Appendix A – Lighting Zones

The use of lighting zones (LZ) was originally developed by the International Commission on Illumination (CIE) and appeared first in the US in IES Recommended Practice for Exterior Environmental Lighting, RP-33-99. The original system employed four lighting environmental zones named E-1 through E-4, respectively. The system was changed to "Lighting Zones" and the zones renamed LZ-1 through LZ-4 as a result of legal issues raised when the California Energy Commission used the lighting zone system to establish outdoor lighting power limits in the 2008 Title 24 Part 6 Building Efficiency Standards.

Recently, the CIE, IDA and IES have all addressed a fifth zone of extreme environmental sensitivity (LZ-0) that will be incorporated into future standards.

Lighting Zones allow lighting to be tailored to the conditions of a specific community or neighborhood. Lighting zones reflect the base (or "ambient") light levels desired by a community. By adopting lighting zones, a community should implement lighting zones that support its vision and desired character. It is recommended that the adopting authority adopt the lowest possible lighting zone(s) that reflect its vision for the community. Small communities may choose only one or two lighting zones that reflect the limited number of different existing and/or desired ambient light levels, while larger communities and/or urban regions may choose to adopt three to five lighting zones.

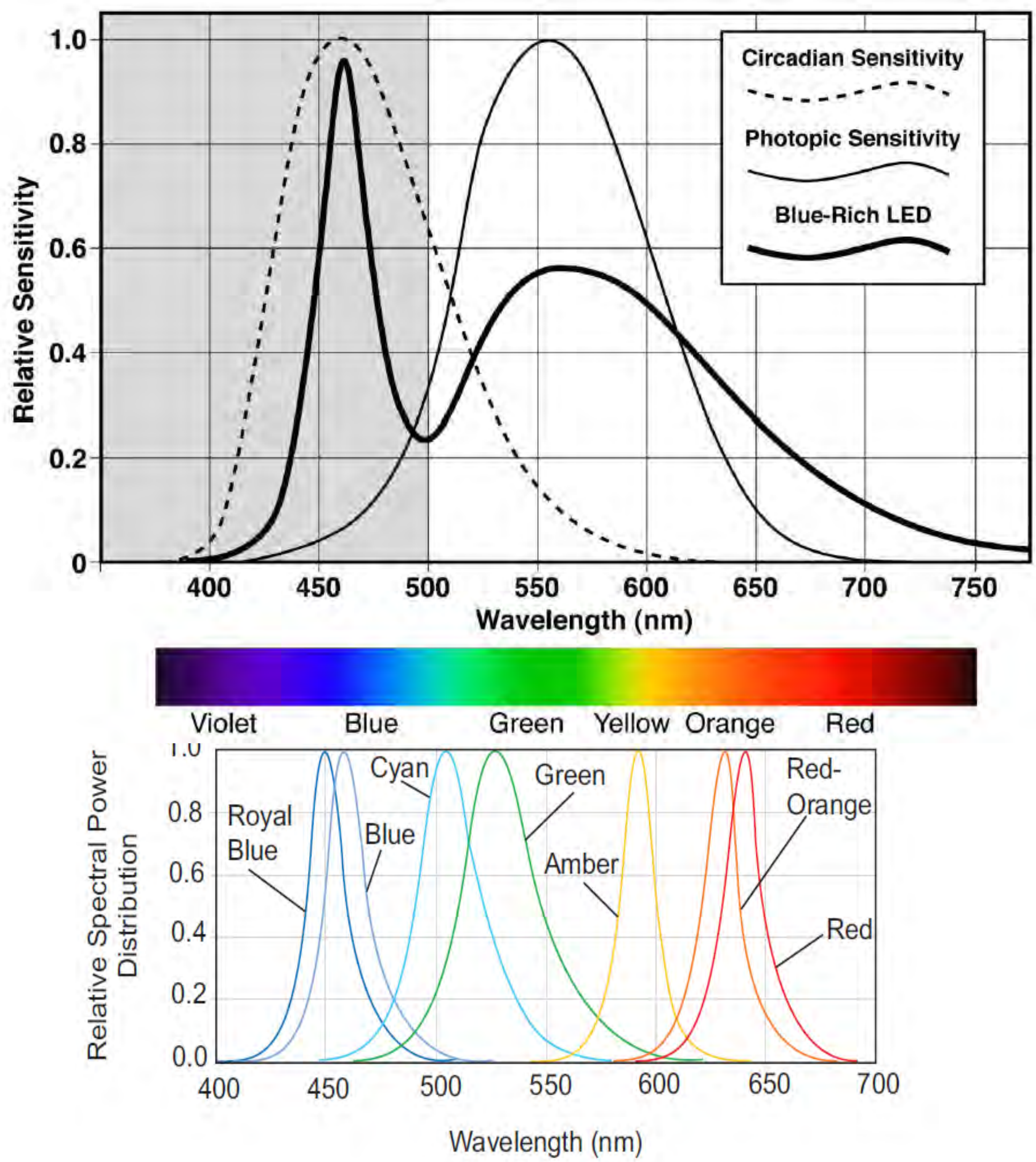
Lighting Zones are best implemented as an overlay to the established zoning—especially in communities where there is a variety of zone districts within a defined area or along an arterial street. However, when zone districts are cohesive, it may be possible to assign lighting zones to established land use zoning. In some cases such as mixed use zoning, a jurisdiction may choose to adopt a lower lighting zone for mixed use areas or establish vertical lighting zones with lighting zone at street level at a higher lighting zone than the residential housing on upper levels.

The following table may aid the process of understanding lighting zones. As a general rule, most of Yosemite should be considered LZ-0, with the high activity areas limited to LZ-1. There is no reason for any part of the park to have a higher lighting zone rating.

