GMO-2802

Exhibit No.:	
Issue:	Rate Design, LED Lighting
Witness:	Robert Wagner
Sponsoring Party:	Robert Wagner
Type of Exhibit:	Rebuttal Testimony
Case No.:	ER-2010-0355 ER-2010-0356
Date Testimony Prepared:	December 10, 2010

MISSOURI PUBLIC SERVICE COMMISSION

CASE NO. ER-2010-0355

CASE NO. ER-2010-0356

REBUTTAL TESTIMONY

OF

ROBERT WAGNER

ON BEHALF OF

ROBERT WAGNER

Kansas City, Missouri
December 2010

Wagner Exhibit No. GMO2802
Date 2/4/11 Reporter LMB
File No. ER-2010-0356 & 0355

Q PLEASE STATE YOUR NAME AND ADDRESS

A My name is Robert Wagner and my address is 9005 N Chatham Avenue, Kansas City, MO 64154.

Q WITH WHAT ORGANIZATION ARE YOU AFFILIATED WITH AND IN WHAT CAPACITY?

A The International Dark-Sky Association. I serve as the President of the Board of Directors. See RAW2010-1

Q ON WHOSE BEHALF ARE YOU TESTIFYING?

A I am testifying on behalf of myself, Robert Wagner, Pro Se Intervener

Q HAVE YOU FILED TESTIMONY PREVIOUSLY BEFORE THE COMMISSION?

A Yes, I filed direct testimony in ER-2010-0355 and ER-2010-0356.

Q WHAT IS THE PURPOSE OF YOUR REBUTTAL TESTIMONY?

A I would like to present additional information on the Staff's recommendation to require KCP&L to complete its evaluation of LED SAL systems and file LED lighting tariff sheet(s) if the systems are cost-effective. In particular, the testimony of Michael S. Scheperle and Hojang Kang.

Q WHAT ARE YOUR CONCERNS WITH LED SYSTEMS?

A Light Emitting Diode (LED) luminaires currently have some positive aspects and they also have some negative aspects. I am concerned that the information presented will lead the Commission to believe there are only positive aspects to LED lights.

Q WHAT ARE SOME OF THE POSITIVE ASPECTS YOU AGREE WITH?

A LED lights have a huge potential for better control of light pollution issues such as uplight, light trespass and glare. They also have the ability to dim and can be connected to adaptive lighting systems. This allows for the light to adjust lighting levels based on traffic volume and realize addition energy conservation savings.

Q **WHAT ARE SOME OF THE NEGATIVE ASPECTS TO LED LIGHTING?**

A There are several negative aspects the Commission should be well aware of before approving any LED rates. This includes:

- Human health and environmental issues
- Marketing of improved night visibility
- Energy Efficiency
- Potential Regulation as a hazardous product

Q **WHAT HUMAN HEALTH AND ENVIRONMENTAL ISSUES ARE RELATED TO LED LIGHTING?**

A There are many outstanding health questions related to white-blue LED lighting and exposure to light at night (LAN). Historically, this has been focused on disruption of the human circadian rhythm. I have included four articles from the Environmental Health Perspectives journal that outlines the issues (See RAW2010-27, RAW2010-28, RAW2010-29, RAW2010-30). Additionally, ANSES, the French Agency for Food, Environmental and Occupational Health & Safety has raised concerns over the issue of cellular oxidative stress and possible macular degeneration from exposure to blue and white-blue light (See RAW2010-31 and RAW2010-32). In particular, they recommend: "avoiding the use of light sources emitting cold white light (light with a strong blue component) in places frequented by children (maternity wards, nurseries, schools, leisure centres, etc.) or in the objects they use (toys, electronic display panels, game consoles and joysticks, night lights, etc.)". In response to some of these concerns, the Department of Energy released a paper in November 2010 (See RAW2010-33).

Q **WHAT ARE THE CONCERNS WITH IMPROVED NIGHT VISIBILITY?**

A I have attached a paper from the International Dark-Sky Association that goes into detail on this subject (See RAW2010-34). To summarize, there is no consensus among lighting standards organizations that a blue-white LED light provides improved nighttime visibility over existing lighting methods.

Q **WHAT ARE THE CONCERNS WITH ENERGY EFFICIENCY?**

A There is a perception in the public that LED lights alone can offer significant savings over high-pressure sodium (HPS) or low-pressure sodium (LPS) lights. Many of the current LED lights are only 10-15 percent more efficient than HPS lights. These are still less efficient than LPS lights. The most efficient LEDs are blue and have the above-mentioned health concerns associated with them. These lights only achieve a significant reduction in electrical use when combined with a comprehensive municipal streetlight warranting policy overhaul, identifying exactly when to illuminate the street, at what time and to what level. When combined with intelligent systems that can analyze traffic and pedestrian volume and increase or decrease brightness based on real-time conditions the dimming aspects can be fully utilized and true energy efficiency realized. Due to their high initial investment, the slight energy efficiency improvement of LED lights alone has not led to a rate of return acceptable to municipalities without federal grants.

Q **WHAT ARE THE CONCERNS WITH POTENTIAL REGULATION AS A HAZARDOUS PRODUCT?**

A In 2009 I filed a hazardous pollutant petition with the EPA asking them to determine if certain wavelengths of light are hazardous to human and environmental health (See RAW2010-35). If the EPA determines that blue-white lights are hazardous, then those responsible for the lights will need to take some sort of remediation action and may be subject to lawsuits.

Q WHAT IS YOUR RECOMMENDATION REGARDING STAFF'S RECOMMENDATION TO MAKE LED LUMINAIRES AVAILABLE WITHIN A YEAR?

A LED technology is undergoing significant research and developments on a monthly basis. The above-mentioned concerns may be resolved within the next year. It should be noted that there are wide variances in the exposure levels of both interior and exterior lighting. Much of the existing health research has been based on bright, interior workplaces. However, based on these concerns I would recommend the state of Missouri seek a formal response from the EPA on the hazardous pollutant petition before requiring any utility to have LED rates regardless of the efficiency improvements. It is my opinion that having state officials require a utility to offer these products while being aware of outstanding potential public health issues is negligence. In my earlier testimony I identified a part-night photocell that is inexpensive and can save 47% on electricity use. I also testified for the conversion of outdoor lighting rates from listing lumens/wattages to light on the ground. If such a conversion took place, KCP&L would not need to file a separate rate for LED lights, they would be allowed to use them as long as they produced the same amount of light on the ground. The Commission should not be distracted with possible future technology advances while real and significant savings can be achieved with a $12 twistlock photocell replacement and a conversion in rates. Additionally, the Public Service Commission should identify the appropriate state official and request an immediate advisory regarding the known and potential concerns of white-blue LEDs and their impact on public health and especially children.

Q DOES THIS CONCLUDE YOUR TESTIMONY TODAY?

A Yes.

BEFORE THE PUBLIC SERVICE COMMISSION
OF THE STATE OF MISSOURI

In the Matter of the Application of Kansas City Power & Light Company to Modify Its Tariffs to Continue the Implementation of Its Regulatory Plan	)))	**Case No. ER-2010-0355**
In the Matter of the Application of KCP&L Greater Missouri Operations Company to Modify Its Electric Tariffs to Effectuate a Rate Increase	)))	**Case No. ER-2010-0356**

AFFIDAVIT OF ROBERT WAGNER

STATE OF MISSOURI)
) ss
COUNTY OF PLATTE)

Robert Wagner, being first duly sworn on his oath, states:

1. My name is Robert Wagner, I live at 9005 N Chatham Ave, Kansas City, MO, and I am the President of the Board of Directors for the International Dark-Sky Association.

2. Attached hereto and made a part hereof for all purposes is my Direct Testimony on behalf of Robert Wagner consisting of Five (5) pages, having been prepared in written form for introduction into evidence in the above captioned dockets.

3. I have knowledge of the matters set forth therein. I hereby swear and affirm that my answers contained in the attached testimony to the questions therein propounded, including any attachments thereto, are true and accurate to the best of my knowledge, information and belief.

[signature]
Robert Wagner

Subscribed and sworn before me this 10 day of December, 2010.

Judith A. Wagner
Notary Public

My commission expires: March 27, 2011

JUDITH A. WAGNER
MY COMMISSION EXPIRES March 27, 2011
NOTARY SEAL
#07023015
PLATTE COUNTY
NOTARY PUBLIC, STATE OF MISSOURI

Index of Schedules

Robert Wagner - Curriculum Vitae	RAW2010-1
Environmental Health Perspectives, *Missing the Dark Health Effects of Light Pollution*, Ron Chepesiuk, Jan 2009	RAW2010-27
Environmental Health Perspectives, *Switch On the Night Policies for Smarter Lighting*, Luz Claudio, Jan 2009	RAW2010-28
Environmental Health Perspectives, *Lose Sleep, Gain Weight Another Piece of the Obesity Puzzle*, Angela Spivey, Jan 2010	RAW2010-29
Environmental Health Perspectives, *Light at Night and Breast Cancer Risk Worldwide*, Angela Spivey, Dec 2010	RAW2010-30
ANSES Press Kit, Lighting systems using light-emitting diodes: health issues to be considered, 25 October 2010	RAW2010-31
ANSES Opinion, in response to the internally-solicited request entitled "Health effects of lighting systems using light-emitting diodes (LEDs)"	RAW2010-32
U.S. Department of Energy, Solid-State Lighting Programs, *Light at Night: The Latest Science*, November 2010	RAW2010-33
IDA, *Visibility, Environmental, and Astronomical Issues Associated with Blue-Rich White Outdoor Lighting*, May 4, 2010	RAW2010-34
EPA Hazardous Air Pollutant Petition, Robert Wagner, December 4, 2009	RAW2010-35

Robert Wagner
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Kansas City, MO 64154
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rwagner@eruces.com

EDUCATION

University of Missouri - Rolla
B.S. Engineering Management **1991**
Preference: Electrical Engineering

WEBSITES

Midwest Citizens for Responsible Outdoor Lighting	http://mcrol.trianglealumni.org/
Boy Scout's Dark-Sky Camping	http://darkskycamping.googlepages.com/
Missouri Night Sky Protection Act	http://missourinspa.googlepages.com/
Kansas Night Sky Protection Act	http://ksnspa.googlepages.com/

LIGHT POLLUTION ACTIVITES

Kansas City, MO - Exterior Lighting Section Included in Current Drafts of City Ordinance Overhaul **2007-2008**
Worked with various groups to ensure inclusion.

Missouri Night Sky Protection Act **2007-Present**
Developed initial concept and found legislators to get the Act filed. Working with various state agencies to develop light pollution policy for the state.

Kansas Night Sky Protection Act **2008-Present**
Working with various state agencies to develop light pollution policy for the state. Gathering organizations and individuals to support the Act.

US National **2006-Present**
Working to establish coalition of organizations for congressional push. Efforts within the EPA to get light pollution identified as an visibility impairment in Federal Class 1 Areas. Pushing for the release of human health impact studies.

Various Regional **2006-Present**
Provided light pollution education to various localities.

PUBLICATIONS AND PAPERS

- "Dark-Sky Camping Best Practices in Illumination for the Boy Scouts"
  Co-author with Chad Moore and Leo Smith 2007
- "Light Pollution Impact on United States Class 1 Federal Areas"
  Used Google Earth overlay to show the impact of light pollution on EPA protected areas. 2007

OCCUPATION

ERUCES, Inc. 11142 Thompson Avenue, Lenexa, KS 66219
IT Manager responsible for company infrastructure. Providing training and support for encryption products used by various customers.

MEMBERSHIPS

- International Dark-Sky Association – President, Board of Directors
- Sierra Club, The National Audubon Society, Missouri Parks Association
- Eagle Scout; Assistant Scoutmaster, Troop 1495; Den Leader, Pack 4348
- Philmont Staff Association, Charles L. Sommers Alumni Association, Sea Base Alumni and Friends Association, National Eagle Scout Association – Boy Scouts of America

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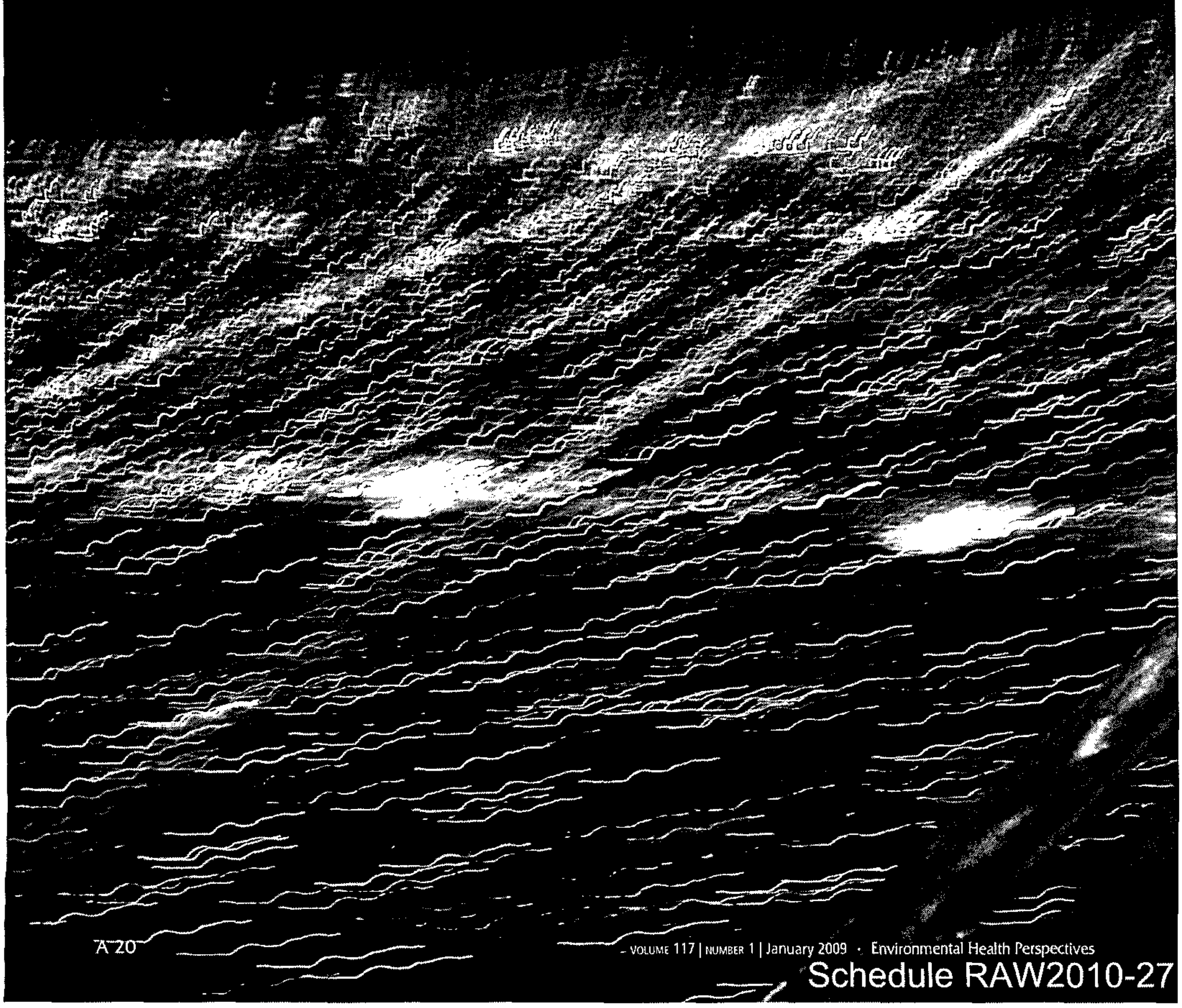
Missing the Dark
Health Effects of Light Pollution



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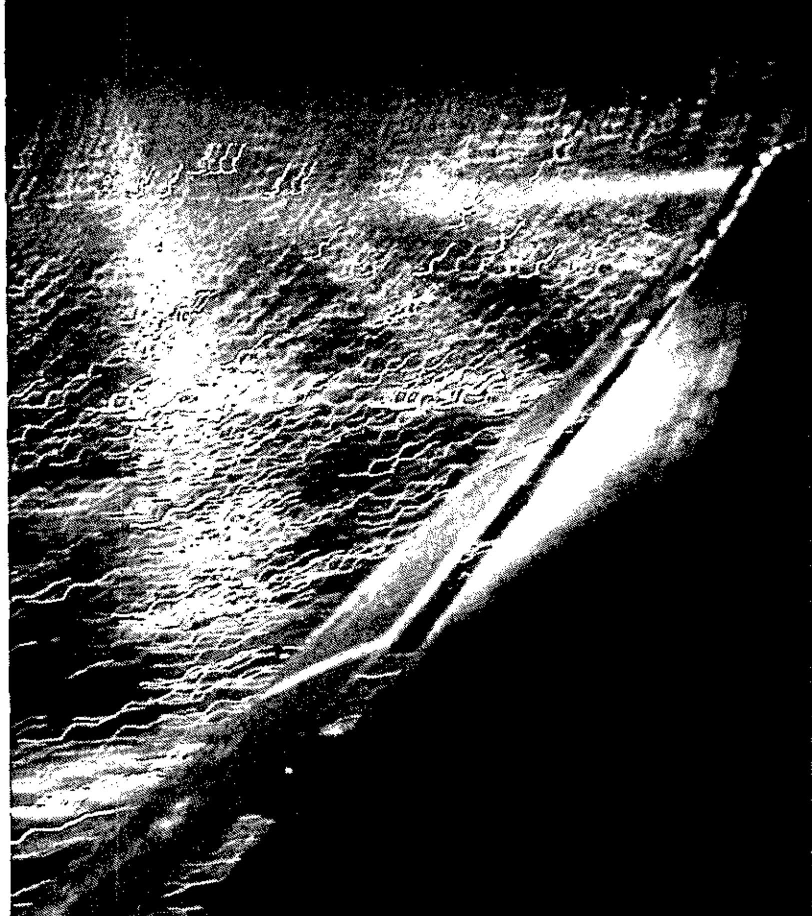

Aerial view of Los Angeles, California

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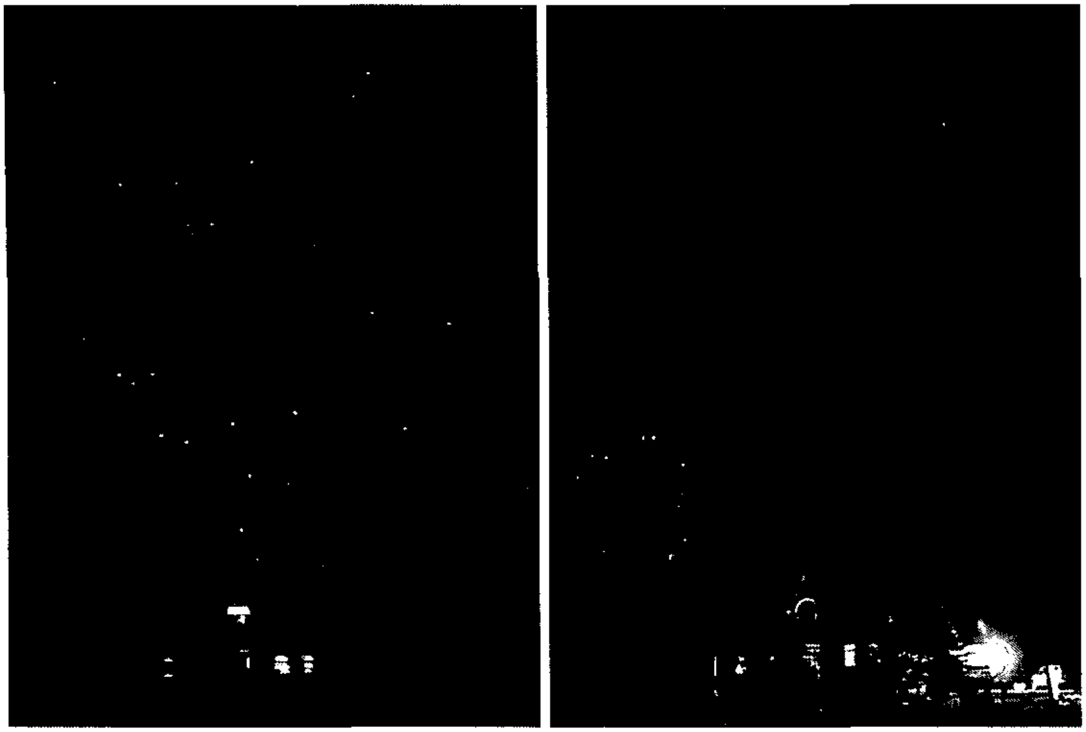

Glare, overillumination, and sky glow (which makes the sky over a city look orange, yellow, or pink) are all forms of light pollution. These photos were taken in Goodwood, Ontario, a small town about 45 minutes northeast of Toronto during and the night after the regionwide 14 August 2003 blackout. The lights inside the house in the blackout picture were created by candles and flashlights.

Todd Carlson

pollution can have lasting adverse effects on both human and wildlife health.

When does nuisance light become a health hazard? Richard Stevens, a professor and cancer epidemiologist at the University of Connecticut Health Center in Farmington, Connecticut, says light photons must hit the retina for biologic effects to occur. "However, in an environment where there is much artificial light at night—such as Manhattan or Las Vegas—there is much more opportunity for exposure of the retina to photons that might disrupt circadian rhythm," he says. "So I think it is not only 'night owls' who get those photons. Almost all of us awaken during the night for periods of time, and unless we have blackout shades there is some electric lighting coming in our windows. It is not clear how much is too much; that is an important part of the research now."

According to "The First World Atlas of the Artificial Night Sky Brightness," a report on global light pollution published in volume 328, issue 3 (2001) of the *Monthly Notices of the Royal Astronomical Society*, two-thirds of the U.S. population and more than one-half of the European population have already lost the ability to see the Milky Way with the naked eye. Moreover, 63% of the world population and 99% of the population of the European Union and the United States (excluding Alaska and Hawaii) live in areas where the night sky is brighter than the threshold for light-polluted status set by the International Astronomical Union—that is, the artificial sky brightness is greater than 10% of the natural sky brightness above 45° of elevation.

Light pollution comes in many forms, including sky glow, light trespass, glare, and overillumination. Sky glow is the bright halo that appears over urban areas at night, a product of light being scattered by water droplets or particles in the air. Light trespass occurs when unwanted artificial light from, for instance, a floodlight or streetlight spills onto an adjacent property, lighting an area that would otherwise be dark. Glare is created by light that shines horizontally. Overillumination refers to the use of artificial light well beyond what is required for a specific activity, such as keeping the lights on all night in an empty office building.

Distracted by the Light

The ecologic effects of artificial light have been well documented. Light pollution has been shown to affect both flora and fauna. For instance, prolonged exposure to artificial light prevents many trees from adjusting to seasonal variations, according to Winslow Briggs's chapter on plant responses in the 2006 book *Ecological Consequences of Artificial Night Lighting*. This, in turn, has implications for the wildlife that depend on trees for their natural habitat. Research on insects, turtles, birds, fish, reptiles, and other wildlife species shows that light pollution can alter behaviors, foraging areas, and breeding cycles, and not just in urban centers but in rural areas as well.

Sea turtles provide one dramatic example of how artificial light on beaches can disrupt behavior. Many species of sea turtles lay their eggs on beaches, with females returning for decades to the beaches where they were born to nest. When these beaches are brightly lit at night, females may be discouraged from nesting in them; they can also be disoriented by lights and wander onto nearby roadways, where they risk being struck by vehicles.

Moreover, sea turtle hatchlings normally navigate toward the sea by orienting away from the elevated, dark silhouette of the landward horizon, according to a study published by Michael Salmon of Florida Atlantic University and colleagues in volume 122, number 1–2 (1992) of *Behaviour*. When there are artificial bright lights on the beach, newly hatched turtles become disoriented and navigate toward the artificial light source, never finding the sea.

Jean Higgins, an environmental specialist with the Florida Wildlife Conservation Commission Imperiled Species Management Section, says disorientation also contributes to dehydration and exhaustion in hatchlings. "It's hard to say if the ones that have made it into the water aren't more susceptible to predation at this later point," she says.

Bright electric lights can also disrupt the behavior of birds. About 200 species of birds fly their migration patterns at night over North America, and especially during inclement weather with low cloud cover, they routinely are confused during passage by brightly lit buildings, communication towers, and other structures. "Light attracts birds and disorients them," explains Michael Mesure, executive director of the Toronto-based Fatal Light Awareness Program (FLAP), which

How Outdoor Lighting Translates into Light Pollution

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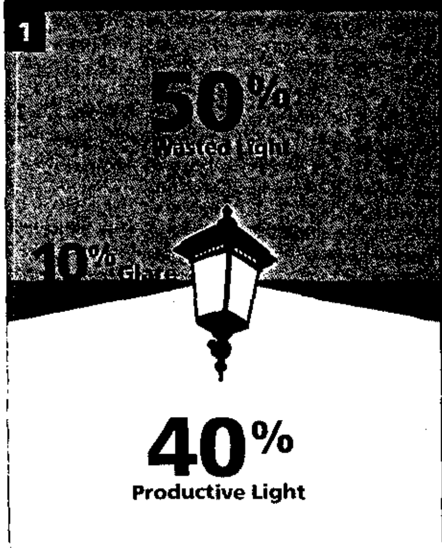

According to the National Park Service, 50% of the light from a typical unshielded light fixture is wasted, shining upward where it is not needed (figure 1). About 40% of the light shines downward to illuminate the intended target. Light emitted horizontally tends to create glare.

Globe lights typically distribute light poorly and contribute to glare (figure 2). Floodlights can fill a space with light, but they may be too bright for their intended task, and much of the light is wasted (figure 3).

Good lighting is shielded in a manner that directs all the light where it is needed and wanted. The International Dark-Sky Association (IDA) recommends that all lighting be installed such that no light is emitted above a horizontal plane running through the lowest part of the fixture (figure 4).

IDA further recommends the use of low-pressure sodium (LPS) lights wherever possible. LPS lights are the most energy-efficient lights currently available. They emit a yellow light at the wavelength where the human eye is most sensitive, but the monochromatic light makes it difficult to distinguish the colors of objects below. For outdoor lighting where color perception is important (to enhance security, for instance), IDA recommends high-pressure sodium lights.

