The Biological Basis for the Canadian Guideline for Outdoor Lighting 2—Impact of the Brightness of Light

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Abstract

One of the most obvious attributes of light is brightness. This paper will address specific brightness thresholds that have been found to impact animal health and behaviour, including humans. However, the meaning of brightness is vague and must be further refined and quantified. This paper will introduce and define these terms and will discuss the sensitivity of wildlife biology and behaviour to levels of luminance and illuminance.

It may not be apparent from the common metrics used for "brightness" that a lamp will impact the ecosystem or human health. Our focus is on biology, which depends on the energy carried by the light, or its spectrum, and not strictly its apparent brightness. However, the subject of spectrum will be deferred to the third paper in this series.

Luminance

The luminance of a light source is a measure of how bright it looks—its "perceived brightness." The source can be a star, lamp, or light that reflects or scatters off a surface. A star or lamp emits light in all directions (4π steradians), which is called its luminous flux. But a surface cannot emit light in all directions, so it is more common to report its brightness as being somewhat directional.

Industry defines this angular flux density or "intensity" as the light directed out from a source (lamp or surface) within a solid angle of 1 steradian[1]. If it emits 1 lumen of photopic light in this angle, it is defined as 1-candela (cd). So an omni-directional light source (a light bulb) that emits 1-cd per 1-steradian emits a total of 12.57 lumens of light in all directions (1-lumen × 4π).

A quick review of spherical geometry reminds us that a steradian covers an area of 1 square metre at a distance of 1 metre. At a distance of 2 metres, the area increases by 4 times, which dilutes the light resulting in the inverse-square law $(r/r_o)^2$, but the angle remains the same, so the luminance does not change with distance.

It is important to put the magnitude of this metric into perspective. The planet Venus at magnitude –3.5 has a luminance of about 1 cd/m^2, which is also called a "nit," and the full Moon is about 4,500 cd/m^2. In a city, streetlights and traffic lights are about 1–4 million cd/m^2. Other comparisons are shown in Figure 2. This figure reveals the incredible dynamic range of light in our environment: from 1 mcd/m^2 (4th magnitude star) to the Sun at 1.6 x 10^9 cd/m^2 (Wikipedia)—a factor of 1.6 trillion:1. Our vision accommodates this with complex processes of light absorption and photochemistry in the retina (Lamb 2004), which render our vision decidedly non-linear.