Lighting Zones (from IDA/IES Model Lighting Ordinance Second Public Review Draft 6/23/2010)

Zone	Recommended Uses or Areas	Zoning Considerations
LZ-0	Lighting Zone 0 should be applied to areas in which permanent lighting is not expected and when used, is limited in the amount of lighting and the period of operation. LZ-0 typically includes undeveloped areas of open space, wilderness parks and preserves, areas near astronomical observatories, or any other area where the protection of a dark environment is critical. Special review considerations should be required for any permanent lighting in this zone. Some rural communities may choose to adopt LZ-0 for residential areas.	**Recommended default zone for wilderness areas, parks and preserves, and undeveloped rural areas**. Includes protected wildlife areas and corridors.
LZ-1	Lighting Zone 1 pertains to areas that desire low ambient lighting levels. These typically include single and two family residential communities, rural town centers, business parks, and other commercial or industrial/storage areas typically with limited nighttime activity. May also include the developed areas in parks and other natural settings. Note: it is recommended that the Lighting Zone includes churches, schools, parks and other uses embedded within residential communities.	**Recommended default zone for rural and low density residential areas**. Includes residential single or two family; agricultural zone districts; rural residential zone districts; business parks; open space include preserves in developed areas.
LZ-2	Lighting Zone 2 pertains to areas with moderate ambient lighting levels. These typically include multifamily residential uses, institutional residential uses, schools, churches, hospitals, hotels/motels, commercial and/or businesses areas with evening activities embedded in predominately residential areas, neighborhood serving recreational and playing fields and/or mixed use development with a predominance of residential uses. Can be used to accommodate a district of outdoor sales or industry in an area otherwise zoned LZ-1.	**Recommended default zone for business districts and high density or mixed use residential districts.** Includes neighborhood business districts; churches, schools and neighborhood recreation facilities; and light industrial zoning with modest nighttime uses or lighting requirements.
LZ-3	Lighting Zone 3 pertains to areas with moderately high lighting levels. These typically include commercial corridors, high intensity suburban commercial areas, town centers, mixed use areas, industrial uses and shipping and rail yards with high night time activity, high use recreational and playing fields, regional shopping malls, car dealerships, gas stations, and other nighttime active exterior retail areas.	**Not a default zone.** Includes business zone districts; commercial mixed use; and heavy industrial and/or manufacturing zone districts.
LZ-4	Lighting zone 4 pertains to areas of high ambient lighting levels and limited to specific intense night uses within large metropolitan areas such as downtowns, entertainment districts or outdoor sales districts. LZ-4 should only be used for extreme cases and is not appropriate for most communities. May include professional sports, theme parks, and heavy industrial uses such as oil refineries.	**Not a default zone**. Includes high intensity business or industrial zone districts.

APPENDIX B – LIGHT SPECTRUM CONSIDERATIONS



The upper diagram illustrates the issues of night light exposure spectrum (from the International Dark Sky Association, 2009). The fine dotted line represents the circadian action spectrum for humans. The intent of the adaptive color LED system is to avoid wavelengths shorter than 550 nanometers (nm) after activity hours, resulting in the least light scattering wavelengths and the smallest interruption to human circadian rhythms (also applies to most mammals and other wildlife). The lower diagram are the spectra of common LED sources from Luxeon showing no radiation at 550 nm and shorter wavelengths when using red, red-orange and/or amber LED sources.

APPENDIX C: IDA Paper on Spectral Effects of Light at Night

This paper was intended to raise awareness to the potential of introducing green and blue light into exterior lighting through the use of LED's and other lighting products favoring the short wavelengths.

International Dark-Sky Association

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

May 4, 2010

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

International Dark-Sky Association

3225 North First Avenue
Tucson, Arizona 85719

717 D Street, NW Suite 300
Washington, DC 20004

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.

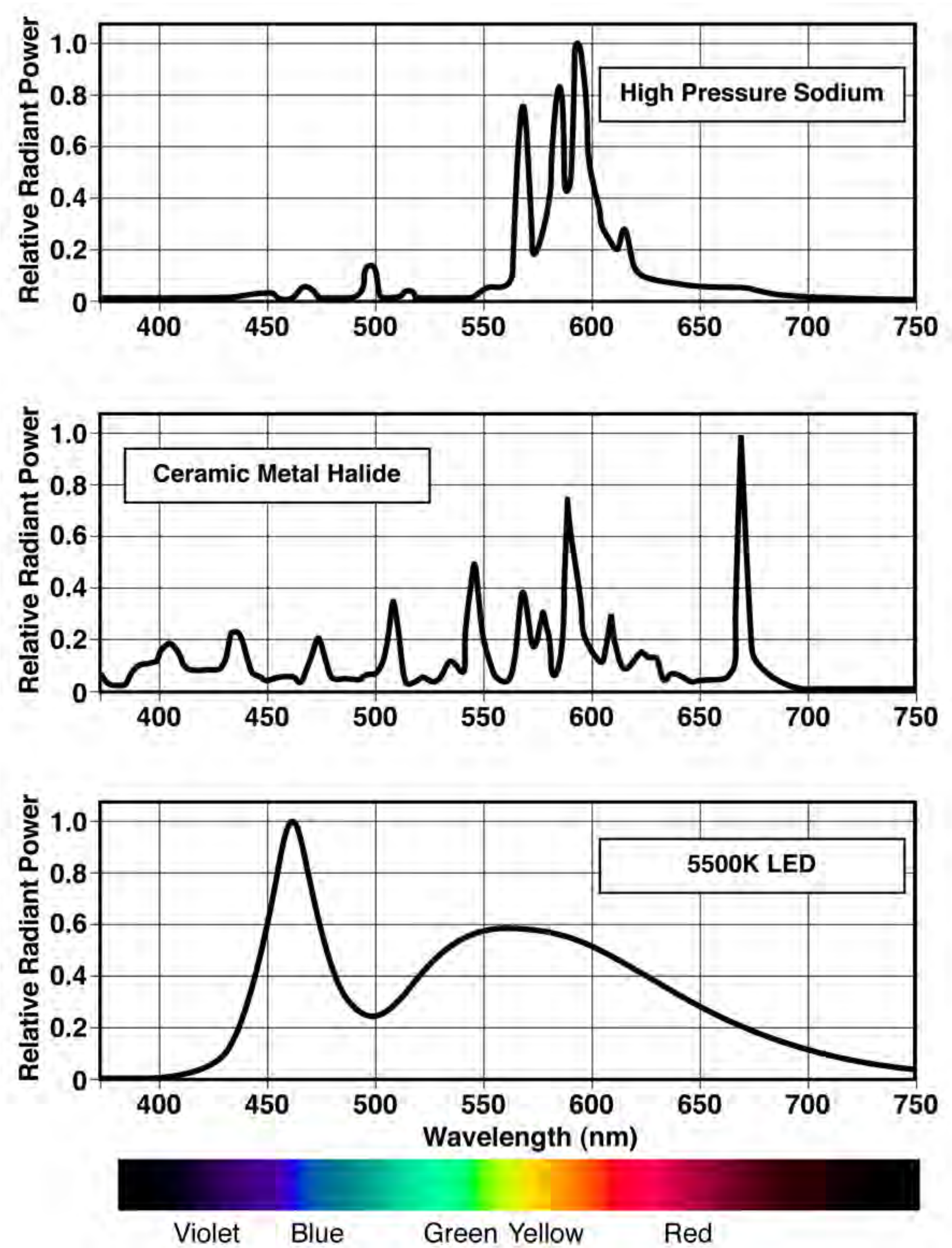


Figure 1. Typical spectral power distributions of HPS (orange); ceramic metal halide (cyan); white LED (blue).

