International Dark-Sky Association

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

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Abstract

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

Introduction

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

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

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

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

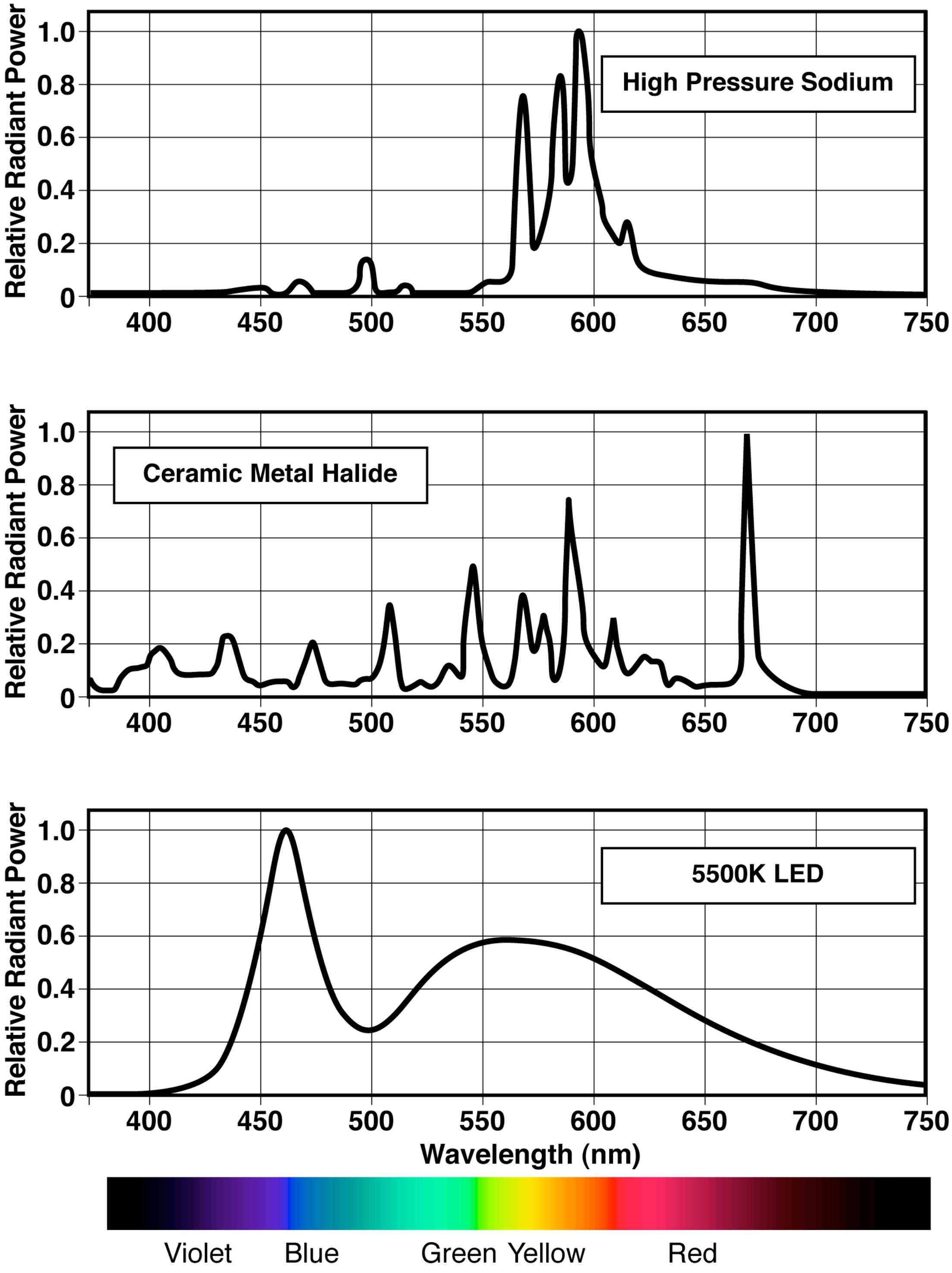

Figure 1. Typical spectral power distributions of HPS (orange); ceramic metal halide (cyan); white LED (blue).

