Feature Articles / Articles de fond

The Biological Basis for the Canadian Guideline for Outdoor Lighting 4—Impact of the Spectrum of Lighting

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Abstract

We refer to light by its colour, but colour is a construct created in our brain. Biology is sensitive to the spectrum of the light–the energy it carries, which is a function of its wavelength. So the impact of light is best studied with its spectrum. The first paper of this series on scotobiology (Dick 2020a) introduced the importance of spectrum on the way we interpret the world. The diurnal change in the incident light spectrum complicates our assessment of the impact of artificial light. This paper presents how some wildlife react to the spectra of light, and the spectral characteristics of artificial light that undermine the ecological balance, and human vision.

Introduction

Our current knowledge of the environmental sensitivity to the colour of artificial light at night (ALAN) is at best spotty. Too few animals have been studied to clearly understand all its consequences. However, by assuming the environment is in an initial state of balance, then any change to specific animals in the environment will change that balance. Therefore, we need not wait for a complete data set before we can assess, at least in general terms, the sensitivity of the environment to ALAN. Light thresholds may have to be revised if we find more sensitive animals, but over the past 12 years of study this general approach has not required our lighting limits to change.

There are three ways that light "colours" the landscape. First, there is the colour of the incident light. Second, there is the inherent colour of the surface—or its spectral reflectivity. And third, the spectral sensitivity of our biology and our vision. The combination of these affects how we see the landscape, and its effect on our biology.

Photographers are well aware of how the hue of ambient light changes from dawn to dusk —affected by the clarity of the air, its moisture content, and the elevation of the Sun in the sky. In the morning, the Sun's direct illumination looks "yellow." This is neutralized to "white" around midday (Mie scattering when suspended particles are larger than the wavelength of light and results in forward scattering of light). Later in the afternoon, with increasing humidity, sunlight becomes more "orange" as smaller particles scatter the shorter wavelength blue light over the sky (Rayleigh scattering when particles are smaller than the wavelength of light and is omni-directional), giving it a more saturated shade of blue (Mainster and Turner 2014). At sunset, without the Sun's yellow disk, the dominant colours are red from the lingering glow on the horizon and the blue of the sky. The red illumination dims as the sunset continues to fade, leaving the landscape bathed in blue light, which over time appears to de-saturate as our photopic colour vision grows blind and our more blue sensitive scotopic vision takes over (Raymond 2011).

The evolving hues of the ambient light are not just aesthetically interesting; they provide a survival advantage for some animals. These changes are most evident during the fading twilight. This is the time when the diurnal animals give way to the nocturnal wildlife—changing the competitive players and the ecological balance.

Surfaces change their spectral reflectivity in response to exposure, weathering, or aging. Small fish can change from transparent to opaque as they mature. Most studies have been on relatively small aquatic life forms, but other animals change colour with maturity or for camouflage in response to stress

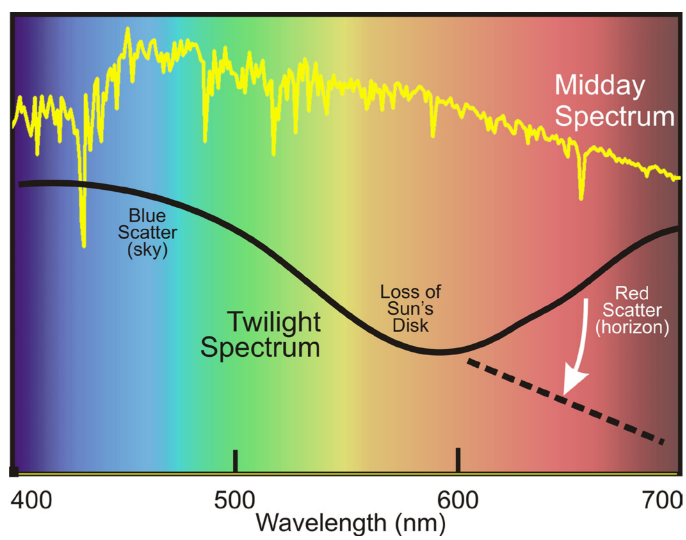

Figure 1 — Evolving spectrum of the day and twilight sky. On clear days, the ambient colour changes from morning to night. This provides visual cues to wildlife as to the period of the day and the approach of night.