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.

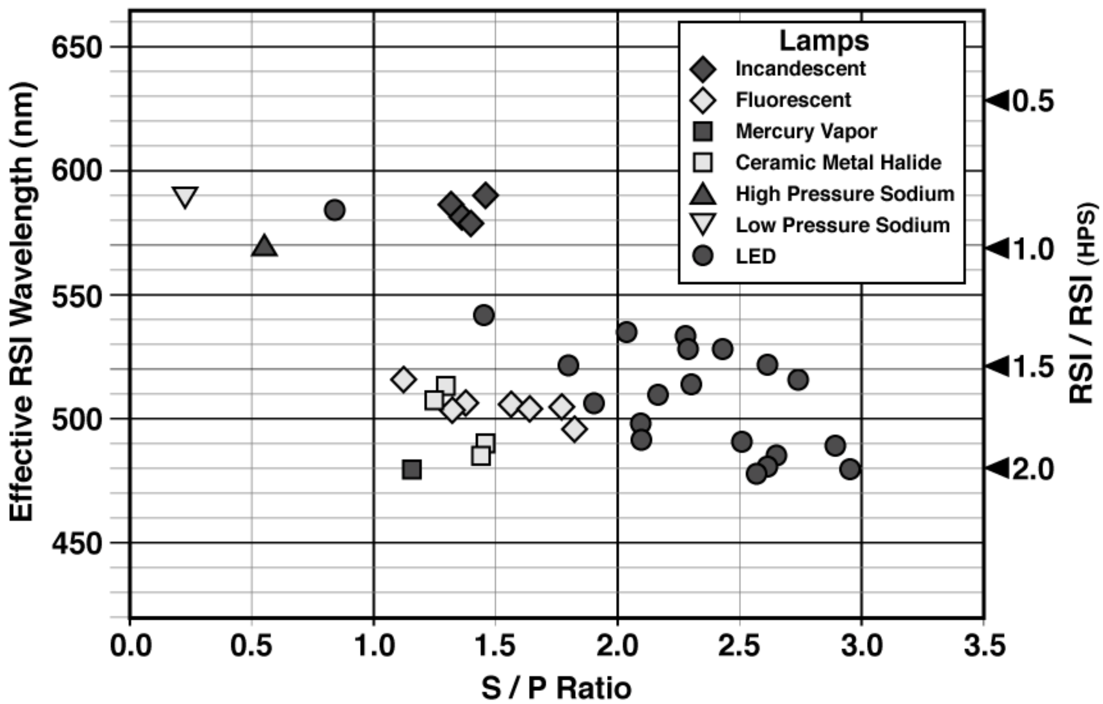


Figure 2. Rayleigh Scattering Index relative to HPS, and effective RSI wavelength for a selection of lamp types vs. their scotopic/photopic ratios S/P.

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.

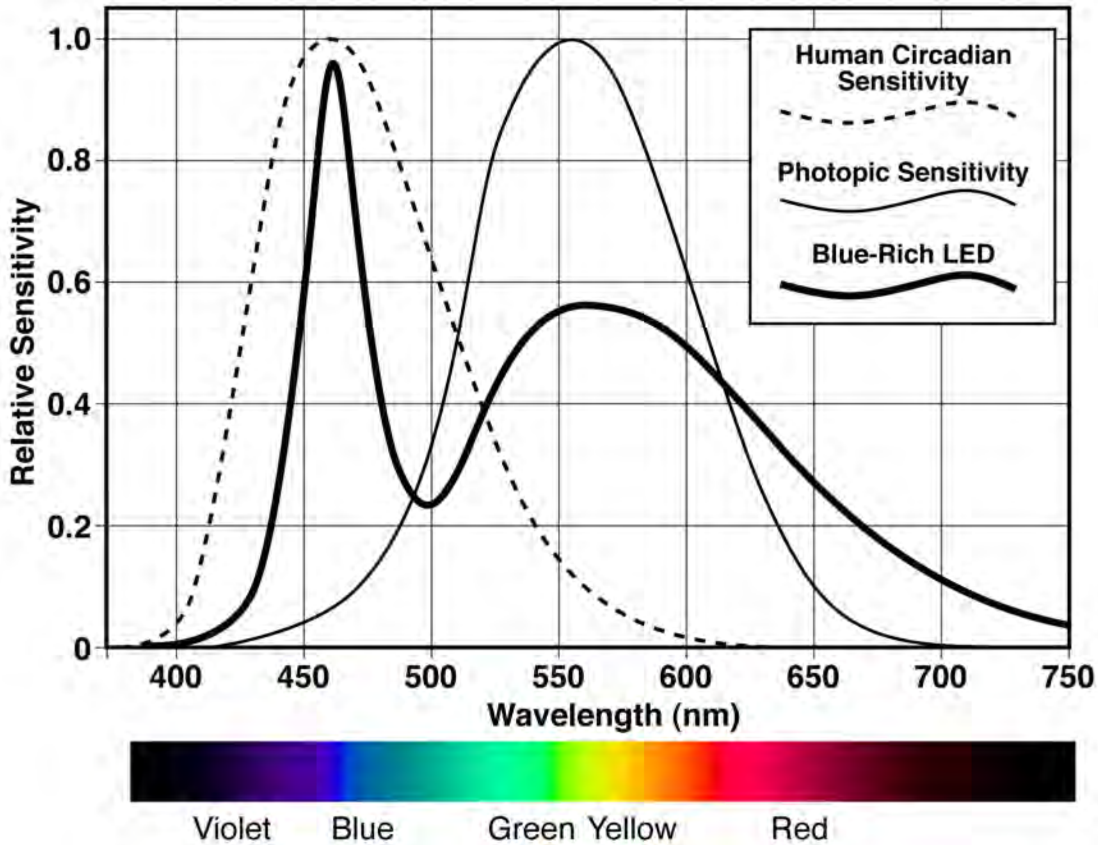


Figure 3. Human photopic and circadian sensitivity curves displayed against a typical blue-rich LED light source spectrum.