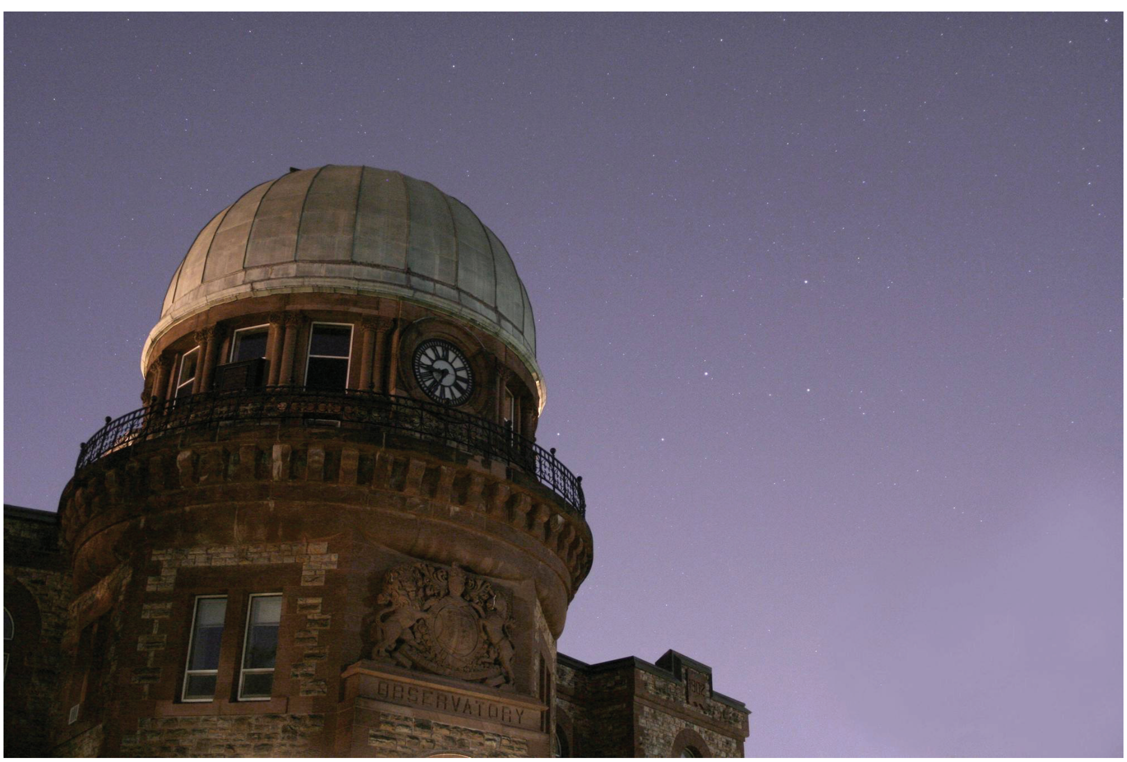

Figure 1 — The Dominion Observatory in Ottawa, beside the Central Experimental Farm. Streetlights, greenhouses, and soon a large regional hospital will illuminate buildings throughout the night. Although a heritage building, there is no policy to protect its scientific heritage. The constellation Cassiopeia is visible to the right of the dome suggesting a photographic limiting magnitude of mag. 5, but visually it was about mag. 2.5.

Rod Cells Only						Cone Cells Only
10^{-6} cd/m^2	10^{-3} cd/m^2	0.1 cd/m^2	1 cd/m^2	4,500 cd/m^2	1M cd/m^2	10^{9} cd/m^2
Rod Limit **DIM**	Urban Star Limit	Rod Bleach	Venus Cone Limit	Full Moon	Traffic Light	Sun **BRIGHT**

Figure 2 — The range of luminance for typical natural and artificial light sources. The low rod limit is not practical for vision because there is insufficient information to form an image. A practical urban rod cell limit is a mag. 4 star, though some people can see to less than 1/10 this limit under dark skies. The difference between the luminance of Venus and the Moon is the concentration of the light. Venus appears as a near-point source, whereas the Moon is an extended source with the light spread out over many detector cells.

Rod Cells Only							Cone Cells Only
0.001 lux	0.01 lux	0.1 lux	1 lux	10 lux	100 lux	1000 lux	10K lux
Night Sky **DIM**	Crescent Moon	Moon Rods Only	Reading Limit (Mesopic)	Cone Cells Only	Home Room	Office	Cloudy Day **BRIGHT**

Figure 3 — The range of illuminance in the rural and urban environment extends beyond this figure from a dark sky at 0.1 mlux to a limit of 127,000 lux under a clear sunny day—a range of 1.3 billion:1.

Our practical photopic (daylight) cone limit extends from the luminance of Venus up to brighter than a traffic light but dimmer than a streetlight—since staring at the signal will not leave a blind spot, though looking at modern streetlights may leave a blind spot. Glancing at the Sun will leave a blind spot but staring at it will cause permanent blindness.

As astronomers, we understand our vision is made more complicated because the perceived brightness depends on the sensitivity of our eyes to different wavelengths. The apparent brightness of Cepheid variable stars changes primarily as its emission shifts from visible light into the infrared.

The metrics used by the lighting industry use the spectral response of our daytime photopic vision, so the metric of lumens is based on the action spectrum of our cone cells. The peak spectral sensitivity of our cones is 591 nm where one joule of energy is used to produce 685 lumens, or 685 $_{P}$Lumens/watt.

