spectrum that in most places suffers relatively little artificial sky glow from current lighting practices.. HPS, still the dominant area-lighting technology in most communities, contributes very little light to the blue portion of the night sky spectrum. In those communities utilizing low-pressure sodium (LPS), the blue portion of the night sky spectrum is even less affected (Luginbuhl, 1999). From the astronomical science perspective, the effect of this added short wavelength flux is compounded because the natural sky is darker at bluer wavelengths (the sky at 440 nm is approximately 45% as bright as at 550 nm). The net effect is that astronomical research at most observatory sites will be hampered to a greater degree for an equal unit of blue-rich light as compared to HPS due to the unequal effect upon contrast.

In comparison to the impacts on scientific astronomical observation, which is affected most by increased artificial radiance in the upper portion of the sky (within about 70° of the zenith), impacts on the nightscape as viewed by human observers are strongly influenced by the interplay of the spectral sensitivity of human vision with the spectral content of light sources, and the appearance of light domes over cities. To the dark-adapted human eye, the so-called “scotopic advantage” (or in this case disadvantage) of blue-rich light sources is fully realized.For example, a given amount of artificial light (measured in radiance units, not photopic lumens) scattered from the night sky and with an S/P ratio of 3 will appear up to 5 times as bright as the same amount of light produced by HPS with an S/P ratio of 0.6 (e.g., 3.0/0.6 = 5). As light domes from urban areas impinge on many rural and natural areas, including national parks (Duriscoe et al., 2007), increased use of blue-rich light sources will increase these impacts to distances of 100 km or more (Luginbuhl et al., 2010). The cultural impacts arising from the loss of a natural star-filled night are hard to quantify. Yet these impacts affect a much larger proportion of the population than commonly thought of when discussing the value of night skies (see e.g. Moore et al., 2010).

Conclusions

While there is substantial interest in using lighting that is richer in blue wavelengths, the complex interrelationships between visual performance and light source spectral distribution are not adequately understood, especially at mesopic luminance levels. Within the range of blue wavelengths, there are multiple opposing functions that may diminish or overwhelm the advantages of scotopic stimulation, including glare, delayed dark adaptation, pupil constriction, and factors associated with the aging eye. Also of special importance is the threshold of luminance where such benefits accrue. Most outdoor lighting levels lie in the high mesopic range; the benefits of blue-rich light found at low mesopic or scotopic levels should not be wrongly applied to brighter ranges.

With only a cursory familiarization with the advantages of blue-rich lighting, one might assume that the potentially lower illumination levels allowed would reduce environmental impacts to the same degree that photopic luminances were reduced. This assumption is not correct. There are substantially more deleterious effects to humans, wildlife, and astronomical resources associated with blue-rich light. First, the atmosphere scatters shorter wavelengths to a much greater degree than longer wavelengths, and dark-adapted eyes observing a sky contaminated with artificial sky glow are more sensitive to blue-rich light. As compared to HPS, blue-rich light sources scatter 1.1–1.2x more; to the dark-adapted eye this light will appear 3–5x as bright when observed from nearby. Thus, blue-rich light will greatly exacerbate visible sky glow close to the light source and retain greater impacts to very large distances.

Second, from the perspective of astronomical observation at distant observatories, short-wavelength emission from blue-rich lighting sources increases sky glow in the (naturally) relatively dark and unpolluted (by HPS and LPS) blue portion of the spectrum. The resultant decrease in contrast erodes the effectiveness of astronomical facilities.

The current state of knowledge regarding the health effects of light at night, and in particular blue-rich light at night, permits no firm conclusions. Yet, the clear linkage between short-wavelength emission, the blue-sensitive response of the photoreceptors involved in the human circadian system, and the suppression of melatonin production by short-wavelength emission, indicates at least that widespread use of blue-rich light sources at night should be considered with caution. There is an urgent need for further research in this area, due to the potentially grave impacts hinted at by much research.

The science of photobiology indicates that blue-rich light at night is more likely to alter circadian rhythm and photoperiod in the animal kingdom. With this field of study in its infancy, the evidence is widely scattered across the animal kingdom. Yellow-rich light, such as HPS, or even monochromatic yellow light, such as LPS, is environmentally preferred in many situations, but there are notable exceptions. However, the balance of evidence points to blue-rich light being more likely to impact wildlife than yellow light. The ecological differences between light rich in blue and light devoid of blue can be several-fold for some critical species.