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.

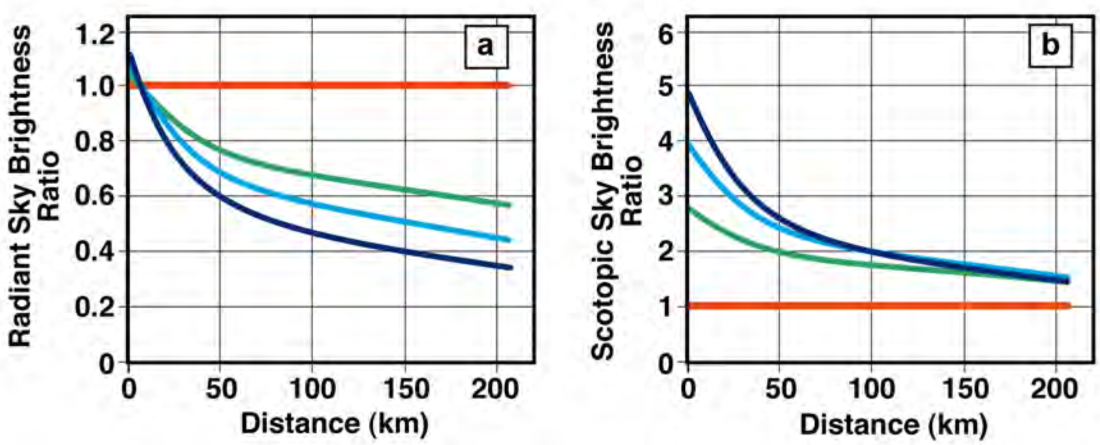


Figure 4. a) Radiant and b) visual (scotopic) sky brightness ratio as a function of distance for equal-radiance light sources with effective wavelengths of 480nm (blue), 500nm (cyan), and 520nm (green), all relative to HPS (yellow) (from Luginbuhl et al., 2010).

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.

APPENDIX D – KEY STUDIES OF LIGHT LEVELS

This report summarized the findings of experiments involving acceptance and perception of safety at low light levels among subjects fully adapted to the ambient light level of the Yosemite Valley Floor near Curry Village.

Yosemite National Park
Lighting Guidelines and Standards Project

BENYA LIGHTING DESIGN

Project Report #1

Outdoor Lighting Mockup Recommendations

Submitted for review and comment September 27, 2005
Final Report Submitted April 6, 2006

Introduction

During 1997, draft Guidelines were developed for outdoor lighting at Yosemite. These Guidelines introduced four major considerations for future construction projects at the Park:

1. Electric lighting must be provided for safety and security in certain areas of the Park.
2. The amount of electric lighting must be held to an absolute minimum and limited to only where it is needed, saving energy and helping preserve the night sky.
3. Luminaires must be fully shielded to prevent glare and aid in maintaining night adaptation.
4. In addition to all of the above, luminaire choices should be based on an appropriate combination of appearance, durability, maintainability, and other factors unique to each project.

In addition to considerations for park visitors, the draft Guidelines specifically identified the need for better lighting for park employees, notably late night and early morning workers, moving between their quarters and jobs. Lighting designs for the Curry Village employee housing project and Yosemite Lodge developed between 1999 and 2004 included consideration of the draft Guidelines. In addition, field studies and tests were conducted by the designers, NPS and DNC staff, and further input was made by Park security personnel. The project contract included a requirement that the contractor provide a mockup of the principal lighting systems.

In August, 2005, work began on finalizing the Guidelines and Standards for lighting in the Park. At the first project meeting, it was determined that the Curry Village mockup could be adapted to gather additional information suitable for the Guidelines project. The purpose of this report is to address the manner in which the mockup and the Guidelines projects should be devised to provide maximum mutual benefit.

The Curry Village Mockup

The original intent of the mockup was to test the lighting design and luminaire choices of the project design team. The test was to be conducted on the Employee Housing site amidst project construction and was originally intended to be in place for only a single night for review. October 3 was selected because it is the new moon and night conditions would be the darkest.

At the site meeting on September 7, 2005, a discussion was held with the Curry Village contractor and the site was inspected. It was determined that, if carried out according to plan, the mockup would be erected in and around the construction site, among partially completed buildings and site work. The limit of the duration of the mockup was principally due to its interference with construction work and the need to restrict pedestrian traffic on the construction site.

In the course of the discussion and follow up site walkthrough, the following were established:

- Provided appropriate insurance and approvals, the mockup could be conducted on the adjacent Curry Village parking lot and housekeeping cabin site.
- The mockup could be left in place for a month or longer at no additional cost.
- Moving the mockup off the construction site was beneficial to the project and introduced no delays or added construction costs.
- Decisions on luminaires and lighting related issues would have to be made by approx. November 30 in order to permit timely ordering of lighting equipment and materials.

In its design, the Curry Village team selected two principal luminaires. A 16' tall pole luminaire, suitable for large areas, has been proposed for the parking lot, and a 10' tall pole luminaire, suitable for pedestrian areas, has been proposed for the walkways in and around the housing area. In the proposed mockup, three of each will be located in the parking and cabin area close to the construction site.

Discussion

The Lighting Guidelines project has several key objectives:

A. Review Draft Lighting Guidelines originally produced in 1997.
B. Coordinated with current projects, review and/or develop proposed design concepts.
C. Implement lighting mockups of key concepts.
D. Review the mockups and survey Park employees, NPS and DNC staff, and other stakeholders
E. Analyze survey and measurement data, including Illumination levels.
F. Complete a scientific and legal foundation for the Illumination criteria.
G. Revise and complete the Lighting Guidelines.
H. Recommend Lighting Standards.
I. Coordinate with the efforts of the NPS Dark Sky Task Force.

The products being used in the Mockup are manufactured by Architectural Area Lighting (AAL), a division of Hubbell Lighting with facilities in La Mirada, California. Photometric data for the products being supplied to the mockup and all compatible products are presently being obtained from AAL.

