
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 Philadelphia¹, with the intention of providing an update on current research and a forum for discussion. While these issues are not unique to LEDs,

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

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 CO₂ 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

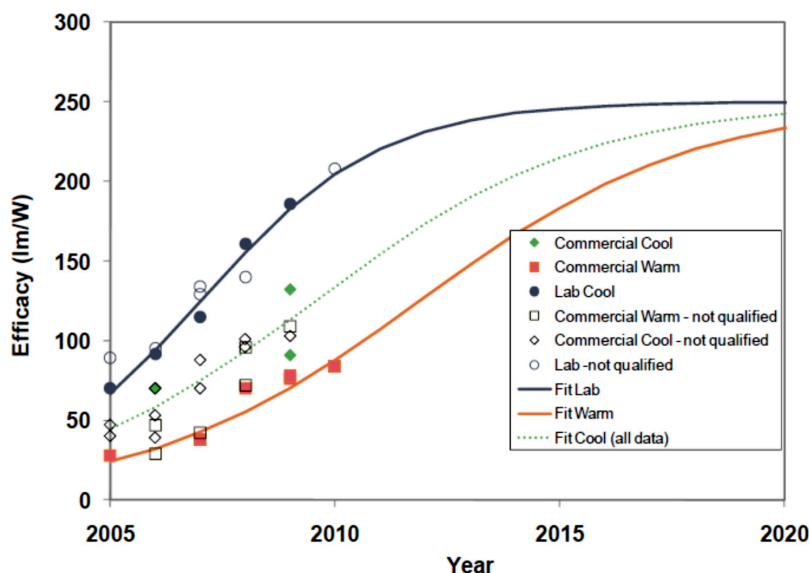


Figure 1. White-light LED package photopic efficacy targets, laboratory and commercial³

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

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.

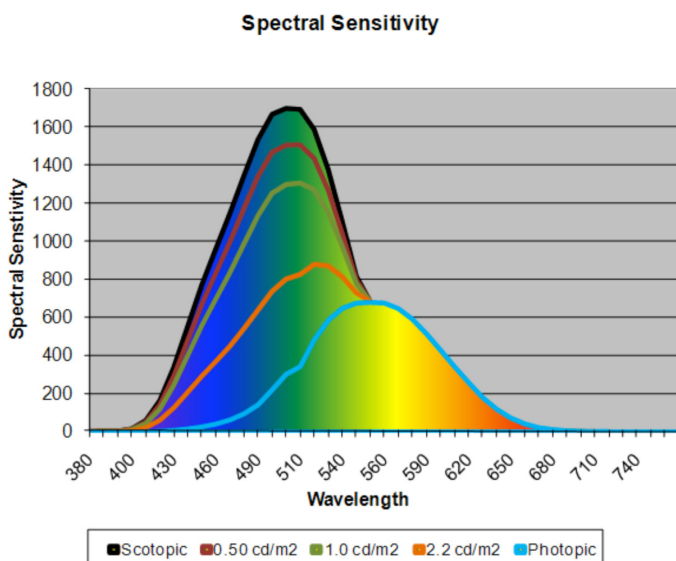


Figure 2. The Purkinje shift⁴

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 chromatic-

ity 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

⁴ Diagram courtesy of Ronald Gibbons.

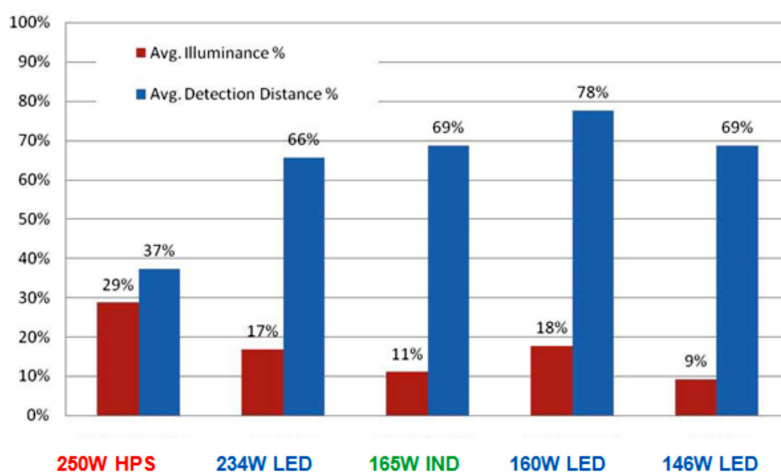


Figure 4. Anchorage: Average illuminance vs. detection distance, relative to 400W HPS

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 ex-

plain 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-

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.

