Seeing Blue

Poorly designed outdoor lighting is one of the most conspicuous forms of energy waste. The global call to conserve energy resources has cities scrambling to replace public lighting with brand new systems. In the U.S., changes are further spurred by federal economic stimulus funding. Technology under development for decades has produced a number of options, many with a potential for energy savings. Of these, high brightness white light emitting diodes (LEDs) have emerged as an industry favorite.

Many of these new options have never been applied on a broad scale, and may have unexpected consequences if widely used for outdoor lighting. In particular, the stronger blue emission produced by white light sources, such as LEDs, has been shown to have increased negative effects on astronomy and sky glow, and has a greater impact on animal behavior and circadian rhythms than other types of light. Widespread installation of white light sources rich in blue emission is among the largest concerns of the dark sky movement.

Lamp choices made today will affect night lighting for decades, maybe longer. It is imperative that decision makers understand the consequences—both positive and negative—of lighting choices. On 4 May 2010, IDA released a comprehensive review paper titled *Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting*, to raise awareness of likely or potential negative consequences of blue-rich white light (BRWL) and to help governments and the industry balance these consequences against the more widely touted benefits.

This article provides an introduction to the controversy surrounding BRWL. To fully understand the problems, we must first understand its properties.

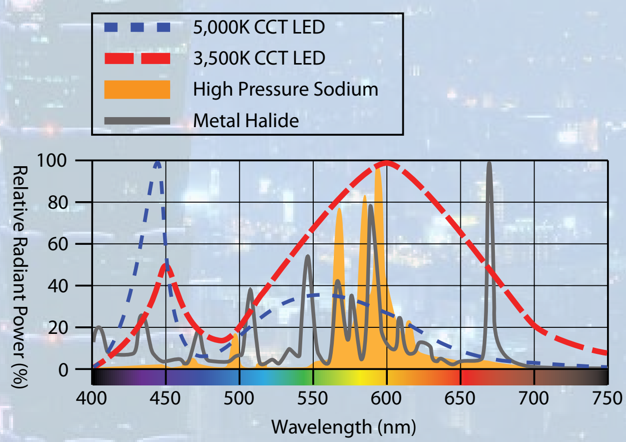
Spectral power

Beauty may be in the eye of the beholder, but the eye relies upon light. Light visible to humans has wavelengths from about 380 to 760 nanometers (nm), with longer wavelengths appearing red and shorter wavelengths appearing blue and violet.

Different lamps have different spectra: a lamp's spectral power distribution is a quantitative measure of the amount of energy (or power) emitted at different wavelengths. The broad spectral characteristics of different lamps are often discernible to the naked eye. "Warm white" sources that emit more strongly at the middle and longer (red) wavelengths, such as incandescent bulbs, are often aesthetically preferred. "Cool white" sources with a spectral power distribution favoring short wavelengths cast a light that appears harsher and colder to many observers when used for artificial lighting, even though it may approximate the color of daylight.

Much of the recent interest in BRWL sources stems from two factors. The first is the rapid improvement in the efficiency of white LED lighting. LEDs promise to soon surpass current lighting technologies in the ability to produce light for less energy. Further, LEDs produce light in a way that can be more effectively controlled, increasing efficiency of fixtures and allowing light to be delivered precisely to the areas where and when it is needed.

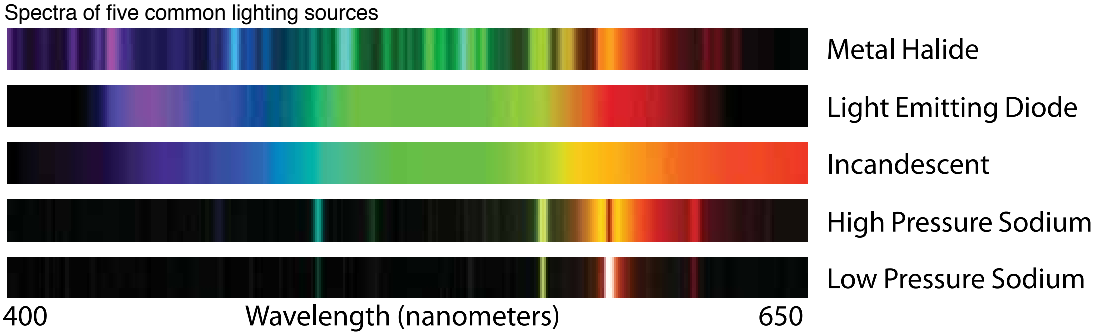
The second factor is more complex, and more controversial. LEDs can be made in nearly every visible color, but the most efficient formulations are rich in blue light, because blue wavelengths activate phosphors which provide the other colors necessary for high quality white light.