Our brain continually "white balances" our vision so this change is not evident to most people. However, when taking pictures, photographers must compensate for this change with coloured filters, image settings in digital cameras, or image processing programs. (Ref: Solar Spectrum – ASTM G173-03, Twilight Spectrum Lee, 2011)

(Duarte 2017). Our skin darkens over a few days in sunlight to protect us from excessive Sun exposure and for most of us, our hair grows grey with age.

Plants

Plants get their energy from the Sun, in particular from the blue and red light. The threshold for photosynthesis for most plants is only about 1000 lux. Some indoor plants die in draped rooms but receive sufficient light in offices. This illumination level is far greater than typical outdoor ALAN, so it may not contribute to energy harvesting, but it is detected nevertheless and affects plant development during the night.

At night, plants concentrate on development that complements that during the day. ALAN, with the characteristic daylight spectrum, provides a cue to daytime development processes at the expense of the nocturnal growth patterns. Though not detrimental to all plants, ALAN will provide undue advantage to some species, unbalancing the natural ecology and possibly encouraging invasive species at the cost of indigenous varieties.

Experiments dating back to the 1920s have shown that the growth pattern of some plants changes from a lengthening of the stock during the day (vegetative growth) to producing leaves at night (flowering) (Tincker 1924, Withrow and Benedict 1936). In the paper by Tincker, a clover plant grew short and bushy with more typical dark periods (night) but grew tall and spindly when exposed to artificially long periods of light (extended day).

The reason, in part, is the spectrum of the light. Plants chemically record the passage of time after the fading of twilight with the decay in darkness of light-transformed molecules. In the longer term, the length of time these molecules decay signals the plant to respond to the changing length of night that occurs with the seasons. This primarily occurs in the temperate latitudes where there are significant differences in the length of night in spring/autumn to that in summer.

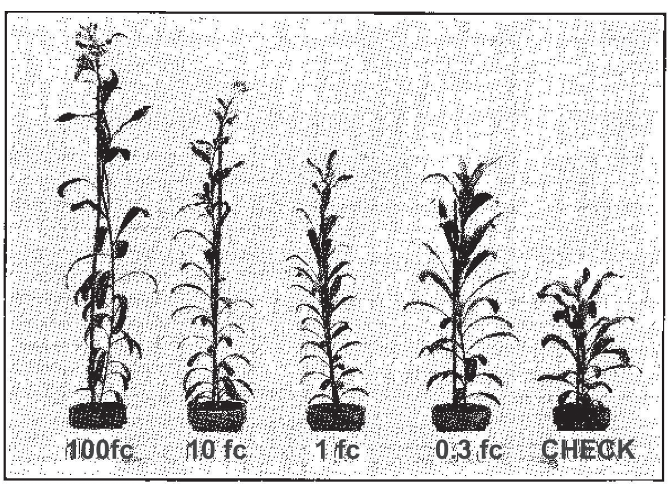

Figure 2 — The perceived length of night changes the growth pattern of some plants. Some plants may benefit from extended daylight. However, the growth of "Short Day Plants" may stimulate vegetative growth instead of flowering, leading to tall spindly stocks. (Withrow and Benedict 1936).

A shortening night indicates spring, and a lengthening night occurs in summer and autumn. Detecting this difference, allows plants to flower at the appropriate time—synchronized with pollinating insects, and birds that will pick and carry off the fruit and seeds. Plants later prepare for winter by withdrawing the nutrients from leaves, which results in the autumn colours and dropping of leaves.

More specifically, this growth cycle is caused by the accumulation and atrophy of red- and far-red absorbing chemicals (phytochrome-R and phytochrome-FR) (Smith 1978). The P_R (phytochrome-R) has an action spectrum between 650–670 nm, and that for P_{FR} (phytochrome-FR) is somewhat longer (705–740 nm) (Bennie 2016). P_R transforms to P_{FR} in sunlight, which is rich in red light. The P_{FR} reverts back to P_R during the night. This reversion of the P_{FR} enables different types of growth. The critical characteristic is not the length of day, but the length of night (Hillman 1973). Indeed, exposure after dark of only a few minutes of light can convert the P_R back into P_{FR}, causing the plant to interpret the light-break as two short nights (spring or summer instead of autumn) and will alter the plant's growth and subsequent survival.