This mockup can be modified to contribute significant data to items (C.) and (D.) above. Among other opportunities, the relocated mockup can obtain useful data relative to the lighting needs of employees, visitors, and management, including security, safety and wayfinding.

The Guidelines project will add the following components to the original mockup:

- Periodic changing of light source. AAL has confirmed that the luminaires supplied for the mockup can be converted from one light source, wattage and/or optical package in a few hours per change.
- Making light level measurements at the beginning of each specific light source or level mockup.
- Distributing and collecting survey data.
- Taking photographs and documenting activities during the mockup period.

The only responsibilities added to the construction contractor will be the changing of the lighting system. All other activities listed above will be carried out by Benya Lighting, NPS, or DNC personnel.

Proposed Mockup Design

The mockup design is now planned to encompass three tall poles for the Curry Village parking lot, on the Housekeeping Cabin side of the lot and located immediately adjacent to the Employee Housing job site, and three pedestrian poles located nearby in the vicinity of the central cabins. Spacing should match that shown on the drawings.

The tall pole will be initially mocked up as a 50 watt ceramic metal halide per the O'Mahony and Meyer design. We propose to add the following trials:

- 2 weeks later, change to 70 watt CMH
- 1 week later, change to 39 watt CMH

The shorter pole will be initially mocked up as a 13 watt compact fluorescent. We proposed to add the following trials:

- 2 weeks later, change to 39 watt CMH
- 1 week later, change to 20 watt CMH

The sequence of these tests is to first introduce an optimum design and lighting amount, chosen based on the theory proposed in the Draft Guidelines, and then to increase the amount and determine if there is a change in reaction. Following, we will decrease the amount, likewise looking for changes in reaction. From the data, we expect to draw curves suggesting increasing acceptance with increasing light level, but what we really don't know is the shape of the curve. A relatively flat curve suggests that differences are modest, and a steep curve suggests that the differences are close to a threshold of significance.

We also expect to extract some sort of bell curve of acceptance. Depending on the volume and quality of data, we will attempt to discover trends, preferences, tendencies, and other information that will guide the balance of the work. We should be prepared for a wide variety of reactions, as similar research work in outdoor lighting has already shown.

AAL has offered to send the alternative optical assemblies and ballasts at no additional charge. Both GE and Sylvania have offered lamps.

Summary

This mockup represents a unique opportunity to investigate the opportunities for safe and secure lighting at Yosemite while achieving the highest practical caliber of sustainable design. I believe from this one mockup we can collect a significant portion of the data needed to move forward in our work.

Jim Benya
September 27, 2005

Yosemite National Park
Lighting Guidelines and Standards Project

BENYA LIGHTING

Outdoor Lighting Test Questionnaire

October 3, 2005

Please indicate your relationship to the Park.

☐

A. Management Staff (NPS or DNC)
B. Security Staff
C. Resident Employee (except Management or Security)
D. Non-resident Employee (except Management or security)
E. Architect, Engineer, Contractor, Consultant
F. Visitor or Guest

These comments relate to (CHECK ONE – use a separate sheet to review the other):

☐ The tall light poles nearest the construction trailers

☐ The shorter light poles close to the center of the Curry Village Housekeeping Cabins area

PLEASE USE THE FOLLOWING SCALE TO MAKE THE FOLLOWING EVALUATIONS

1	2	3	5	5
Strongly Disagree	*Disagree*	*Neutral*	*Agree*	*Strongly Agree*
Most Negative	*Negative*		*Positive*	*Most Positive*

EVALUATIONS – PLEASE READ CAREFULLY. YOUR COMMENTS WILL AFFECT FUTURE LIGHTING PROJECTS AT THE PARK. THANK YOU FOR YOUR INPUT.

Rating	Lighting Quality
_____	A. I like the lighting.
_____	B. The lighting seems necessary.
_____	C. I feel safer and more secure in areas with the lighting.
_____	D. The lighting is glaring.
_____	E. There is too much lighting.
_____	F. I don't think that lighting is needed here.
_____	G. There is not enough lighting.
_____	H. The lighting is too spotty.
_____	I. There are too many shadows from the lighting.
_____	J. The lighting is just right.

DATE OF REVIEW AND SURVEY ______________________________, 2005.

Project Report #2

Outdoor Lighting Mockup Results

Submitted for review and comment December 4, 2005
Final Report April 6, 2006

Introduction

As a result of Draft Guidelines for outdoor lighting developed in 1997 and their application to the Curry Village Employee Housing projects currently under construction, a mockup of proposed lighting systems was undertaken. The purpose of the mockup was both to demonstrate the performance of specified lighting equipment, and to gather data for completion of the Lighting Guidelines. Details of the mockup plans were reported in Project Report #1.

Between October 3 and November 28, 2005, these plans were carried out, and lighting measurements and observations were made. Employees and management were encouraged to observe the installation and comment using survey forms. The results of the mockup and survey included:

1. Confirmation of the need for security lighting in this application.
2. Confirmation that light levels as proposed in the Draft Guidelines are appropriate.
3. Confirmation of the acceptability of approx. 20' parking lot poles and 10' high pedestrian poles.
4. Confirmation that luminaire scale is an important factor, and that the smaller pedestrian pole and luminaire are highly desirable.
5. Suggestion that lower levels than those proposed by the Draft Guidelines may be possible.
6. Suggestion that light trespass and glare thresholds were very low.
7. Suggestion that uniformity was not as critical as specified by the Draft Guidelines.
8. Suggestion that the color of ceramic metal halide and 2700K compact fluorescent are acceptable.
9. Suggestion that the mockup may have applicability to other parts and uses in the Park.

The Curry Village Mockup Results

There following mockups were carried out:

Parking Lot – Tall Poles

- Bases set at locations to match proposed Curry Village locations. Approximate spacing is 85' apart, lighting from one side only. Back light is used to illuminate the adjacent path.
- All tests using forward throw optics.
- First test: 50 watt ED-17 clear ceramic metal halide lamps as specified. Operated between October 3 and 25. Survey group A-1.
- Second test: 39 watt T-6 clear ceramic metal halide lamps. Operated between October 26 and November 14. Survey group A-2.
- First test: 20 watt T-4 clear ceramic metal halide lamps as specified. Operated between November 14 and 28. Survey group A-3.