Warm white LEDs under 3,500K CCT emit a smaller fraction of their energy in the blue portion of the spectrum.

Eric Chen

Spectra of five common lighting sources



Dark-adapted (nighttime) eyes are more sensitive to shorter (bluer) wavelengths than light adapted (daytime) eyes. Therefore, all else being equal, a light source producing more blue light will tend to appear brighter to the dark-adapted eye. Some lighting researchers have proposed "correction" factors that allocate extra lumens (a measure of visible light output) to cool-white sources. This leads to an apparent additional increase in efficiency for blue-rich white LEDs. Those with more blue emissions—called *high Correlated Color Temperature (CCT) LEDs*—benefit the most from this correction. The controversy arises, however, because under night lighting conditions the eyes are not fully dark-adapted. Instead, under typical outdoor environments illuminated by artificial lighting, our eyes have a mixed visual response, with a complex and only partly understood combination of the characteristics of light-adapted and dark-adapted vision (from the eye's cone cells and rod cells respectively). This means that the benefits of BRWL sources in the real world are usually less, often much less, than predicted by the simple correction factors that have been proposed to explain response under laboratory conditions. In other words, much of the benefit of BRWL sources is only realized when illumination is much fainter than commonly encountered in artificially illuminated outdoor environments and when the distribution of light is tailored to take advantage of the eye's response.

Research in visual, environmental, and health sciences indicates that our understanding of the effects of light at night, in particular BRWL, lags behind the development and use of lighting technologies. From a historical perspective, increases in lamp efficiency have not yielded expected savings, as such technological advancements were often utilized to apply more light, light areas and tasks that were not previously lighted, or otherwise not matched by changes to lighting practices that leveraged these technological advancements. The current initiative to create the most energy efficient lamp technology threatens to disappoint those who look to LEDs and other BRWL sources as a technological salvation. Furthermore, such light carries a greater impact to the dark nighttime environment and may have unintended consequences for human vision and health.

The IDA white paper

In October 2009, IDA convened a panel of 16 experts in Tucson, Arizona to evaluate concerns about BRWL. The group produced a press release on 10 October 2009 and initiated work on a comprehensive paper reviewing the issues. A draft white paper was released to a select audience in February 2010. In the months that followed, the BRWL draft white paper received dozens of comments as part of a formal review. After constructive feedback, refining and expanding the research, and substantive changes to the text, the endeavor grew into a comprehensive review of BRWL in a number of contexts. It was released on 4 May 2010 as a white paper entitled *Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting*.

The paper documents the effects of BRWL and examines existing research to define what is and is not known about the benefits and limitations of BRWL. The review of current knowledge illuminates specific concerns about the impacts of BRWL on the nighttime environment, as well as gaps in research, that suggest directions for future studies. It will be used as a basis for official IDA recommendations and position statements, and has been offered as a resource to the lighting industry. It is the intention of IDA to assist government and industry officials in gaining full knowledge of the impact of BRWL on vision, ecosystems, and the nighttime environment, thus enabling these bodies to avoid pitfalls that may otherwise undermine the transition to a very promising new technology.

Known effects of blue-rich white light

BRWL sources are popular options wherever LED streetlights are installed. Cities or municipalities considering changes to their public lighting would benefit from increased awareness of these lamps' potential effects. Members and advocates are encouraged to disseminate this research. Findings are summarized below. The full white paper is available for download on the IDA Web site, *www.darksky.org*

Visibility

Most illumination levels at night engage mesopic vision, which is comprised of both photopic (high light level vision using cones) and scotopic (low light level vision using rods) function. There is currently no universally applicable metric to define or measure mesopic function, as the eye-brain system blends the two realms of vision in complex ways. Several efforts to articulate how such mesopic vision works have been proposed; perhaps the most developed system is the one proposed by the International Commission on Illumination (CIE) (described in TC 1-58). Many age-, time-, and illumination-level-variable visual functions are of concern when

This test street in Anchorage, Alaska, USA compares the quality of light from warm, low CCT LEDs (right foreground), high pressure sodium vapor (left middle) and cool, high CCT LEDs (right background). The residents of this street preferred the warm LEDs in the foreground.

designing outdoor lighting, including utility, detection of objects (in both central and peripheral vision), identification, adaptation, and aesthetics. The interrelation of all of these with lamp spectral power distribution is poorly understood outside of controlled laboratory experiments. The premature adoption of a mesopic system would substantially skew the engineering metrics used to define lamp efficiency while not capturing the true utility of such light for human needs.