The chlorophyll molecules that help harvest solar energy are sensitive to both blue and red light (Larkum and Kuhl 2005). In addition to these, there is another set of blue sensitive molecules (cryptochromes) that are responsible for

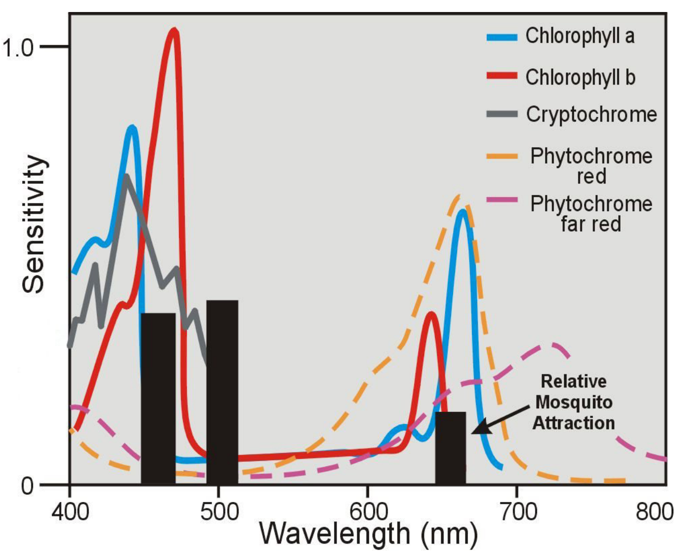

Figure 3 — Action spectra for plants and insects. These plots show the relative sensitivity of plants to the blue and red/IR spectrum for three general types of molecules. Since many plants have less use for green light, it is reflected from the surface giving plants their green colour.

Mosquitoes are also sensitive primarily to blue spectra. The amber colour of commercial bug lights falls between their peak sensitivities.

stem elongation. As twilight fades, the blue light of the day and twilight sky falls below their threshold—it pauses the nocturnal growth of the plant's stock and allows the stored energy to be used for the development of leaves.

The cyclic balance between the phytochrome-R and phytochrome-FR, and cryptochrome raises concern over the impact of the evolving colour characteristics of ALAN. Recent changes from amber high-pressure sodium to white LED lamps alter the phytochrome balance, and the bright emission of blue light bathes the plants in perpetual twilight. The blue light components enable the stock to grow through the night—leading to tall but spindly plants. Taken to the extreme, this would prevent the survival of short-day plants in urban areas, and the birds and insects that depend on them.

Aquatic Life

Light in the water column was discussed in the second paper in this series (Dick 2020b) but there is a spectral component as well. Water transparency studies use a Secchi disk (Wikipedia), a disk with white and black sectors that is viewed at increasing depths to determine the water's transparency. However, it does not provide spectral data.

Figure 4 — Enhanced Plant Growth under White Shoreline Lighting. The consequences of white ALAN tends to be overlooked until it leads to disruption of the water quality and vitality of aquatic life. Excessive plant growth is followed by plant death and decay, which releases toxins into the water. These affect the water quality and produce a rotting smell that affects the enjoyment of waterfront property and recreational fishing.

Increasing the amount of light at night, above natural levels, alters the brightness and spectrum of light deeper in the water column. Whether this is desirable or not depends on the context. Fishing lights increase the harvest of fish, but it stresses the habitat.

As the light penetrates the water column, longer wavelengths are absorbed by suspended particles more than the blue light components. This effect is subtle for inland waterways and can be overwhelmed by the opacity of turbid water but becomes more important in clearer lakes and coastal waters, which are favoured for vacation homes.