Light pollution and other negative effects of outdoor lighting reach great distances. Cities and lit roadways are intertwined with the natural world and also with those places where society values darkness and a natural starry sky. A shift toward blue-rich light, especially in place of HPS, would substantially increase the deleterious effects of outdoor lighting. The roots of the dark sky movement stemmed from the simple desire to enjoy the view of the starry sky. Under wilderness, rural, and even some suburban conditions, this is a purely scotopic visual function. Thus, S/P ratios are working against the observer who is viewing the night sky—the higher the scotopic content of the light, the greater the perceived light pollution. Even at distances up to at least 200 km, where blue light is preferentially scattered away, the detriment to stargazing is still greater with blue-rich light than an HPS source, particularly in clear atmospheres.

The current trend toward blue-rich white outdoor lighting will result in a large increase in radiant flux being emitted below 500 nm. There is a suite of known and likely detrimental effects to the ecosystem, to the enjoyment of the night sky, to astronomical research, and possibly to human health. If these detrimental consequences are to be given serious consideration by lighting designers, lighting manufacturers, and public officials, then metrics that better describe the ramifications of shorter wavelengths of lamp spectra must be developed. Color Rendering Index, Correlated Color Temperature, and the Scotopic/Photopic ratio are too blunt to model the range of known significant impacts. Furthermore, better metrics will help lighting science navigate the complex vision questions that surround mesopic conditions and the confounding issues of the Purkinje shift, pupil size, adaptation, and glare. Alternatively, lamps can be selected or filtered to limit emissions shorter than 500 nm. Such light would in general exhibit only a light yellow hue and still enable scotopic vision while decreasing deleterious effects.

References

American Medical Association, 2009, Resolution of the American Medical Association on Lighting, June 15, 2009, http://current.com/news/90214626_ama-officially-supports-light-pollution-reduction.htm

Barbur, J. L., Harlow, A. J., and Sahraie, A., 1992, “Pupillary responses to stimulus structure, colour and movement, ” Opthalmic and Physiological Optics, 12: 137–141.

Bartlett, N. R., 1965, “Dark and Light Adaptation,” in *Vision and Visual Perception*, Graham, C. H. (ed), New York: John Wiley and Sons, Inc., chapter 8.

Berman, S., 1992, “Energy efficiency consequences of scotopic sensitivity,” Journal of the Illuminating Engineering Society, winter 1992, pp. 3–14.

Berman, S. and Josefowicz, J., 2009, “Incorporating Spectrum Effects for Brightness Perception and Visual Detection at Mesopic Light Levels,” LED Roadway Lighting Ltd.

Berson, D.M., Dunn, F.A. and Takao, M., 2002, “Phototransduction by retinal ganglion cells that set the circadian clock,” Science 295: 1070–1073.

Blackwell, H. R., 1946, “Contrast threshold of the human eye,” Journal of the Optical Society of America, 36(11): 624–643.

Bouma, H., 1962, “Size of the static pupil as a function of wavelength and luminosity of the light incident on the human eye,” Nature, 193: 690–691.

Boyce, P., Akashi, Y., Hunter, C.M., Bullough, J.D. 2003, “The impact of spectral power distribution on the performance of an achromatic visual task,” Lighting Research and Technology, 35: 141–156.

Brainard, G. C., et al., 2001, “Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor,” Journal of Neuroscience, 21: 6405–6412.

Brown, J. L., Metz, J. W. and Yohman, J. R., 1969, “Test of scotopic suppression of the photopic process,” Journal of the Optical Society of America, 59: 1677–1678.

Buchanan, B. W., 2006, “Observed and potential effects of artificial night lighting on anuran amphibians,” in *Ecological consequences of artificial night lighting*, Rich, C., and Longcore, T. (eds.), Island Press, Washington, D.C., pp. 192–220.

Bullough, J. D, van Derlofske, J., Fay, C. R., and Dee, P.A., 2003, “Discomfort glare from headlamps: interactions among spectrum, control of gaze and background light level,” in *Lighting Technology*, Warrendale, PA. Society of Automotive Engineers, pp: 21–25.

Campbell, F.W., 1957, “The depth of field of the human eye,” Optica Acta, 4: 157–164.

Clarke, G. L., and Oster, R. H., “The Penetration of the Blue and Red Components of Daylight into Atlantic Coastal Waters and its Relationship to Phytoplankton Metabolism,” The Biological Bulletin*,* 1967: 59-75.