Glare

Glare reduction is a critical design aspect for all outdoor lighting installations and lamp types. Research done as early as 1955 indicates that BRWL causes more glare, with later studies confirming a wavelength of approximately 420 nm to be most closely linked with discomfort glare. It has been widely observed that BRWL headlights on automobiles are perceived as more glaring than conventional halogen headlights. A light source with increased spectral output below 500 nm will increase the perception of glare, particularly for older people, and is more likely to hinder vision than a conventional source of the same intensity.

Blue-rich artificial light

Adaptation and the aging eye

Several studies indicate that blue light reduces pupil size more than other types of light, especially at lower lighting levels. Blue light also increases the time it takes for the eye to adapt to darkness or low-level lighting.

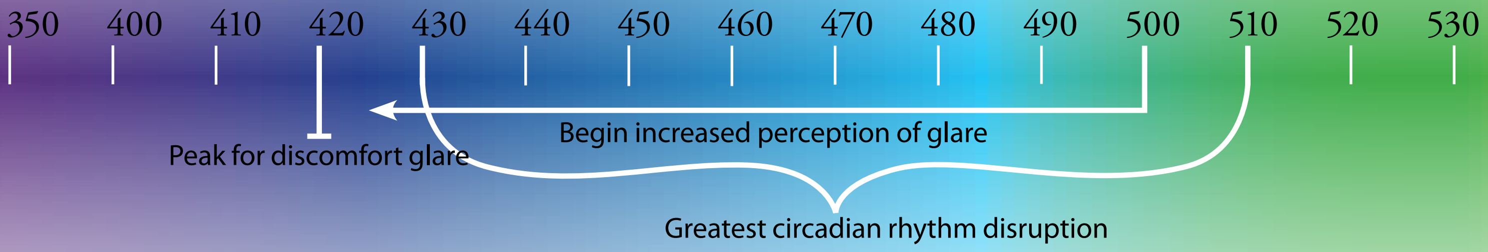
As the eye ages, it requires more light and greater contrast to see well. The lens yellows and becomes less transparent with time, and yellowed lenses absorb more blue light; thus, less total light reaches the retina of older people, especially when BRWL sources are used. In addition, older pupils are in general more constricted, increasing the amount of time it takes to adjust to different light levels. BRWL contributes to slowing these adaptation processes.

Atmospheric scatter and sky glow

Increased scattering from BRWL sources leads to 15% to 20% more sky glow detectable by an astronomical instrument than high-pressure sodium (HPS) or low-pressure sodium (LPS). Due to the eye's increased sensitivity to blue light at lower levels, the visual brightness of sky glow produced by BRWL can appear three to five times brighter than it appears with HPS and up to 15 times as bright when compared to LPS.

BRWL contributes to sky glow in a portion of the spectrum that currently suffers little artificial sky glow. Further, under natural conditions the brightness of the sky in the blue portion of the spectrum

Recommended wavelength range for minimizing adverse effects of blue light on sky quality



is lower. In other words, BRWL introduces a different type of light pollution, to a part of the spectrum that is relatively dark and relatively less polluted. Thus, widespread use of BRWL will substantially increase the degradation of visual and astronomical sky quality.

Ecological considerations

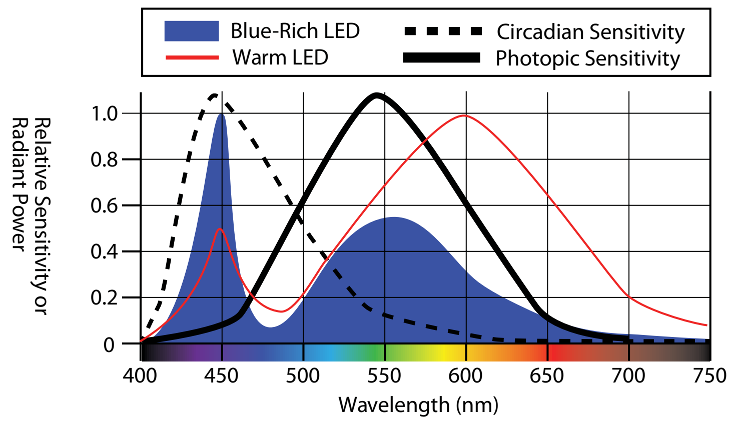
Artificial light in the environment must be considered a chronic impairment of habitat. However, while there is evidence that artificial light affects species behavior, diet, movement, and mating, the relationship between artificial light and wildlife has rarely received the level of study that definitively answers questions about spectrum and illumination threshold.