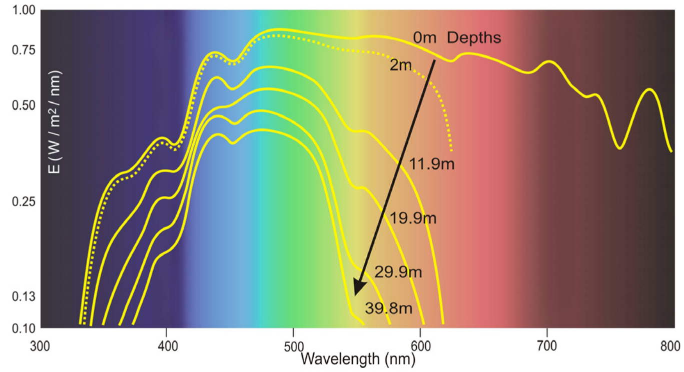

Figure 5 — Marine water transparency as a function of wavelength and depth. Clean water becomes progressively opaque at longer wavelengths. Blue light penetrates deeper. Therefore, longer wavelengths >500 nm will have less of an impact at depth (from Morel 2007).

The natural attenuation of long-wavelength illumination with water depth narrows the spectral range of illumination toward the blue. The wavelength of peak rod sensitivity for fish (roughly 520 nm) lengthens with natural turbidity and shortens with habitat depth (Schweikert 2018). Thus, rods cells of deeper fish can take advantage of the shorter-wavelength blue light that can penetrate to those depths.

Short-wavelength ALAN has three affects. It will increase the visibility of small fish—increasing the predatory success for larger fish. The semi-transparent zooplankton are made more visible to predators by the light they scatter. And it can extend the visible range to enable fish to forage or hunt for food at greater depths. This will affect the ecological balance in the deeper and cooler waters, which are more sensitive to over-grazing.

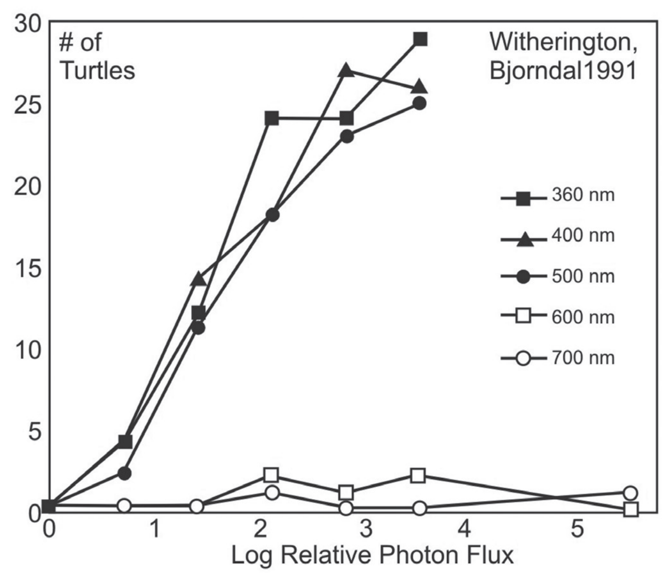

Figure 6 — Attraction of loggerhead turtle hatchlings as a function of wavelength. There was an approximately linear decrease in attraction from 500 nm to 600 nm for a constant brightness. (Witherington and Bjorndal 1991). Note, the "Log Relative Flux" of 2.78 is about 2.5 lux, and 3.5 is approximately 13 lux.

Amphibious creatures also suffer from unshielded fixtures and light with blue-spectral content. A popular example is turtle hatchlings. After breaking free from their shells and surfacing through the sand, they head to the light, which is usually the blue fluorescence of the sea's breaking surf. Landward light, with blue light components, can overwhelm this innate behaviour and attract the hatchlings away from the water, and safety. Studies show that light ≤550 nm is particularly dangerous.

Insects

ALAN distracts insects from more important duties, such as feeding, mating, and migrating, and has additional more-homocentric impacts.

The light spectrum is important in the navigation and survival of insects. Some flying insects avoid predation from birds during the day by foraging during twilight (crepuscular activity). Flying insects are attracted to the light of the blue sky (positive phototaxis). As a result, they have greater sensitivity to blue and ultraviolet light. Thus, blue light attracts insects, whereas longer wavelength light is less attractive.