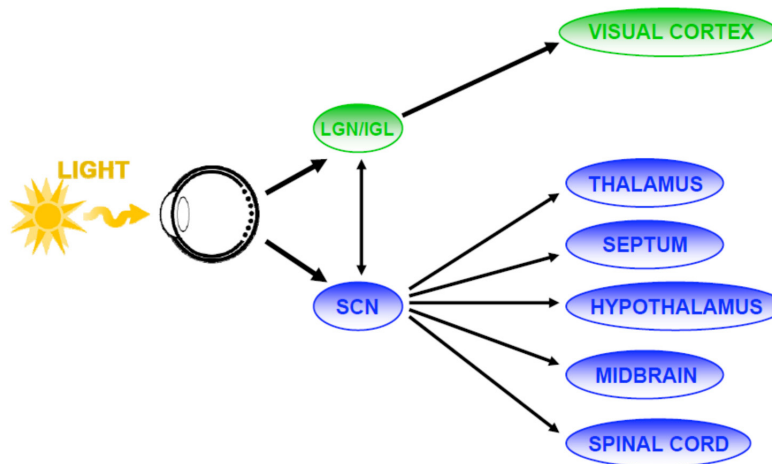


Figure 5. Processing light for visual and circadian functions⁶

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.

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 fo-

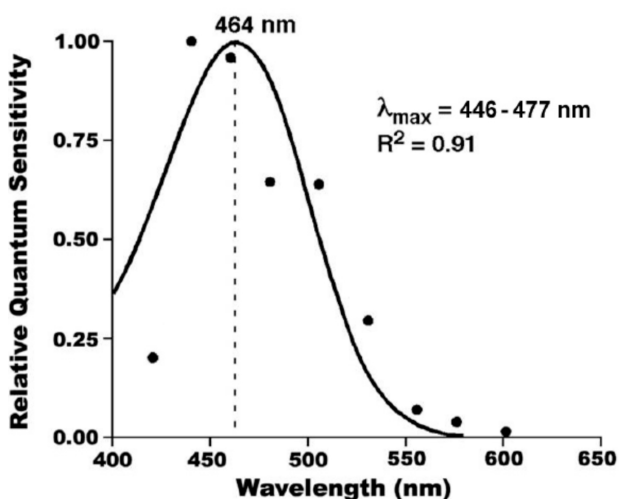


Figure 6. Action spectrum for melatonin production in healthy humans^{8,9}

cused 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.

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

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.