When night vision is used, we should use the unit of "scotopic lumens," which matches the spectral sensitivity of our rod cells. It peaks at about 508 nm with a sensitivity of 1700 $_{S}$Lumens/watt (Yao and Lin 2018). A rod cell detects 2.5× more lumens than our cone cells. However, the structure of neurons that connect the rod cells is different for the cone cells, and there are about 20× the number of rods than cones. So, our night vision is much more sensitive than our day vision by 100–1000×.

Generally, the photopic lumen is assumed if the scotopic lumen is not stated.

The ratio of the perceived brightness of the scotopic vision and photopic vision is the SP ratio convolved with the specific spectrum of the illumination that is being compared. Since scotopic lumens are rarely used in specifying outdoor lighting, this distinction is not critical to this paper. However, it is important in our discussion of the emitted light spectra in the next paper of this series.

Illuminance

When light falls on a surface, it "illuminates" that surface. This "illuminance" depends on the amount of light that shines on the surface and the area that is illuminated (lumens/m^2) and has the metric unit of "lux." However, most city officials continue to use the imperial (American) unit of foot-candles, which is 1 lumen/ft^2 (10.764 fc = 1 lux).

Surface Coating

We see a surface by the light that reflects toward our eyes, but if the surface is inherently dark, then the surface will absorb most of the incident light. To see the surface, we need more incident light than if it was covered with a more reflective material. For example, we will use less than 1/10 the light (and 1/10 the energy) by changing a pathway from asphalt to crushed stone, such as dolomite.

Most natural surfaces are not very reflective. Of particular interest here is grass. Visually, grass is only slightly more reflective than asphalt, but crushed stone stands out—even under starlight.

Street lighting can be specified by surface luminance or illuminance, but surface luminance is complicated by its colour and texture as well as the angle between the incident and reflected,

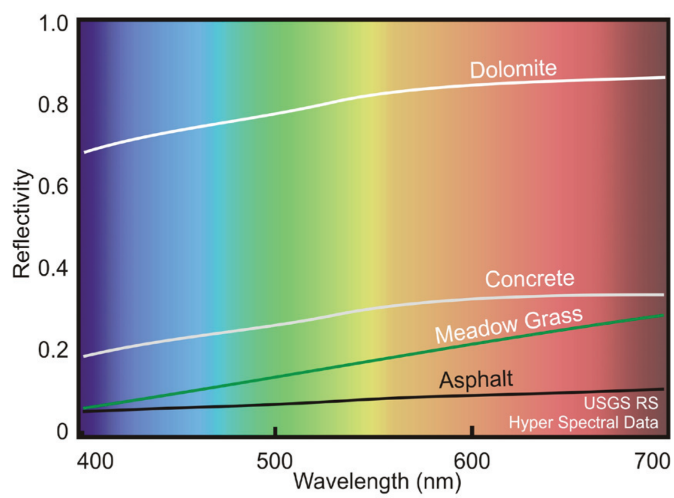

Figure 4 — Reflectance of various ground coverings. Although some ground coverings are quite visible and contrast well with the surroundings in daylight, at night we lose our colour sense and longer wavelength colours appear darker. If a pathway is covered with asphalt, it will not stand out from the grass to the side. However crushed stone cover, or a white paint or lime edging can be used to delineate the path. (USGS)

or scattered light. So, there is a complex relationship between the amount of light that illuminates a surface and its apparent luminance.

The surface spectral reflectivity is subject to change as surfaces age, if wet or dry, or degraded by dirt. Surface texture also affects the directional reflectivity of the surface. So, a lighting design based on a surface luminance is problematic.

In contrast, it is easy to design to a surface illuminance because it depends only on the spectrum, distance, and direction of the light source, which are relatively easily to engineer.

Brightness Limits For Wildlife Behaviour

There are two contributing features to ecology: animal behaviour and their biology. Animals can quickly adapt their behaviour to a change in the environment. However, biology is based on environmental cues and a bio-chemical response to those cues. These responses are encoded in the animal's DNA and require very long periods (100s–10,000s years to change). An environment that changes slowly encourages evolution. One that changes quickly causes extinction.