2 3 4

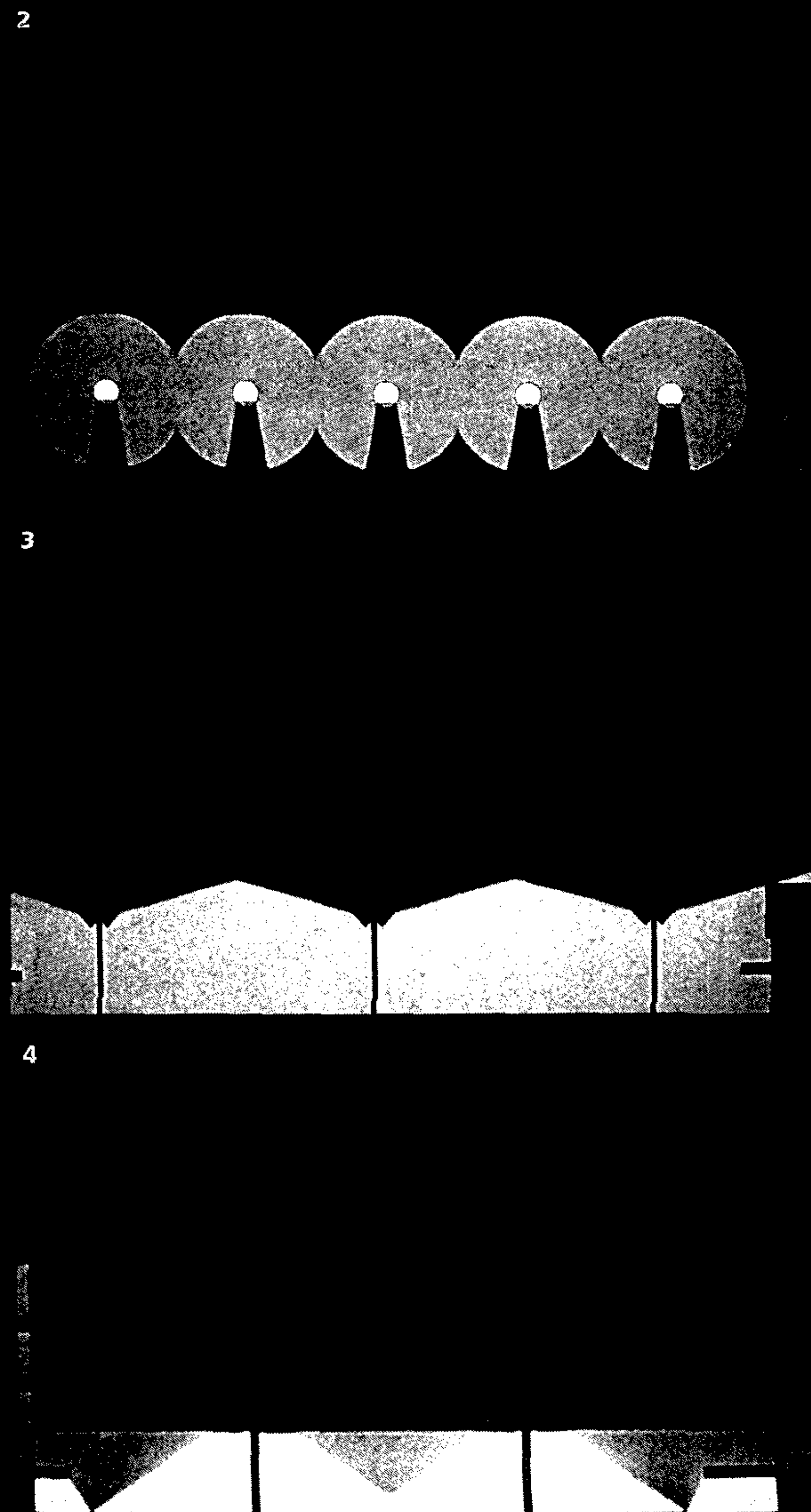

Figure 1: U.S. National Park Service; Matthew Ray/EHP, figures 2–4: International Dark-Sky Association

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works to safeguard migratory birds in the urban environment. "It is a serious situation because many species that collide frequently are known to be in long-term decline and some are already designated officially as threatened."

Each year in New York City alone, about 10,000 migratory birds are injured or killed crashing into skyscrapers and high-rise buildings, says Glenn Phillips, executive director of the New York City Audubon Society. The estimates as to the number of birds dying from collisions across North America annually range from 98 million to close to a billion. The U.S. Fish and Wildlife Service estimates 5–50 million birds die each year from collisions with communication towers.

Turtles and birds are not the only wildlife affected by artificial nighttime lighting. Frogs have been found to inhibit their mating calls when they are exposed to excessive light at night, reducing their reproductive capacity. The feeding behavior of bats also is altered by artificial light. Researchers have blamed light pollution for declines in populations of North American moths, according to *Ecological Consequences of Artificial Night Lighting*. Almost all small rodents and carnivores, 80% of marsupials, and 20% of primates are nocturnal. "We are just now understanding the nocturnality of many creatures," says Chad Moore, Night Sky Program manager with the National Park Service. "Not protecting the night will destroy the habitat of many animals."

Resetting the Circadian Clock

The health effects of light pollution have not been as well defined for humans as for wildlife, although a compelling amount of epidemiologic evidence points to a consistent association between exposure to indoor artificial nighttime light and health problems such as breast cancer, says George Brainard, a professor of neurology at Jefferson Medical College, Thomas Jefferson University in Philadelphia. "That association does not prove that artificial light causes the problem. On the other hand, controlled laboratory studies do show that exposure to light during the night can disrupt circadian and neuroendocrine physiology, thereby accelerating tumor growth."

The 24-hour day/night cycle, known as the circadian clock, affects physiologic processes in almost all organisms. These processes include brain wave patterns, hormone production, cell regulation, and other biologic activities. Disruption of the circadian clock is linked to several medical disorders in humans, including depression, insomnia, cardiovascular disease, and cancer, says Paolo Sassone-Corsi, chairman of the Pharmacology Department at the University of California, Irvine, who has done extensive research on the circadian clock. "Studies show that the circadian cycle controls from ten to fifteen percent of our genes," he explains. "So the disruption of the circadian cycle can cause a lot of health problems."

On 14–15 September 2006 the National Institute of Environmental Health Sciences (NIEHS) sponsored a meeting that focused on how best to conduct research on possible connections between artificial lighting and human health. A report of that meeting in the September 2007 issue of *EHP* stated, "One of the defining characteristics of life in the modern world is the altered patterns of light and dark in the built environment made possible by use of electric power." The meeting report authors noted it may not be entirely coincidental that dramatic increases in the risk of breast and prostate cancers, obesity, and early-onset diabetes have mirrored the dramatic changes in the amount and pattern of artificial light generated during the night and day in modern societies over recent decades. "The science underlying these hypotheses has a solid base," they wrote, "and is currently moving forward rapidly."

The connection between artificial light and sleep disorders is a fairly intuitive one. Difficulties with adjusting the circadian clock can lead to a number of sleep disorders, including shift-work sleep disorder, which affects people who rotate shifts or work at night, and *delayed sleep–phase syndrome*, in which people tend to fall asleep very late at night and have difficulty waking up in time for work, school, or social engagements.

The sleep pattern that was the norm before the invention of electric lights is no longer the norm in countries where artificial light extends the day. In the 2005 book *At Day's Close: Night in Times Past*, historian Roger Ekirch of Virginia Polytechnic Institute described how before the Industrial Age people slept in two 4-hour shifts ("first sleep" and "second sleep") separated by a late-night period of quiet wakefulness.

Thomas A. Wehr, a psychiatrist at the National Institute of Mental Health, has studied whether humans would revert back to the two-shift sleep pattern if they were not exposed to the longer photoperiod afforded by artificial lighting. In the June 1992 *Journal of Sleep Research*, Wehr reported his findings on eight healthy men, whose light/dark schedule was shifted from their customary 16 hours of light and 8 hours of dark to a schedule in which they were exposed to natural and electric light for 10 hours, then darkness for 14 hours to simulate natural durations of day and night in winter. The subjects did indeed revert to the two-shift pattern, sleeping in two sessions of about 4 hours each separated by 1–3 hours of quiet wakefulness.

Turtle hatchlings instinctively orient away from the dark silhouette of the nighttime shore. Here hatchlings have been temporarily distracted by a bright lamp. Hatchlings and mother turtles distracted by shorefront lights can wander onto nearby roadways.

Lynda Richardson/Corbis

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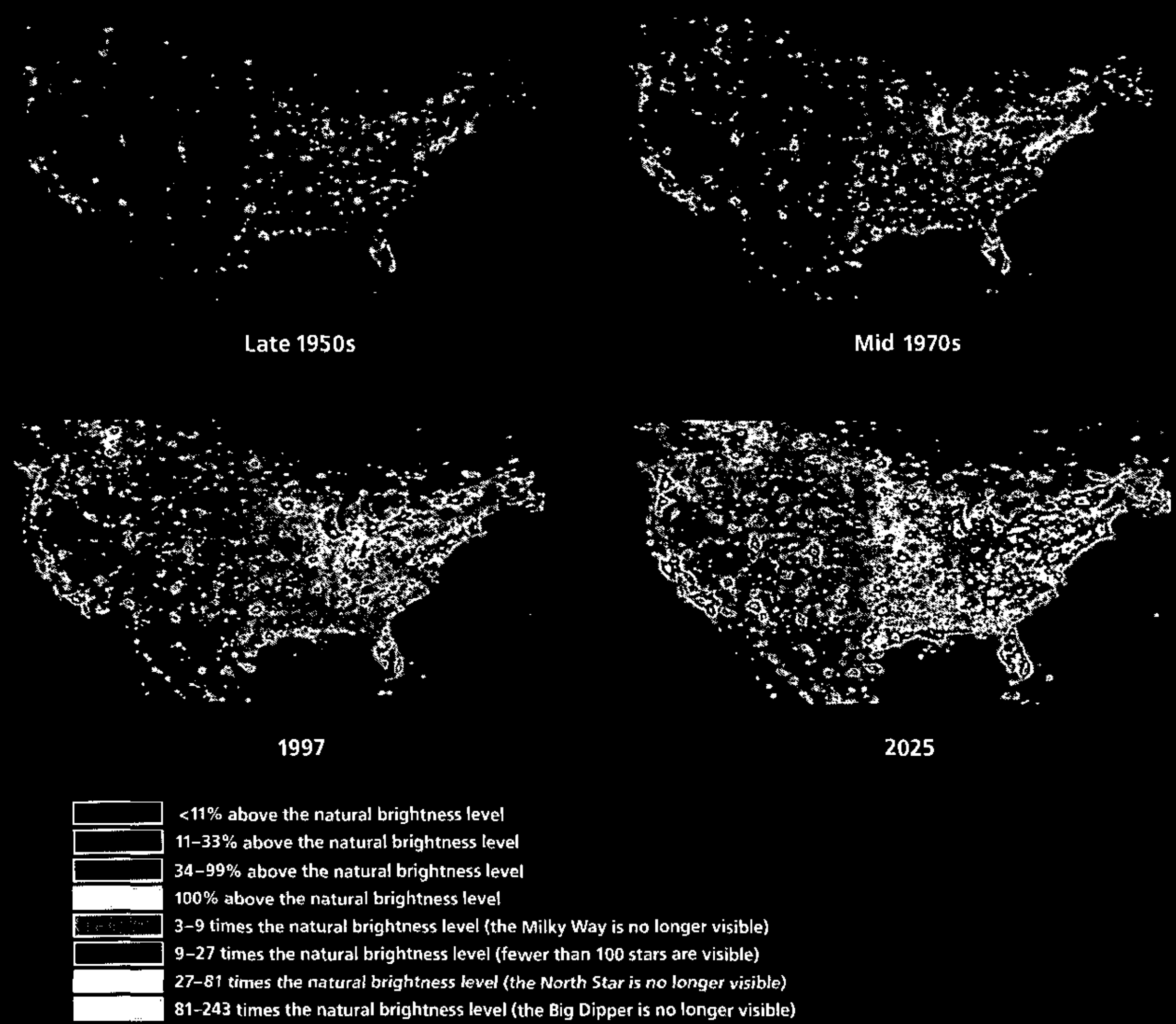
Increase in Artificial Night Sky Brightness in North America



Artificial night sky brightness at zenith, at sea level, for a standard clean atmosphere as a fraction of the average natural night sky brightness. These maps are based on upward light measured by the Defense Meteorological Satellite Program after accounting for propagation and scattering of that light in the atmosphere. The 2025 map assumes a constant population growth rate of 6% per year.

Source: http://www.lightpollution.it/ © 2001 P. Cinzano, F. Falchi, C.D. Elvidge

Beyond Sleep Disorders

Alteration of the circadian clock can branch into other effects besides sleep disorders. A team of Vanderbilt University researchers considered the possibility that constant artificial light exposure in neonatal intensive care units could impair the developing circadian rhythm of premature babies. In a study published in the August 2006 issue of *Pediatric Research*, they exposed newborn mice (comparable in development to 13-week-old human fetuses) to constant artificial light for several weeks. The exposed mice were were unable to maintain a coherent circadian cycle at age 3 weeks (comparable to a full-term human neonate). Mice exposed for an additional 4 weeks were unable to establish a regular activity cycle. The researchers concluded that excessive artificial light exposure early in life might contribute to an increased risk of depression and other mood disorders in humans. Lead researcher Douglas McMahon notes, "All this is speculative at this time, but certainly the data would indicate that human infants benefit from the synchronizing effect of a normal light/dark cycle."

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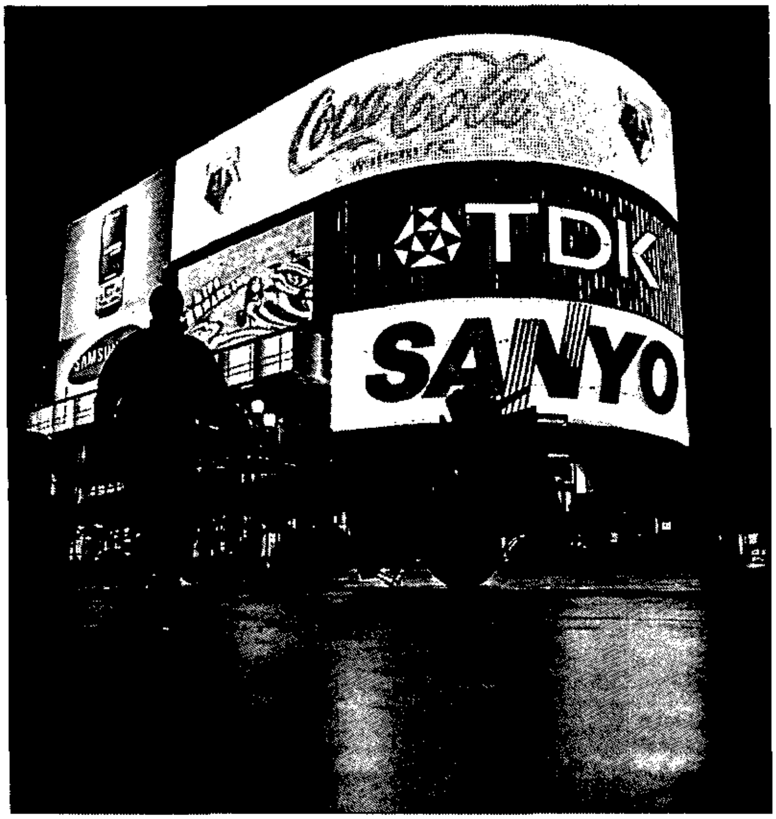

The International Agency for Research on Cancer has classified shift work as a probable human carcinogen. A study in the December 2008 issue of Sleep found that use of light exposure therapy, sunglasses, and a strict sleep schedule may help night-shift workers achieve a better-balanced circadian rhythm.

Akira Suemori/AP Photo

Since 1995, studies in such journals as *Epidemiology, Cancer Causes and Control*, the *Journal of the National Cancer Institute*, and *Aviation Space Environmental Medicine*, among others, have examined female employees working a rotating night shift and found that an elevated breast cancer risk is associated with occupational exposure to artificial light at night. Mariana Figueiro, program director at the Lighting Research Center of Rensselaer Polytechnic Institute in Troy, New York, notes that permanent shift workers may be less likely to be disrupted by night work because their circadian rhythm can readjust to the night work as long as light/dark patterns are controlled.

In a study published in the 17 October 2001 *Journal of the National Cancer Institute*, Harvard University epidemiologist Eva S. Schernhammer and colleagues from Brigham and Women's Hospital in Boston used data from the 1988 Nurses' Health Study (NHS), which surveyed 121,701 registered female nurses on a range of health issues. Schernhammer and her colleagues found an association between breast cancer and shift work that was restricted to women who had worked 30 or more years on rotating night shifts (0.5% of the study population).

In another study of the NHS cohort, Schernhammer and colleagues also found elevated breast cancer risk associated with rotating night shift work. Discussing this finding in the January 2006 issue of *Epidemiology*, they wrote that shift work was associated with only a modest increased breast cancer risk among the women studied. The researchers further wrote, however, that their study's findings "in combination with the results of earlier work, reduce the likelihood that this association is due solely to chance."

Schernhammer and her colleagues have also used their NHS cohort to investigate the connection between artificial light, night work, and colorectal cancer. In the 4 June 2003 issue of the *Journal of the National Cancer Institute*, they reported that nurses who worked night shifts at least 3 times a month for 15 years or more had a 35% increased risk of colorectal cancer. This is the first significant evidence so far linking night work and colorectal cancer, so it's too early to draw conclusions about a causal association. "There is even less evidence about colorectal cancer and the larger subject of light pollution," explains Stevens. "That does not mean there is no effect, but rather, there is not enough evidence to render a verdict at this time."

The research on the shift work/cancer relationship is not conclusive, but it was enough for the International Agency for Research on Cancer (IARC) to classify shift work as a probable human carcinogen in 2007. "The IARC didn't definitely call night shift work a carcinogen," Brainard says. "It's still too soon to go there, but there is enough evidence to raise the flag. That's why more research is still needed."

The Role of Melatonin

Brainard and a growing number of researchers believe that melatonin may be the key to understanding the shift work/breast cancer risk association. Melatonin, a hormone produced by the pineal gland, is secreted at night and is known for helping to regulate the body's biologic clock. Melatonin triggers a host of biologic activities, possibly including a nocturnal reduction in the body's production of estrogen. The body produces melatonin at night, and melatonin levels drop precipitously in the presence of artificial or natural light. Numerous studies suggest that decreasing nocturnal melatonin production levels increases an individual's risk of developing cancer. [For more information on melatonin, see "Benefits of Sunlight: A Bright Spot for Human Health," *EHP* 116:A160–A167 (2008).]

One groundbreaking study published in the 1 December 2005 issue of *Cancer Research* implicated melatonin deficiency in what the report authors called a rational biologic explanation for the increased breast cancer risk in female night shift workers. The study involved female volunteers whose blood was collected under three different conditions: during daylight hours, during the night after 2 hours of complete darkness, and during the night after exposure to 90 minutes of artificial light. The blood was injected into human breast tumors that were transplanted into rats. The tumors infused with melatonin-deficient blood collected after exposure to light during the night were found to grow at the same speed as those infused with daytime blood. The blood collected after exposure to darkness slowed tumor growth.

"We now know that light suppresses melatonin, but we are not saying it is the only risk factor," says first author David Blask, a research scientist at the Bassett Healthcare Research Institute in Cooperstown, New York. "But light is a risk factor that may explain [previously unexplainable phenomena]. So we need to seriously consider it."

The National Cancer Institute estimates that 1 in 8 women will be diagnosed with breast cancer at some time during her life. We can attribute only about half of all breast cancer cases to known risk factors, says Brainard. Meanwhile, he says, the breast cancer rate keeps climbing—incidence increased by more than 40% between 1973 and 1998, according to the Breast Cancer Fund—and

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"we need to understand what's going on as soon as possible."

Linking Light Pollution to Human Health

The evidence that indoor artificial light at night influences human health is fairly strong, but how does this relate to light pollution? The work in this area has just begun, but two studies in Israel have yielded some intriguing findings. Stevens was part of a study team that used satellite photos to gauge the level of nighttime artificial light in 147 communities in Israel, then overlaid the photos with a map detailing the distribution of breast cancer cases. The results showed a statistically significant correlation between outdoor artificial light at night and breast cancer, even when controlling for population density, affluence, and air pollution. Women living in neighborhoods where it was bright enough to read a book outside at midnight had a 73% higher risk of developing breast cancer than those residing in areas with the least outdoor artificial lighting. However, lung cancer risk was not affected. The findings appeared in the January 2008 issue of *Chronobiology International.*

"It may turn out that artificial light exposure at night increases risk, but not entirely by the melatonin mechanism, so we need to do more studies of 'clock' genes—nine have so far been identified—and light exposure in rodent models and humans," Stevens says. Clock genes carry the genetic instructions to produce protein products that control circadian rhythm. Research needs to be done not just on the light pollution–cancer connection but also on several other diseases that may be influenced by light and dark.

Travis Longcore, co-editor of *Ecological Consequences of Artificial Night Lighting* and a research associate professor at the University of Southern California Center for Sustainable Cities, suggests two ways outdoor light pollution may contribute to artificial light–associated health effects in humans. "From a human health perspective, it seems that we are concerned with whatever increases artificial light exposure indoors at night," he says. "The effect of outdoor lighting on indoor exposure could be either direct or indirect. In the direct impact scenario, the artificial light from outside reaches people inside at night at levels that affect production of hormones. In an indirect impact it would disturb people inside, who then turn on lights and expose themselves to more light."

"The public needs to know about the factors causing [light pollution], but research is not going at the pace it should," Blask says. Susan Golden, distinguished professor at the Center for Research on Biological Clocks of Texas A&M University in College Station, Texas, agrees. She says, "Light pollution is still way down the list of important environmental issues needing study. That's why it's so hard to get funds to research the issue."

"The policy implications of unnecessary light at night are enormous," says Stevens in reference to the health and energy ramifications [for more on the energy impact of light pollution, see "Switch On the Night: Policies for Smarter Lighting," p. A28 this issue]. "It is fully as important an issue as global warming." Moreover, he says, artificial light is a ubiquitous environmental agent. "Almost everyone in modern society uses electric light to reduce the natural daily dark period by extending light into the evening or before sunrise in the morning," he says. "On that basis, we are all exposed to electric light at night, whereas before electricity, and still in much of the developing world, people get twelve hours of dark whether they are asleep or not."

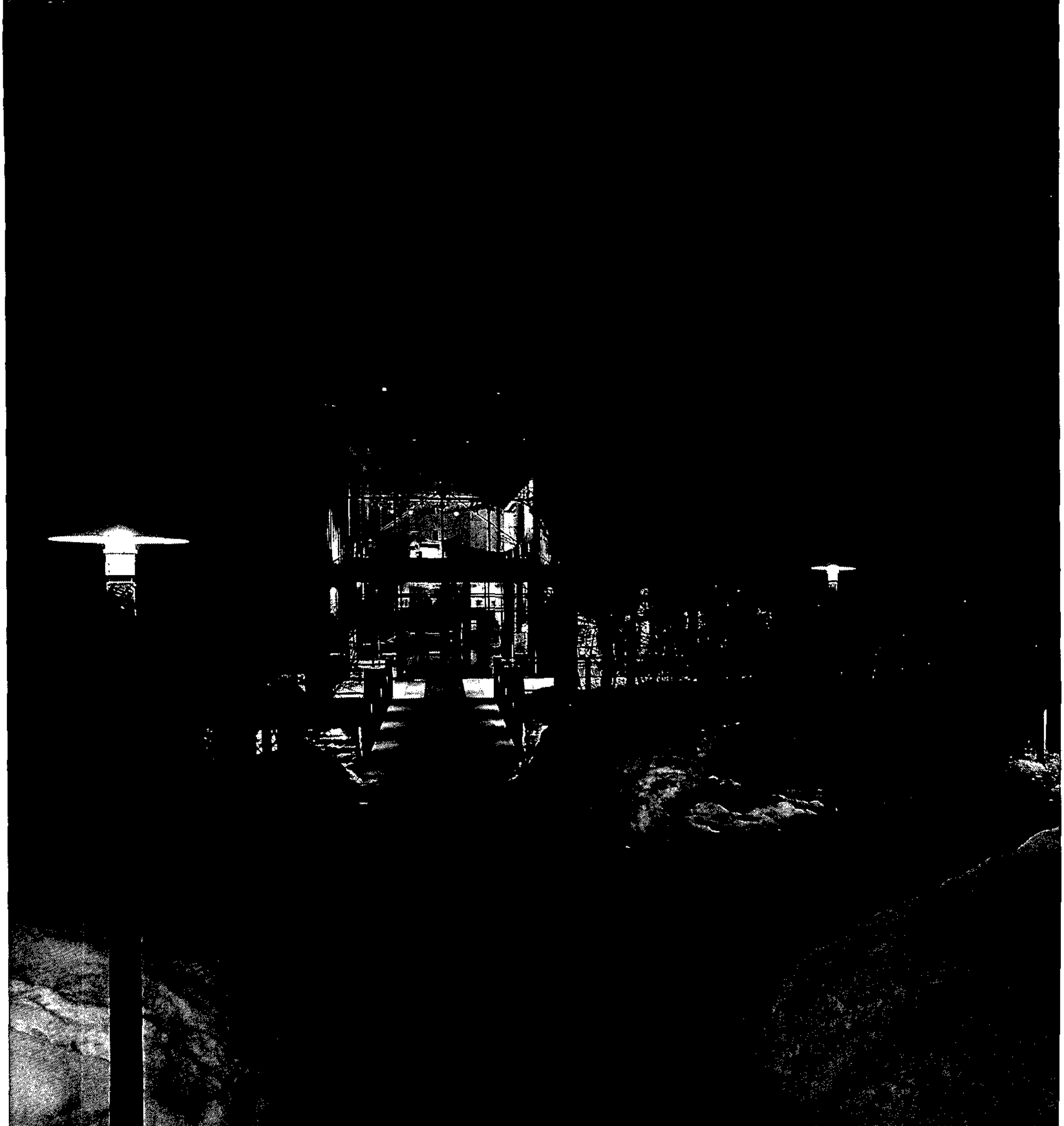
Sources believe that the meeting at the NIEHS in September 2006 was a promising beginning for moving forward on the light pollution issue. "Ten years ago, scientists thought something was there, but couldn't put a finger on it," says Leslie Reinlib, a program director at the NIEHS who helped organize the meeting. "Now we are really just at the tip of the iceberg, but we do have something that's scientific and can be measured."