Commission Internationale de l’ Eclairage (CIE), 2009, Recommended System for Visual Performance Based Mesopic Photometry. CIE Technical Committee 1-58 — Visual Performance in the Mesopic Range.

de Boer, J. B., 1967, “Public lighting,” Eindhoven, The Netherlands: Philips Technical Library.

de Boer, J. B. and van Heemskerck Veeckens, J. F. T., 1955, “Observations on discomfort glare in street lighting,” Proceedings of the Commission Internationale de l’Éclairage, Zurich, Switzerland.

Duriscoe, D. M., Luginbuhl, C. B., and Moore, C. A., 2007, “Measuring Night-Sky Brightness with a Wide-Field CCD Camera,” Pub. Astron. Soc. Pacific, 119: 192–213.

Eisenbeis, G., 2006, “Artificial night lighting and insects: attraction of insects to streetlamps in a rural setting in Germany,” in *Ecological Consequences of Artificial Night Lighting*, Rich, C., and Longcore, T. (eds), Island Press, Washington, D.C., pp. 281–304.

Flannagan, M. J., Gellatly, M. J., Luoma, J., and Sivak, M., 1992, “A field study of discomfort glare from high-intensity discharge headlamps.” Report No. HS-041 319, UMTRI-92-16, University of Michigan Transportation Research Institute, Ann Arbor, MI.

Frank, K. D., 1988, “Impact of Outdoor Lighting on Moths: An Assessment,” Journal of the Lepidopterists’ Society, 42: 63–93.

Garstang, R. H., 1986, "Model for Night Sky Illumination," Pub. Astron. Soc. Pacific, 98: 364–375.

Garstang, R. H., 1989, “Night-Sky Brightness at Observatories and Sites,” Pub. Astron. Soc. Pacific, 101: 306–329.

Gehring, W. and Rosbash, M., 2003, “The coevolution of blue-light photoreception and circadian rhythms,” Journal of Molecular Evolution, 57: S286–S289.

Goodman, T., et al., 2007, “Mesopic Visual Efficiency IV: A model with relevance to night-time driving and other applications,” Lighting Research and Technology*,* 39: 365–392.

Hailman, J. P. and Jaeger, J. G., 1974, “Phototactic responses to spectrally dominant stimuli and use of colour vision by adult anuran amphibians: a comparative survey,” Anim. Behav. 22: 757–795.

He, Y., Bierman, A., Rea, M., 1998, “A system of mesopic photometry,” Lighting Research Technology, 30: 175–181.

Ikeda, M. and Shimozono, H., 1981, “Mesopic luminous-efficiency function,” Journal of the Optical Society of America, 71: 280–284.

Illuminating Engineering Society of North America (IESNA), 2008, “Light and Human Health: An Overview of the Impact of Optical Radiation on Visual, Circadian, Neuroendocrine and Neurobehavioral Responses.” New York. Publication TM-18-08.

Illuminating Engineering Society of North America (IESNA), 2009, “Use of Spectral Weighting Functions for Compliance with IES Recommendations,” PS-02-09.

Kimura, E. and Young, R. S. L., 1999, “S-cone contribution to pupillary responses evoked by chromatic flash offset,” Vision Research, 39: 1189–1197.

Knox, J. F. and Keith, D. M., 2003, “Sources, Surfaces and Atmospheric Scattering: The Rayleigh Scatter Index,” paper presented at the International Dark-Sky Association Annual General Meeting, March 2003.

Kooi, F. L. and Alferdinck, J. W. A. M., 2004, “Yellow lessens discomfort glare: physiological mechanism(s),” Report for the US Air Force, F-WR-2003-0023-H.

Lewin, I., 2001, “Lumen Effectiveness Multipliers for Outdoor Lighting Design,” Journal of the Illuminating Engineering Society, Summer, 2001, pp. 40–52.

Lewin, I., 1999, “Lamp Color and Visibility in Outdoor Lighting Design,” developed from a Paper Delivered to the 1999 Conference of the Institution of Lighting Engineers, Portsmouth, England.

Lewis, A., 1999, “Visual performance as a function of spectral power distribution of light sources used for general outdoor lighting,” Journal of the Illuminating Engineering Society, 28: 37–42.

Longcore, T. and Rich, C., 2004, “Ecological light pollution,” Frontiers in Ecology and the Environment, 2: 191–198.

Luginbuhl, C. B., 1999, “Why Astronomy Needs Low-Pressure Sodium Lighting,” in *Preserving the Astronomical Sky: Proceedings of the 196th Symposium of the International Astronomical Union, 12-16 July 1999*, R. J. Cohen, W. T. Sullivan III, (eds.), Astronomical Society of the Pacific, San Francisco, pp. 81–86.