While no absolute conclusions have been drawn, previous research suggests BRWL heightens response in certain species. Loggerhead sea turtles are ten times more likely to be attracted to light at 450 nm than 600 nm, with four Atlantic sea turtle species showing a similar spectral misorientation response. Light sources that have a strong blue and ultraviolet component are particularly attractive to insects, though broad spectrum sources are known to attract insects as well. Changes in insect behavior often affect numerous other species that prey on insects, including amphibians and bats. Additionally, the circadian response of wildlife often resembles that of humans; thus even if a species exhibits no behavioral or orientation response to BRWL, such light may be altering the diurnal and nocturnal patterns of wildlife.

Evidence does not indicate that the behavior of all species is altered by short-wavelength light. Some birds have exhibited a stronger attraction to red light, while others avoid it. It is because of these discrepancies and interspecies behavioral unpredictably that IDA advocates for comprehensive studies that investigate spectral effects to be performed before radically different light sources are widely introduced into nocturnal ecosystems.

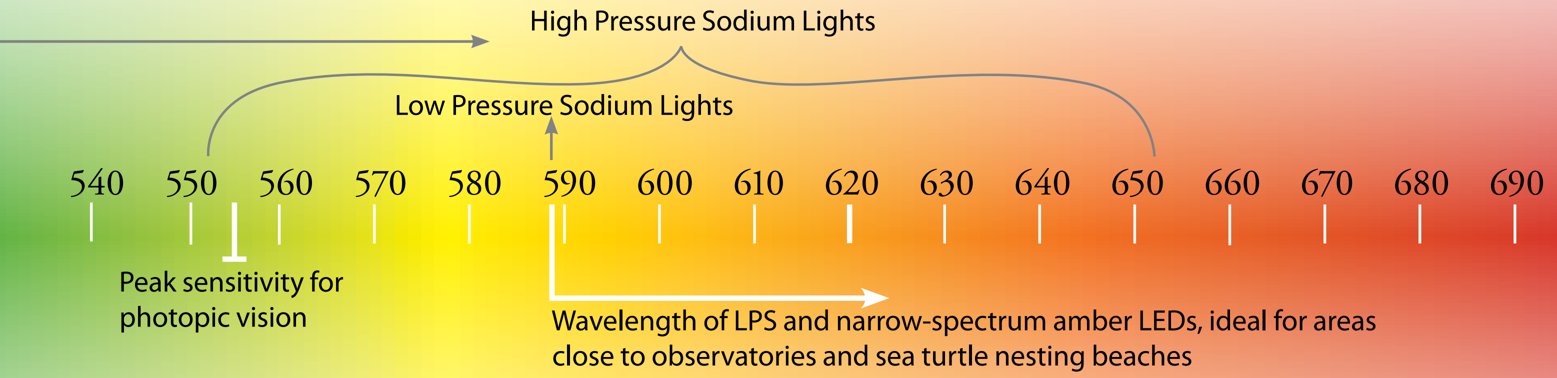
Circadian disruption

Light inhibits secretion of the hormone melatonin. Blue light between 430 and 510 nm shows the greatest disruption of circadian rhythm and melatonin secretion, with peak sensitivity around 460 nm. Melatonin levels dictate circadian cycles and play a role in immune system function of animals and humans. Studies have effectively linked low melatonin production with the growth of some human cancers, notably breast cancer. Some studies suggest that the illumination threshold for melatonin disruption is quite low, but no exact amounts have been found. 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 light on melatonin production, and the effects of melatonin on human cancer growth in certain laboratory experiments, are uncontroversial. 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.



Human photopic and circadian sensitivity curves displayed against a typical blue-rich and warm white LED spectrum.