The 23 participants at the NIEHS-sponsored meeting identified a research agenda for further study that included the functioning of the circadian clock, epidemiologic studies to define the artificial light exposure/disease relationship, the role of melatonin in artificial light–induced disease, and development of interventions and treatments to reduce the impact of light pollution on disease. "It was a very significant meeting," Brainard says. "It's the first time the National Institutes of Health sponsored a broad multidisciplinary look at the light-environmental question with the intent of moving to the next step."

Ron Chepesiuk

Schedule RAW2010-27

Spheres of Influence



The Aspen Recreation Center in Aspen, Colorado, won the 2004 IDA Lighting Design Award. The award recognizes lighting designs that are free of glare, use optimal levels of light, are energy-efficient, and provide pleasant ambience with minimal obtrusive light and contribution to sky glow. Lights that are fully shielded and well spaced keep light where it is directed, minimizing light pollution.

Schedule RAW2010-28

International Dark-Sky Association

Switch On the Night

Policies for Smarter Lighting

It was an August afternoon in 2003 when the lights went out on Broadway, and for that matter, throughout most of the Northeast, Midwest, and Ontario—a power blackout left 50 million customers in the dark overnight. Despite complaints about the inconveniences, the stranded commuters, and the food spoilage in restaurants and markets, many city dwellers were also awed; as evening came on, they gazed upward, and between the dark skyscrapers they could see something amazing—the starry night sky. *The New York Times* reported spontaneous stargazing gatherings in the usually electrified cities of the Northeast.

On ordinary nights with electric power, the bright sky glow surrounding cities at night can extend some 150 miles from population centers, thus obscuring the view of the stars for most of the population. In a December 2006 survey, the nonprofit Campaign to Protect Rural England and the British Astronomical Association's Campaign for Dark Skies asked people across the United Kingdom to count how many stars they could see in the constellation Orion. More than half the 2,000 respondents could see fewer than 10 of Orion's stars, whereas astronomers say around 250 should be visible to the naked eye on a moonless night.

Artificial nighttime lighting does more than just obscure the stars. A growing number of studies are linking light pollution to a variety of human and environmental health effects [see "Missing the Dark: Health Effects of Light Pollution," p. A20 this issue]. Moreover, polluting light is often wasted light involving unnecessary energy costs and carbon dioxide (CO_2) emissions. In response to these concerns—as well as a desire for better night sky viewing—many cities are exploring ways to regulate artificial lighting and implement smarter lighting strategies.

Blinded by the Light

Artificial lighting does not necessarily produce light pollution. *Light pollution* is the term for artificial light that is excessive or intrudes where it is not wanted. Well-designed lighting, on the other hand, sends light only where it is needed without scattering it elsewhere. Experts in the field agree that light pollution can be easily controlled with well-designed lighting and simple measures such as turning off indoor and outdoor lights when not in use.

Defining and measuring light pollution is not yet quite as easy, however. In the November/December 2004 issue of the *IMSA* [International Municipal Signal Association] *Journal*, researcher Michele McColgan of the Lighting Research Center at Rensselaer Polytechnic Institute wrote, "The problem facing authorities is twofold: how to identify the balance between useful lighting and light pollution; and how to quantify lighting objectively to see if this balance is being met." McColgan and colleagues have developed a so-called shoebox metric that may make it easier to quantify and thus regulate light pollution. The "shoebox" moniker refers to the rectangular area described by the vertical and horizontal planes surrounding a site. The researchers propose that architects and planners consider the amount of light leaving the shoebox along each plane as a way of characterizing a site's lighting impact. Policy makers could also regulate how much light is allowed to exit each plane.

Contrary to popular belief, bright lighting can actually hinder visibility rather than improve it, according to the nonprofit International Dark-Sky Association (IDA), which provides guidance on selecting good outdoor lighting and creating local lighting ordinances. For example, light that shines horizontally (as from headlights and some styles of light fixtures) produces glare that can momentarily obstruct visibility, especially on roadways and on wet nights.

There is also some debate over whether brighter outdoor lighting actually improves security. *Preventing Crime: What Works, What Doesn't, What's Promising*, a 1996 report submitted to the U.S. Congress by the National Institute of Justice and the Department of Criminology and Criminal Justice at the University of Maryland, concluded that "lighting is effective in some places, ineffective in others, and counter productive in still other circumstances" in deterring crime. The authors hypothesized that high levels of artificial lighting can conceivably increase the likelihood of crime when one considers that offenders need the light to detect potential targets and low-risk situations. The report also proposed that bright outdoor lighting may make pedestrians feel safer but also make them more visible to offenders. However, in the 27 February 2007 issue of *JAMA*, Dana Loomis and colleagues from the University of North Carolina at Chapel Hill demonstrated that bright lighting both indoors and outdoors at business establishments lessened the likelihood of workers being murdered on the job.

IDA contends that it is poorly designed lighting that compromises safety. For instance, glare can create safety issues around buildings by causing very sharp shadows and temporarily blinding passersby to would-be assailants. In its information sheet "Security Lighting: Let's Have Real Security, Not Just Bad Lighting," the group makes several recommendations for effective security lighting, such as the use of "full cutoff" fixtures, meaning the bulb is recessed within an opaque lampshade or shield that focuses the light downward, which prevents glare.

Sometimes less light can be an effective deterrent to crime. On 25 November 2008 the *Colchester* (U.K.) *Gazette* reported that towns in Essex County, United Kingdom, had seen a reduction in crime during an 18-month pilot project in which most residential streetlights were turned off between midnight and 5:00 A.M. In Maldon, the number of recorded offenses fell by 14% during the hours the streetlights were off, and offenses overall fell by 12.6%. The Essex County Council, which originally intended the measure as a way to curb energy-related CO_2 emissions, is currently considering whether to implement the program countywide.

A Basis in Astronomy

Advocacy for mitigating light pollution has been especially strong in the astronomy community. Some of the first proponents of reducing outdoor light at night were astronomers, both amateurs with backyard telescopes and professionals whose work is impeded by light in the environment.

IDA, in conjunction with Lowell Observatory and the U.S. Naval Observatory, has worked with the city of Flagstaff, Arizona, and surrounding Coconino County to issue ordinances requiring proper shielding of outdoor lights. Flagstaff was already a pioneer in light pollution awareness; the city council passed the first ever lighting ordinance in April 1958, banning advertising searchlights that interfered with work at nearby Lowell Observatory. Flagstaff's commitment to the preservation of dark skies through proactive lighting codes and public education led to the city being designated the first International Dark-Sky City by IDA in 2001.

Truly dark skies have become somewhat of a rarity and, for many people, a natural treasure worth preserving. In 1999 the National Park Service formed the Night Sky Team to address increasing public concern about light pollution. "We are charged with protecting the scenery and habitats of our national parks, and that includes the night sky," says Chad Moore, Night Sky Program manager. The Night Sky Team is developing instruments and methods to help measure light pollution, such as a portable field instrument that can quantify natural and artificial sky lighting and quickly image the entire sky in high resolution. The team is also creating an inventory of present night sky conditions in national parks where the viewing is clearest, to set a baseline against which light pollution can be assessed.

For several national parks, darkness has become a main attraction. For example, Natural Bridges National Monument in Utah is known as a prime place to view the Milky Way. For Bryce Canyon National Park, also in Utah, and the Chaco Culture National Historical Park in New Mexico, stargazing is the number one attraction, drawing 15,000 to 30,000 visitors per year.

Stargazing is not the only pastime that depends on the dark to draw tourists. Puerto Rico is famous for its bays where bioluminescent *Pyrodinium bahamense* dinoflagellates set the water aglow at night, and swimming and kayaking in the dark bay waters releases swirls of blue–green light. Although pollution from boat fuel and pesticide runoff threatens the dinoflagellates themselves, according to a 9 June 2008 report on National Public Radio's *Morning Edition*, light pollution affects the tourist value of the bays by greatly reducing the visual impact of the bioluminescence. In part to protect these and other sensitive ecosystems on the island and thereby also protect the country's ecotourism trade, the government of Puerto Rico signed into law the Program for the Control and Prevention of Light Pollution in August 2008.

Preserving the Rhythm of the Night

Although astronomers were the first to express concern about the effects of artificial nighttime lighting, Travis Longcore, a research associate professor at the University of Southern California Center for Sustainable Cities, says concern about the effects of light pollution on wildlife and plants has been a more recent phenomenon. Today, much of the impetus for addressing light pollution comes from its disruptive ecologic effects.

In Florida's Sarasota County, the problem of light pollution was particularly acute because this area of the Florida coast is a significant sea turtle nesting zone, where a number of threatened and endangered species lay their eggs every season from May through October. Adult females and turtle hatchlings alike are affected by artificial nighttime light, which interferes with their ability to navigate to and from nesting areas.

Several methods for saving the turtles were tried, including caging and artificial hatcheries, but none of these efforts worked as well as mandatory lighting codes. In 1997, the county passed the Marine Turtle Protection Code. Among other measures, the code prohibits floodlights, uplights, and spotlights that are directly visible from the beach or that indirectly illuminate the beach, and requires the use of motion detectors for exterior security lights.

As of January 2008, 27 counties and 58 municipalities in Florida had enacted lighting ordinances aimed at protecting sea turtles. "There are successes that would show that the [statewide] program has been effective in raising public awareness regarding lights and sea turtles," says Jean Higgins, an environmental specialist with the Florida Wildlife Conservation Commission Imperiled Species Management Section. "All in all, the program works hard to see improvements in areas. But it is definitely at times an uphill battle—development continues along Florida's coastline, and making sure that everyone is aware of the issues at hand as well as equipped with the correct information is difficult."

Migrating birds also are particularly affected by bright and blinking lights, which confuse them and cause them to crash into buildings and communication towers as they fly their nighttime migration patterns. In the city of Toronto alone, the nonprofit Fatal Light Awareness Program has documented more than 42,000 bird collisions since 1993. Many of the birds are endangered or threatened species.

Toronto issued its Bird-Friendly Development Guidelines in 2007 to provide developers, building managers, architects, and urban planners with design-based strategies to reduce artificial light and glare from buildings. The authors of the guidelines emphasize the need to reduce upward-pointed lighting and turn off unnecessary indoor and outdoor lights at night, especially during the migratory season. For businesses where people work at night, the authors recommend the use of task lighting at individual work stations and drawing the blinds or curtains to minimize the amount of light leaving the building.

Targeting Energy Consumption

Various estimates posit that lighting accounts for about 8–9% of the electricity used in the United States. In unpublished calculations, the IDA Technical Committee recently estimated that 17.4 billion kilowatt-hours of electricity—requiring 186.3 trillion BTU of energy to produce at power plants—is wasted each year. This waste arises, for instance, from lighting that is directed upward, illuminating nothing but sky or that is left on when not needed. According to the Energy Information Administration, it takes more than 9 million tons of coal or 32 million barrels of oil to produce that amount of energy. This translates into annual CO_2 emissions of nearly 1 ton or 2.5 tons, depending on the fuel, according to EPA conversion factors.

On a March evening in 2007, in an effort to raise public awareness about energy waste and climate change, the World Wildlife Fund (WWF) held the first Earth Hour in Sydney, Australia. The WWF estimated that turning off nonessential lights for 1 hour in the evening would result in a 5% reduction in energy consumption, but later reported the event resulted in a 10% drop in energy use in the city.

An added effect of lowering the lights during Earth Hour was increased public awareness about light pollution. "The symbolic gesture of turning out the lights for Earth Hour gave people a voice on this issue and increased people's awareness about the unnecessary lighting we have in our homes and that adorn buildings around the world," says Dan Forman, public relations manager for the WWF. Forman says an estimated 50 million people in more than 35 countries participated in the second annual Earth Hour. The next Earth Hour is scheduled for 8:30 P.M. local time on 28 March 2009. The WWF hopes 1 billion people in 1,000 cities worldwide will participate.

Using the Night Sky to Foster Scientific Literacy

January kicks off the International Year of Astronomy 2009, an effort by the International Astronomical Union and UNESCO to help citizens around the world rediscover both the nighttime and daytime sky, and thereby better appreciate how basic science affects our daily life. As part of the commemorations, the StarPals International Young Astronomers Network will link students via the Internet to remotely operated research-grade telescopes in New Mexico, Israel, and Australia with which they will be able to view and record images of deep space. StarPals has also launched the StarParks Program for Girl and Boy Scouts, which establishes small oases within a community that are kept dark for night sky viewing.

"StarParks can offer a place to view the International Space Station fly-bys or to even observe a meteor shower, comet, or lunar eclipse," says IDA member Audrey Fischer, who created and leads StarPals. With these projects, Fischer says, children are not just reading about what it is like to be a scientist; they actually become young scientists, "then yearn to learn more." She adds, "The average child in America is unaware of what a starry sky is meant to be."

There are no studies that show whether being able to see the stars influences scientific curiosity in children, but Nadine G. Barlow, an associate professor in the Department of Physics and Astronomy at Northern Arizona University in Flagstaff, believes that it does, based on her own experience. "Here in Flagstaff, because of the lighting restrictions, we can actually see our Milky Way galaxy from the middle of campus," she says. "Students get more interested in the topic when they can see things with their own eyes."

The Dark Sky Society, a Long Island, New York–based advocacy group, has published guidance that clearly illustrates the types of light fixtures that best protect against light pollution, which often are the most energy-efficient choices as well. Most of the recommended fixtures have full cut-off designs. Susan Harder, founding member of the Dark Sky Society, says many towns on Long Island attach this guidance to every building permit, and local planning departments can also consult the society's *Guidelines for Good Exterior Lighting Plans* when developing new sites. "We have been very successful with the ordinances we have promoted because, unlike other codes such as noise, once a light has been changed, it will not be a repeat offender," says Harder.

Fernando Abruna, an architect and past president of the U.S. Green Building Council Caribbean Chapter, says many of the remedies to light pollution are easily applied. "There are very simple architectural changes that reduce energy consumption and make a huge difference in the light pollution problem. Most times, it is just as simple as changing a light bulb or fixture," he says.

Lighting designers are looking at other ways to simultaneously curb light pollution and save energy. The Civil Twilight Design Collective, a design group based in San Francisco, has conceptualized a "lunar-resonant" streetlight. Current streetlights are outfitted with photosensitive cells that prompt them to turn on as darkness approaches. The lunar-resonant streetlights would have a similar but much more sensitive cell that would respond to ambient moonlight, allowing the lights to dim and brighten according to the phases of the moon. The designers estimate the lights could save as much as 80–90% of the energy used in streetlighting. In 2007 the project won *Metropolis Magazine*'s Next Generation® Design Prize.

The National Level

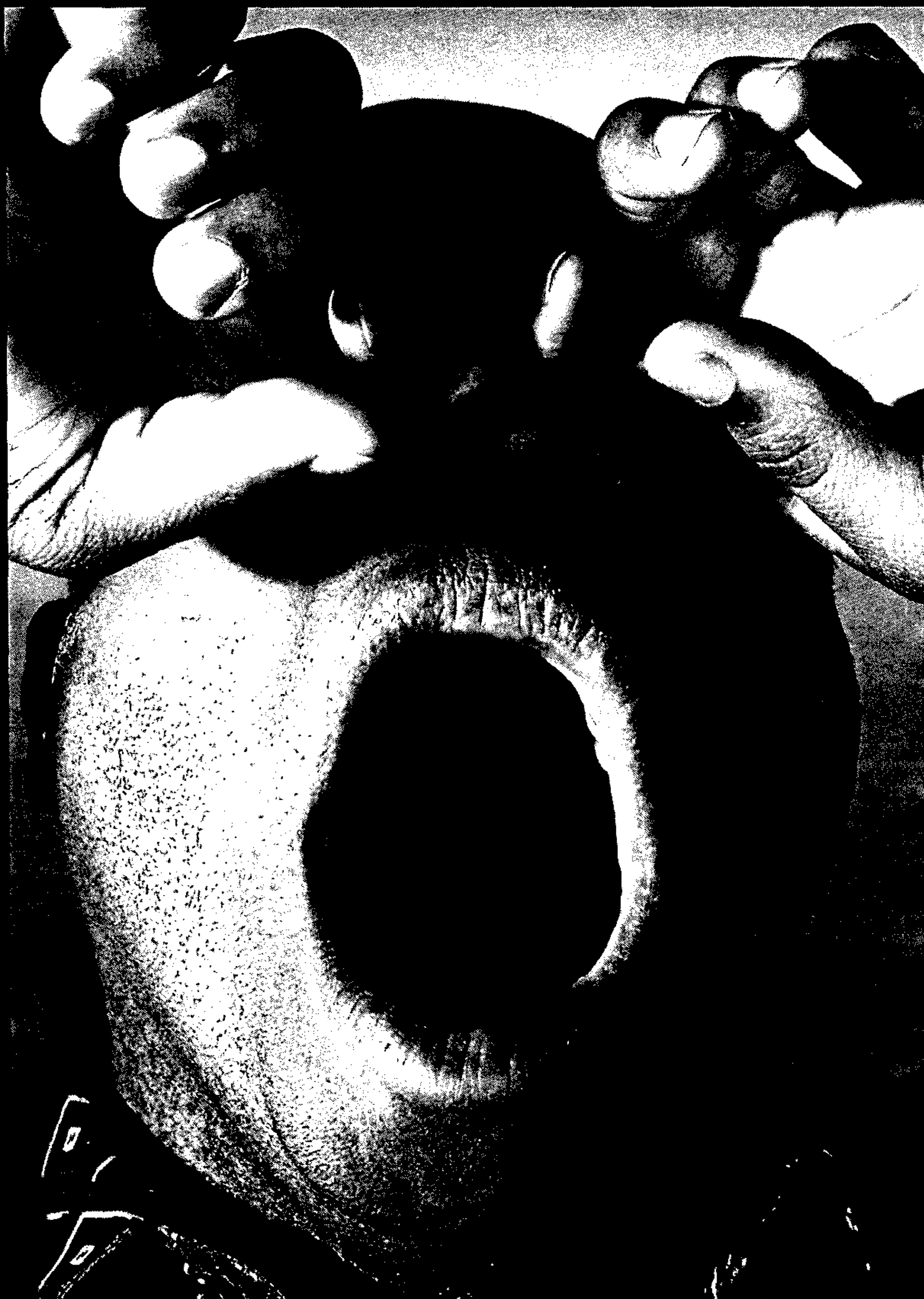
To date the drive to address light pollution has been spearheaded by individual communities, but the idea of a national response to the problem is now being broached. For instance, as part of its Leadership in Energy and Environmental Design program for sustainable design, the U.S. Green Building Council recommends the use of electric fixtures that reduce energy consumption and light pollution. In summer 2008, IDA sponsored briefings before the U.S. Senate and the House of Representatives at which Longcore and other experts presented data on the energy, human health, and environmental health ramifications of light pollution.

On 30 July 2008, 11 members of the U.S. Congress signed a bipartisan letter to Environmental Protection Agency (EPA) administrator Stephen L. Johnson urging the agency to take action on the issue of light pollution. The congressional members proposed four actions the EPA should take to address light pollution: codify an official definition of light pollution that captures the detrimental effects of unchecked nighttime lighting; incorporate research on light pollution in future programs; support education about light pollution in the agency's education, outreach, and grants programs; and expand the agency's Energy Star publications and standards to include discussion of appropriate outdoor light fixtures.

Energy Star is a joint effort of the Department of Energy (DOE) and the EPA, begun in 1992 to promote more efficient energy use in homes and businesses. On 20 August 2008 the DOE released a draft proposal to add full shielding and other design specificiations for LED (light-emitting diode) streetlights to the Energy Star standards. The goal is to increase energy efficiency, but the benefit is multifold: "Good design saves money, saves energy, and also just happens to save the night time sky," says IDA managing director Pete Strasser. (In the particular case of LED streetlights, however, he notes that the whiter light they emit is of concern for both luminance levels and visual response, as well as for potential health concerns pertaining to circadian rhythm disruption.)

It remains to be seen whether regulation of light pollution will take effect as part of a broad national effort or continue to be addressed by local communities. Regardless, an increasing body of research suggests that exposure to artificial light at night disrupts a number of biologic functions in humans, especially those influenced by cyclical hormones such as melatonin. Says Steven Lockley, an assistant professor of medicine in the Division of Sleep Medicine at Harvard Medical School, "We are in desperate need of controlled studies to measure the health impact of street lighting and other exposure to artificial light at night."

Luz Claudio



Schedule RAW2010-29

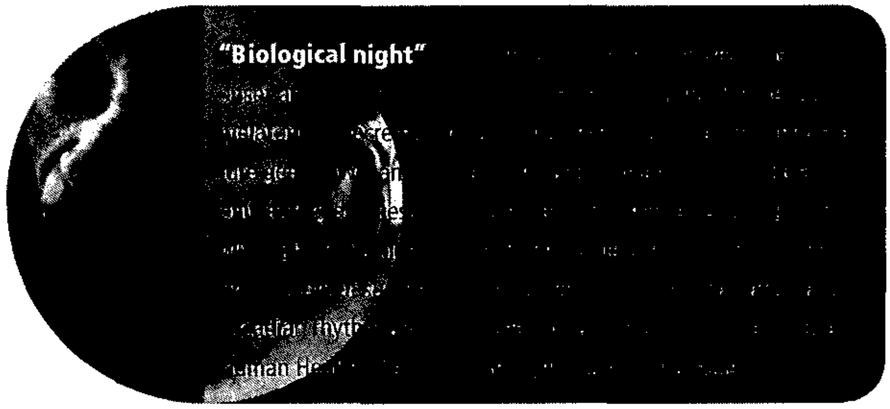
Lose Sleep, Gain Weight

It's 11 P.M., and you sit in front of a glowing computer screen, writing e-mails and eating a sandwich. You'll work until after midnight, when you'll fall asleep in front of the light and blare of a TV before rising again at 6 A.M. What's wrong with this picture? Because of modern conveniences and pressures, many of us keep our bodies exposed to light, food, and activity at times when our organs and cells expect dark, quiet, and sleep.

In epidemiologic studies, shorter sleep has been correlated with incidence of obesity, hypertension, and other metabolic disorders. Experimental sleep studies find a similar connection. Increasingly, studies of the possible mechanisms behind these associations suggest that lack of sleep is part of a bigger problem with the 24/7 lifestyle many people today lead. Increasingly, scientists are finding that many physiologic activities related to metabolism don't happen continuously but oscillate on a regular schedule. Studies in mice as well as humans suggest that when our internal clock is disrupted, it may throw off many bodily functions, especially metabolism.

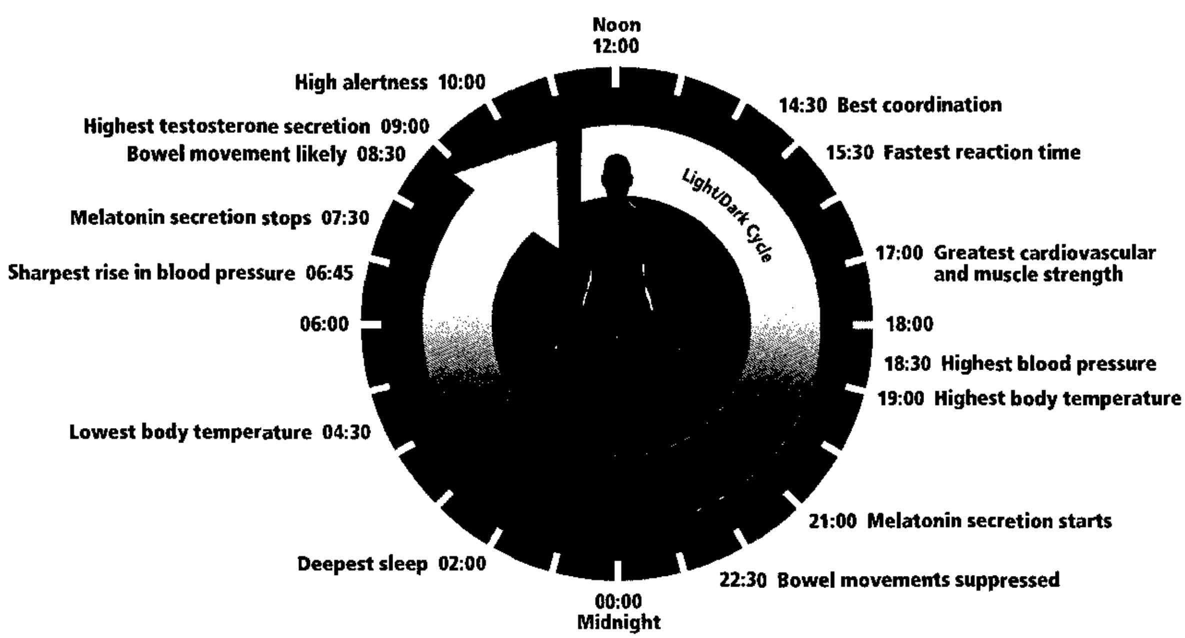
Many environmental factors have been shown to contribute to circadian disruption. Noise in busy hospitals, street noise, and airport noise have all been reported to disrupt sleep or reduce its quality. Research in animals and humans shows that exposure to light during early biological night resets the main circadian clock by producing a phase delay (the biological urge to go to sleep and wake up later than usual), and exposure during late biological night results in a phase advance (going to sleep and waking up earlier than usual).

We live in a world where air passengers can see the glow of major cities 200 miles away. So the fact that human circadian systems appear sensitive even to low-level artificial light exposure raises significant concerns for the health effects of our electrified modern society. For instance, exposure to a few hours of ordinary room light of about 100 lux brightness (which most people get every night before they go to bed) can significantly reset the human circadian pacemaker, Jamie Zeitzer and colleagues reported in the September 2005 *American Journal of Physiology—Regulatory, Integrative and Comparative Physiology*. However, it's not certain what the effects of very brief light exposures may be. The duration of light exposure needed to cause shifts hasn't been well studied, according to a review by Charles Czeisler and Joshua Gooley in volume 27 (2007) of *Cold Spring Harbor Symposia on Quantitative Biology*. [For more information about the health effects of too much artificial light, see "Missing the Dark: Health Effects of Light Pollution," *EHP* 117:A20–A27 (2009).]