Luginbuhl, C. B., Boley, P. A., Keith, D. M. and Moore, C. A., 2010, "The Impact of Light Source Spectral Distribution and Atmospheric Aerosols on Sky Glow," in preparation.

Mace, D. et al., 2001, "Countermeasures for Reducing the Effects of Headlight Glare," a report prepared for the AAA Foundation for Traffic Safety, Washington, DC.

McFarlane, R.W., 1963, "Disorientation of loggerhead hatchlings by artificial road lighting," Copeia, 1963: 153.

Mie, G., 1908, "Beiträge zur Optik trüber Medien, speziell kolloidaler Metallösungen," Leipzig, Ann. Phys. 330: 377.

Moore, C. A., Richman, A. M. and Chamberlain, V. D., 2010, "Finding Inspiration in the Face of Endangered Starry Nights," in *Proceedings of the Sixth International Conference on The Inspiration of Astronomical Phenomena*, Venice 18-23 Oct. 2009, ASP Conference Series (in press).

Moore, M. V., et al., 2000, "Urban light pollution alters the daily vertical migration of Daphnia," Verhandlungen der Internationalen Vereinigung für Theoretische and Angewandte Limnologie, 27: 779–782.

Nightingale, B., Longcore, T., and Simenstad, C. A., 2006, "Artificial night lighting and fishes," in *Ecological Consequences of Artificial Night Lighting*, Rich, C. and Longcore, T. (eds.), Island Press, Washington, D.C., pp. 257–276.

Phillips, J. B. and Borland, S. C., 1992, "Behavioral evidence for the use of a light-dependent magnetoreception mechanism by a vertebrate," Nature 359: 142–144.

Plotkin, P.T. (ed.), 1995, "National Marine Fisheries Service and U. S. Fish and Wildlife Service Status Reviews for Sea Turtles Listed under the Endangered Species Act of 1973," National Marine Fisheries Service, Silver Spring, Maryland.

Provencio, I., et al., 2000, "A novel human opsin in the inner retina," Journal of Neuroscience, 20: 600–605.

Poot, H., et al., 2008, "Green light for nocturnally migrating birds," Ecology and Society 13: 47.

Rea, M., Bullough, J., Freyssinier-Nova, J., Bierman, A., 2004, "A proposed unified system of photometry," Lighting Research & Technology, 36: 85.

Rich, C. and Longcore, T., (eds.), 2006, "Ecological Consequences of Artificial Night Lighting," Washington D.C., Island Press.

Rose, A., 1948, “The Sensitivity Performance of the Human Eye on an Absolute Scale,” Journal of the Optical Society of America, 38: 196–208.

Royal Commission on Environmental Pollution, 2009, Artificial Light in the Environment, The Stationary Office, 11/2009.

Rydell, J., 2006, “Bats and their insect prey at streetlights,” in *Ecological Consequences of Artificial Night Lighting*, Rich, C., and Longcore, T., (eds), Island Press, Washington, D.C., pp. 43–60.

Rydell and Speakman, 1994, “Evolution of nocturnality in bats: Potential competitors and predators during their early history,” Biological Journal of the Linnean Society, 54: 183–191.

Salmon, M., 2006, “Protecting sea turtles from artificial night lighting at Florida’s oceanic beaches,” in *Ecological Consequences of Artificial Night Lighting*, Rich, C., and Longcore, T., (eds), Island Press, Washington, D.C., pp. 141–168.

Sagawa, K. and Takeichi, K., 1986, “Spectral luminous efficiency function in the mesopic range,” Journal of the Optical Society of America, 3: 71.

Stevens, R. G., et al., 2007, “Meeting Report: The Role of Environmental Lighting and Circadian Disruption in Cancer and Other Diseases,” in *Environ Health Perspectives* 115: 1357-1362.

Stevens, R. G., 2009, “Light-at-night, circadian disruption and breast cancer: assessment of existing evidence,” International Journal of Epidemiology, 38: 963–970.

Stockman, A, Sharpe, L. T., 2006, “Into the twilight zone: the complexities of mesopic vision and luminous efficiency,” Ophthalmic and Physiological Optics, 26: 225–39.

Strutt, J. W., 1871, “On the light from the sky, its polarization, and colour,” Philosophical Magazine XLI, pp. 107–120, 274–279.

Sugita, Y., Suzuki, H. and Tasaki, K., 1989, “Human Rods are Acting in the Light and Cones are Inhibited in the Dark,” Tohoku Journal of Experimental Medicine, 157: 365–372.

Sugita, Y. and Tasaki, K., 1988, “Rods also participate in human color vision,” Tohoku Journal of Experimental Medicine, 154: 57–62.