Less than two weeks after IDA published this white paper, the Rensselaer Polytechnic Institute's Lighting Research Center released the study *The Potential of Outdoor Lighting for Stimulating the Human Circadian System*. The study expresses skepticism of claims that BRWL can affect circadian rhythm to the point of serious harm, yet shows that exposure to 6,500K CCT light



at streetlight lighting levels for just one hour is expected to show measurable effects on human melatonin production. Its statement that "…continued investigations of light-induced disruption of the human circadian system are clearly warranted" corroborates IDA's assertion that further testing is necessary before the widespread introduction of new BRWL technologies. While IDA clearly does not want to raise undo alarm or over-generalize the connection between human health and artificial light, the widespread adoption of BRWL sources and the number of people potentially affected result in a risk factor that must be acknowledged by engineering, environmental and human health professionals.

A unified approach

Thomas Edison quipped that he had to first learn 1,000 ways to not build a light bulb before he learned how to build one. With each attempt, he drew upon his wide-ranging intellect, his concern for his fellow man, and his fortitude for hard work. His efforts resulted in the first viable electric lamp 130 years ago. Today we are still "always finding a better way" to use electric lighting, particularly outdoors.

The question before us now is far deeper and wider than what is the optimal technology for producing light. Though cultural tastes, government initiatives, short-term economics, and environmental ethics may dictate market fads, professional lighting engineers recognize that the best light is one that balances a range of needs and concerns. Objective, professional research is needed to provide manufacturers with data needed to minimize light pollution while considering other variables. A light source, fixture, or design that optimizes only one aspect will likely fail miserably when introduced in a wider context. Sustainable lighting must cross multiple realms—technical, environmental, and socioeconomic. The IDA encourages such a holistic approach, and will continue to ensure that the environmental, cultural, social, and civic aspects of protecting dark skies and the nighttime environment are collectively addressed by the lighting industry, government, and community leaders.

Technical editing by Christian Luginbuhl, Chadwick Moore and Terry McGowan

What do we do now?

Cities ready to make immediate changes to their outdoor lighting may not have time to wait for results of extensive testing of new light sources. IDA offers the following suggestions for communities currently planning lighting retrofits using LEDs:

Always choose fully shielded fixtures that emit no light upward.

Use "warm-white" or filtered LEDs (CCT lower than about 3,000K) to minimize blue emission.

Look for products with dimming capabilities; consider dimming or turning off the lights at late hours.

Work with utility companies to establish a reduced rate for dimmed or part-time lighting.

Consider the longevity of the entire fixture over the longevity of the light source alone. Power supply or conduit failure will require fixture maintenance even if there is nothing wrong with the lamp itself.

The future of light?

Solid state lighting has the potential to revolutionize outdoor lighting in a profoundly positive way. LED lighting in particular can be fine tuned to decrease most negative impact on the night environment. Their directionality and controllability opens the door to energy saving innovations and facilitates the large scale implementation of automatic timers, dimmers, and sensors. LED efficiency and longevity may provide a real contribution to the world's lighting needs.

Right now, the variance and speed in LED product development is nothing short of astounding. Basic SSL technology has advanced to the point where a broad range of finely tuned and radically different LED applications are appearing more or less continuously on the market.

If developers concentrate on creating high efficacy lamps rich in warm hues, LED technology could become an outstanding source for energy efficient, night sky friendly outdoor lighting. Already, some LED developers are creating a highly efficient product with a spectral power distribution (SPD) that avoids peaks in any wavelength. Driven by an indicated aesthetic preference for warm-toned hues, these manufacturers are developing high efficacy commercial LED products with significantly reduced blue spectrum emissions. Philips Lumileds, Osram, and Seoul Semiconductor have created notably broad spectrum light sources at efficiencies that are among the industry's best, and tout a significantly increased Color Rendition Index. Cree is developing a product that emits less blue light than some conventional High Intensity Discharge lamps used today. If development continues to advance in this way, dark sky advocates and industry leaders will soon have a number of eminently usable LED products for residential, commercial, and public application.

However, warm white LED technology cannot by itself provide the answer to the world's outdoor lighting needs without the continual application of sensible lighting principles and practices. While lamp efficiency and consideration of SPD are significant accomplishments, true night sky friendly lighting can still only be achieved by vigilant examination of how much light actually needs to be used and routine implementation of minimum levels required for security and recreation. LED innovations represent an important tool in the dark skies movement, but we must be sure to wield it wisely.