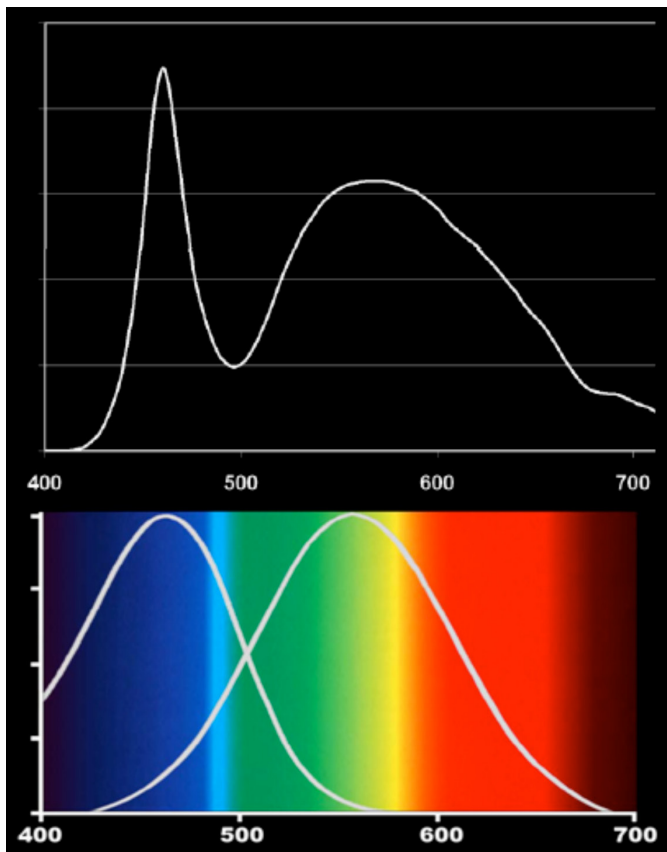


Figure 7. SPD for a 4800K light source (top) and action spectra for melatonin suppression (lower left) and photopic vision (lower right)⁶

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 exposure¹⁴

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

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.

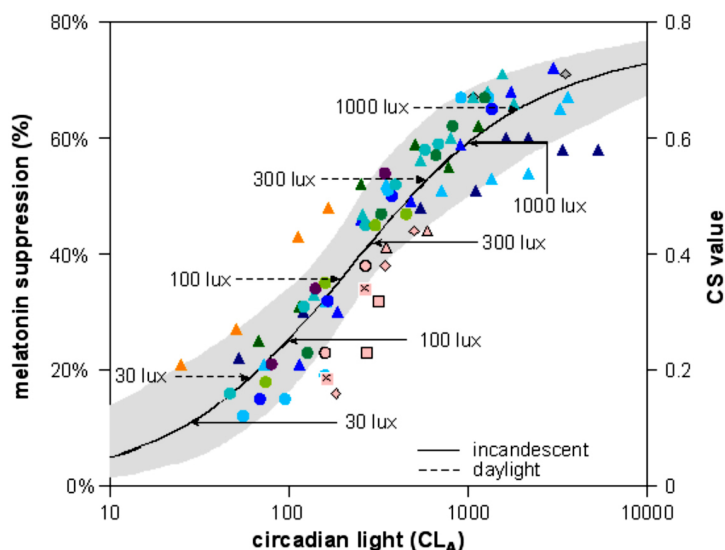


Figure 8. Circadian light transfer function¹⁸

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, $\lambda_{\text{peak}} = 470 \text{ nm}$)	30

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

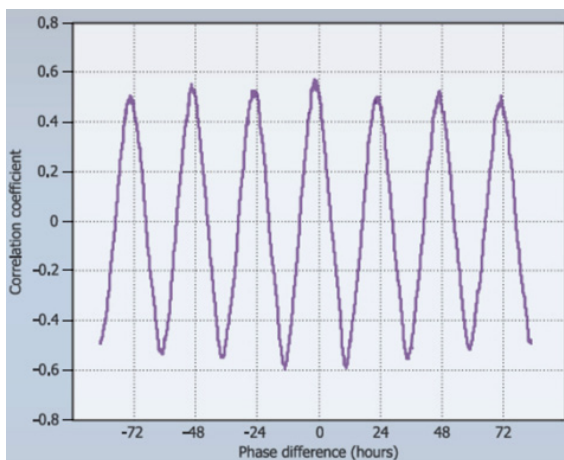


Figure 9a. Circadian entrainment of day-shift nurses

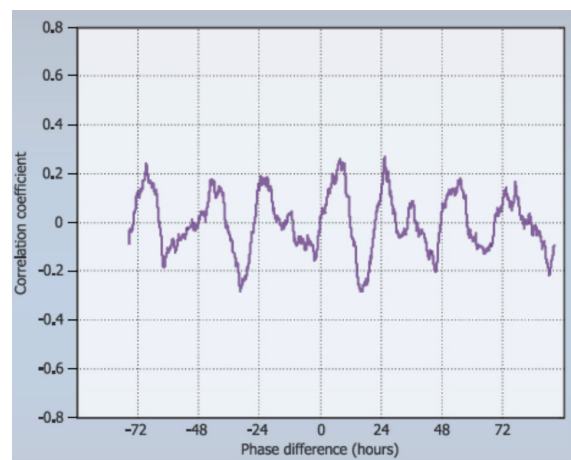


Figure 9b. Circadian entrainment of rotating-shift nurses

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

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.