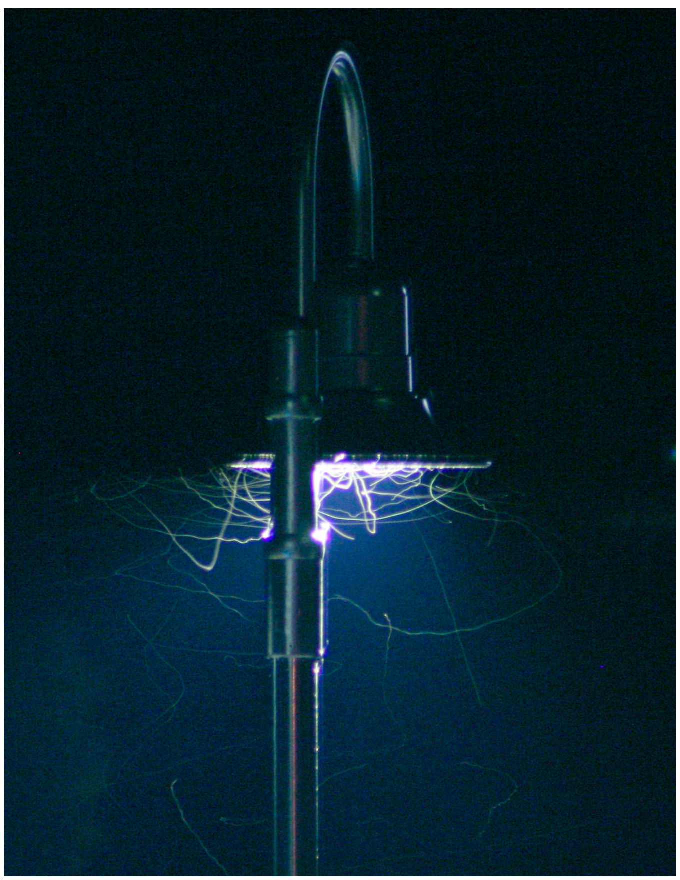

Figure 7 — Positive phototaxis of flying insects, as they are attracted to white light. Insects are attracted by both brightness and the colour of light. Their propensity to short wavelength light draws them to the luminance of the lamp. Their sensitivity to blue light makes a white light appear brighter than humans perceive. The light distracts the insects from their normal behaviour of feeding, mating, and migrating. Since light is usually installed where humans congregate, it increases the nuisance of the swarm.

The main insects amateur astronomers are concerned about are mosquitoes. Some people will recall grandfatherly advice about using amber "bug lights" to reduce the number of mosquitoes on patios and around building entranceways. Using "white light" at night, with its blue-light spectral components, goes against this "common sense." White light attracts insects from afar and increases the "insect density" of an area, which in turn enhances the success of their feeding, and also predation from other insects and animals. Use of white lights also increases the risk of communicable diseases that are borne by flying insects (Barghini and Medeiros 2010).

These are good reasons to not emit blue light and to limit the catchment area of insects by ensuring light fixtures are shielded (2020c).

Birds

Birds "inhabit the skies," so it is to be expected that their cone cells are more attuned to bluer wavelengths. They have four sets of cone cells (tetrachromatic vision) with the blue and UV receptors being more plentiful and sensitive than the green-yellow and orange-red sensitive cells (Hart 2001), and human cone cells, which are somewhat insensitive to blue light. The bright blue spectral components of ALAN from "white" urban lighting are more of a distraction for birds than longer wavelength light. Once distracted they become "lost" in the multiple reflections on glass and steel of buildings and unshielded flood lighting.

Birds are also distracted by aircraft navigation beacons on towers and wind farms where red and white beacons are in common use. Although studies suggest white strobes attract birds less than red lights (Gehring 2009), there are several other characteristics that confuse these findings. There are four specifications that concern the impact of a beacon on the ecology: the colour and brightness, dispersion angle, and the flash duration.