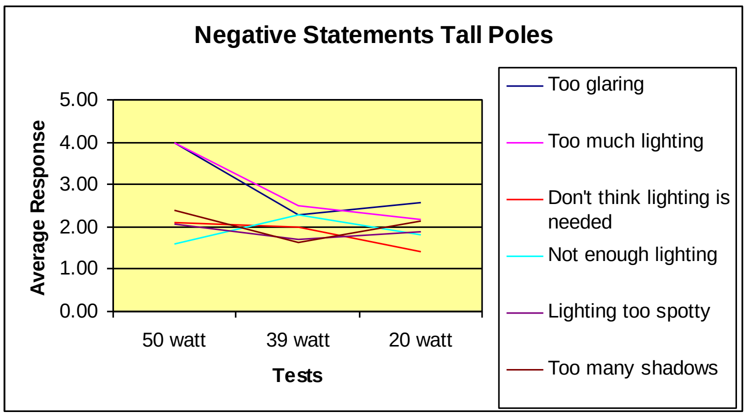
Tall pole mockup. Photo: Debbie Cooper

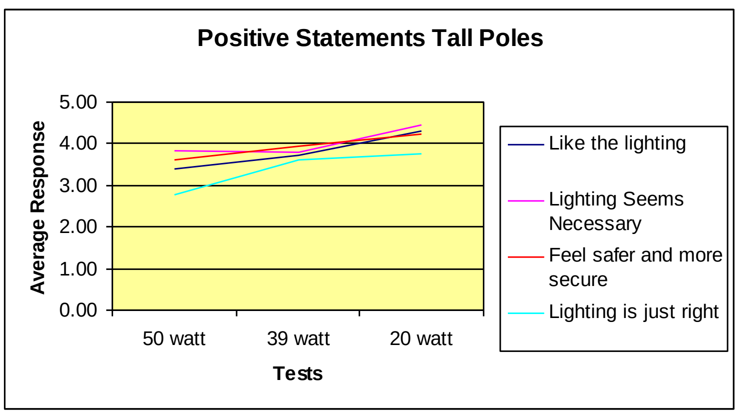
Study Methodology

For each test, park management, employees and others were asked to review the site at night during specific periods during which the lights would be turned on. Surveys using the attached forms were collected.

Sample groups averaged 17 persons, ranging from 15 to 21. For all surveys, 35.3% of respondents were NPS or DNC management employees; 5.9% were security or law enforcement personnel; 9.4% were resident employees (except management, law enforcement, or security); 21.2% were architects, landscape architects, engineers, and other consultants; and 7.1% were park visitors or guests.

At this time, data analysis has been limited to simple averages and observations with respect to the data trends. For tall poles, the survey results were as follows:

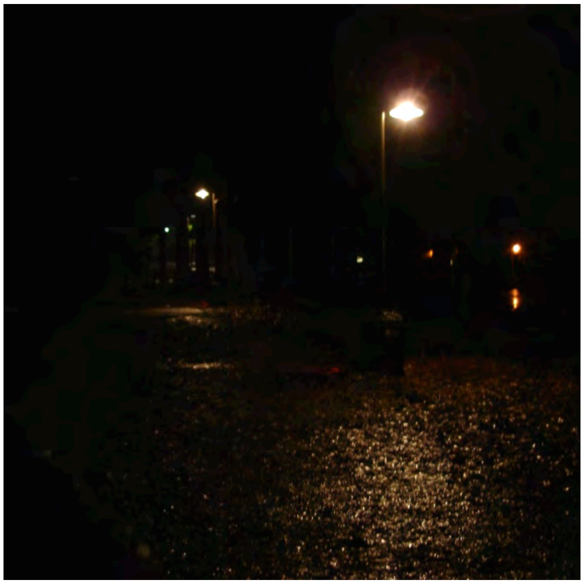




Reviewing the data, there are no anomalous data points among the 20 watt data set; however, among the 39 and 50 watt sets, there were apparently two subjects opposing the majority. The impact of their opinions are included in these results.

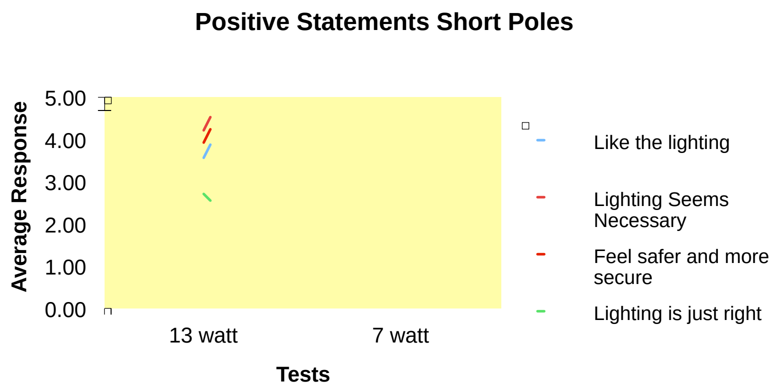
Walkway – Pedestrian Poles

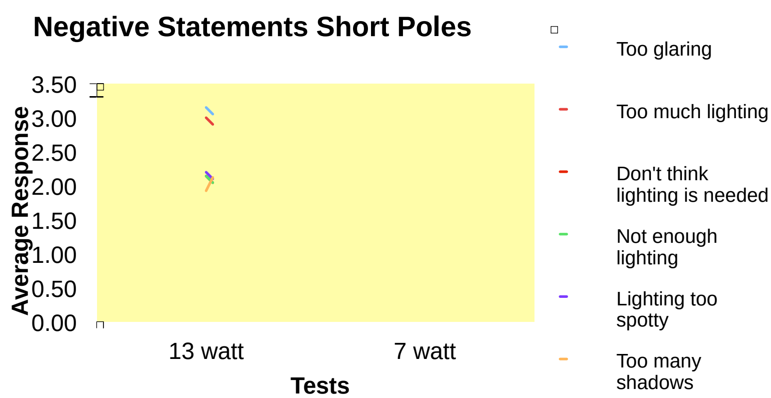
- Bases set at locations to match proposed Curry Village locations. Approximate spacing is 50' apart, lighting from one side only. .
- First test: 13 watt compact fluorescent lamps as specified in large full cut off luminaires with 4" diameter poles. Operated between October 3 and November 22. Survey group B-1.
- Second test: 7 watt T-6 compact fluorescent lamps in smaller glass jar luminaires "bow-tie" side shielded luminaires mounted to 4" diameter poles. Operated between November 22 and November 28. Survey group B-2.