Epidemiologic studies suggest that lack of sleep or sleeping on an altered schedule is an independent risk factor for gaining weight. But it's still not certain whether short sleep actually causes obesity and its associated health effects. For instance, some scientists have suggested that the association between obesity and lack of sleep may be due to the fact that people who are obese may be more likely to have a sleep disorder such as sleep apnea, or that the reported lack of sleep is a symptom of psychosocial stress. But a body of studies have shown a connection between short sleep and obesity, other health effects

The Circuit of a Day



The word "circadian" derives from the Latin *circa*, meaning "approximately," and *dies*, meaning "day." The circadian clock (as shown here representing a person who rises early in the morning and sleeps at night) synchronizes with cycles of light/dark, eating, and activity.
Source: School of Biological Sciences, Royal Holloway University of London. Adapted by Matthew Ray/EHP.

Photo, top of page: Mark Viveen/iStockphoto associated with obesity, and increased appetite or food intake.

The Obesity Connection

In one such study, Sanjay R. Patel and colleagues analyzed data from the Nurses' Health Study and found that women who reported sleeping 5 or fewer hours per night were at greater risk for weight gain and in general weighed more compared with women who slept 7–8 hours per night. These findings appeared in the 15 November 2006 *American Journal of Epidemiology*. Because this type of study relies on self-report of amount of time slept—which people tend to overestimate, according to a study by Diane Lauderdale and colleagues in the 1 July 2006 *American Journal of Epidemiology*—the magnitude of the effect may actually be greater than estimated.

Other epidemiologic studies have measured actual sleep time with wrist actigraphy, which involves attaching an instrument that measures physical movement to participants' wrists and using lack of wrist movement as an indicator of actual time slept. These studies also showed a link between reduced sleep and obesity, with weight gain attributed to increases in fat, not muscle mass. Sleep apnea was ruled out as a cause for the association through the use of recordings of brain waves and other physical measurements (polysomnography) in a portion of the study participants.

In a November 2009 special issue of *Obesity Reviews* devoted to the role of circadian biology in obesity and metabolism, sleep epidemiologist Jim Gangwisch of the University of Columbia and colleagues also pointed to the need to explore how quality of sleep affects obesity. Some studies have shown, for instance, that it may not be the total sleep time that matters but how much time is spent in the various stages of sleep—in other words, your sleep architecture. In the 1 April 2009 issue of *Sleep*, Madhu Rao and colleagues reported using polysomnography to find that men who got less slow-wave sleep (a stage considered the deepest sleep, which occurs just before "rapid eye movement" sleep) were more likely to currently be obese, even after controlling for total sleep time.

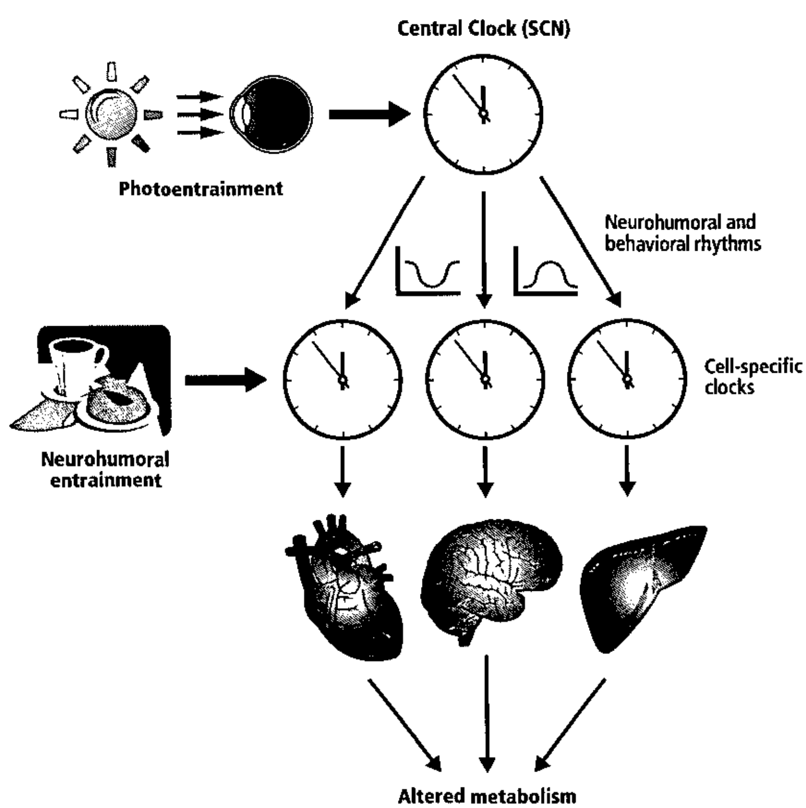
Several studies have linked weight gain associated with short sleep to changes in appetite-regulating hormones such as leptin and ghrelin. Among this work are reports from Karine Spiegel and colleagues in the 7 December 2004 *Annals of Internal Medicine*, and from Shahrad Taheri and colleagues in the December 2004 *PLoS Medicine*. But a study led by University of Chicago endocrinologist Plamen Penev that tried to approximate long-term sleep deprivation in everyday life suggests the relationship between sleep and appetite regulation may be somewhat complex.

As they reported in the January 2009 *American Journal of Clinical Nutrition*, Penev and colleagues had 11 middle-aged, sedentary participants slumber in a controlled sleep laboratory, sleeping fewer than 5.5 hours a night for one 14-day period and more than 7 hours a night during a different 14-day period. The order of the sleep periods (whether the short-sleep period or the normal-sleep period came first) was randomized. The participants were served meals made up of foods they reported eating at home, and they had free access to snacks. "The food they received was served in excess so they could determine their portion sizes themselves," Penev says.

During the sleep-deprived period, the participants ate more calories—mostly from carbohydrate-rich snacks rather than meals—but their leptin and ghrelin levels did not change. In contrast, participants in previous studies were fed a controlled amount of calories via glucose infusion, and that may have made the difference, Penev says.

"I think the changes in leptin and ghrelin in controlled laboratory experiments have been seen mostly at times when the food intake of participants has been limited or mildly restricted," Penev says. "But when the subjects have recently consumed excess calories, then sleep loss does not seem to trigger those changes." Still, the effects on food intake in Penev's study, although modest, were enough to cause increased weight gain in the long run. Larger and longer studies

One Body, Many Clocks



Increasing evidence links disruptions in the body's various circadian timekeepers to obesity and malfunctions in metabolism. It's generally accepted that light exposure can reset the main clock in the suprachiasmatic nucleus of the brain, and that cues from the main clock as well as from eating and activity can reset peripheral clocks that operate in almost all the body's cells.

Source: Bray MS, Young ME. 2009. The roil of cell-specific circadian clocks in metabolism and disease. Obes Rev 10(suppl. 2):6–13. Adapted by Matthew Ray/EHP.

are needed to confirm these findings, he says.

Other preliminary findings from Penev's research group, presented in an abstract at the 2009 meeting of the Associated Professional Sleep Societies, suggests lack of sleep may make it harder to lose fat. In a small experimental study, people on a reduced-calorie, nutritionally balanced diet were sleep-restricted to fewer than 5.5 hours for one 14-day period and in a separate 14-day period were allowed to sleep more than 7 hours a night. The two study periods were several months apart, and again, their order was randomized. The participants lost similar amounts of weight during the two periods, but during sleep restriction, fat made up only 26% of the weight loss, while during the normal sleep period fat made up 57% of the weight loss.

More than Just Gaining Weight

Many epidemiologic and experimental studies link short or disrupted sleep to elements of one of the major health problems linked to obesity: metabolic syndrome, which includes a variety of symptoms that can lead to heart disease, stroke, or diabetes, including high triglycerides and cholesterol, hypertension, insulin resistance, and glucose intolerance.

In a November 2001 study in *Occupational and Environmental Medicine*, Berndt Karlsson of University Hospital in Sweden analyzed data from a study of more than 27,000 workers and found that high triglycerides and low concentrations of high-density lipoprotein ("good") cholesterol seemed to occur more often in shift workers than in day workers. People with restricted sleep in experimental studies have also shown increased blood pressure as well as increased excretion of noradrenaline in the urine. These changes suggest increased activity of the sympathetic nervous system, which in general raises heart rate and blood pressure.

In addition, Gangwisch suggests short sleep can contribute to hypertension by disrupting the normal nightly decrease in blood pressure. "When we sleep, our blood pressure dips by ten to twenty percent," he says. "So the less we sleep, the higher our average twenty-four-hour blood pressure is going to be, and over time that can entrain our blood pressure to operate at a higher equilibrium."

Sleep has also been shown to influence how the body uses insulin and processes glucose. In Penev's study of middle-aged adults with self-determined consumption of meals and snacks, at the end of the sleep-deprived periods the participants showed increased insulin resistance and decreased glucose tolerance, as reported in the September 2009 *Journal of Clinical Endocrinology and Metabolism*.

Previous studies have shown this effect from short-term severe sleep restriction (sleeping fewer than 4 hours a night), but this study was the first to show it with more prolonged and milder sleep restriction, which is more likely to occur in everyday life. If experimental studies continue to link lack of sleep with elements of metabolic syndrome, a larger-scale interventional study may be in order, some researchers suggest.

"Lack of sleep is just one of many risk factors for metabolic syndrome," Gangwisch says. "All things being equal, would improving sleep . . . help reverse the condition? Presumably it would, based upon the evidence we have, but that question needs to be studied." Experimental studies have been of short duration, but Penev says following a group for months or years after a behavioral intervention to reduce chronic loss of sleep may be informative.

Summer All the Time

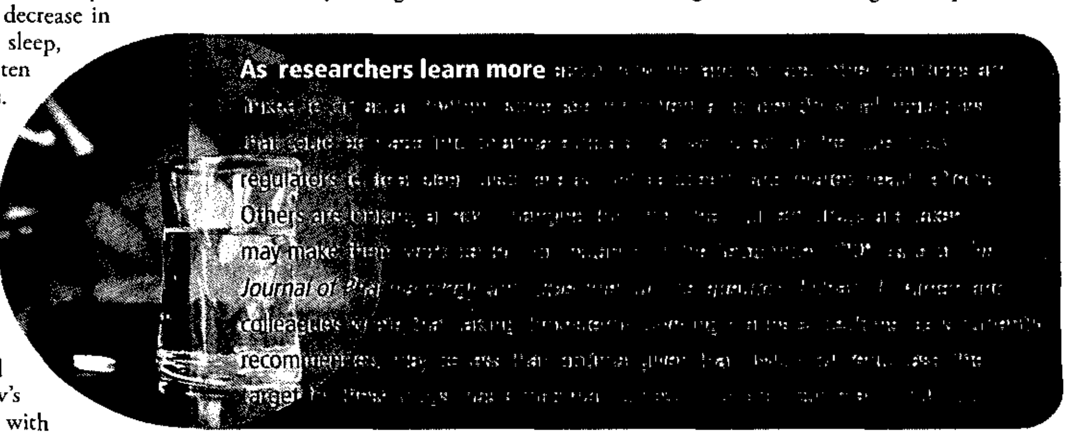
In making conceptual links between obesity and short sleep, some scientists point to the idea that our body clocks evolved to fit the lifestyles of our hunter–gatherer ancestors, who had no artificial lighting. They may have slept less in the longer days of summer, which was also the time for storing up fat reserves for the lean winter ahead. But today's common sleep-deprived, electrified modern lifestyle, combined with readily available food year-round, may be telling our internal clocks it's summer all the time. "The short sleep durations could be a signal to our metabolic regulatory systems that it's summertime—it's time to go out, gain weight, build up fat reserves, to prepare for winter," says Gangwisch.

That sounds logical, but to really test the idea, scientists study the mechanisms of the body's circadian clock, which is run not by gears and springs but by a set of positive and negative transcription factor feedback loops that regulate the expression of themselves as well as other downstream genes. "As the amounts of the positive factors rise, they stimulate expression of the . . . proteins that will 'sit on top' and inhibit the positive factors' expression," says Molly Bray, a molecular geneticist at the University of Alabama at Birmingham. "As the positive loop gets inhibited, then of course the negative factors decrease because there is nothing to stimulate their production."

This process cycles every 24 hours. Some of the genes known to be involved in these loops include *CLOCK*, *BMAL1*, and *PER1* and *PER2*. Mouse models in which these genes are mutated in all body tissues exhibit disruptions in their eating, sleep, and metabolic functions, highlighting the role of the circadian clock in metabolism and obesity.

When most people speak of the circadian clock, they think of the central clock in the brain, located in the suprachiasmatic nucleus of the hypothalamus. But over the last 20 years, scientists have learned that almost all cell types—including fat cells, heart cells, and liver cells—have clock mechanisms, too. Increasingly, it seems these peripheral clocks can be entrained by (that is, changed to align with) environmental cues other than light, such as eating and activity. Moreover, exposure to these cues at times when they aren't "expected" by the body may lead to obesity and related health effects.

For instance, in a study published in November 2009 in *Obesity*, PhD candidate Deanna Arble and colleagues from Northwestern University showed that mice fed during the day (when these nocturnal animals are normally asleep) gained a large amount of weight compared with



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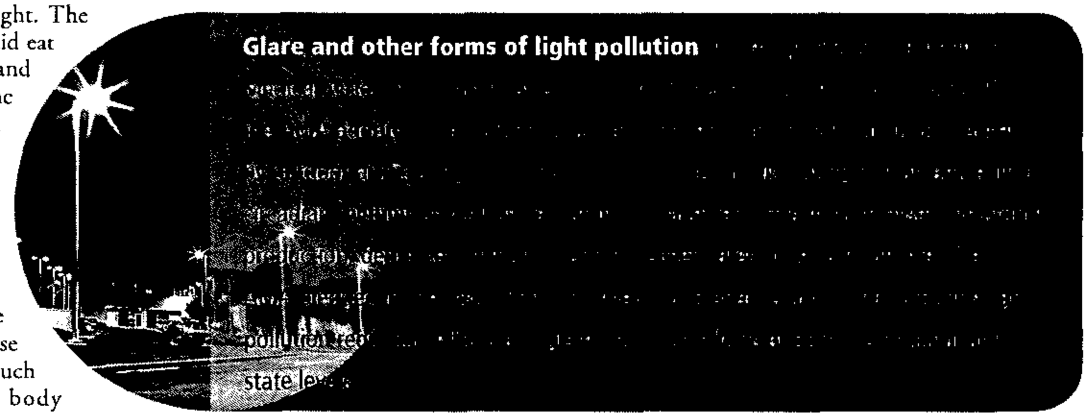

control animals fed at night. The mice fed during the day did eat just a tiny amount more and moved a bit less than the control mice, which could have contributed to the weight gain. But the differences in activity and caloric intake were statistically insignificant, and it's unlikely those factors were the sole cause of the weight gain because the two groups showed such drastic differences in body weight, says Arble.

In similar preliminary findings currently being written up for submission, Bray and Martin Young, an associate professor of cardiology also of the University of Alabama at Birmingham, found that rodents fed a high-fat diet at the end of their active phase gained more weight and had decreased glucose tolerance compared with animals that ate a high-fat diet at the beginning of their active phase but ate a protein-matched, low-fat control diet at the end of their active phase. "Evidence is beginning to accumulate to suggest that the time of day at which we consume not only total calories but also fat versus carbohydrates does quite profoundly influence how those calories are metabolized and therefore the risk of these metabolic diseases," says Young.

In a human study published in the 17 March 2009 issue of *Proceedings of the National Academy of Sciences* by Frank A.J.L. Scheer and colleagues, symptoms of metabolic syndrome resulted when participants ate and slept at the wrong times—that is, out of alignment with their habitual circadian cycle. Over a 10-day experimental study, participants ate and slept at all phases of the circadian cycle. When they ate and slept about 12 hours out of phase from their habitual times, they showed decreased leptin levels, increased glucose (despite increased insulin), and increased mean arterial pressure. Three of the subjects showed post-meal glucose responses in the range typical of a prediabetic state.

Other research hints at the mechanisms involved in these links between disruption of circadian rhythms and metabolic syndrome. Using a mouse model in which heart-specific clock cells were disrupted, Young found these cells directly regulated triglyceride metabolism, as reported 25 November 2009 ahead of print in the *Journal of Biological Chemistry*. In beating hearts removed from normal mice—and thus free from hormonal and other factors in the body that influence triglyceride levels—Young observed normal fluctuation in the synthesis and breakdown of these esters throughout the day. But in hearts removed from heart-specific clock mutant mice, that oscillation was completely lost. "Those data showed that the cell-specific clock is regulating triglyceride metabolism," Young says.

In another example, Jeff Gimble, a professor of stem cell biology at the Pennington Biomedical Research Center, has found evidence that levels of lipoprotein lipase, which prevents buildup of fats in the liver and arteries by moving them from the bloodstream into adipose tissue, oscillate throughout the day, peaking during mice's active phase. Extrapolating from those data to speculate on what this may mean for humans, Grimble says, "If you're eating fat when lipoprotein lipase is at its bottom level, you're going to clear fats that much more slowly."

The Tip of the Iceberg?

Big questions still to be answered include which functions are regulated by the central clock, which are regulated by the peripheral clocks, and how the various clocks interact. It's hard to separate out those questions in many of the classic mouse models, which are global knockouts of clock genes in all tissues. These models show very different phenotypes. For example, global loss of *Bmal1* leads to a mouse that tends to be lean but has complete loss of circadian clock function in almost every cell type, problems with glucose homeostasis, and a reduced life span. Mice with a mutated *Clock* gene are obese and have features of metabolic syndrome, but they show relatively normal activity levels under normal light/dark cycles and show abnormal behavior only in complete darkness.

Are these differences caused by the knockout of the central clock, the knockout of the peripheral clocks, the way activity and feeding changes are affecting peripheral clocks, or even the strain of mouse used? Researchers are beginning to address those questions with cell-specific models. For instance, by knocking out the clock only in fat cells in a mouse model, Bray and Young have induced metabolic syndrome in the animal. "Most of the phenotypes observed in the global clock knockout are also present in the adipocyte-specific model," Bray says.

Some scientists also wonder whether the effects seen from disruption of clock genes are caused by the genes' roles in circadian rhythms or by some other unknown functions of the genes. "This is a little controversial, but there are some data out there suggesting that some of these clock genes, such as *PER2*, have functions independent of the clock," Young says. For example, a study from Rainer Spanagel and colleagues published in the January 2005 issue of *Nature Medicine* suggested *Per2* influenced alcohol consumption in mice via the neurotransmitter glutamate.

Because of such observations, some see very widespread ramifications of learning more about metabolism, obesity, and circadian clock functions. A leading researcher in circadian rhythm studies, Fred Turek of Northwestern University, has suggested the close relationship between metabolism and clock functions may just be the tip of the iceberg. Writing in the 18 December 2008 issue of *Nature*, he proposed the clock may be the "conductor of the orchestra" that keeps all the body's behavioral and physiological functions working in harmony.

"I don't think Dr. Turek is reaching by saying that," Bray says. "We know that disruptions in the DNA sequence of some clock-related genes are associated with seasonal affective disorder and bipolar disorder. But how that works is just not known."

Angela Spivey writes from North Carolina about science, medicine, and higher education. She has written for *EHP* since 2001 and is a member of the National Association of Science Writers.

LIGHT POLLUTION

Light at Night and Breast Cancer Risk Worldwide

Several studies over the last decade have suggested that the modern practice of keeping our bodies exposed to artificial light at night, or LAN, increases cancer risk, especially for cancers (such as breast and prostate cancers) that require hormones to grow. Women who work night shifts have shown higher rates of breast cancer,[1] whereas blind women, who are not likely to be exposed to or perceive LAN, have shown decreased risks.[2] In 2007, the International Agency for Cancer Research declared shiftwork a probable human carcinogen.[3] Now a large study of 164 countries adds another piece of evidence, implicating overall light pollution.

The study, conducted by University of Connecticut epidemiologist Richard Stevens and colleagues at the University of Haifa, showed that higher population-weighted country-level LAN levels were associated with higher incidence of breast cancer.[4] A sensitivity test indicated a 30–50% increased risk of breast cancer in countries with the highest versus lowest LAN levels. No such association was found between LAN and incidence of non-hormone-dependent lung, colorectal, larynx, or liver cancers in women.

"We took the top-level view and said, 'If there really is causation going on, LAN levels worldwide should correlate well with breast cancer incidence,'" Stevens says. "This is a necessary but not sufficient condition for a potentially large effect. If we had seen no relationship between country LAN level and breast cancer risk, that would have been good evidence against a large effect of LAN on breast cancer risk."

Tulane University cancer biologist David Blask points out the implications go beyond shiftwork. "This study suggests that all of us who live in industrialized society have the potential to have our circadian system disrupted by too much light at night, and this risk is potentially not restricted to a smaller percentage of the population that is exposed because of their occupation," Blask says.

Harvard epidemiologist Eva Schernhammer agrees that the positive result from this study adds more evidence to the idea that LAN exposure contributes to breast cancer risk. But as an ecological study,[5] even if the result had been negative, it would not be strong enough to rule out evidence from prior case–control studies, she says.

The study authors point out that because of the ecological nature of the study, it did not control for behavior that would reduce individuals' exposure to LAN, such as sleeping. If people are actually asleep, then little to no light would reach their retinas, Stevens says, adding, "Three of four good prospective studies have reported a lower risk of breast cancer in women who report a long sleep duration."[6] Stevens thinks of reported sleep duration as a surrogate for time spent in the dark. But people do wake in the middle of the night, he points out, and even brief periods of open eyes during the night could expose the retina to LAN.

The new study highlights the need to understand the mechanisms behind the association between cancer and LAN, which aren't clear, Stevens says. Previously, Blask and colleagues famously showed that a key factor in the connection is melatonin, a hormone produced in nighttime darkness that promotes sleep.[7] They showed that growth and metabolism of human breast cancers growing in rats slowed when the tumors were perfused with melatonin-rich human blood collected during the night. In contrast, growth and metabolism were unchanged in tumors perfused with blood in which melatonin levels had been suppressed because of even a brief LAN exposure. Using the same model, Blask and George Brainard of Thomas Jefferson University have begun conducting pilot studies of the effects of melatonin and LAN on human prostate cancer.

Other studies are implicating over- or underexpression of genes known to be involved in the body's circadian clock. For instance, Stevens and colleagues at Yale including Yong Zhu found that healthy control women showed lower expression of the *CLOCK* gene than women with breast cancer.[8] They also found that epigenetic changes—the switching on or off of genes as a result of environmental factors—may play a role. For instance, an epigenetic change called promoter methylation, which turns off expression of *CLOCK*, was associated with lower risk of breast cancer.[8] Stevens and Zhu are now studying whether women who work night shifts exhibit lower *CLOCK* promoter methylation.

Ways to reduce circadian disruption resulting from LAN exposure[9–11]

» Consider extending the dark period at night to 9 or 10 hours. Install room-darkening shades in bedrooms.

» Avoid even brief light exposures. Turn off the lights, television, and computer in the bedroom when you are sleeping. Avoid watching television or working on the computer right before you shut your eyes.

» If you get up in the night, forgo the usual bathroom lights for a dim red nightlight. Red light suppresses melatonin production less than other wavelengths.

» Do not take melatonin tablets unless directed by a physician. The spike in circulating melatonin may actually worsen, not alleviate, circadian disruption.

Another big question is how much of a contribution LAN makes to cancer risk. "Light at night is likely to be one of a number of factors that contributed to the increase in breast cancer over the last few decades," says Les Reinlib, the program director who coordinates NIEHS grants related to health effects of LAN. "It seems to be significant, and if it is, then that's something we can control."

Angela Spivey writes from North Carolina about science, medicine, and higher education. She has written for *EHP* since 2001 and is a member of the National Association of Science Writers.

NASA

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anses
French agency for food, environmental and occupational health & safety

Press Kit

Lighting systems using light-emitting diodes: health issues to be considered

\- 25 October 2010 -

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Lighting systems using light-emitting diodes (LEDs): health issues to be considered

Today, the French Agency for Food, Environmental and Occupational Health & Safety (ANSES)[1] is publishing its expert appraisal on the health issues surrounding lighting systems using LEDs; such a study has never been carried out before. Because of their low electricity consumption and high efficiency, lighting systems using LEDs are at the forefront of technology in terms of energy performance and are well-fitted to play a role in energy-saving policy. The market for these systems is growing rapidly. However, risks have been identified concerning the use of certain LED lamps, raising potential health concerns for the general population and professionals.

The principal characteristic of diodes sold for lighting purposes is the high proportion of blue in the white light emitted and their very high luminance ("brightness"). The issues of most concern identified by the Agency concern the eye due to the toxic effect of blue light and the risk of glare.

The blue light necessary to obtain white LEDs causes toxic stress to the retina. Children are particularly sensitive to this risk, as their crystalline lens is still developing and is unable to filter the light efficiently.

These new lighting systems can produce "intensities of light" up to 1000 times higher than traditional lighting systems, thus creating a risk of glare. The strongly directed light they produce, as well as the quality of the light emitted, can also cause visual discomfort.

As part of its expert appraisal, ANSES carried out various pioneering studies to evaluate the risks of these new lighting systems, on the basis of the European photobiological safety standard[2]. Some of these products fall into higher Risk Groups than certain traditional lighting systems which are still available to the general public.

In this context, ANSES recommends that only LEDs belonging to Risk Groups similar to those of traditional lighting systems be accessible to the general public, with higher-risk lighting systems being reserved for professional use under conditions in which it is possible to guarantee the safety of workers.

Furthermore, ANSES emphasises the need to reduce the perceived luminous intensity, in order to mitigate the risk of glare.

The agency also recommends avoiding the use of light sources with a strong blue component in places frequented by children.

Lastly, ANSES has made various recommendations concerning consumer information, modifications to and implementation of the standards in force and the need for further knowledge of health issues surrounding artificial lighting.

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[1] Since 1 July 2010, ANSES has assumed all the missions that were previously the responsibility of the French Food Safety Agency (AFSSA) and the French Agency for Environmental and Occupational Health Safety (AFSSET).
[2] NF EN 62471. This standard applies to lamps and devices using lamps. It recommends exposure limits for radiation from these light sources. It considers all of the photobiological hazards that may affect the eye (thermal and photochemical hazards) and defines 4 risk groups: risk group 0 (no risk), risk group 1 (low risk), risk group 2 (moderate risk), risk group 3 (high risk).