The luminance threshold for most species has not been determined. However, we can determine a limiting illuminance by monitoring animal activity in various natural settings and during different phases of the Moon. For example, studies indicate an aversion to foraging during a bright Moon (Daly 1992, CIP 2015, Benoit-Bird 2009). Periodic moonlight attracts the activity of predators that prefer the evening and periods of a bright Moon for hunting but has also moulded the foraging schedule of small animals that wish to remain anonymous.

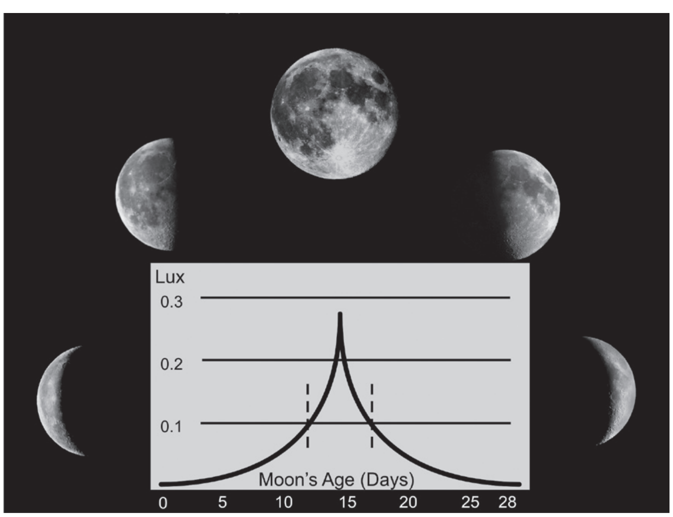

Figure 5 — Illumination from the moon over a lunar month. The Moon illuminates the countryside for about a week every month to a maximum possible illumination of 0.267 lux. The enhanced illumination at full Moon is due to the optical properties of the Moon. The maximum illumination assumes the Moon is at the zenith and clear air. The more typical illumination is about 0.1 lux.

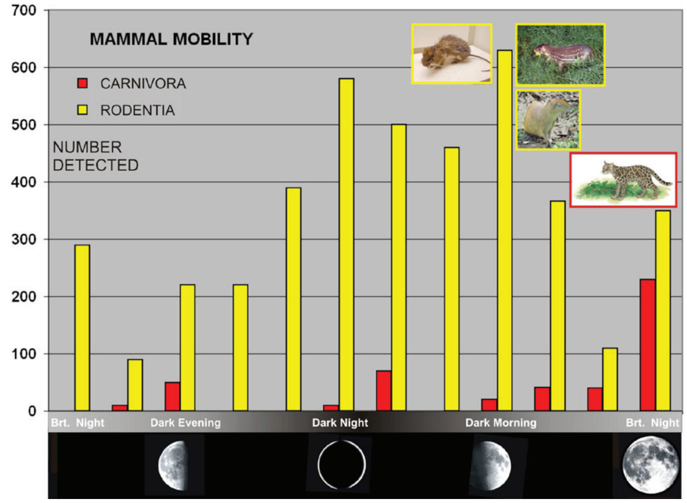

Figure 6 — Mobility of predator and prey animals with lunar phase. Predatory species are most mobile during the evening and especially with the illumination of the Moon. A foraging species (the prey) prefers the early morning and the anonymity of a dark Moon. (data from Yanachaga Chimillen National Park, Peru, July 2011–September 2013, TEAM Network)

Moonlight affects the landscape for roughly 1 week per lunar month centred on the full Moon and reaches a maximum brightness of almost 0.3 lux, but more typically 0.1 lux (Kyba 2017) due to atmospheric extinction and typically low incidence angles. From our general experience, this is sufficient for walking about, especially if the path surface is sandy soil, but it becomes more difficult when walking on grass or asphalt due to their low albedo.

If we assume there is a balanced ecology, then an impact on one species will change that balance and will affect, to some degree, the survival of all species in that ecosystem. Therefore, the sensitivity of foragers to the illumination by the Moon suggests an illumination threshold of less than the full Moon, and preferably a crescent Moon of roughly 0.02 lux.