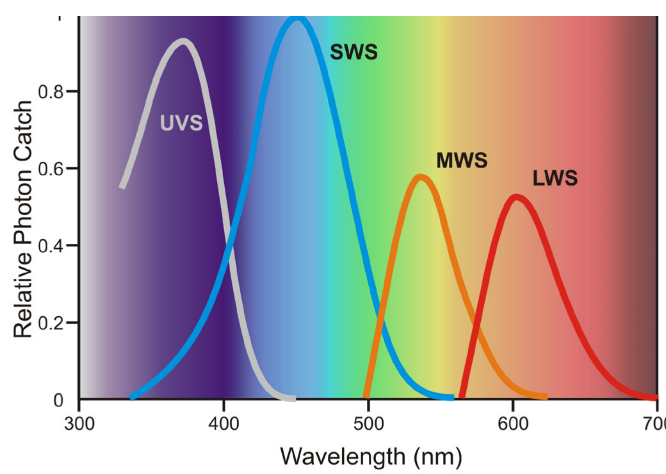

Figure 8 — Relative sensitivity of bird vision cells. In contrast to humans, birds have two sensitive receptor types for short wavelength vision (Ref. Hart 2001). Although human rod cells are sensitive to blue, at these high luminances, the rod cell pigments are bleached.

1) The FAA specifies medium intensity red flashing lights at night (L-864[1]) or white flashing lights (L-865)—both emit 2000 candela. Humans have relatively few blue-sensitive cone cells (Calkins 2001) so the white light will appear much brighter to birds than to humans. The bright white light distracts and attracts the birds toward the light and away from their migration route, sometimes resulting in collisions with buildings and tower guy wires, and more generally wastes time and energy.

2) Older incandescent lamps in red flashing beacons have flash durations of about 1/2–2/3 the flash period, which makes it easier to get a bearing on the location. In the case of 40 flashes per minute (L-857 - white), the bright phase is only 100–250 msec and appears like a "strobe." The frequency and duration of the more modern strobe lights vary depending on the beacon requirement and lamp type (FAA 2016, FAA 2019).

   Their short duration gives little time to orient on the direction of the light. Motorists and pilots will see the flash but may not be able to determine its precise direction either. Therefore, an emission with a longer pulse is more easily identified. Modern white strobes with a very short duration (low lamp duty cycle) may be all that reduces their attraction to birds. Therefore, in earlier studies, it may not be the colour, but the duration that was attracting birds. A red light "slow strobe" may be best for getting a bearing on towers (bad for birds but good for pilots), but the red light is less attractive to birds (good for birds).

3) The electrical power for these beacons can be reduced by collimating the emitted light into narrow cones (20 degrees horizontally and 3 degrees vertically). This reduces their apparent brightness when viewed from the ground and makes them more energy efficient, while retaining high visibility to pilots and birds.

Mammals and Humans

We share our eye structure, visual chemistry, and circadian rhythms with other species, so we should expect that what applies to one species may apply to others—until research determines otherwise.

ALAN affects all life but it may have greater health impact on humans than other animals. Humans consciously illuminate themselves, whereas animals attempt to avoid the light, and our longevity allows the adverse effects to accumulate for a longer period of time.

The circadian rhythm schedules our biochemistry over a 24-hour period (Kothari and Sothern 2006). These rhythms are synchronized to our diurnal cycle of activity by the detection of the end-of-day by non-visual blue-sensitive intrinsically photosensitive Retinal Ganglion Cells in our retina (ipRGCs).

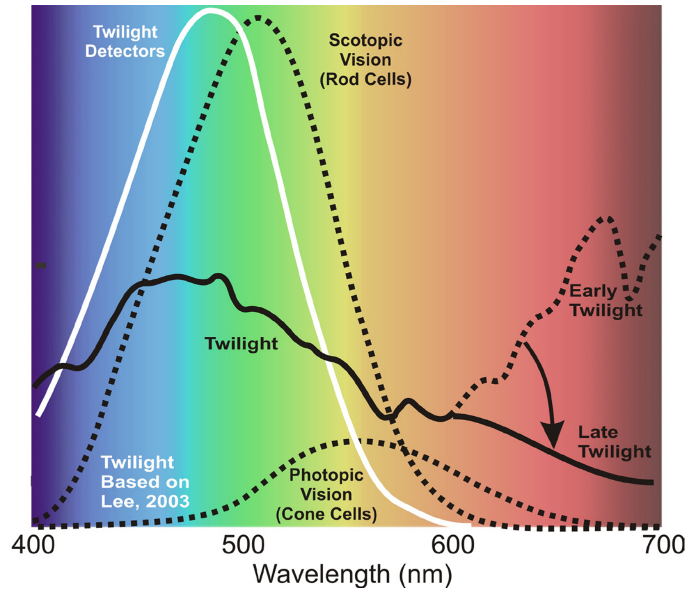

Figure 9 — Comparison between "twilight detector" cells and the rod and cone cells. The action spectrum of the twilight detectors (ipRGCs) peaks about 480 nm in the blue part of the spectrum corresponding to the clear twilight sky. ALAN that is used specifically for scotopic vision will inadvertently affect these cells and alter the circadian rhythm and the subject's chronobiology.