Trezona, P. W., 1991, “A system of mesopic photometry,” Color Research and Application, 16: 202–216.

Tsujimura, S., Wolffsohn, J. S. and Gilmartin, B., 2001, “A linear chromatic mechanism drives the pupillary response,” Proceedings: Biological Sciences, 268: 2203–2209.

U.S. Census Bureau. July 8, 2008, www.census.gov/population/socdemo/statbriefs/agebrief.html

U.S. Department of Defense, 2006, “UNIFIED FACILITIES CRITERIA (UFC) Design: Interior and Exterior Lighting and Controls,” UFC 3-530-01.

Walkey, H. C, Harlow, J. A. and Barbur, J. L., 2006, “Characterising mesopic spectral sensitivity from reaction times,” Vision Research, 46: 4232–4243.

Wiltschko, W., Munro, U., Ford, H. and Wiltschko, R., 1993, “Red light disrupts magnetic orientation in migratory birds,” Nature, 365: 525–527.

Witherington, B. E., 1992, “Behavioral responses of nesting sea turtles to artificial lighting,” Herpetologica, 48: 31–39.

Witherington, B. E., and Martin, R. E., 2000, “Understanding, assessing, and resolving light-pollution problems on sea turtle nesting beaches,” 2nd ed. rev., Florida Marine Research Institute Technical Report TR-2.

Zuclich, J. A. et al., 2005, “Veiling Glare: the visual consequences of near-UV/blue light induced fluorescence in the human lens,” Ophthalmic Technologies XV. Manns, et al., (eds.), Proceedings of the SPIE, 5688: 440–447.

December 4, 2009

Honorable Lisa P. Jackson
Administrator
United States Environmental Protection Agency
Ariel Rios Building
1200 Pennsylvania Avenue, NW
Mail Code 1101A
Washington, DC 20460

Re: CAA §112(b)(3), 42 U.S.C. §7412(b)(3) hazardous air pollutants petition to add anthropogenic light to the list of hazardous air pollutants

Dear Administrator Jackson:

Current trends in illumination toward the use of hi-efficiency Light Emitting Diodes and Compact Fluorescent Lights have resulted in the mass production of luminaires that emit far more blue-white light than their predecessors. Blue-white light is known to have impacts upon the human endocrine system[1], human fetal cell tissue[2], human macular degeneration[3], plants[4] and various bacteria[5][6][7][8][9]. Serious concerns exist related to the impact upon humans and exposure to light at night, especially during periods of rest.

I therefore petition the Administrator of the United States Environmental Protection Agency ("Administrator" or "EPA"), pursuant to the Clean Air Act §112(b)(3), 42 U.S.C. §7412(b)(3), to add anthropogenic light to the list of hazardous air pollutants and determine acceptable exposure levels and wavelengths that protect humans and the environment from harm at night.

Sincerely,

Robert Wagner
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[1] Sensitivity of the human circadian pacemaker to nocturnal light: melatonin phase resetting and suppression Jamie M Zeitzer, Derk-Jan Dijk, Richard E Kronauer, Emery N Brown, and Charles A Czeisler

[2] Blue Light Induces Apoptosis in Human Fetal Retinal Pigment Epithelium Ophthalmology & Visual Science, University Chicago, Chicago, IL

[3] http://www.mdsupport.org/library/hazard.html

[4] Koning, Ross E. 1994. Blue-Light Responses. *Plant Physiology Information Website*. http://plantphys.info/plant_physiology/bluelight.shtml . (12-2-2009).

[5] http://esciencenews.com/articles/2009/01/29/blue.light.destroys.antibiotic.resistant.staph.infection

[6] Differential Activation of *Escherichia coli* Chemoreceptors by Blue-Light Stimuli Stuart Wright, Bharat Walia, John S. Parkinson, and Shahid Khan

[7] Electron acceptor taxis and blue light effect on bacterial chemotaxis. B L Taylor, J B Miller, H M Warrick, and D E Koshland, Jr

[8] Blue Light May Fight Bacteria Associated with Periodontitis J Am Dent Assoc, Vol 136, No 5, 584. © 2005 American Dental Association

[9] Blue light suppresses black-pigmented bacteria in microcosm biofilms K. RUGGIERO[1], A. ABERNETHY[1], A.G. DOUKAS[2], J.M. GOODSON[1], and N.S. SOUKOS[1], [1]Forsyth Institute, Boston, MA, USA, [2]Massachusetts General Hospital, Boston, USA 2007