(Left) Mockup showing three lights in a row; (right) interior detail showing type II shield. Photos: Debbie Cooper.

The survey results were as follows:





In reviewing the data, during the 7watt test there was some anamolous data with respect to the “spotty” question. All other data from both tests appeared reasonably normal and distributed.

About Light Levels

Side conditions did not permit appropriate measurement of resulting exterior light levels. Limiting factors included rain, topography, and extremely low light levels below the accuracy of available field meters. It was determined to employ calculations based on fixture photometry to determine light levels for the mockup conditions.

In addition, given the extreme conditions of the environment, it is critical to establish boundaries on where light levels should be calculated or measured. Since it is intended to maintain a natural light level (<<.01 footcandle on a new moon) in immediately adjacent areas wherever possible, classical calculations using averages and factors such as max:min ratio can deliver misleading results. A complete photometric summary will be provided in a later report based on tests not yet completed by AAL.

For the purposes of this report, the following are approximate light levels from the study:

Study	*Average light level, horizontal classical (paved area only)*	*Key Horizontal light level and location*	*Key Vertical Light Level and Location*	*Note*
Parking Lot, 20 watt lamp	0.10 fc initial	0.10 fc initial isocandle line approx. 30' from curb line nearest base of light poles	.05 fc average on the vertical plane between 0 and 5' high, facing the lights 50' away	The vertical measurement point corresponds with the trunk loading area of vehicles parked opposite the lights.
Parking Lot, 39 watt	0.20 fc initial	0.20 fc same spot	0.10 fc same average	
Parking Lot, 50 watt	0.25 fc initial	0.25 fc same spot	0.125 fc same average	
Walkway, 13 watt shoebox optical system	0.10 fc initial	.02 fc at center of walk between two fixtures	.05 fc at 5' above grade facing luminaire 20' away	The vertical measurement point is approximately where subjects suggested the need to achieve facial recognition
Walkway, 7 watt type II modified jelly jar optic with shade	0.10 fc initial	.02 fc at center of walk between two fixtures	.05 fc at 5' above grade facing luminaire 20' away	

These light levels will be confirmed in the final Guidelines.

Interpretation and Discussion

On November 28, stakeholders including design team, NPS management and security, DNC manag
ement and security, and contractor personnel reviewed the last phase of the mockup together. Most attendees had also attended the start of the mockups on October 3 as well.

There is a very strong correlation between the opinions of stakeholders and the data collected from them and other viewers. During discussions at the conclusion of the viewing period on November 28, the on site consensus was that

- Light levels were adequate under the final conditions (20 watt metal halide lamps in taller poles, and the new 7 watt lamps in shorter poles)
- The lighting seemed about right and appropriate
- The tall parking lot lighting levels were discussed with a consensus that light levels were probably minimally acceptable.
- The new walkway poles were appropriate in scale and light level, with a minor concern about glare caused by the visible lamp tip and perhaps a need for a little more light.

Because lighting systems were clean and using new lamps, it was understood that the lighting systems were generating as much light as they ever would, and typical light levels would be 30-40% lower.

Based on observations and data, we recommend:

1) Proceed with taller poles using 20 watt lamps. The trend lines of the surveys clearly indicate growing preference as light levels were reduced, without loss of sense of security and safety. If in the long term light levels prove to be inadequate, the 20 watt lamp can be directly replaced with a 39 watt lamp by changing the lamp and ballast only.
2) Modify the shorter poles as follows:
    a. Reduce pole to 3” diameter.
    b. Improve lamp cut off side shielding to correspond to approx. ½ of the distance between poles.
    c. Consider higher wattage lamp, e.g. quad 13 watt.
    d. Pull globe up into fixture further.

Jim Benya
April 6, 2006

Yosemite National Park
Lighting Guidelines and Standards Project

BENYA LIGHTING DESIGN

Project Report #3

Project Status Report

Submitted for review and comment April 6, 2006
Resubmitted August 24, 2006

Introduction

In 1997, Draft Lighting Guidelines were developed by Benya Lighting Design, and have served as an interim guide to lighting for new projects. In September, 2005, work began to complete the Guidelines, using new projects as an opportunity to test original theories and to produce lighting Standards for future projects. Some mockups were planned (see Project Report #1) and carried out (see Project Report #2.) This Report is intended to summarize all work to date and to establish plans to complete the balance of the Project.

Work Completed

The following work has been completed. In general it closely follows the tasks of the contract, deviating only to take maximum advantage of the Curry Village Housing project to permit two significant mockups and related surveys.

Consultant Services

- Consult on Curry Village Employee Housing project.
- Be available on a consultant basis to provide professional advice and opinion on current and ongoing projects.

Guidelines

- Review Draft Lighting Guidelines originally produced in 1997.
- Establish a scientific foundation for the Illumination Criteria set in the
- Guidelines.
- Expand Guidelines to include interior lighting to the extent that it affects exterior lighting.
- Based on experimental data and scientific conclusions, confirm Illumination criteria.

- Attend and/or conduct review meetings necessary to obtain support and buy-in from NPS, DNC, and/or current A/E consultants.

Standards

- Develop initial proposed Standard design concepts and products for all exterior lighting applications.
- Based on Stakeholder comments, engineer and review the installation of lighting mockups of significant proposed specific lighting products and applications.
- Review the mockups and survey Stakeholders as well as Park employees, NPS and DNC staff, and other interested parties.

Work to be Done

Consultant Services

- Be available on a consultant basis to provide professional advice and opinion on current and ongoing projects.

Guidelines

- Update Draft Lighting Guidelines originally produced in 1997. This will include adding supporting graphics such as diagrams, photos, light patterns, etc.
- Establish a legal foundation for the Illumination Criteria set in the Guidelines. This will include a literature survey, and interviews with Park Personnel and Solicitors General.
- Expand Guidelines to include interior lighting to the extent that it affects exterior lighting.
- Based on experimental data and scientific conclusions, confirm Illumination criteria.
- Revise and produce a Final Draft of the Guidelines to be circulated for review. The Guidelines shall reference Standards developed as part of this work.
- Attend and/or conduct review meetings necessary to obtain support and buy-in of the document from NPS, DNC, and/or current A/E consultants.
- Complete the Lighting Guidelines including internal and external reviews. Prepare camera-ready printed documents and PDF documents and deliver to DNC and NPS in both hard copy and electronic formats.