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

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

Physical Processes

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

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

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

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

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

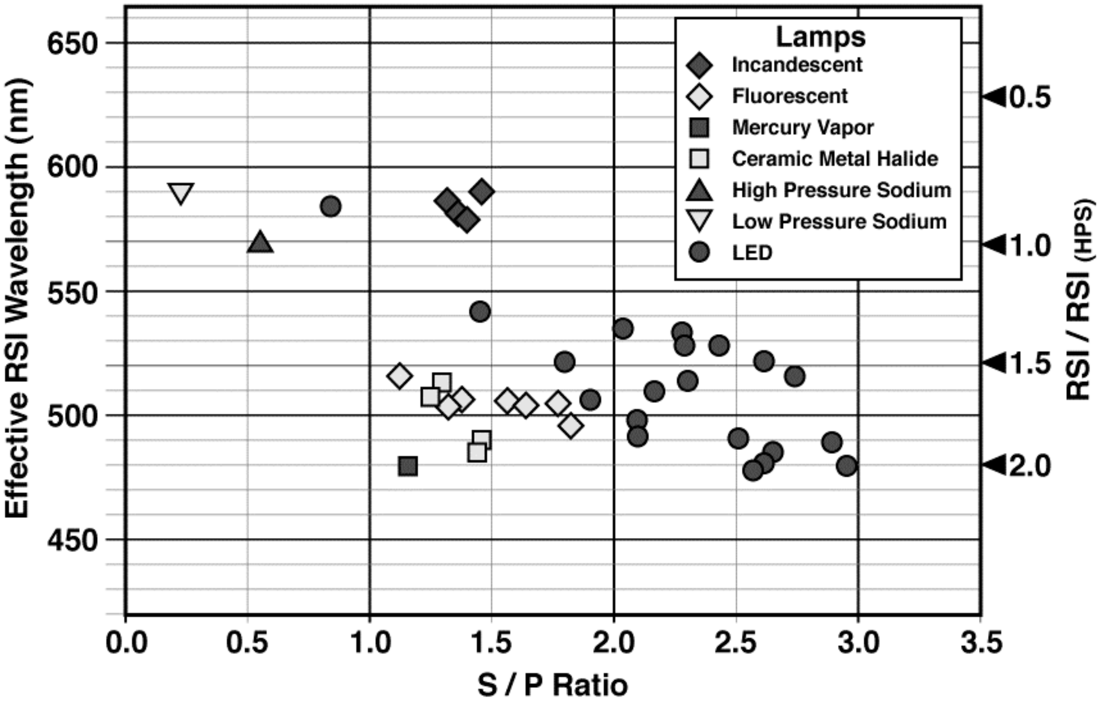

Figure 2. Rayleigh Scattering Index relative to HPS, and effective RSI wavelength for a selection of lamp types vs. their scotopic/photopic ratios S/P.