This conclusion can be generalized to other habitats. Aquatic and marine zooplankton are near the base of the food chain and are vulnerable to predation by larger fish. They forage at night and seek anonymity in the cool dark depths during the day—a behaviour called Diel Vertical Migration (DVM). Not all zooplankton avoid the light. In some cases, remaining in the warm nutrient-rich surface water may be worth the risk of higher predation. However, records of DVM suggest the threshold illuminance is at about a half lunar phase, or roughly 0.02 lux (Benoit-Bird 2009).

There should be a luminance limit for birds since they use stars to navigate. A bright light source may confuse their use of stars. For example, the stars around the North Celestial Pole (Foster 2018) (roughly magnitude 2.5) have luminances of roughly 0.003 cd/m^2. However, the Moon has a luminance on the order of thousands. How can this sensitivity be reconciled with moonlight?

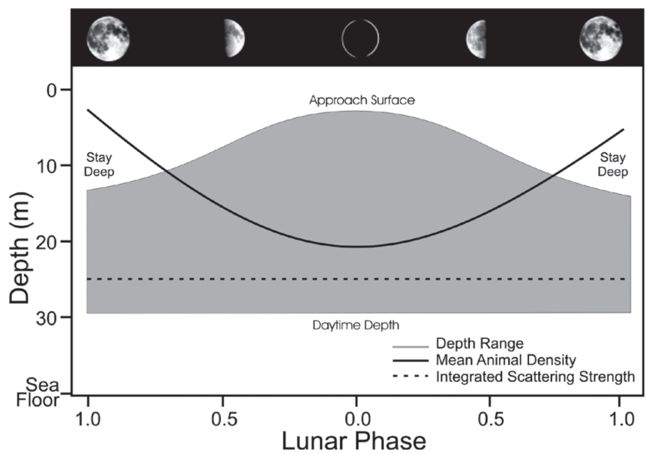

Figure 7 — Variation in zooplankton distribution over a lunation. Zooplankton avoid the surface during the bright lunar phase resulting in a compress (higher density) distribution (grey band). At new Moon, they approach the surface, which reduces the density (dark line). (from Benoit-Bird 2009)

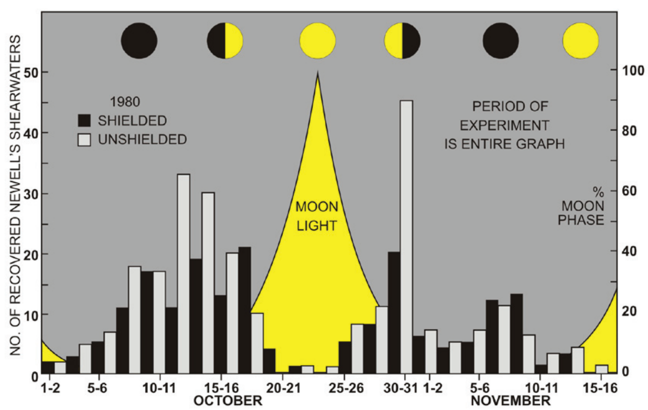

Figure 8 — Number of birds recovered during light shielding experiments. Most ALAN is ignored during the bright lunar phases, but is particularly distracting when they do not compete with moonlight. Even shielded lights cause a problem, but unshielded lights are particularly distracting. (Ref: Reed et.al. 1985)

There is no research on this point. However, the bright Moon could be differentiated from the fainter starlight. When low in the east and west it might be used in a similar fashion to the rising and setting Sun to identify the east and west. And, during migration in the early and late autumn the full Moon is roughly halfway up the sky in the south, leaving the lower altitude southern stars for navigation.

Artificial light at night (ALAN) is particularly distracting for birds during the Moon's partial phases (Reed 1985). Light sources on the ground and on towers distract birds from navigating by real stars—drawing them off course and wasting flight time. Even shielded lights are distracting but the intense luminosity of unshielded light appears to be more distracting.