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anses
French agency for food, environmental and occupational health & safety

Contents:

1- ANSES recommendations

- **Adapt the regulatory framework and applicable standards**

Considering the health risks related to the blue light emitted by certain lighting systems using LEDs, the risk of significant glare caused by such systems and the marketing of LED-based products for light therapy, comfort or well-being, the agency recommends that:

- only LEDs falling into risk groups similar to those of traditional lighting systems be available to the general public, and that the highest risk lighting systems be reserved for professional use under conditions in which it is possible to guarantee the safety of workers.
- manufacturers and integrators of lighting systems using LEDs be encouraged to:
  - design lighting systems in which beams of light emitted by LEDs cannot be seen directly, to avoid glare. In particular, ANSES recommends the use of optical devices to reduce the intensity of light perceived directly or by reflection and to make the sources of LED light more diffuse;
  - take account of the progressive wear of layers of phosphor in white LEDs, which in time could lead to devices being moved from one photobiological risk group to a higher one
- the safety and compliance of devices for light therapy, comfort or well-being be assessed and their use regulated.

Considering that the standards in force for designing LED-based lighting installations are not always applied by professionals (electricians, lighting technicians and designers) and that the photobiological safety standard seems unsuited to lighting systems using LEDs, ANSES recommends:

- obliging professionals designing lighting systems using LEDs to apply all standards concerning the quality of lighting[3]
- adapting the standard entitled "Photobiological safety of lamps and lamp systems" to cover lighting systems using LEDs so as to make it easier for manufacturers to take them into account and remove any ambiguity concerning the way in which they should apply to LED systems.

  ANSES considers that it is necessary to:
  - give precise instructions in the standard for the measurement and evaluation of LED systems
  - publish a guide for applying this standard, especially for LED systems
  - determine the risk group for the worst case of observation (at a distance of 200 mm from the system) that will thus constitute the most unfavourable risk group
  - adapt the standard to cover children and people with either no lenses or artificial crystalline lenses (aphakic or pseudophakic), taking into account the phototoxicity curve of the relevant type of light published by the ICNIRP[4]

[3] French standard NF X 35-103 (*'Ergonomie : Principes d'ergonomie visuelle applicables à l'éclairage des lieux de travail'* – Ergonomics: Principles of visual ergonomics applicable to lighting in the workplace), and European standards NF EN 12464-1 ('Lighting of workplaces – Part 1: indoor workplaces'), NF EN 12464-2 ('Lighting of workplaces – Part 2: outdoor workplaces'), the series of standards NF EN 13201 ('Street Lighting') and NF EN 12193 ('Sports Lighting').

[4] International Commission on Non-Ionizing Radiation Protection

  - consider proposing sub-groups for each risk group that would allow the risk to be assessed more precisely as a function of exposure time;
  - in the case of risk groups greater than 0, evaluate safe distances (distance at which observation corresponds to Risk Group 0) and for these to be indicated explicitly on products intended for consumers (the case of devices for the general public) or for professionals responsible for installing lighting systems.

- photobiological safety requirements be included in all safety standards concerning LEDs[5].

- **Use, information and traceability**

ANSES recommends that consumer information about health risks related to the use of LED lighting systems be made available immediately while waiting for an appropriate regulatory framework to be implemented.

Considering the proven risk resulting from acute exposure to blue light and the uncertainty surrounding the effects of chronic exposure at low doses, as well as the fact that certain populations are sensitive to light in general[6], ANSES recommends:

- that the use of light sources emitting bright cold light (light with a strong blue component) be avoided in places frequented by children (maternity wards, nurseries, schools, play areas, etc.) or in the objects they use (toys, electronic display panels, game consoles and joysticks, night lights, etc.);

- that patients taking medicines that increase sensitivity to light be informed about the risks related to exposure to light with a strong blue component.

Considering that there are populations of workers that are likely to be exposed to bright LED lighting systems, ANSES recommends that appropriate means of protection[7] be developed for workers particularly exposed to LED lighting systems.

Considering the lack of information available to the public concerning the LED lighting systems on the market, ANSES recommends:

- ensuring that manufacturers and integrators of LEDs carry out quality controls and qualify their products with regard to the different Risk Groups

- setting up a clear, easy to understand labelling system for consumers, particularly concerning the technical characteristics of the lighting and any potential health and safety issues

- making it mandatory to indicate the photobiological safety Risk Group, assessed at a distance of 200 mm, on the packaging of LED products. For light sources falling under Risk Group 1, it would be necessary to indicate the safety distance beyond which the classification returns to Risk Group 0.

[5] Especially the series of French standards NF EN 60598 ('Luminaires' and NF EN 62031: ('LED modules for general lighting. Safety specifications'); IEC standard 62560 ('Self-ballasted LED-lamps for general lighting services by voltage > 50 V - Safety specifications'); the draft IEC standard 62663-1 ('Non-ballasted single-capped LED lamps for general lighting – safety requirements').

[6] Children, aphakic and pseudophakic persons, patients suffering from certain eye and skin diseases, patients consuming substances increasing sensitivity to light, etc.

[7] Such as safety goggles specifically to protect against exposure to LEDs

- making it mandatory to indicate the photobiological safety Risk Group for all types of lighting.

- **Studies and research to be undertaken**

Concerning the lack of data about exposure of the general and working population to artificial light, ANSES recommends:

- enriching the available documentation on exposure of the population to artificial light in both occupational and general environments
- defining an index suitable for evaluating the intensity of glare produced by an LED source. This is because the Unified Glaring Rate used for the other types of lighting is unsuitable for LEDs, which are sources of low-angle light.

Concerning studies and research on the health issues surrounding lighting systems using LEDs, ANSES recommends:

- developing clinical research to define exposure limit values for blue light and, for this purpose, paying particular attention to the accumulative medium and long-term effects of exposure to blue light by means of prospective and retrospective studies of populations undergoing light therapy with the use of blue LEDs
- undertaking research for improved characterisation of the effects of artificial light and in particular light emitted by LED systems on biological rhythms. ANSES therefore recommends:
  - further studies for improved characterisation of the spectrum of action of the mechanisms by which light regulates the human biological clock
  - quantifying the consequences of exposure to cold artificial lights on circadian rhythms and pupil contraction
  - in general, studying the health effects of light pollution (and any links with possible maladjustment of the biological clock) and systematic installation of LED lighting systems
- studying the triggering or aggravation of photo-dermatoses caused by LED lighting
- organising measurement campaigns to characterise the electromagnetic fields generated by LED lighting systems.

Concerning studies and research to be carried out on LED technology to mitigate potential health risks, ANSES recommends:

- encouraging research for the development of new emissive materials coupled with optimised luminophores, to obtain high quality white light, with the highest possible luminous efficacy
- developing research into the design of lighting units adapted to LEDs with a view to reducing the luminance, by applying optical solutions
- studying the mechanisms that cause the degradation of the layers of phosphor in white LEDs thus potentially leading to an increase in the amount of blue light emitted

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2- LEDs and health: what are the risks?

The risks identified by ANSES as causing the most concern, both because of the seriousness of the corresponding dangers and because of the probability of their occurring due to the increasingly widespread use of LEDs for lighting purposes, are related to the photochemical effects of blue light on the eye and the glare phenomenon. These are long-term risks, resulting from:

- the spectral imbalance in LEDs (high proportion of blue light in white LEDs)
- the very high luminance of LEDs[8] (high density of brightness per surface unit emitted by these very small sources)

Risks related to blue light

Photochemical risk is associated with blue light. The risk level depends on the accumulated dose of blue light to which the person has been exposed, which is generally the result of low intensity exposure repeated over long periods. Evidence from human observation and experimental studies on cell cultures and various animal species has converged to demonstrate the particular toxicity of shortwave (blue) light for the retina. Blue light is therefore recognised as being harmful and dangerous for the retina, as a result of cellular oxidative stress.

Three populations have been identified as either particularly sensitive to the risk or particularly exposed to blue light:

- **children** (because of the transparency of their crystalline lens) and both aphakics (with no crystalline lens) and pseudophakics (with artificial crystalline lenses) who consequently either cannot or can only slightly filter short wavelengths (particularly blue light);
- **populations which are already light-sensitive**: patients suffering from certain eye diseases (e.g. ARMD) and skin conditions, patients consuming substances that increase sensitivity to light, etc. for whom blue light can be an aggravating factor for their condition;
- **populations particularly exposed to LEDs** (certain categories of workers: those installing lighting systems, theatre and film industry professionals, etc.) who are subjected to high-intensity lighting, and are therefore likely to be exposed to large quantities of blue light.

Risk related to glare

In indoor lighting, it is generally agreed that luminance higher than 10,000 cd/m^2 causes visual discomfort whatever the position of the lighting unit in the field of vision. Because the emission surfaces of LEDs are highly concentrated point sources, the luminance of each individual source can be 1000 times higher than the discomfort level. The level of direct radiation from this type of source can therefore easily exceed the level of visual discomfort, far more than is the case with "traditional" lighting.

According to the existing scientific literature, other risks related to the use of LED lighting systems have been raised and are dealt with more extensively in the Report and the Opinion published by the Agency. However, knowledge of risks is still partial and requires further study. ANSES has made a series of recommendations to overcome this lack of data.

[8] Luminance is the unit used to quantify the light emitted by a non-point source, per surface unit, in other words, the light density. It is expressed in candela per square metre. Candela (cd) is the unit used to quantify light intensity, in other words the brilliance of a light source as perceived by the human eye. A normal candle emits approximately 1 cd.

At the European level, a working group has been set up by the SCENIHR[9] whose mission is to evaluate the health issues surrounding artificial lighting in the widest sense, including LEDs.

3- Regulatory framework and applicable standards: room for improvement

The Directive relative to general product safety[10] applies to all products classified in sectors not covered by specific legislation. The "EC" label, which is mandatory on all electrical devices sold in Europe, is a 'self-declaration', indicating that the manufacturer considers that the product complies with all the EU conditions for use of the label.

Where LED lighting is concerned, EC labelling testifies that the product complies with the following essential European Directives: "Low voltage"[11], "Electromagnetic compatibility"[12] and "Ecodesign" (for Energy-using Products)[13], with particular attention to product safety, their energy consumption, their emissions (noise, vibrations, radiation, electromagnetic fields), whether they can be recovered for recycling, etc.

Products that satisfy these requirements comply with specific standards, known as harmonised standards, published in the Official Journal of the European Union. Regarding LED lighting, the safety requirements that have been declared mandatory for EC labelling are described in the standards covering electrotechnical aspects of hardware safety, electromagnetic compatibility and personal exposure to optical[14] and electromagnetic[15] radiation.

Furthermore, the Government Decree 2010-750 of 2 July 2010, integrating directive 2006/25/EC into French law, lays down the measures to be applied to ensure that workers are protected against the risks of exposure to artificial optical radiation.

The need to adjust the standards framework

In the context of its work on the health effects of lighting systems using light-emitting diodes, ANSES examined the current standards framework and how it could be adapted to the specific features of LEDs. It found in particular that the photobiological safety standard[16] seems ill-adapted to lighting systems using LEDs and furthermore that:

- the exposure limit values used to define the Risk Groups are not appropriate for repeated exposure to blue light as they were calculated for exposure of one 8-hour day and do not take into account the possibility of exposure over an entire lifetime;
- it contains ambiguities concerning the measurement protocols for attributing Risk Groups: the same LED could be assigned to different Risk Groups if considered individually or if part of an integrated lighting system, as the evaluation distance required by the standard could be different;

[9] Scientific Committee on Emerging and Newly Identified Health Risks
[10] Directive 2001/95/EC
[11] Directive 2006/95/EC
[12] Directive 2004/108/EC
[13] Directive 2005/32/EC
[14] NF EN 62471 standard concerning photobiological safety of lamps
[15] NF EN 62311 standard concerning electromagnetic fields
[16] NF EN 62471 standard

- it does not take into account the sensitivity of certain specific populations (children, aphakics, pseudophakics, etc.).

In its Report, the Agency therefore makes a series of recommendations for adapting the regulatory framework and applicable standards to take into account identified health risks and the specific features of LEDs.

4- The LED report: how did ANSES proceed?

ANSES studied the health issues arising from lighting systems using LEDs as the result of a request made on its own initiative. The expert appraisal was entrusted to the Expert Committee on "Physical agents, new technologies and development areas", which, after a public call for applications, set up a working group including experts in ophthalmology, dermatology, lighting and the physics of optical radiation. This Report was therefore compiled by a group of experts with complementary experience and knowledge. It was carried out in compliance with the French Standard NF X 50-110 "Quality in Expert Appraisal Activities" in order to comply with the following points: competence, independence and transparency, while at the same time ensuring traceability. Such a study has never been carried out before.

The experts in this working group considered five main themes:
- a review of the current situation regarding lighting;
- a presentation of the technology behind LEDs;
- an analysis of the way light interacts with biological systems (the eyes and skin);
- a summary of the standards currently applicable to LEDs;
- an analysis of the potential health issues surrounding LEDs when used for lighting purposes.

To produce its appraisal, the working group carried out a broad review of the international scientific literature to be found in international, English-language, peer-reviewed journals, in addition to interviews with French and international scientific experts and representatives of the French Association of Lighting Professionals (*Association Française de l'Eclairage* – AFE). At the group's request, the French Environment and Energy Management Agency (ADEME) submitted a written contribution on the French and European market for lighting systems and the recycling of lamps.

Members of the working group

Chairperson

- Mrs Francine BEHAR-COHEN – Director of Research at the National Institute for Health and Medical Research (INSERM), Physiopathology of eye diseases: innovative therapies

Members

- Mrs Annick BARLIER-SALSI – National Research and Safety Institute (INRS), specialist on optical radiation in the workplace
- Mr Jean-Pierre CESARINI – Anatomo-pathologist (past Director of the laboratory for research into tumours of human skin, A. de Rothschild Foundation and INSERM) – Ultra-violet radiation. Member of the "Physical agents, new technologies and development areas" CES
- Mr Olivier ENOUF – Engineer responsible for compliance tests of laser devices and LED products, National testing Laboratory (LNE)
- Mr Michel GARCIA – Engineer in the Lighting, Electricity and Electromagnetism (3E) Unit at the French scientific and technical centre for building (CSTB)

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- Mr Christophe MARTINSONS – Head of the Lighting, Electricity and Electromagnetism (3E) Unit at the French scientific and technical centre for building (CSTB)
- Mr Serge PICAUD – Director of Research, Vision Institute, INSERM, Processing visual information in the retina, pharmacology and pathologies
- Mrs Françoise VIENOT – Professor at the Natural History Museum, Manager of the "Vision, light and appearance" Team at the Centre for research into the conservation of collections (CRCC)
- Mr Georges ZISSIS – Deputy-Director of the Plasma and Energy Conversion Laboratory, LaPlaCE, University of Toulouse 3

5- Lighting and LEDs: an overview

In France, lighting accounts for 10% of total energy consumption, or 350 kW/h per year and per household. In application of the European Eco-design Directive[17], the European Commission plans a progressive ban on the sale of the most high-energy lamps. Compact fluorescent or "low-energy" lamps or other sources of energy-saving lighting such as light-emitting diodes, seem destined to replace them eventually. The French Environment and Energy Management Agency (ADEME) published an Opinion concerning the latter (LEDs) in February 2010[18].

To avoid confusion:

- **A lumen (lm)** is the unit used to quantify a luminous flux.
- **A lux (lx)** is the unit used to express the illumination, in other words the luminous flux hitting a surface.
- **A candela (cd)** is the unit used to quantify the intensity of light, in other words the intensity of a light source perceived by the human eye. A normal candle emits approximately 1 cd.

Light-emitting diodes are light sources that are currently undergoing rapid technological and financial development. They have been used for several years in electronics as weak, monochromatic light sources for indicator or warning lights and are now commonly used as normal light sources in various lighting systems: traffic lights, portable lighting, vehicle lights and domestic room lighting, for example.

History of LEDs

The first visible spectrum LED was created in 1962 and emitted only very low intensity light. The blue diode was invented in the 1990s, followed by improvements to the white diode that made it possible to use it in new and important applications (mainly for lighting and for television and computer screens). The first white LEDs appeared on the market gradually, particularly for domestic lighting, and have now become increasingly powerful.

Where do LEDs stand in relation to other types of lighting?

Because of their low electricity consumption and high efficiency, these lighting systems are at the forefront of technology in terms of energy performance and are well-fitted to play a role in energy-saving policy.

Compared to the other types of lighting systems, LEDs offer greater energy efficiency. As an example, some LEDs have an efficiency as high as 100 to 150 lm/W[19] whereas incandescent lamps achieve only 10 to 15 lm/W, halogen lamps 15 to 30 lm/W, and compact fluorescent lamps in the region of 50 to 100 lm/W. As for their lifecycles, current LEDs are estimated to last 50 times longer than incandescent lamps and 3 to 5 times longer than compact fluorescent lamps.

LED technology has certain disadvantages, however; the quality of the light they emit (temperature and colour rendering index) is not always equivalent to that of other systems.

[17] Directive 2005/32/EC, also known as "EuP" (Energy using Products), aims to improve the energy efficiency of certain consumer goods. This Directive was transposed into national law by the Member States of the European Union in 2007 with a schedule to bring it into force between 2008 and 2010.

[18] Opinion of ADEME "Lighting using light-emitting diodes (LEDs)", *L'éclairage à diodes électroluminescentes (LED)* – available from www.ademe.fr (in French)

[19] Lumens per Watt is the unit for expressing the efficacy of lighting. The lumen is the unit used to quantify luminous flux.

6- Where are LEDs found?

As a result of their low energy consumption, the market for LEDs is expanding rapidly. They are used in a growing number of sectors for a wide range of applications, including the following examples:

- Signposting: traffic lights, city lighting, road and traffic safety (automobile lights), warning lights etc.

- Lighting at home and in the workplace: torches and head lamps, lighting units, spotlights, decorative lighting (spotlights, arrays, decorative strings of electrical lights, etc.), lighting for operating theatres and dentists' chairs, etc.

- Medical or beauty applications: lamps for light-therapy applications, for medical or beauty treatment.

The Director General

Maisons-Alfort, 19 October 2010

OPINION
OF THE FRENCH AGENCY FOR FOOD, ENVIRONMENTAL AND OCCUPATIONAL HEALTH & SAFETY

in response to the internally-solicited request entitled "Health effects of lighting systems using light-emitting diodes (LEDs)"

ANSES's public health mission involves ensuring environmental, occupational and food safety as well as assessing the potential health risks they may entail.

It provides the competent authorities with the necessary information concerning these risks as well as the requisite expertise and technical support for drafting legislative and statutory provisions and implementing risk management strategies (Article L.1313-1 of the French Public Health Code).

1. PRESENTATION OF THE QUESTION

The European Eco-design Directive (2005/32/EC), known as "EuP" for Energy-using Products, aims to improve the energy efficiency of certain consumer goods. This Directive was transposed into national law by the Member States of the European Union in 2007 and came into force between 2008 and 2010.

On 18 March 2009, in application of the EuP Directive, the European Commission decided in favour of a gradual ban on the sale of the most energy-consuming lamps, scheduled for implementation from 1 September 2009 to 1 September 2016. Compact fluorescent or "low-energy" lamps, or other sources of energy-saving lighting such as light-emitting diodes, are destined to replace them eventually.

Light-emitting diodes are light sources that are currently undergoing rapid technological and financial development. They have been used for several years in electronics as weak, monochromatic light sources for indicator or warning lights and are now commonly used as normal light sources in lighting systems.

The first visible spectrum LED was created in 1962 and emitted only very low intensity light. The blue diode was invented in 1990, followed by the development of the white diode that made it possible for new and important applications to be adopted, mainly for lighting, television and computer screens. The first white LEDs appeared on the market gradually and are now increasingly powerful[1] (consuming from a few Watts to a few tens of Watts). The most widely-used procedure for producing white light couples a blue LED and a yellow phosphor.

[1] Source – ADEME: "Low-power LEDs (i.e. lower than 1 Watt) are used as indicator lights on domestic appliances, for example. High-power LEDs (i.e. higher than 1 Watt) can withstand stronger currents (up to 1500 mA) and supply more light (135 lm/W)".

The French company OSYRIS[2] expressed concern in a letter addressed to the French Institute for Public Health Surveillance (InVS), dated 27 December 2007, about the possible impact on the retina of light from LEDs. The letter underlined the possible link between exposure of the eye to shortwave radiation, close to ultraviolet light (characteristic of the light spectra of LEDs) and the risk of macular degeneration, an eye disease. The InVS forwarded the OSYRIS letter to the French Agency for Environmental and Occupational Health Safety (AFSSET[3]) in a letter dated 14 January 2008.
Simultaneously, the question of the impact of LEDs on occupational health was raised during informal discussions between AFSSET and the Directorate-General for Labour (DGT), the latter having recently been alerted by projects for the use of indoor LED lighting for buildings. The development of this type of lighting solution is likely to accelerate mainly due to cost considerations, for applications involving both general and professional populations.

2. SCIENTIFIC CONTEXT AND APPLICABLE STANDARDS

In France, lighting accounts for 10% of total electricity consumption, or 350 kWh per year and per household[4]. LEDs consume far less energy than other types of lighting and have much longer lifetimes.
The luminous efficacy of incandescent lamps is of the order of 10 to 15 lumens[5] per Watt (lm/W), for halogen lamps it is from 15 to 30 lm/W and for compact fluorescent lamps it is in the range of 50 to 100 lm/W. Some of the latest LEDs achieve an efficacy of up to 100 to 150 lm/W, with predictions in the region of 200 lm/W for 2020[6].
There is as yet no standard definition of the lifetime of an LED. Estimates for current LEDs, however, predict considerable lifetimes, up to 50,000 hours[7], or 50 times longer than incandescent lamps and 3 to 5 times longer than compact fluorescent lamps.
The technology behind LEDs, which have certain advantages over other types of lighting, (energy efficiency and lifetime), is constantly changing. They are used in a wide variety of fields: public, domestic and workplace lighting, sports facilities, as indicator lights (toys, signage, etc.), vehicle lights and light therapy products. However, the quality of the light (colour temperature[8], colour rendering index[9]) emitted by these lamps does not always achieve the same level of performance as other sources of lighting.

There are currently three methods for creating a light-emitting diode that emits white light:

[2] A French company specialising in lasers and their application in medicine and industry.

[3] The French Agency for Environmental and Occupational Health Safety (AFSSET) and the French Food Safety Agency (AFSSA) merged on 1 July 2010 to create the French Agency for Food, Environmental and Occupational Health & Safety (ANSES).

[4] Source: ADEME 2010.

[5] The lumen is the unit used to quantify luminous flux and expresses the total quantity of light emitted by a source. The candela is the unit used to express the quantity of light emitted in a given direction. The quantity of light received on a surface is expressed in lux.

[6] The theoretical limit for the luminous efficacy of light sources is set at 683 lm/W.

[7] Source: ADEME 2010

[8] The colour temperature of a white light is used to define its hue, which can be warm or cold; lights with warm hues tend towards yellow-orange and have colour temperatures below 3000 K. Higher colour temperatures correspond to "colder" hues.

[9] The Colour Rendering Index (CRI) runs from 0 to 100 and defines the aptitude of a light source to reproduce the different colours of the objects on which its light falls, compared to a reference source. Sunlight has a CRI of 100, while some low-pressure sodium-vapour lamps (used in road tunnels, for example) have a CRI of 20. In shops, schools and offices, the CRI should always be greater than 80.

- *1*: by combining a short wavelength-emitting diode (blue) with a yellow luminophore;
- *2*: by using a diode emitting in the near-ultraviolet, coupled with one or more luminophores;
- *3*: by using at least three visible wavelength-emitting diodes that combine to give a white light.

At the moment, the most economic and widely used is Method 1. The conclusions presented in this Opinion concern LEDs using this first method. They cannot therefore be extrapolated to cover LEDs created using other methods for producing white light.

Strong components in the blue part of the spectrum of light emitted by the LEDs, as well as the associated intensity of the radiation, raise the issue of new health risks related to these sources of lighting.
Some scientific studies [Dawson *et al.*, 2001[10], Ueda *et al.*, 2009[11]], based on laboratory experiments with blue LEDs conducted on monkeys, give reason to suspect a danger for the retina related to exposure to light-emitting diodes.
A study by Altkorn [Altkorn *et al.*, 2005] investigated the health impact of LEDs by reviewing the current debate on the position of LEDs with regard to standards: should they be rated, in terms of photobiological risk, according to the same standards as those applied to lasers or according to the standards applied to incoherent light sources? Indeed, until 2008, LEDs were considered in the same way as laser sources. Since January 2008, the NF EN 60825-1 'Lasers' standard has recommended using, for LED devices, the CIE[12] S009:2002 'Photobiological safety of lamps and lamp systems' photobiological safety standard concerning incoherent sources, which became a French standard (NF EN 62471) in December 2008.

3. ORGANISATION OF THE EXPERT APPRAISAL

At its meeting on 23 September 2008, the AFSSET Expert Committee (CES) on "Physical agents, new technologies and development areas" discussed the impact of LEDs on human health. The CES judged the subject to be a matter of some concern and decided that the Agency should investigate the question on its own initiative.
The Scientific Council issued an Opinion, on 29 September 2008, in favour of AFSSET investigating on its own initiative the health consequences of exposure to lighting systems using light-emitting diodes. The expert appraisal was entrusted to the CES on "Physical agents, new technologies and development areas". At the suggestion of the CES, the Agency set up a Working Group with a mandate to carry out the expert appraisal. After a public call for applications from 12 December 2008 to 12 March 2009, the Working Group was formed with experts in ophthalmology, dermatology, lighting and optical radiation physics.
The Working Group convened ten times in plenary session between 13 May 2009 and 26 March 2010. It also interviewed French and international scientific experts, and representatives of the French Lighting Association (*Association Française de l'Eclairage* – AFE) in order to obtain all relevant information for carrying out the investigation. To conduct its appraisal, the Working Group carried out a broad review of the international

[10] Dawson, *et al*, *Local fundus response to blue (LED and laser) and infrared (LED and laser) sources*, Exp. Eye Res., 73(1):137-47 2001
[11] Ueda *et al*, *Eye damage control by reduced blue illumination*, Exp. Eye Res, 89(6):863-8. 2009
[12] CIE: International Commission on Illumination

scientific literature alongside its interviews with leading scientists. At the group's request, the French Environment and Energy Management Agency (ADEME) submitted a written contribution on the French and European market for lighting systems and the recycling of lamps.

The bibliographical analysis carried out by the 'LED' Working Group was as thorough as possible. The scientific studies taken into account in the report were all published in international, English-language, peer-reviewed journals.

The methodological and scientific aspects of the work were regularly submitted by the Working Group to the CES. The report produced by the Working Group takes account of observations and additional information supplied by the members of the CES.

This expert appraisal was therefore conducted by a group of experts with complementary skills. It was carried out in accordance with the French Standard NF X 50-110 "Quality in Expertise Activities" to ensure compliance with the following points: competence, independence and transparency, while at the same time ensuring traceability.