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

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

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

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

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

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

Human Vision

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

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

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

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

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

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

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

Pupillary Response

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

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

Adaptation

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

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

Glare

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

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

The Aging Eye

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

Health Effects

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

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

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

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

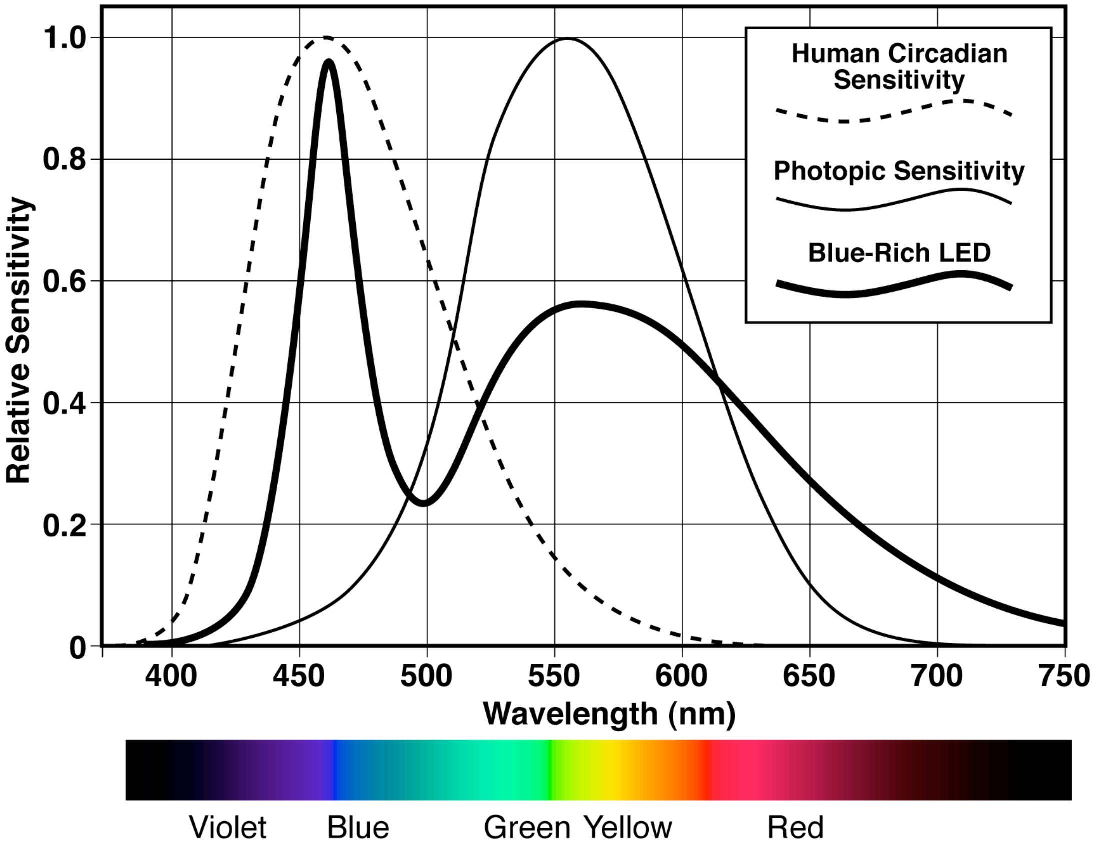

Figure 3. Human photopic and circadian sensitivity curves displayed against a typical blue-rich LED light source spectrum.

Environmental Effects

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

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

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

Examples of Wildlife Disturbance

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

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

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

Circadian Disruption in Wildlife

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

Sky Glow, Astronomy, and the Natural Nightscape

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

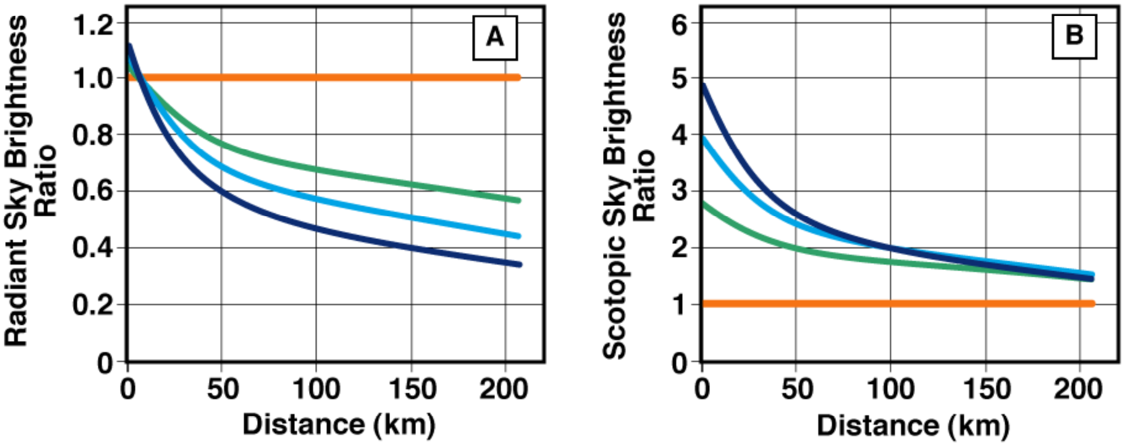

Figure 4. a) Radiant and b) visual (scotopic) sky brightness ratio as a function of distance for equal-radiance light sources with effective wavelengths of 480nm (blue), 500nm (cyan), and 520nm (green), all relative to HPS (yellow) (from Luginbuhl et al., 2010).

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

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

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

Conclusions

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

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

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

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

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

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

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

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