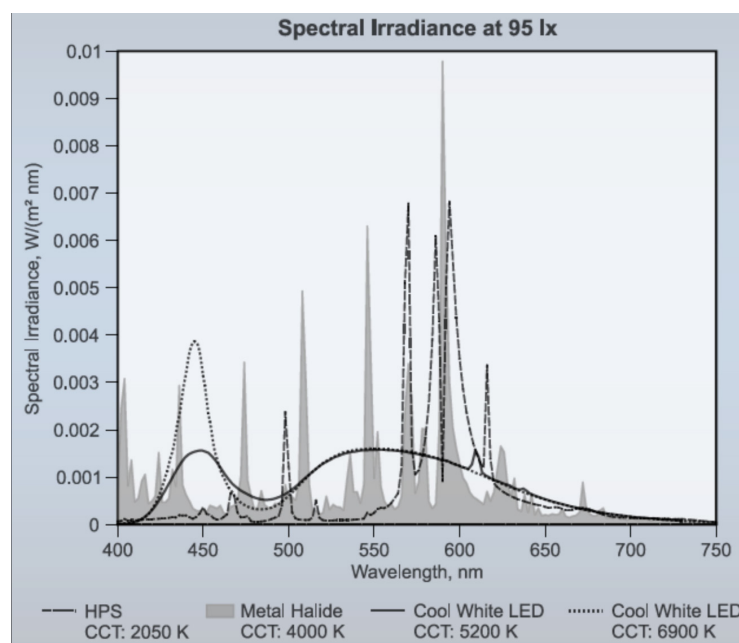


Figure 10. SPDs for different light sources, normalized for equal photopic light levels

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.

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.

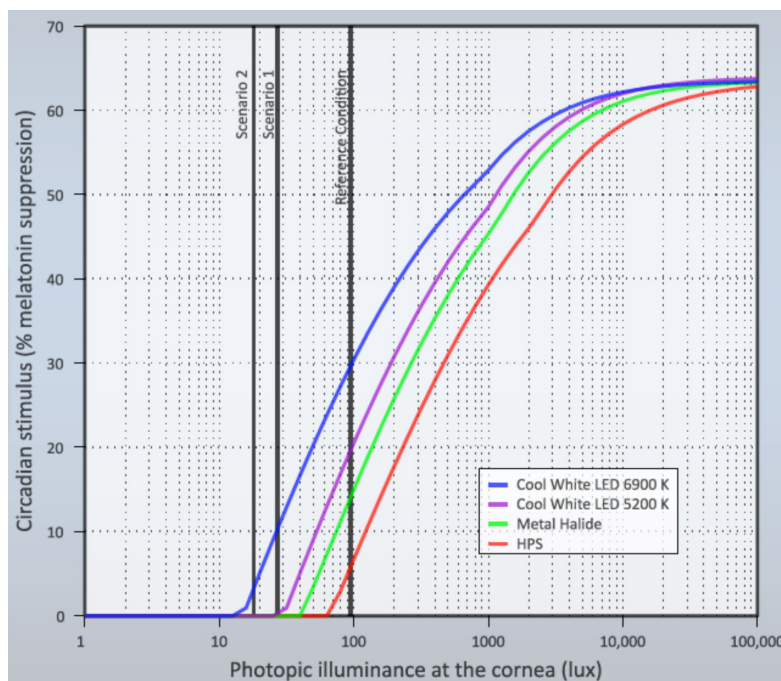


Figure 11. Predicted melatonin suppression after one hour of exposure with freely reactive pupils

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 day-time 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 has been installing luminaires with a nominal CCT of 4300K. 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

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.

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.

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	