4. RESULT OF THE COLLECTIVE EXPERT APPRAISAL

The work of the experts was based on five main themes:

- a review of the current situation regarding lighting;
- a presentation of the technology behind LEDs;
- an analysis of the way light interacts with biological systems (the eyes and skin);
- a summary of the standards currently applicable to LEDs;
- an analysis of the potential health effects of LEDs.

A special feature of this study concerned the calculations and measurements conducted by the members of the Working Group in their respective laboratories (CSTB[13], INRS[14], LNE[15]) to assign some examples of LED lighting systems to specific Risk Groups in accordance with the photobiological standard applicable to LEDs (NF EN 62471).

The CES on "Physical agents, new technologies and development areas" adopted the collective expert appraisal together with its conclusions and recommendations at its meeting on 3 June 2010 and informed the Agency's General Directorate.

5. OPINION AND RECOMMENDATIONS

This Opinion is based on the collective expert appraisal of the 'LED' Working Group and the CES on "Physical agents, new technologies and development areas". It restates the conclusions and recommendations in the report and the summary of the collective expert appraisal by the CES, and makes supplementary proposals for risk management.

CONCLUSIONS OF THE COLLECTIVE EXPERT APPRAISAL

As a result of the analysis of the existing scientific literature and the information collected during the additional hearings, potential health issues related to the use of LEDs were identified. Those of greatest concern, due to both the severity of the corresponding

[13] CSTB: *Centre Scientifique et Technique du Bâtiment* (French Scientific and Technical Centre for Construction)

[14] INRS: *Institut National de Recherche et de Sécurité pour la prévention des accidents du travail et des maladies professionnelles* (National Research and Safety Institute)

[15] LNE: *Laboratoire National de Métrologie et d'Essais* (the Metrology Institute and Reference Laboratory for French Industry)

dangers and the probability of their occurring as a result of the increasingly widespread use of LEDs, relate to the photochemical effects of blue light on the eye and the glare phenomenon. They result from:

- the spectral imbalance in LEDs (high proportion of blue light in white LEDs)
- the very high luminance[16] of LEDs (high brightness density per surface unit emitted by these very small sources).

Risks related to blue light

The photochemical risk is associated with blue light, and depends on the accumulated dose to which the person has been exposed, which is generally the result of low intensity exposure repeated over long periods. There is a high level of proof of such a risk.

Evidence from human observation and experimental studies on cell cultures and various animal species has converged to demonstrate the specific toxicity of shortwave (blue) light to the retina. Blue light is therefore recognised as being harmful and dangerous to the retina, as a result of cellular oxidative stress.

There is a strong suspicion that blue light aggravates age-related macular degeneration (ARMD), based on converging observations on experimental models. Epidemiological studies carried out up to now have proved inconclusive as a result of their lack of precision in assessing exposure and the data concerning individual predisposition.

Three population groups have been identified as being either especially sensitive to the risk or highly exposed to blue light:

- children (because of the transparency of their crystalline lens) and both aphakics (with no crystalline lens) and pseudophakics (with artificial crystalline lenses) who consequently either cannot or can only insufficiently filter short wavelengths (particularly blue light);
- population groups which are already light-sensitive: patients suffering from certain eye (e.g. ARMD) and skin diseases, patients taking photosensitising substances, etc., for whom blue light may aggravate their condition;
- population groups highly exposed to LEDs (certain categories of workers: those installing lighting systems, theatre and film industry professionals, etc.) which are subjected to high-intensity lighting, and are therefore likely to be exposed to large quantities of blue light.

Risk related to glare

In indoor lighting, it is generally agreed that luminance higher than 10,000 cd/m^2[17] causes visual discomfort irrespective of the position of the lighting unit in the field of vision. Because the emission surfaces of LEDs are highly concentrated point sources, the luminance of each individual source can be 1000 times higher than the discomfort level. The level of direct radiation from this type of source can therefore easily exceed the level of visual discomfort, far more than is the case with "traditional" lighting (halogen and low-energy lamps).

[16] Luminance is the unit used to quantify the light emitted by a non-point source, per surface unit, in other words, the light density. It is expressed in candela per square metre (cd/m^2) and defines the brilliance of a light source as perceived by the human eye. It can therefore be used to measure glare.

[17] This value is generally quoted as being the upper limit beyond which subjects experience discomfort from glare in indoor lighting. The French NF X 35 103 standard: *Principes ergonomiques visuels applicables à l'éclairage des lieux de travail* (Ergonomic principles applicable to the lighting of workplaces for visual comfort) mentions admissible luminance of 2000 cd/m^2 for a small source on the working surface.

Other risks related to exposure to LEDs
The experts considered other potential risks such as disruption of circadian rhythms (biological clock) and stroboscopic effects (visually imperceptible fluctuation of the intensity of light).
There is very little risk of thermal effects, associated with burns to the retina and generally resulting from short-term exposure to very intense light, from the normal uses of LEDs.

LED technology can lead to the emission of electromagnetic fields insofar as such systems are combined with a power and voltage transformation device. Because of the low levels of exposure generated, the Working Group did not undertake a specific study of potential associated risks.

Assessment of the photochemical risks of LEDs
There is currently little information about human exposure to lighting, whether for systems using LEDs or other types of light sources. The Working Group was only able to present quantified risk assessments for exposure to blue light, under the terms of the NF EN 62471 standard for photobiological safety. This standard, which concerns the photobiological safety of lamps and devices using lamps, recommends exposure limits for radiation from these light sources. It provides a system of classification based on radiance and actual irradiance. The standard considers all of the photobiological hazards that may affect the eye (thermal and photochemical hazards) for ultraviolet to infrared wavelengths and defines four risk groups: Risk Group 0 (no risk), Risk Group 1 (low risk), Risk Group 2 (moderate risk), Risk Group 3 (high risk).

Due to the lack of information on exposure, the Working Group asked certain national laboratories to take radiance measurements. These readings were taken as an exploratory measure and were not intended to be exhaustive. Furthermore, as the standard was not designed to cover LED systems, these experiments are inadequate for a rigorous assessment of the photobiological risks related to LEDs, and are intended simply to determine the risk group of these new lighting systems in comparison to those for traditional lighting.

The radiance[18] measurements show that certain LEDs currently on sale to the general public and potentially used in domestic lighting situations, for signage and guide lights, fall into Risk Group 2, whereas all the other light sources currently on sale to the public fall into either Risk Groups 0 or 1. The safe exposure limit times implied by placing these items in Group 2 vary from a few seconds for certain royal blue LEDs to a few tens of seconds for certain cold white LEDs.

Furthermore, it seems that the NF EN 62 471 standard is unsuited to lighting systems using LEDs:

- the maximum exposure limits defined by the ICNIRP[19] and used to define the Risk Groups are not appropriate for repeated exposure to blue light as they were calculated for exposure of one 8-hour day and do not take into account the possibility of exposure over an entire lifetime;
- it contains ambiguities concerning the measurement protocols for allocating Risk Groups: the same LED could be assigned to different Risk Groups if considered

[18] The readings taken were of the radiance (which depends on the wavelength) weighted by the degree of phototoxicity of the blue light.
[19] ICNIRP: International Commission for Non-Ionising Radiation Protection.

individually or if integrated in a lighting system, as the evaluation distance imposed by the standard could be different;

- it does not take into account the sensitivity of certain specific population groups (children, aphakics, pseudophakics, etc.).

It is important to emphasise that other widely-used sources of lighting, particularly high-pressure gas discharge lamps (metal-halide lamps for outdoor lighting), are also in Risk Group 2. However, this last example is intended for clearly identified uses and can only be installed by professionals who are required to limit the exposure level for the population.
With the arrival on the domestic lighting market of LEDs, light sources falling into Risk Group 2 thus become available to the general public, without details of the risk incurred appearing on the labelling.
The methodology adopted in this report enabled the experts to evaluate the photobiological risks related to LEDs producing a luminous flux close to the mean of LEDs found on the market at the time of writing this document. At present and in the next few years it seems unlikely that technological progress will yield LEDs that can be classified in Risk Group 3. On the other hand, with the increase in both luminous flux and radiance, there is no doubt that more and more LEDs will fall into Risk Group 2.

Compliance with standards concerning glare

With regard to glare-related risks, the standards lay down certain references[20] covering visual ergonomics and safety. In LED lighting systems available on the market, the LEDs are often directly visible in order to avoid attenuating the level of brightness produced. This could lead to non-compliance with the requirements laid down in the standards.

RECOMMENDATIONS

The purpose of the following recommendations is to protect both the general public and working populations exposed to LED lighting in the workplace.

Concerning regulations and standards

Directive 2001/95/EC concerning general product safety applies to all products classified in sectors not covered by specific legislation (toys, etc.). The "EC" label, which is mandatory on all electrical devices sold in Europe, is a 'self-declaration', indicating that the manufacturer considers that the product complies with all the EU conditions for use of the label.
Where LED lighting is concerned, EC labelling ensures that the product complies with the essential requirements of the following European Directives: "Low voltage" (2006/95/EC), "Electromagnetic compatibility" (2004/108/EC) and "Eco-design" (for Energy-using Products) (2005/32/EC), concerning product safety, power consumption and emissions (noise, vibrations, radiation, electromagnetic fields), recycling potential, etc.
To satisfy these requirements, products must comply with specific standards, known as harmonised standards, published in the Official Journal of the European Union (e.g. NF EN 62311 concerning electromagnetic fields and NF EN 62471 concerning the photobiological safety of lamps). Furthermore, the Government Decree 2010-750 of 2 July 2010,

[20] The text refers to the French standard NF X 35-103: '*Ergonomie : Principes d'ergonomie visuelle applicables à l'éclairage des lieux de travail*' (Ergonomics: Ergonomic principles applicable to the lighting of workplaces for visual comfort), the European standards NF EN 12464-1: 'Lighting of workplaces – Part 1: indoor workplaces', NF EN 12464-2: 'Lighting of workplaces – Part 2: outdoor workplaces', and the series of standards NF EN 13201: 'Street Lighting' and NF EN 12193: 'Sports Lighting'.

transposing Directive 2006/25/EC into French law, stipulates the measures to be applied to ensure that workers are protected against the risks of exposure to artificial optical radiation.

Considering:

- the health risks related to blue light emitted by LED lighting systems falling into Risk Groups higher than 1 (according to the NF EN 62 471 standard);
- the significant risks of glare induced by LED lighting systems;
- the need to protect the general and working population from excessive radiance produced by LED systems and any risk of glare associated with the different uses of these new lighting systems;
- the marketing of LED products intended for light therapy, comfort or well-being purposes;

ANSES recommends:

- limiting the sale of LEDs for domestic use or for the general public to LEDs falling into Risk Groups equal to or less than 1 (when assessed at an observation distance of 200 mm);
- regulating the installation of LED lighting systems falling into Risk Groups greater than 1, by limiting them to professional uses, under conditions in which risks can be prevented;
- encouraging manufacturers and integrators of LED lighting systems to:
    - design lighting systems in which beams of light emitted by LEDs cannot be seen directly, to avoid glare. In particular, ANSES recommends the use of optical devices that reduce the intensity of light perceived directly or by reflection and to make the sources of LED light more diffuse;
    - take account of the progressive wear of phosphor layers in white LEDs, which in time could lead to devices moving to a higher photobiological risk group.
- assessing the safety and compliance of devices for light therapy, comfort or well-being and regulating their use.

Considering:

- that the standards in force for designing LED-based lighting installations are not always applied by professionals (electricians, lighting technicians and designers);
- that current photobiological safety standards seem unsuited to lighting systems using LEDs;

ANSES recommends:

- obliging professionals designing lighting systems using LEDs to apply all standards concerning the quality of lighting:
    - NF X 35-103 ('Ergonomics: Ergonomic principles applicable to the lighting of workplaces for visual comfort');
    - NF EN 12464-1 ('Lighting of workplaces – Part 1: indoor workplaces');
    - NF EN 12464-2 ('Lighting of workplaces – Part 2: outdoor workplaces');

   - the series of NF EN 13201 standards ('Street Lighting');
   - NF EN 12193 ('Sports Lighting').
- adapting the NF EN 62 471 standard ('Photobiological safety of lamps and lamp systems') to cover lighting systems using LEDs. It is essential to make it easier for manufacturers to take this standard into account and remove any ambiguity concerning how it should apply to LED systems. ANSES therefore recommends:
   - specifying in the NF EN 62 471 standard the conditions for measuring and evaluating LED systems;
   - publishing a guide to applying this standard, geared exclusively to LED systems;
   - determining the risk group for the worst case of observation (at a distance of 200 mm from the system) that will thus constitute the most unfavourable risk group;
   - adapting the standard to cover children and aphakic or pseudophakic individuals, taking into account the phototoxicity curve of the relevant type of light published by the ICNIRP;
   - considering proposing sub-groups for each risk group that would allow the risk to be assessed more precisely as a function of exposure time;
   - in the case of risk groups greater than 0, evaluating safe distances (at which observation corresponds to Risk Group 0) and indicating these explicitly on products intended for consumers (for devices for the general public) or for professionals responsible for installing lighting systems.
- introducing photobiological safety requirements in all safety standards concerning LEDs. This mainly concerns the following standards:
   - the NF EN 60 598 series of standards 'Luminaires';
   - NF EN 62 031: 'LED modules for general lighting. Safety specifications';
   - IEC 62 560: 'Self-ballasted LED lamps for general lighting services by voltage > 50 V – Safety specifications';
   - draft IEC standard 62 663-1 'Non-ballasted single capped LED lamps for general lighting – safety requirements'.

Concerning use, information and traceability

ANSES recommends that consumer information about health risks related to the use of LED lighting systems be made available immediately pending the implementation of an appropriate regulatory framework.

Considering:

- the proven risk resulting from acute exposure to blue light and the uncertainty surrounding the effects of chronic exposure at low doses, together with the uncertainty concerning the effects on the biological clock and diminished pupil contraction;
- that certain populations are sensitive to light in general (children, aphakics, pseudophakics, patients suffering from certain eye and skin diseases, patients taking photosensitising treatments, etc.);

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ANSES recommends:

- avoiding the use of light sources emitting cold white light (light with a strong blue component) in places frequented by children (maternity wards, nurseries, schools, leisure centres, etc.) or in the objects they use (toys, electronic display panels, game consoles and joysticks, night lights, etc.);
- informing patients taking photosensitising drugs about the risks related to exposure to light with a strong blue component.

Considering:

- that there are populations of workers likely to be exposed to bright LED lighting systems;

ANSES recommends:

- developing appropriate means of protection (such as safety goggles specifically to protect against exposure to LEDs) for workers highly exposed to LED lighting systems.

Considering:

- the lack of information available to the public concerning the LED lighting systems on the market;

ANSES recommends:

- ensuring that manufacturers and integrators of LEDs carry out quality controls and qualify their products with regard to the different Risk Groups;
- setting up a clear, easy-to-understand labelling system for consumers, particularly concerning the technical characteristics of the lighting and any potential health effects;
- mandatory indication of the photobiological safety Risk Group on the packaging of LED products, after assessing the product at a distance of 200 mm. For light sources falling into Risk Group 1, the labelling should also indicate the safety distance beyond which the risk moves down to Group 0;
- mandatory indication of the photobiological safety Risk Group for all types of lighting.

CONCERNING STUDIES AND RESEARCH THEMES

Considering the lack of data about exposure of the general and working populations to artificial light, ANSES recommends:

- enriching the available documentation on exposure of the population to artificial light in both occupational and general environments;
- defining a suitable index for evaluating the intensity of glare produced by an LED source, as the Unified Glare Rating used for other types of lighting is unsuitable for LEDs, which are sources of low-angle light.

Concerning studies and research on the health effects of LED lighting systems, ANSES recommends:

- developing clinical research to define maximum exposure limits for blue light and, for this purpose:
    - studying the cumulative medium- and long-term effects of exposure to blue light;
    - carrying out prospective and retrospective studies of populations undergoing light therapy with the use of blue LEDs;
- undertaking research to improve characterisation of the effects of artificial light, and in particular light emitted by LED systems, on biological rhythms. ANSES therefore recommends:
    - further studies to improve characterisation of the spectra of action of the mechanisms by which light regulates the human biological clock;
    - quantifying the impact of exposure to cold artificial lights on circadian rhythms and pupil contraction;
    - in general, studying how health is affected by light pollution (linked with possible disruption of the biological clock) and systematic installation of LED lighting systems;
- studying the triggering or aggravation of photodermatoses caused by LED lighting;
- organising measurement campaigns to characterise the electromagnetic fields generated by LED lighting systems.

Concerning studies and research to be carried out on LED technology to prevent potential health risks, ANSES recommends:

- encouraging research for the development of new emissive materials coupled with optimised luminophores, to obtain a high quality white light, with the highest possible luminous efficacy;
- developing research into the design of lighting units adapted to LEDs with a view to reducing luminance, by applying optical solutions;
- studying the mechanisms that cause the degradation of the phosphor layers in white LEDs, potentially leading to an increase in the amount of blue light emitted.

The Director General

Marc Mortureux

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EXPERT COLLECTIVE APPRAISAL: SUMMARY AND CONCLUSIONS

concerning the internally-solicited request entitled "Health effects of lighting systems using light-emitting diodes (LEDs)"

This document summarises the work of the Expert Committee and the Working Group

Presentation of the question

The European Eco-design Directive (2005/32/EC), known as "EuP" for Energy-using Products, aims to improve the energy efficiency of certain consumer goods. This Directive was transposed into national law by the Member States of the European Union in 2007 and came into force between 2008 and 2010.
On 18 March 2009, in application of the EuP Directive, the European Commission decided in favour of a gradual ban on the sale of the most energy-consuming lamps, to be implemented from 1 September 2009 to 1 September 2016. Compact fluorescent or "low-energy" lamps, or other sources of energy-saving lighting such as light-emitting diodes, are destined to replace them eventually.
Light-emitting diodes are currently undergoing rapid technological and financial development. They have been used for several years in electronics as weak, monochromatic light sources for indicator or warning lights and are now commonly used as normal light sources in lighting systems such as traffic lights, portable lighting, vehicle lights and domestic room-lighting.

The first visible-spectrum LED was created in 1962 and emitted only very low intensity light. The blue diode was invented in 1990, and was followed by the development of the white diode that made it possible for new and important applications to be adopted, mainly for lighting and for television and computer screens. The first white LEDs appeared on the market gradually and have now become increasingly powerful[1] (attaining several Watts). The most widely-used procedure for producing white light couples a blue LED and a yellow phosphor.

The French company OSYRIS[2] expressed concern in a letter addressed to the French Institute for Public Health Surveillance (InVS), dated 27 December 2007, about the possible impact on the retina of light from LEDs. The letter underlined the possible link between exposure of the eye to shortwave radiation, close to ultraviolet light (characteristic of the light spectra of LEDs) and the risk of age-related macular degeneration, an eye disease. The InVS forwarded the OSYRIS letter to the French Agency for Environmental and Occupational Health Safety (AFSSET) in a letter dated 14 January 2008.
Simultaneously, the question of the impact of LEDs on occupational health was raised during informal discussions between AFSSET and the Directorate-General for Labour (DGT), the latter having recently been alerted by the projected use of indoor LED lighting for buildings. The development of this type of lighting solution is likely to accelerate, mainly due to cost considerations.

[1] Source - ADEME: "Low-power LEDs (i.e. lower than 1 Watt) are used as indicator lights on domestic appliances, for example. More energy-consuming LEDs (i.e. higher than 1 Watt) can withstand stronger currents (up to 1500 mA) and supply more light (135 lm/W)".
[2] A French company specialising in lasers and their application in medicine and industry.

Scientific context and applicable standards

In France, lighting accounts for 10% of total electricity consumption, or 350 kWh per year and per household[3]. LEDs consume far less energy than other types of lighting and last much longer.

The luminous efficacy of incandescent lamps is of the order of 10 to 15 lumens[4] per Watt (lm/W), for halogen lamps it is from 15 to 30 lm/W and for compact fluorescent lamps it is in the range of 50 to 100 lm/W. Some of the latest LEDs achieve an efficacy of up to 100 to 150 lm/W, with predictions in the region of 200 lm/W for 2020[5].

There is as yet no standard definition of the lifetime of an LED. Current LEDs have considerable lifetimes (estimated at up to 50,000 hours[6], or 50 times longer than incandescent lamps and 3 to 5 times longer than compact fluorescent lamps).

The technology behind LEDs, which have certain advantages over other types of lighting, (energy efficiency and lifetime), is constantly changing but the quality of the light (colour temperature[7], colour rendering index[8]) emitted by these lamps is not always as high as for other types of lighting. At present, LEDs have a greater impact on the environment than other types of lighting.

Strong components in the blue part of the light spectrum emitted by LEDs, as well as the intense radiation of what are highly concentrated point sources, raise concern about new potential health risks.

Some scientific studies [Dawson *et al.*, 2001[9], Ueda *et al.*, 2009[10]] based on laboratory experiments with blue LEDs conducted on monkeys, have concluded that the retina is in danger of being damaged by exposure to light-emitting diodes.

Another study by Altkorn [Altkorn *et al.*, 2005] investigated the health impact of LEDs by reviewing the current debate on the position of LEDs with regard to standards: should they be rated, in terms of photobiological risk, according to the same standards as those applied to lasers or according to the standards applied to incoherent light sources? Indeed, until 2008, LEDs were treated in the same way as laser sources. Since January 2008, the NF EN 60825-1 'Lasers' standard has recommended using, for LED devices, the CIE[11] S009:2002 'Photobiological safety of lamps and lamp systems' standard, which became a French standard (NF EN 62471) in December 2008.

Organisation of the expert appraisal

At its meeting on 23 September 2008, the AFSSET Expert Committee (CES) on "Physical agents, new technologies and development areas" discussed the impact of LEDs on human

[3] Source ADEME 2010
[4] The lumen is the unit used to quantify luminous flux
[5] The theoretical limit for the luminous efficacy of light sources is set at 683 lm/W.
[6] Source ADEME 2010
[7] The colour temperature of a white light is used to define its hue, which can be warmer or colder; lights with warm hues tend to yellow-orange and have colour temperatures below 3000 K. Higher colour temperatures correspond to "colder" hues.
[8] The Colour Rendering Index (CRI) runs from 0 to 100 and defines the aptitude of a light source to reproduce the different colours of the objects on which its light falls, compared to a reference source. Sunlight has a CRI of 100, while some low-pressure sodium-vapour lamps (used in road tunnels, for example) have a CRI of 20. In shops, school premises and offices, the CRI should always be greater than 80.
[9] Dawson, et al, *Local fundus response to blue (LED and laser) and infrared (LED and laser) sources*, Exp. Eye Res., 73(1):137-47 2001
[10] Ueda et al, *Eye damage control by reduced blue illumination*, Exp. Eye Res, 89(6):863-8. 2009
[11] CIE: *Commission Internationale de l'Eclairage* (International Commission on Illumination)

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health. The CES judged the subject to be a matter of some concern and decided that an internally-solicited request should be made to investigate the issue.

The AFSSET Scientific Council issued an Opinion, on 29 September 2008, in favour of AFSSET itself investigating the health consequences of exposure to lighting systems using light-emitting diodes. AFSSET mandated the CES on "Physical agents, new technologies and development areas" to conduct the expert appraisal. At the suggestion of the CES, the Agency then set up a Working Group to carry out the expert appraisal. After a public call for applications from 12 December 2008 to 12 March 2009, the Working Group was formed with experts in ophthalmology, dermatology, lighting and optical radiation physics.

The Working Group coordinated by AFSSET held 10 plenary sessions between 13 May 2009 and 26 March 2010. It also interviewed leading French and international scientists and also representatives of the French Association of Lighting Professionals (*Association Française de l'Eclairage* – AFE) in order to obtain all relevant information for carrying out the investigation. To conduct its appraisal, the Working Group carried out a broad review of the international scientific literature alongside its interviews with leading scientists. At the group's request, the French Environment and Energy Management Agency (ADEME) submitted a written contribution on the French and European market for lighting systems and the recycling of lamps.

The bibliographical analysis carried out by the 'LED' Working Group was as thorough as possible. The scientific studies taken into account in the report had all been published in international, English-language, peer-reviewed journals.

The Working Group's ongoing appraisal was submitted to the CES at regular intervals, regarding both its methodological and scientific aspects. The report produced by the Working Group takes account of feedback and additional information from the members of the CES.

This expert appraisal was therefore conducted by a group of experts with complementary skills. It was carried out in accordance with the French Standard NF X 50-110 "Quality in Expertise Activities" to ensure compliance with the following points: competence, independence and transparency, while at the same time ensuring traceability.

Result of the collective expert appraisal

The work of the experts was based on five main approaches:

- a review of the current situation regarding lighting;
- a presentation of the technology behind LEDs;
- an analysis of the way light interacts with biological systems (the eyes and skin);
- a summary of the standards currently applicable to LEDs;
- an analysis of the potential health effects of LEDs.

A special feature of this study concerned the calculations and measurements conducted by the members of the Working Group in their respective laboratories (CSTB[12], INRS[13], LNE[14]) to assign some examples of LED-based lighting systems to specific Risk Groups in accordance with the photobiological standard applicable to LEDs (NF EN 62471).

[12] CSTB: *Centre Scientifique et Technique du Bâtiment* (French Scientific and Technical Centre for Construction)
[13] INRS: *Institut National de Recherche et de Sécurité pour la prévention des accidents du travail et des maladies professionnelles* (National Research and Safety Institute).
[14] LNE: *Laboratoire National de Métrologie et d'Essais* (the Metrology Institute and Reference Laboratory for French Industry).

The CES on "Physical agents, new technologies and development areas" adopted the collective expert appraisal, together with the conclusions and recommendations in this summary, at its meeting on 3 June 2010 and informed AFSSET's General Directorate.

Conclusions of the expert appraisal

As a result of its analysis of the existing scientific literature and the information collected during the additional hearings, the Working Group identified potential health issues related to the use of LEDs.

Characteristics of LEDs relevant to risk assessment

The technology behind light-emitting diodes is based on the polarisation of a semiconductor by applying a voltage that causes photons to be emitted in the form of quasi-monochromatic radiation, whose wavelength depends on the semiconductor used. There are no semiconductors capable of emitting white light on their own. There are, however, currently three different ways of producing white light indirectly with an LED. Given the technological constraints and the imperatives concerning electrical efficiency, currently the most widely-used method for producing white light uses a yellow luminophore to transform part of the light from a blue diode.