The Audubon Society reports of declining songbird populations (Audubon). Numerous causes have been given that are generally referred to as habitat disruption. Absent from the list of obvious disruptions is light pollution. This is to be expected, as outdoor lighting has only recently been accepted to affect the behaviour of animals. But the evidence is increasing. For example, urban lighting is moving the foraging schedule of birds out of synch with insects on which they feed.

The ALAN simulates an early dawn. One study (Miller 2006) reports that compared to a century ago, birds are aroused an hour earlier in the morning. If their food supply is not also aroused, the birds will be out of synch with their food supply, which can result in about an hour of wasted foraging/hunting activity.

Insects play a critical role in the pollination of plants, which requires their maturation to be synchronized with plant development. The brightness and spectra of ALAN miscues the development of some plants.

The effect of day length on plants has been known for at least a century (Tincker 1924) and is used commercially to artificially prepare some plants for harvest at a time convenient for sales (Cathey 1975). Although the intention of some past research was to assess the benefit of greenhouses, the research reinforces the assertion that plants are profoundly sensitive to their photoperiod.

Plants "foretell" the coming season by the length of the night. The limit for photosynthesis in plants is roughly 1,000 lux (Leopold 1951). The threshold brightness that affects their biochemistry is on the order of 0.1 lux (Bunning 1969). (However, this published value assumed an erroneous maximum Moon illumination of 1 lux.)

Those plants that tolerate urban ALAN are called "long-day" or "day-neutral" plants. However, short-day plants are rarely found in cities, and give rural vegetation its unique character. Plant development is synchronized by the length of night. The ratio of two photo-molecules phytochrome-R (red sensitive) and phytochrome-FR (far-red sensitive) switches the plant between vegetative growth (leaves) and growth of their stalks. An artificially extended daylight is interpreted as summer, and can delay the preparation of seeds and preparations for winter.

There is no single threshold to the sensitivity of plants. But those that have been studied indicate a sensitivity less than 6.6 lux (Poulin 2014).

Brightness Limits For Wildlife Biology

The over-arching transspecies cue for development is the length of night. Although we have not yet found any definitive studies of celestial navigation by mammals, there is significant data that they use light at night in their hunting and foraging strategies. This in turn will be impacted by artificial light that illuminates the landscape—even from distant cities.

All life has internal biological clocks that time and regulate biological processes in synch with its activity. These clocks do not run on a 24-hour period, so they are called circadian (approximate day) rhythms (CR). Although the average human CR is slightly longer than 24 hours, the period for other life forms can be from 18-30 hours. Resetting these clocks to the current 24-hour day is done with the fading light of twilight. There is a wide range of animals with CRs, from prokaryotes (Huang 1990) to higher life forms (Zhdanova 2006), which serve the same general purpose of regulating and synchronizing biology with the environment.

In humans, the intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) detect the fall of twilight (twilight detectors). After twilight, they signal the suprachiasmatic nucleus in the hypothalamus at the base of the brain to release the hormone melatonin from the pineal gland. This process has profound consequences for human physical and mental health that are well documented in many review papers (Vetter 2019, Pauley 2004) and books (Koukkari and Sothern 2006).

Melatonin enables our sleep cycle and the ebb and flow of other hormones in mammals and other species. It is accumulated during the day and the pineal gland releases it when twilight fades below the blue light threshold for our ipRGCs. The hormone enables the release of a suite of other hormones that lower the metabolism in preparation for sleep and initiate tissue repair, the fight against infection, disease, and even purge incipient cancer cells. These hormones help rejuvenate the body prior to the next day's fight for survival.

Not all creatures are diurnal but even nocturnal animals are sensitive to the length of night. Their biochemistry has evolved to exploit the length of night to maximize their survival. For example, some animals have an immune response enhanced when nights are long (winter), which is believed to be an energy conservation mechanism (Walton 2019).

It should be mentioned, however, that there are other synchronizing parameters (zeitgebers) that may take precedence where imposed by the habitat (Wagner 2007). These include temperature, food supply, and others, but for many species, the photoperiod is the dominant zeitgeber.