Standards

- Complete proposed Standard design concepts and products for all exterior lighting applications.
- Present proposed lighting Standards for Stakeholder review and comment. Comments will be received and responses developed.
- Based on Stakeholder comments, engineer and review the installation of one or two lighting mockups of significant proposed specific lighting products and applications not already resolved. Deliverables shall include completely engineered drawings and specifications with California PE Seal.
- Review new mockups and survey Stakeholders as well as Park employees, NPS and DNC staff, and other interested parties.
- On the basis of the mockup and survey results, produce a Final Draft of the Standards to be circulated for review. The Standards shall be coordinated with and reference Guidelines developed as part of this work.
- Attend and/or conduct review meetings necessary to obtain support and buy-in the document from NPS, DNC, and/or current A/E consultants.
- Complete the Lighting Standards including internal and external reviews. Prepare camera-ready printed documents and PDF documents and deliver to DNC and NPS in both hardcopy and electronic formats.

Light Pollution Mitigation Measurement

- Work with NPS Dark Sky Task Force to establish an acceptable measurement system and protocol to track mitigation progress at Yosemite.
- Conduct the initial survey and record the data. Prepare camera-ready printed documents and PDF documents and deliver to DNC and NPS in both hardcopy and electronic formats.

Proposed Schedule

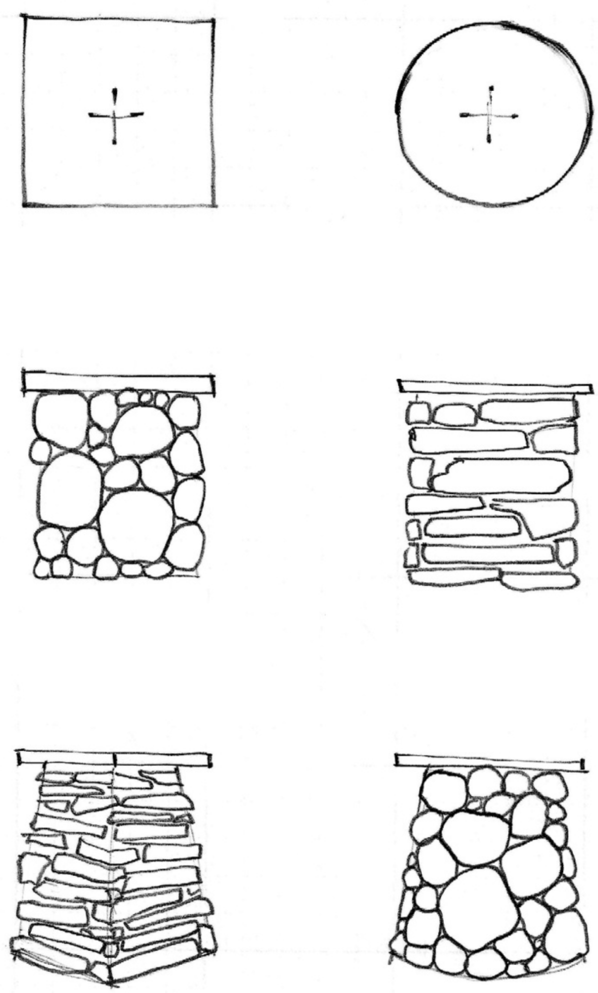
August 2006	Develop proposed lighting Standards. Determine need for mockups. NPS Dark Sky team meeting at Yosemite.
September 2006	Stakeholder first review of proposed standards and mockups at Yosemite. Initiate mockups. Confirm legal aspects of proposed Guidelines. Begin Guidelines revisions.

October 2006	Install mockups. Complete Guidelines revisions. First draft of Guidelines produced for stakeholder review.
October 2006	Data collection from mockups of Standards. Stakeholders submit Guidelines comments. Stakeholder Guidelines review meeting at Yosemite. Dark Sky meeting at Yosemite.
November 2006	Complete mockups. Data Analysis First draft of Standards produced for stakeholder review.
November 2006	Stakeholder Standards review meeting at Yosemite.
December 2006	Final draft of Standards produced for review. Final draft of Guidelines produced for review. Final draft of Dark Sky program produced for review.
December 2006	Review comments from all stakeholders on all project work.
December 2006	Produce final copies of all documents.

Respectfully submitted for approval,

Jim Benya
April 6, 2006 Revised August 24, 2006

APPENDIX E - POLE BASE OPTIONS (DISCUSSED 2008-2009)



The architecture of the base for lighting poles and bollards was discussed without specific resolution. The base should be considered in the context of each project; the above examples are meant to employ indigenous materials to protect and conceal the base.

APPENDIX F LED MOCKUP NOVEMBER 2007

In the fall of 2007, BK Lighting of Fresno manufactured three LED luminaires for testing at Yosemite. These luminaires employed a new high efficiency LED optical system in a pole design that the design team through might be acceptable. These comments were collected by NPS.

Meeting Notes
Yosemite National Park Lighting Program
Mockup Test of LED Luminaires
November 6, 2007

A mockup consisting of (3) short pole luminaires and (2) tall bollard luminaires employing state of the art LED sources was held outside of guest cabins at Curry Village between 5PM and 7PM. The test was witnessed and reviewed by NPS and YCS/DNC personnel, architectural standards team, the lighting consultant, and two representatives of the company supplying the equipment, BK Lighting of Fresno.

The poles were arranged along the main walkway about 45 feet apart. The bollards were placed between cabins nearby about 50 feet apart.

Attendees comments were noted as follows.

Supportive Comments (most reviewers in agreement)

1. The poles are attractive with good proportions and the simple contemporary shape is appropriate.
2. Pole color is good.
3. The quantity and distribution of light was very good to excellent from both sources.
4. The concept works, but improvements are needed before implementation.

Critical Comments (most reviewers in agreement)

5. The poles were glaring. A longer hood is needed. In addition, some form of shielding should be considered for the acrylic shade.
6. The short poles should have larger hoods too.
7. The light color is too cool.

Mixed Comments (no consensus of reviewers)

8. The proportions of the bollards might be improved. Consider a larger diameter base similar to the pole.
9. The bollards might be too tall. Consider shortening to more conventional bollard height.

Summary

The test was a successful proof of concept with both proposed systems performing as well or better than previously tested or used HID and compact fluorescent systems of similar lumen/power levels.


B-K LIGHTING