- ***Spectral imbalance within the blue***

The light spectrum from white LEDs is largely made up of very weak emissions ranging between blue and yellow, but with a high proportion of blue light (a blue spike in the spectrum). These characteristics are highly specific to LEDs, and are not found in other, traditional types of lighting.

- ***High luminance***[15]

LEDs are point sources of light that can be aggregated in lighting units to achieve high luminous flux. Because the emission surfaces of LEDs are highly concentrated point sources, the luminance of each individual source produces very high luminance, at least 1 000 times higher (10^7 cd/m²) than that from a traditional lighting source.

- ***Stroboscopic effect***

Depending on their architecture, the electrical power supplied to LED lighting systems can vary, causing fluctuations in the intensity of the light produced that are barely perceptible to the naked eye. These fluctuations have not yet been characterised in any detail[16]. The frequency of these effects can vary from a few Hertz to several hundred Hertz[17] for those LEDs that have already been studied.

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[15] Luminance (expressed in candela per square meter, or cd/m²) is the unit used to quantify the light emitted by a non-point source, per surface unit. It defines the brilliance of a light source as perceived by the human eye. It can therefore be used to measure glare.

[16] Both the frequency and the modulation rate (the ratio between the amplitude of the fluctuation and the mean value of the light) depend heavily on the type of supply. For a power supply in direct current (rectified and filtered), the frequency of fluctuation is 100 Hz and the modulation rate can attain values from 2% to 20% depending on the quality of filtering. For a Pulse Width Modulation (PWM) power supply, the frequency is of the order of tens of kilo-Hertz and the modulation rate can vary, and may even exceed 50%. Lastly, for the new technology by which LEDs are powered by alternating current, the frequency of fluctuation is 100 Hz and the modulation rate can reach 100 %.

[17] *A Review of the Literature on Light Flicker: Ergonomics, Biological Attributes, Potential Health Effects, and Methods in Which Some LED Lighting May Introduce Flicker*, IEEE Standard P1789 (2010)

Identified health issues

The main health risks associated with LED-based lighting systems result from their high luminance (i.e. the high brightness density per surface unit emitted by these very small sources) associated with the unusual emission spectrum of white LEDs, which have a high proportion of blue (shortwave) light. Other potential effects are raised in the report, such as disturbance to circadian rhythms and stroboscopic effects.

With regard to the many potential health effects identified (photochemical effect, glare, etc.), there is currently little information on human exposure to lighting to enable us to quantify the corresponding health risks adequately, whether for systems using LEDs or other types of light sources.

The Working Group was therefore only able to make quantified risk assessments for exposure to blue light, under the terms of the NF EN 62471 standard for photobiological safety. However, this standard is unsuited to lighting systems using LEDs. In the light of current knowledge, the maximum exposure limits given in this standard do not take account of daily exposure to LEDs.
In the following description of the risks identified by the Working Group, the effects on the eye, both thermal and photochemical, have been dealt with separately from the other effects particularly related to disturbance of circadian rhythms.

Effects on the eye

- ### Risk related to the thermal effect of light

The risk of thermal effects is related to burns to the retina, generally resulting from short-term exposure to a very intense light. This type of danger concerns all wavelengths, from ultraviolet to infrared and the entire visible spectrum. This type of risk, usually associated with lasers, is unlikely in conventional uses of LEDs.

- ### Risk related to the photochemical effects of blue light

The risk of photochemical effects is related to human exposure to blue light and the risk level depends on the accumulated dose to which the person is exposed. It therefore generally involves repeated, low-intensity exposure over long periods.

  - ***Characterisation of the risk***

Evidence from human observation and experimental studies on cell cultures and various animal species has converged to demonstrate the specific toxicity of shortwave (blue) light to the retina.

Blue light can cause photochemical damage. Lesions occur on the outer retina (photoreceptors and cells of the pigment epithelium) and appear after some time has passed. The lesions may not be visible via ophthalmoscopy. Two types of photochemical lesions have been described: those resulting from interaction with visual pigments, which affect the photoreceptors, and those related to interaction with the lipofuscin, which affect the cells of the pigment epithelium.

These interactions lead to the production of high doses of cytotoxic free radicals. The photoreactive pigments (lipofuscin) in the epithelium accumulate with age, increasing the risk of oxidative stress. Cellular death has functional consequences which are particularly significant as they concern the macular region (central vision).

There is no current consensus as to whether accumulated lesions resulting from low doses of oxidative stress could, over long periods, accelerate premature aging of the retina and favour macular degeneration.

At the moment there are no appropriate animal models of age-related macular degeneration (ARMD), as all the models use rodents, whereas only primates and certain birds have maculae. The necessary follow-up times for these species are not compatible with the experimental protocols.
In humans, repeated exposure to very bright sunlight can cause irreversible macular lesions close to those observed in age-related maculopathies, but the epidemiological studies carried out in this field have not all identified exposure to sunlight as a risk factor for ARMD.

Following converging observations on experimental models, there is a strong suspicion that blue light aggravates ARMD. Epidemiological studies in humans have never clearly shown such effects, as a result of difficulties in evaluating the exposure and individual predisposition.

In adults, the crystalline lens (which, as it turns yellow, partly absorbs blue radiation) and the macular pigments partially protect against this toxicity through their capacity to absorb blue light. These protective mechanisms are weaker in children (whose crystalline lenses are transparent), aphakics (with no crystalline lenses) and pseudophakics (with artificial crystalline lenses). There is also less protection available in cases of reduced macular pigment, as observed during certain macular pathologies (e.g. ARMD).

- ***Exposure to LEDs***

There is currently no information about human exposure to lighting, whether for systems using LEDs or other types of light sources.

- ***Photobiological safety standards***

Description of the NF EN 62471 standard and risk groups

The NF EN 62471 standard concerning the photobiological safety of lamps and devices using lamps suggests maximum exposure limits for radiation from light sources commonly used for lighting, and provides a method of classification based on radiance and actual irradiance together with a method for measuring these values. This standard covers all photobiological hazards for the eye (thermal and photochemical hazards), for ultraviolet to infrared wavelengths.

The standard defines four Risk Groups:

- Risk Group 0 (no risk): the product involves no photobiological risk;
- Risk Group 1 (low risk): the product involves no risk in terms of maximum exposure limits under normal conditions of use;
- Risk Group 2 (moderate risk): the product involves no risk in terms of aversion response to very bright light sources or due to thermal discomfort;
- Risk Group 3 (high risk): the product may involve a risk even during momentary or short exposure periods.

Gaps and inadequacies in the standard

- *Maximum exposure limits unsuitable for repeated exposure to blue light*

The maximum exposure limits for the general public designed to avoid acute lesions to the retina have been put forward by the ICNIRP[18,19] and used in the NF EN 62 471 standard and in European Directive 2006/25/CE concerning artificial optical radiation.

These maximum exposure limits were calculated for exposure to a light source in the field of vision for one 8-hour working day. They were calculated from experimental data weighted by a reduction factor of 5 to 10 times the energy necessary to produce observable lesions.

In practice, experiments on animals have established the energy thresholds for inducing lesions to the ocular fundus that can be observed macroscopically by ophtalmoscopy after a single exposure to light. These lesions take the form of a whitening of the neural retina, as a result of an oedema of the superficial retinal layers.

In the light of current knowledge, the maximum exposure limits in force do not allow evaluation of daily chronic exposure limits to blue light. The classification of lamps by these values does not take account of the long-term risk resulting from accumulated exposure. This means that repeated and prolonged exposure could induce an accumulated risk potentially greater than that assessed using the maximum exposure limits.

- *Ambiguity in measurement distances*

For the most common lighting lamps, the NF EN 62 471 standard requires the risk group to be evaluated at the distance at which they produce a brightness of 500 lx. For other types of lamps, the risk group must be determined for the worst observation case, i.e. a distance of 200 mm.
The risk group for any lighting system using LEDs can be determined using either of these measurement protocols, leading to very different classifications (evaluation at 500 lx always gives a lower value than evaluation at 200 mm). There is therefore ambiguity concerning the distance at which these measurements should be taken.

- *Failure to take into account population groups sensitive to blue light*

To assess the risk related to blue light, the NF EN 62 471 standard recommends using the phototoxicity curve for blue light suggested by the ICNIRP. This curve is only suitable for adults. The standard includes no specific recommendations for population groups whose natural mechanisms for filtering blue light are diminished (children, aphakics and pseudophakics), or who are more sensitive to blue light as a result of retinal diseases. In fact, the ICNIRP gives a different phototoxicity curve for blue light for aphakics. The current standard does not take account of the situation of population groups sensitive to blue light.

[18] ICNIRP (International Commission for Non-Ionising Radiation Protection), "*Guidelines on limits of exposure to broad-band incoherent optical radiation (0.38 to 3 μm)*" (1997)
[19] ICNIRP (International Commission for Non-Ionising Radiation Protection), "*ICNIRP statement on light-emitting diodes (LED) and laser diodes : implication for hazard assessment*" (2000)

- ***Measurements taken by the Working Group***

The Working Group made risk assessments defined according to the NF EN 62 471 standard for different lighting systems, in order to compare LEDs with other types of lighting.
It seems that certain LEDs that are very widely used in lighting, signage and guide lights fall into Risk Group 2, whereas all other light sources currently on sale to the public fall into either Risk Group 0 or 1. The maximum exposure times implied by placing these items in Group 2 vary from a few seconds for certain royal blue LEDs to a few tens of seconds for certain cold white LEDs.
LEDs and LED-base lighting systems can be classified in different Risk Groups depending on their radiance and hue (cold white, warm white, etc.), thus increasing the difficulty of preventing this risk.

- ***Sensitive or highly exposed population groups***

Three population groups have been identified as being either especially sensitive to the risk or highly exposed to blue light:

  - children (because of the transparency of their crystalline lens) and both aphakics (with no crystalline lens) and pseudophakics (with artificial crystalline lenses) who consequently either cannot or can only insufficiently filter short wavelengths (especially blue light);
  - population groups which are already light-sensitive: patients suffering from certain eye and skin conditions and patients taking treatments one of whose side-effects is to increase photosensitivity, etc., for whom blue light can be an aggravating factor for their condition;
  - population groups highly exposed to LEDs (certain categories of workers: those installing lighting systems, theatre and film industry professionals, etc.) which are subjected to high-intensity lighting, and are therefore susceptible to exposure to large quantities of blue light.

- ***Conclusions concerning the risk related to blue light***

It is important to emphasise that other widely-used sources of lighting, particularly high-pressure gas discharge lamps (metal-halide lamps for outdoor lighting), also fall into Risk Group 2. However, these lamps are intended for use in clearly-identified applications and can only be installed by professionals who are required to limit the exposure level for the population.

The arrival of LEDs on the lighting market for the general public is an unprecedented development: it is the first time that sources classified in Risk Group 2 have become accessible to the general public, for use in the home and, most importantly, with no indication of the risk.

The same LED considered individually or integrated in a lighting system could be assigned to different Risk Groups depending on the evaluation distance imposed by the NF EN 62 471 standard.
As the technology behind LED lighting evolves over the next few years, lighting performance is likely to improve considerably. The risks associated with exposure to LED-based lighting systems are therefore likely to increase as the radiance increases.

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The methodology adopted in this report enabled the experts to evaluate the photobiological risks related to LEDs producing a luminous flux close to the mean of LEDs found in the range of fluxes available on the market at the time of writing this document. At present and for the next few years it seems unlikely that technological progress will yield LEDs that can be classified in Risk Group 3. On the other hand, with the increase in both luminous flux and radiance, there is no doubt that more and more LEDs will fall into Risk Group 2.

- **Risks related to glare**

There are two types of glare: discomfort glare and disability glare.

Discomfort glare produces a disagreeable sensation, without necessarily impairing the vision of objects. It is related to the luminance of the lighting unit and to contrast differences. It is associated with a momentary reduction in visual performance.

Disability glare perturbs the vision of objects (veiling luminance) without necessarily causing a disagreeable sensation. It is related to the quantity of incident light on the eye and the luminance of the lighting unit. It can cause accidents in the home (either slip-and-trip falls or falls from heights), in traffic (collisions) and elsewhere.

In indoor lighting, it is generally agreed that luminance higher than 10,000 cd/m^2 causes visual discomfort irrespective of the position of the lighting unit in the field of vision. This value is commonly cited for discomfort glare in indoor lighting as being the value above which subjects are bound to suffer the effects of glare.

The French NF X 35 103 standard for visual ergonomics gives a limit value of 2,000 cd/m^2 for discomfort glare, for the case of a small source located in the central area of the field of vision.

Because the emission surfaces of LEDs are highly concentrated point sources, the luminance of each individual source can be at least 1000 times higher than the luminance from traditional lighting sources. The level of direct radiation from this type of source greatly exceeds the level of visual discomfort.

The Working Group recorded luminances of more than 10,000,000 cd/m^2 for certain LEDs with an electrical power of 1 W (in devices on public sale for domestic use).

In LED lighting systems available on the market, the LEDs are often directly visible in order to avoid attenuating the level of brightness produced. This leads to non-compliance with the requirements laid down in the standards (visual ergonomics and safety requirements) for lighting intended to avoid excessive luminance in the field of vision.

Other effects

- ***Risk of deregulating the biological clock and pupil contraction***

In humans, the biological clock and pupil contraction are regulated by wavelengths close to 480 nm which suppress the production of melatonin (a hormone participating in the regulation of the biological clock and therefore the circadian cycle).

The spectrum produced by LEDs differs fundamentally from that of natural light, with a very low proportion near 480 nm. This could expose subjects to a risk of deregulation of their biological clocks and, in consequence, of their circadian rhythms. These risks are exacerbated by high-temperature colours (cold white and blue), which are frequently found in LED-based lighting systems.

Deregulation of the biological clock can affect the metabolism, the thymus (depression, mood swings), the waking/sleeping rhythm, etc.
Furthermore, the pupil contraction reflex is induced in strong light by these same wavelengths. It could be reduced under LED lighting, which could lead to stronger light falling on the retina and an increase in the risks associated with blue light.

- **Risk related to flicker in the light emitted by LEDs**

As a consequence of the manner in which they are powered electronically, the light emitted by LEDs may be subject to rapid fluctuation of great amplitude. This fluctuation, combined with the fact that LEDs have very low remanence, is usually imperceptible to human vision. In situations involving movement or in confined spaces with periodic variations in contrast, it can be responsible for stroboscopic effects. Although such stroboscopic effects have never been studied in depth, they can have a direct impact on health (epileptic seizures for subjects at risk), visual performance and safety. A recent publication[20] showed that LEDs can produce fluctuations in light at frequencies known to produce effects on health (from 3 to 60 Hz for visible fluctuations and from 120 à 150 Hz for non-visible fluctuations).

Recommendations

The following recommendations apply to both lighting systems using LEDs already on the market and future LED-based systems.

Concerning health risks related to exposure to LEDs,

Considering:
the health risks related to blue light emitted by LED lighting systems in products available to the public despite belonging to Risk Groups higher than 1 (according to the NF EN 62 471 standard);

the CES recommends:

- banning the sale to the public of lighting systems falling into Risk Groups higher than 1, evaluated at an observation distance of 200 mm;
- reserving LEDs falling into Risk Groups higher than 1 for applications designed to be installed safely by professionals.

Considering:
the health risks created by LED lighting systems, related to very high luminance and substantial glare;

the CES recommends that manufacturers and integrators:

-in order to protect the population against excessive luminance from LED systems and strong glare,

- design lighting systems such that the beams emitted by LEDs are not directly visible. In particular, the CES recommends the use of optical devices that reduce the intensity of

[20] *A Review of the Literature on Light Flicker: Ergonomics, Biological Attributes, Potential Health Effects, and Methods in Which Some LED Lighting May Introduce Flicker*, IEEE Standard P1789 (2010)

light perceived directly or by reflection and to make the sources of LED light more diffuse;

- take account of the progressive wear of phosphor layers in white LEDs, which in time could lead to devices moving to a higher photobiological risk group.

- in order to protect the drivers of vehicles, pedestrians, cyclists and motorcyclists from the risk of glare related to excessive luminance emitted by LED headlights,
  - only be authorised to install LED-based lighting systems from Risk Groups 0 or 1 for motor vehicle headlights by day or night, given that daytime running lights will be mandatory for all new cars from February 2011 (European Directive on daytime lighting 2008/89/EC);

Considering:

- o the proven risks resulting from acute exposure to blue light and the uncertainty surrounding the effects of chronic exposure at low doses, together with the uncertainty concerning the effects on the biological clock and pupil contraction;
- o that certain population groups are sensitive to light in general (children, aphakics, pseudophakics, patients suffering from certain eye and skin diseases, or who are taking photosensitising drugs, etc.);
- o that there are populations of workers susceptible to exposure to bright LED lighting systems;

the CES makes the following recommendations:

- specifically to protect population groups at risk, such as those sensitive to light and those highly exposed to LEDs. The CES thus recommends:
  - for children, avoiding the use of sources emitting a cold white light or blue light in places frequented by children (maternity wards, nurseries, schools, recreation centres, etc.) or in the objects they use (toys, electronic display panels, game consoles and joysticks, night lights, etc.).
  - developing appropriate means of protection (such as safety goggles specifically to protect against exposure to LEDs) for workers highly exposed to LED lighting systems;
  - informing patients taking medicines one of whose side-effects is to increase photosensitivity about the risks related to exposure to cold light and particularly light emitted by LEDs, even those classified as belonging to Risk Group 0; informing health workers of the existence of this risk;
  - employing caution in the use of devices to increase the effective size of LEDs, even if such devices do not increase the luminance (such as optical collimators and multichip assemblies of LEDs). Indeed, the use of these devices leads to shorter maximum exposure times to blue light than in the case of single chip LEDs without additional optics. A higher Risk Group may then be appropriate.

Considering:
that LED-based products for light therapy, comfort and well-being are available on the market, the CES recommends evaluating the safety and compliance of these devices.

Concerning standards relative to the lighting quality and the photobiological safety of LEDs,

Considering:

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- o that the standards in force for lighting installations are not always applied by professionals (electricians, lighting specialists, designers of lighting systems) in the case of LED systems;
- o that the standards related to photobiological safety might prove to be ill-adapted to LED lighting systems;

the CES makes the following recommendations:

- That professionals installing LED-based lighting systems be obliged to apply all standards relative to lighting quality:

- French standard NF X 35-103 ('*Ergonomie : Principes d'ergonomie visuelle applicables à l'éclairage des lieux de travail* – Ergonomics: Ergonomic principles applicable to the lighting of workplaces for visual comfort);
- NF EN 12464-1 ('Lighting of workplaces – Part 1: indoor workplaces');
- NF EN 12464-2 ('Lighting of workplaces – Part 2: outdoor workplaces');
- the series of NF EN 13201 standards ('Street Lighting');
- NF EN 12193 ('Sports Lighting').

- Adapting the NF EN 62 471 standard ('Photobiological safety of lamps and lamp systems') to cover lighting systems using LEDs. It is essential to make it easier for manufacturers to take this standard into account and remove any doubt as to how it should apply to LED systems. The CES therefore recommends:

- specifying in the NF EN 62 471 standard the conditions for measuring and evaluating LED systems;
- publishing a guide to applying this standard, exclusively for LED systems;
- determining the risk group for the worst case of observation: at a distance of 200 mm from the system, thus giving the most unfavourable Risk Group;
- adapting the standard to cover children and people who are either aphakic or pseudophakic, taking into account the phototoxicity curve of the relevant type of light published by the ICNIRP;
- proposing sub-groups for each risk group that would allow the risk to be assessed more precisely as a function of exposure time;
- in the case of risk groups greater than 0, evaluating safe distances (distance at which observation corresponds to Risk Group 0) and for these to be indicated explicitly on products intended for consumers (the case of devices for the general public) or for professionals responsible for installing lighting systems.

- To reinforce the photobiological safety aspect in the requirements for upgrading existing lighting systems to bring them into compliance with standards:

- introducing photobiological safety requirements into all safety standards covering LED lamps, LED modules and LED lighting units. This mainly concerns the following standards:
  - o the NF EN 60 598 series of standards: 'Luminaires';
  - o NF EN 62 031: 'LED modules for general lighting. Safety specifications';
  - o IEC 62 560: 'Self-ballasted LED lamps for general lighting services by voltage > 50 V – Safety specifications';
  - o draft IEC standard 62 663-1 'Non ballasted single capped LED lamps for general lighting – safety requirements'.

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Concerning information for consumers, traceability and the quality and labelling of LEDs,

Considering:
- the lack of information available to the public concerning LED-based products;

the CES makes the following recommendations:

- That consumers be informed of the quality and performance of the lighting systems they choose to buy. That consumers be given easy access to information about the characteristics of the products they buy. The CES recommends:

- ensuring that manufacturers and integrators of LEDs carry out quality and traceability controls on LEDs; apart from the quality in terms of lighting, it is essential that they ensure that their products comply with their assigned Risk Group;
- considering a labelling system that will be comprehensible for consumers and contain all relevant information (power, voltage, colour temperature, luminous flux, etc.);
- making it mandatory to indicate the photobiological safety Risk Group on the packaging of LED products, after assessing the product at a distance of 200 mm. For light sources falling into Risk Group 1, the labelling should also indicate the safety distance beyond which the risk moves down to Group 0;
- making it mandatory to indicate the photobiological safety Risk Group for all types of lighting;
- considering the creation of a quality label (reproducibility, ecolabelling, etc.).

Recommendations for studies and research themes

Considering the lack of data on exposure of the general public and the working population to artificial light, the CES makes the following recommendations:

- Characterising and studying the exposure of the population to artificial light.

- Defining a suitable index for evaluating the intensity of glare produced by an LED-based source, as the Unified Glare Rating (UGR) used for other types of lighting is not appropriate for LEDs, which are sources of low-angle light.

Concerning studies and research on the health effects of LED lighting systems, the CES recommends:

- Developing clinical research to obtain information for defining exposure limit values for blue light. The CES therefore recommends:
  - studying the cumulative medium- and long-term effects of exposure to blue light;
  - carrying out prospective and retrospective studies of subjects undergoing light therapy with blue LEDs;
  - implementing experimental protocols for evaluating the consequences of prolonged and accumulated exposure at levels inferior to the exposure limit values.

- Undertaking research to improve characterisation of the effects of artificial light, and particularly the light emitted by LED systems, on biological rhythms. The CES therefore recommends:

- further studies to improve characterisation of the spectra of action of the mechanisms by which light regulates the human biological clock;
- quantifying the impact of exposure to cold artificial lights on circadian rhythms and diminished pupil contraction;
- in general, studying how health is affected by light pollution (linked with possible disruption of the biological clock) and systematic installation of LED lighting systems.

- Systematically studying the triggering and/or aggravation of photo-dermatoses caused by LED lighting.

Concerning studies and research to be carried out on LED technology to prevent health risks, the CES makes the following recommendations;

- Improving LED technology. The CES therefore recommends:
  - encouraging research for the development of new emissive materials coupled with optimised luminophores, to obtain a high quality white light, with the highest possible luminous efficacy;
  - developing research into the design of lighting units adapted for LEDs (small size and considerable luminous flux) with a view to reducing luminance, by applying optical solutions;
  - studying the mechanisms that cause the degradation of white LEDs, potentially leading to a drift towards the blue end of the visible spectrum in the light emitted.

Maisons-Alfort, 03/06/2010

On behalf of the experts of the CES "Physical agents, new technologies and development areas",

Chairperson of the CES, Jean-François Doré

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

Light at Night: The Latest Science

BACKGROUND

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

SYNOPSIS

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

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

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

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

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

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

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

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

The goal of the panel was to communicate what we currently know and don't know about the visual and non-visual effects of nighttime light exposures, focusing on differences in spectra between available light source technologies.

THE DOE SSL PERSPECTIVE

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

The broad-spectrum light produced by white LEDs can improve color contrast, and there is evidence that such sources improve visibility. If the Illuminating Engineering Society of North America (IES) adopts a model of mesopic photometry, it is likely that additional energy savings could be realized by switching to broad-spectrum sources like LEDs. Specifically, it might then be possible to reduce photopic light levels (and wattage) in outdoor applications for those sources featuring spectra with a substantial short-wavelength (blue) component. However, even if for the time being only photopic light levels are evaluated (as per the IES), spectral content must be considered in selecting an LED source if optimal energy savings are

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to be realized. This is because unlike other source types, LED efficacy tends to increase with increasing correlated color temperature (CCT) and short-wavelength content. In other words, within any given product line, the LEDs with a "cool" appearance will generally be substantially more efficacious than those having a "warm" appearance. Figure 1 illustrates this phenomenon.