Brightness And Human Health

As daytime creatures, humans require a minimum of light for vigorous activity. A thick overcast of cloud can reduce the Sun's illumination from 120 kLux down to less than 10 kLux. In the evening this can be lower than 1 kLux. Coincidentally, office illumination is recommended to be about 500–1000 lux (IESNA 2004). Our cone cells start to saturate at a luminance of about 500 cd/m^2. These are practical limits for luminance and illuminance for our day (photopic) vision.

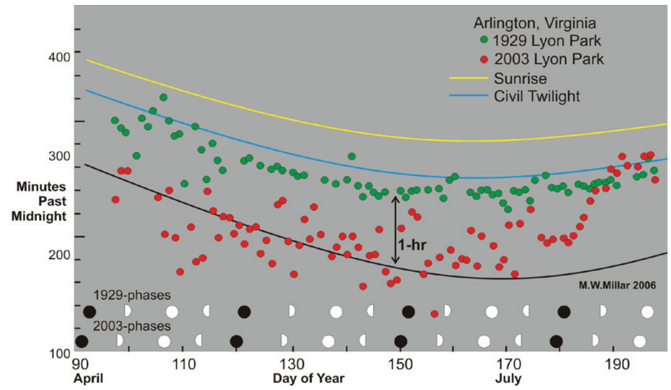

Figure 9 — Initiation of morning birdsong in 1929 and 2003. Between 1929 and 2003 the onset of birdsong has become roughly 1 hour earlier. The main difference cited is the increase of urban lighting. (from Miller 2006)

Reading is a technology we developed in our recent past. It cannot be achieved without ALAN because the high visual acuity required is only provided by our photopic vision. The luminance threshold for reading a typical page of text is about 1 cd/m^2 and the constriction of our iris also begins at the same luminance (Watson and Yellott 2012). The contrast of the print against paper and its size must be increased if we are to use our scotopic vision for reading.

The sensitivity of human biology to ALAN is revealed by studies in biological rhythms (Koukkari, Sothern 2006) and some cancer research. They are based on experiments with mice that have been bred to simulate human biology. Light at night of only 0.2 lux was sufficient to reduce melatonin by 60% of normal (dark night) levels and that cut the effectiveness of a tumour medication (Dauchy 2010, Dauchy 2014). Providing melatonin supplement renewed its effectiveness.

The effect of this melatonin suppression by light is amplified as we grow older. Following early adulthood, our peak night-melatonin concentration decreases with age to 1/2 at about 50 years and 1/4 at 80 years of age (Reiter 1995). Therefore any "artificial" reduction in melatonin will exacerbate the effects of aging.

Summary

The biological priorities of daytime creatures are different at night. Human biological limits to ALAN are similar to those supported by wildlife studies, which should not be surprising since all wildlife evolved to tolerate and even exploit the same natural environments. Generally, the sensitivity threshold of a lit environment for all species is that which is experienced in the wild. Engineering an environment does not change our biological predilections.

Light sources can confuse and disorient animals that use the stars to navigate. The illuminance limits for birds, plants, and some aquatic life, to name a few, is approximately 0.02 lux—

the illuminance produced by the crescent Moon. This is well into our scotopic vision but does not provide sufficient light for most human activity (reading) at night.

Our modern behaviour imposes higher limits on luminance and illuminance than our biology and that of wildlife. A luminance limit of about 1 cd/m^2 may seem reasonable given this is the luminance of the brightest planets. However, the apparent direction of isolated artificial sources will change unexpectedly for migrating birds as they fly past the source. Thus ALAN of even natural level brightness may adversely impact wildlife.

We must therefore look for other strategies to reduce its impact. These problems will be addressed in the next paper in this series that focuses on shielding. ✶

Endnotes

1 steradian is the spherical angle of 180/p degrees. It appears as the extent of a 1-metre diameter circle on a sphere with a 1-metre radius. Its two-dimensional version is called a radian.

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