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

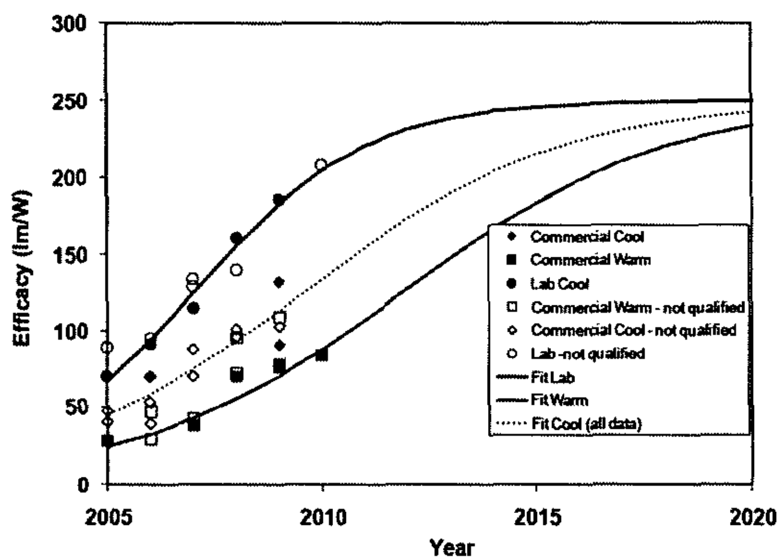

Figure 1. White-light LED package photopic efficacy targets, laboratory and commercial[3]

OUTDOOR LIGHTING AND VISUAL PERFORMANCE

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

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

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

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

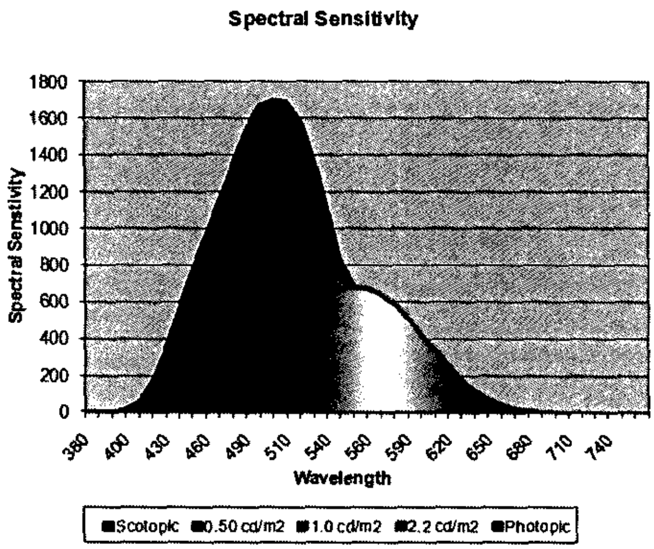

Figure 2. The Purkinje shift[4]

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

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

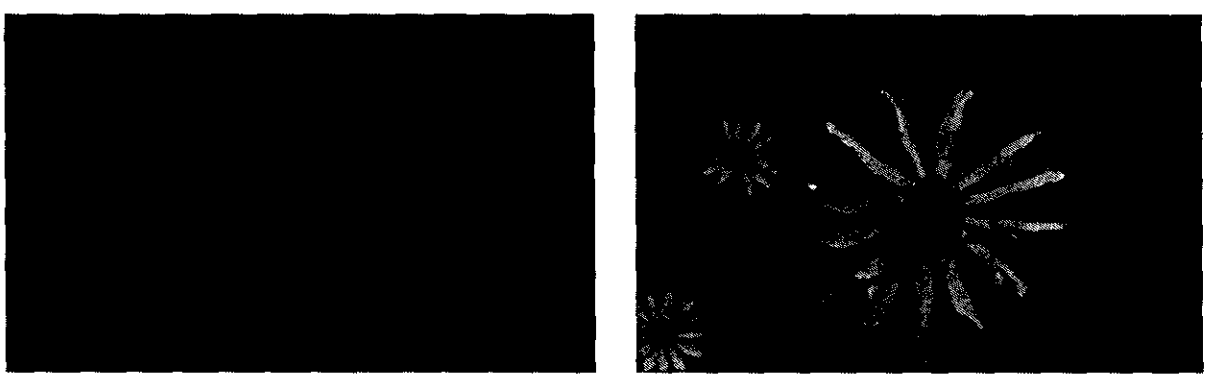

Figure 3. Color contrast provides visual depth between background and foreground

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

4 Diagram courtesy of Ronald Gibbons.

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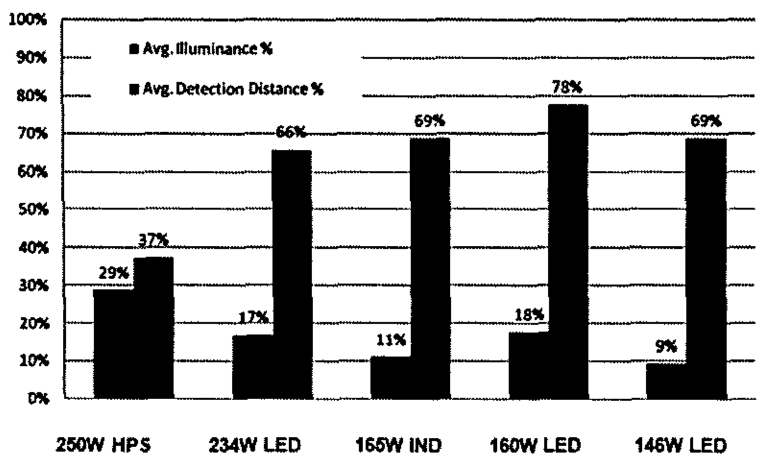

Figure 4. Anchorage: Average illuminance vs. detection distance, relative to 400W HPS

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

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

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

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

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

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

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

CIRCADIAN, NEUROENDOCRINE, AND NEUROBEHAVIORAL RESPONSES TO LIGHT EXPOSURE

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

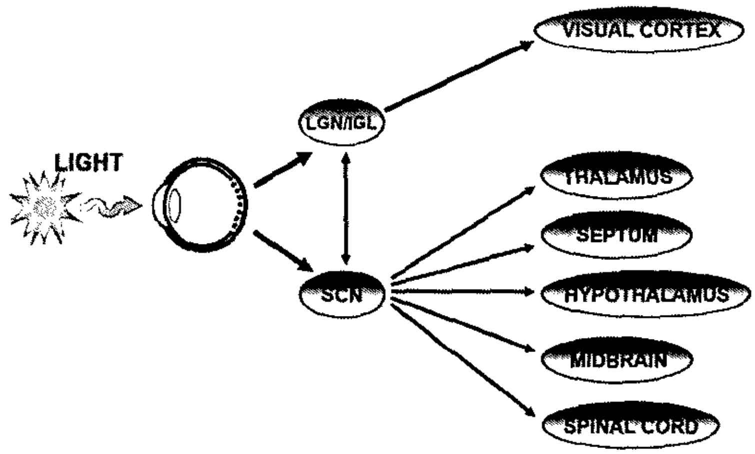

Figure 5. Processing light for visual and circadian functions[6]

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

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

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

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

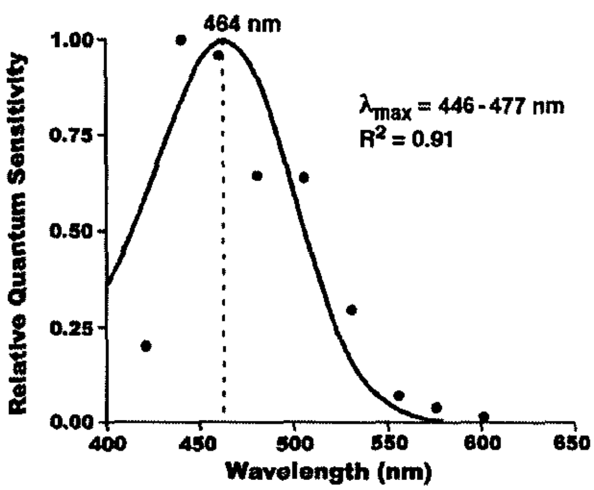

Figure 6. Action spectrum for melatonin production in healthy humans[8,9]

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

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

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

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

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

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

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

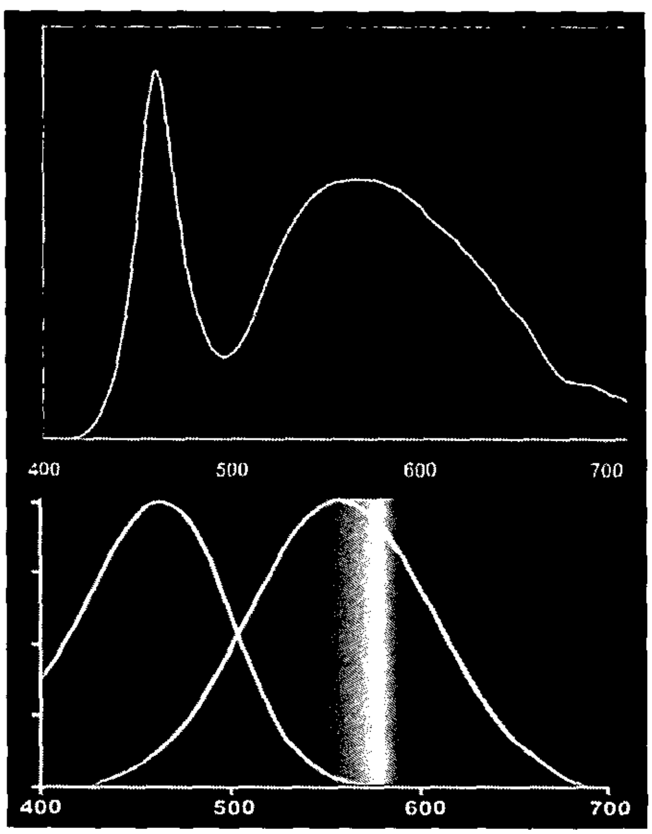

Figure 7. SPD for a 4800K light source (top) and action spectra for melatonin suppression (lower left) and photopic vision (lower right)[6]

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

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

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

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

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

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

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

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

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

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

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

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

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

QUANTIFYING NIGHTTIME LIGHT EXPOSURES

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

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

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

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

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

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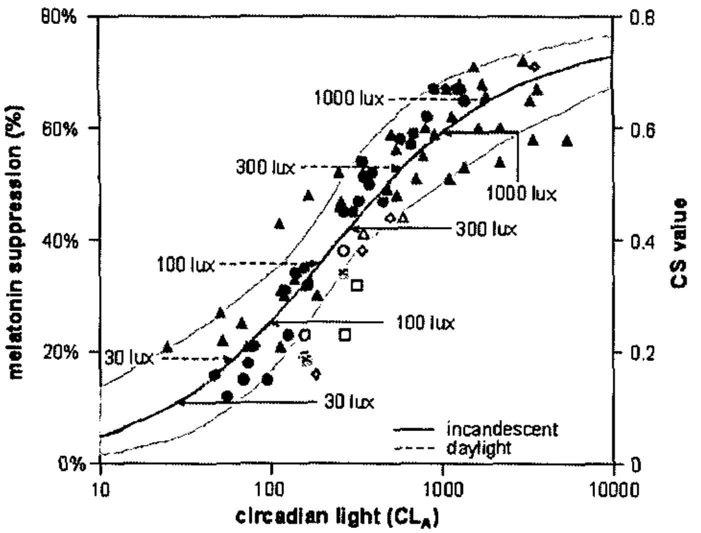

Figure 8. Circadian light transfer function[18]

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

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

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

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

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

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

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

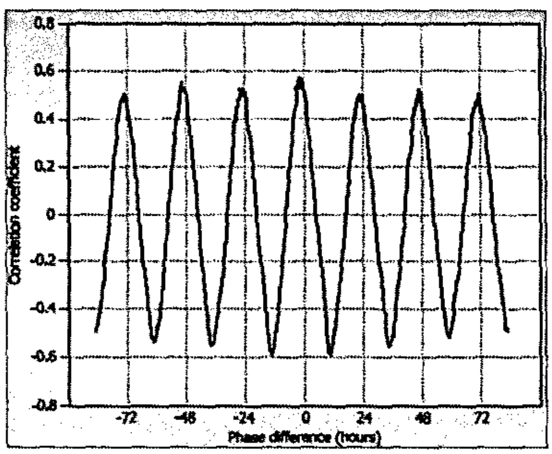

Figure 9a. Circadian entrainment of day-shift nurses

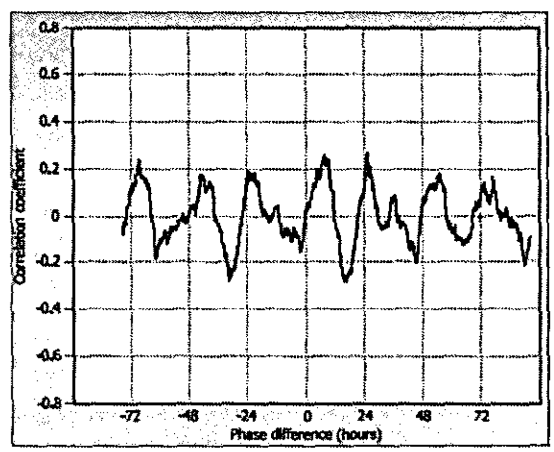

Figure 9b. Circadian entrainment of rotating-shift nurses

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

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

19 Miller et al., in press

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

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

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

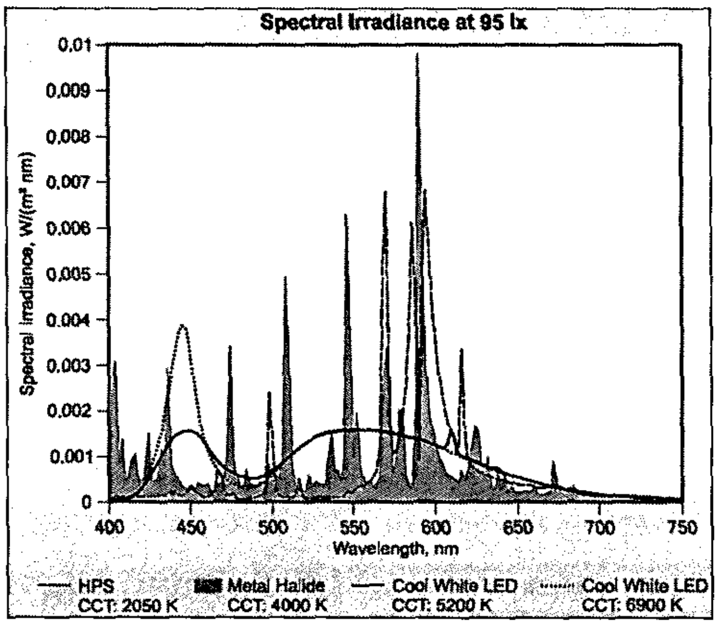

Figure 10. SPDs for different light sources, normalized for equal photopic light levels

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

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

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

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

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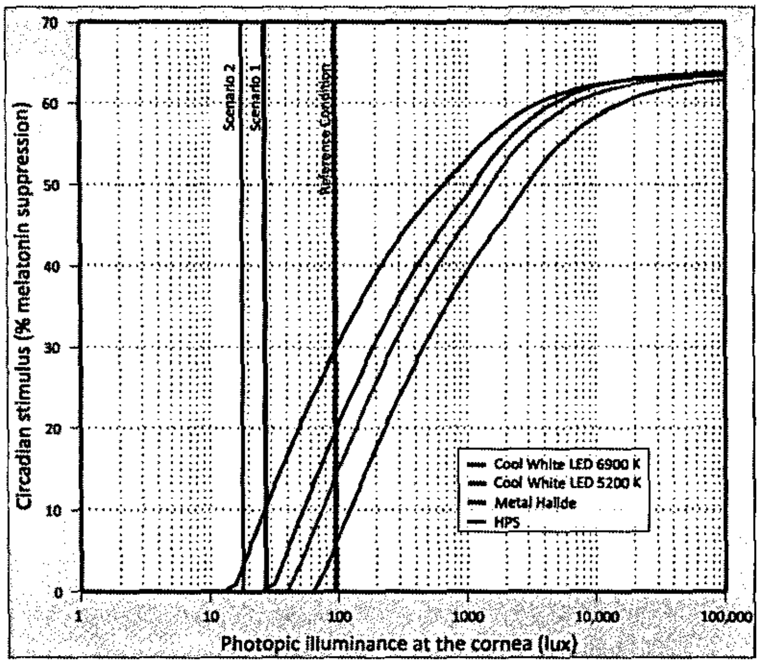

Figure 11. Predicted melatonin suppression after one hour of exposure with freely reactive pupils

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

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

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

DISCUSSION

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

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

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

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

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

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

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

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

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

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

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

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

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

CONCLUSIONS

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

Table 3. Needed research

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

Table 4. Needed guidance from IES

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

Table 5. Needed changes to lighting practice

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

International Dark-Sky Association

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

May 4, 2010

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

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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.

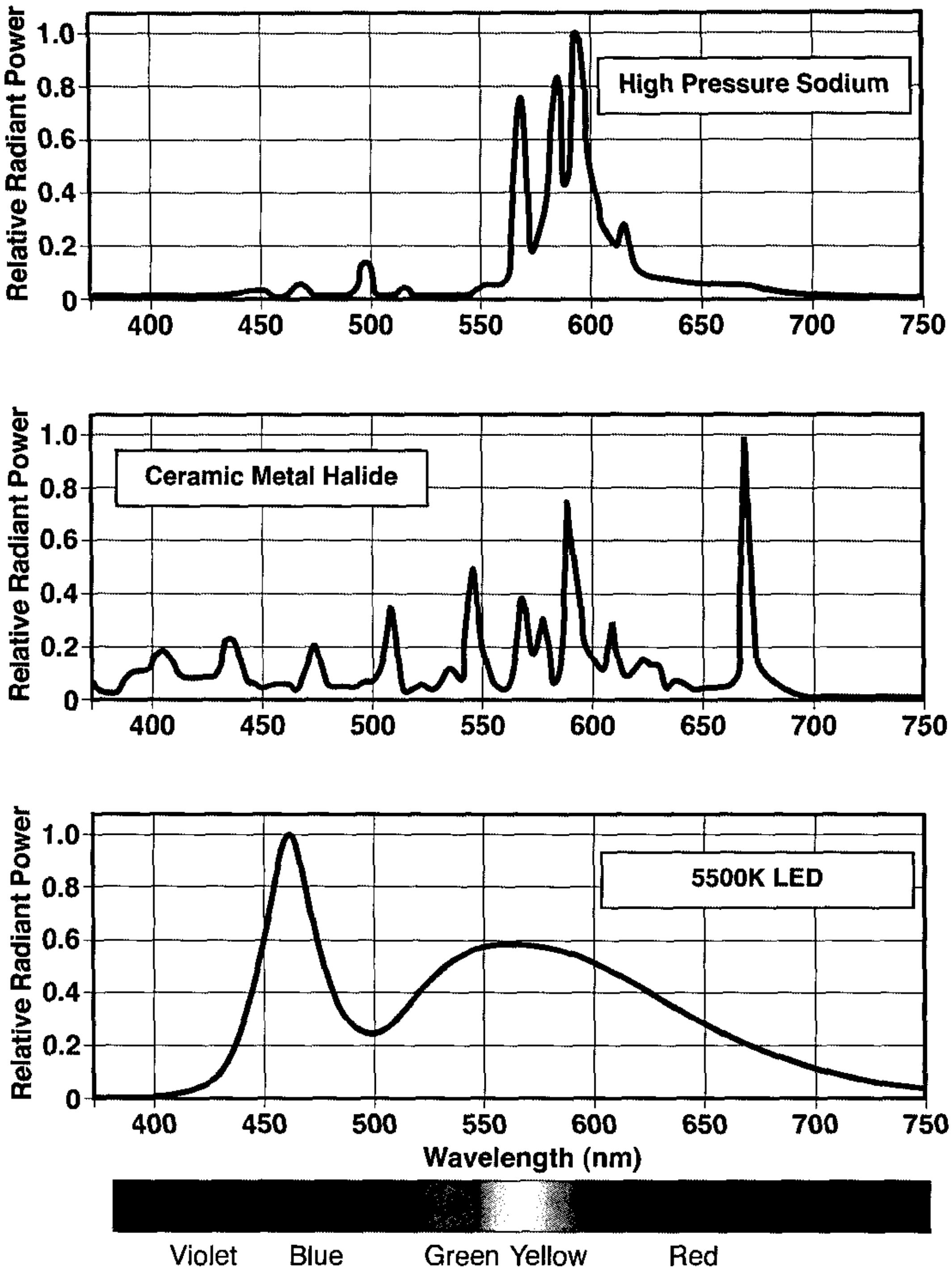

Figure 1. Typical spectral power distributions of HPS (orange); ceramic metal halide (cyan); white LED (blue).

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

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 ($11.36/4.6 \approx 2.5$) 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.

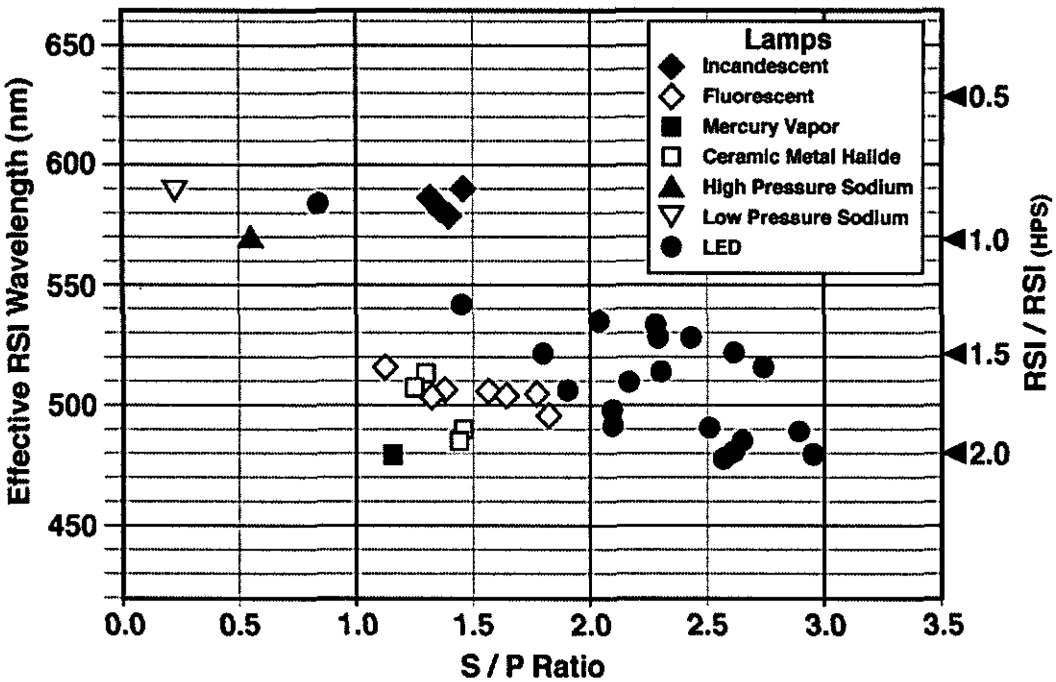

Figure 2. Rayleigh Scattering Index relative to HPS, and effective RSI wavelength for a selection of lamp types vs. their scotopic/photopic ratios S/P.

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.

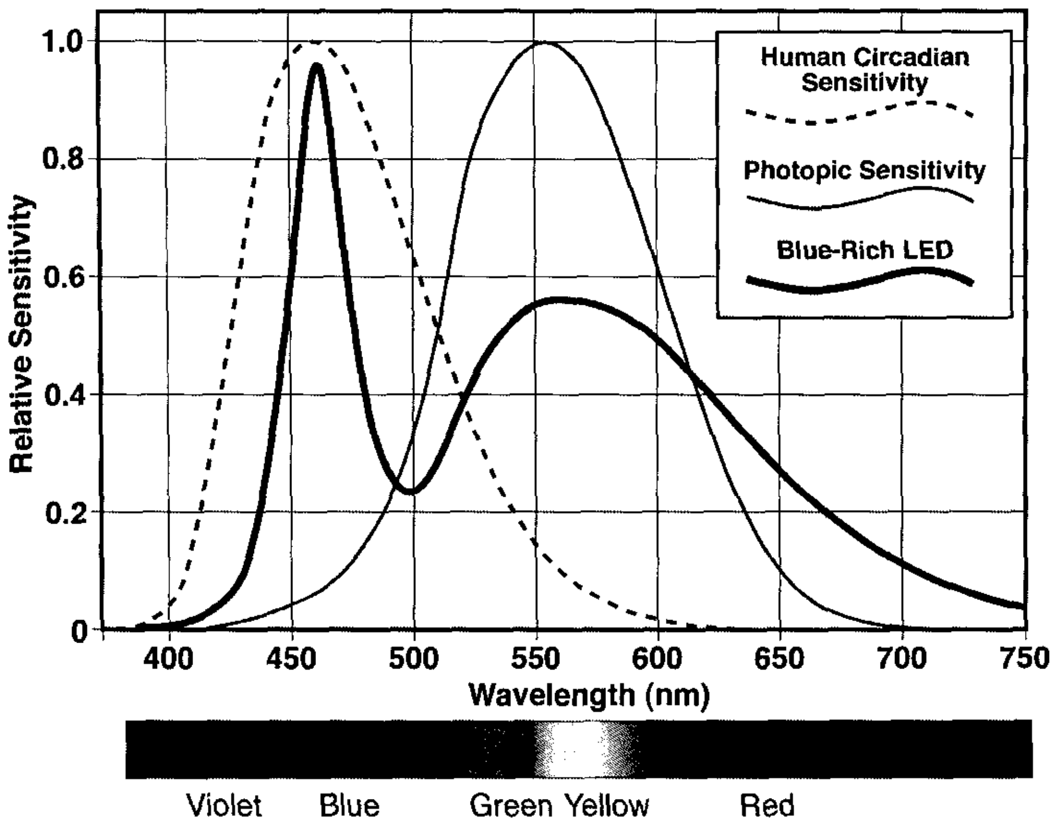

Figure 3. Human photopic and circadian sensitivity curves displayed against a typical blue-rich LED light source spectrum.

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.

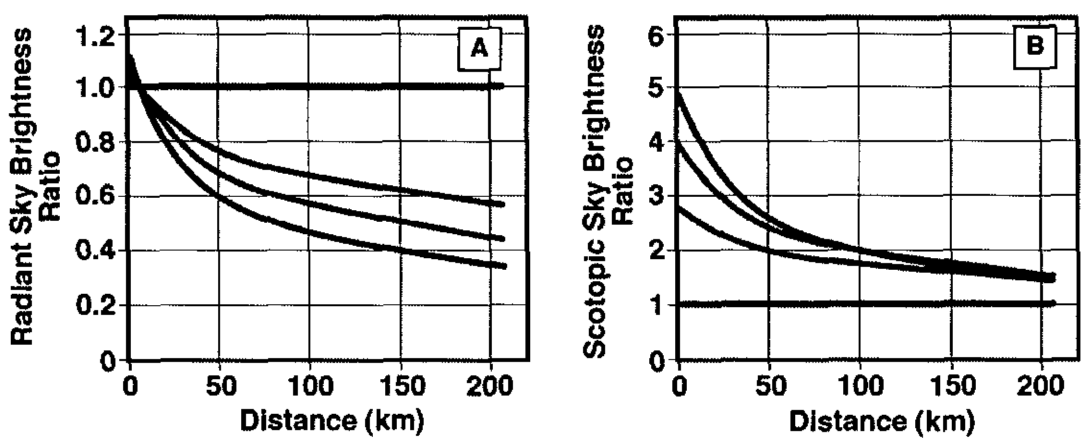

Figure 4. a) Radiant and b) visual (scotopic) sky brightness ratio as a function of distance for equal-radiance light sources with effective wavelengths of 480nm (blue), 500nm (cyan), and 520nm (green), all relative to HPS (yellow) (from Luginbuhl et al., 2010).

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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December 4, 2009

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

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

Dear Administrator Jackson:

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

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

Sincerely,

Robert Wagner
9005 N Chatham Avenue
Kansas City, MO 64154
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