The ipRGCs have an action spectrum that peaks at about 480 nm with a slow decline into the red (Lee 2003). This corresponds to the spectrum of the twilight sky, so they can also be considered "twilight detectors." The fading of blue light at night is an important zeitgeber for the circadian rhythm—though it is also augmented by ambient temperature and the available food supply. Without the contrast between day and night, the phase of this rhythm falls out of step with the animal's activity and environment. So, both the brightness and spectrum of the late-evening light are important for the health and vitality of many species.

The hormone melatonin is accumulated during the day in the pineal gland and is released into our blood when night is detected by the ipRGCs. It prepares our bodies for sleep and also enables the release of other hormones that rejuvenate our bodies as we sleep—in preparation for the next challenging day. Our circadian rhythm prepares this suite of hormones that keep us healthy, but they have a "shelf life," and begin to decay after a few hours, so a delay in their release will reduce their efficacy and the benefit of sleep.

ALAN that is above the ipRGC threshold may delay or abort the release of these hormones. This will undermine subsequent biological activity that should occur at specific times of the night—affecting both our physical and mental health (Bunning 1979, Brainard 1988, Cajochen 2006).

In European experiments, elderly patients have been exposed to bright light during the morning, which prevents the "leakage" of melatonin throughout the day. Darkened bedrooms at night then encourage its release. This has been reported to have significantly reduced the symptoms of dementia in institutionalized patients (Lieshout-van Dal 2019).

As people age, the peak diurnal concentration of melatonin in the blood gets progressively lower, so for senior citizens there is less melatonin for our bodies to use than that in younger people (Reiter 1995). The amount of melatonin can become too low to enable these restorative processes, exacerbating illness and dementia with age (vanHoof 2008, Karasek 2004).

Nocturnal light is problematic when brighter than the threshold limit for the ipRGCs. Determining a precise detection "threshold" has not been possible because of a continuum of effects including the light integration characteristics of these cells (Do 2009). However, the threshold limit seems to be a few times the illumination of the full Moon (Dick 2020), which is needed to enable the release of the hormone melatonin into the blood, though dimmer light over longer time periods might affect other biological processes.

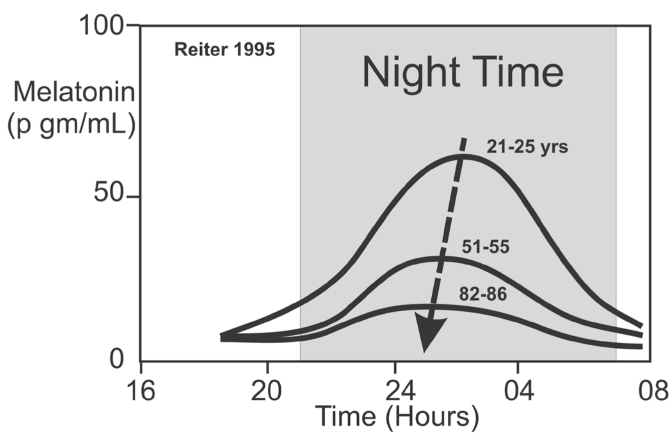

Figure 10 —Variation of melatonin over 24-hours and over a lifetime. The "contrast" between the concentration of melatonin in the day and night steadily declines with age.

Recent studies that combine clinical and geographical data show a direct correlation between ALAN and some diseases attributed to aging: dementia, diabetes (Onaolapo, Onaolapo 2018), obesity (McFadden 2014) and hormonal cancers (Stevens 2013). Figure 10 with data from the Centre for Disease Control (diabetes and obesity) (Willis 2010, Nguyen 2012) and comparing these to the light pollution map of 2012 (www.lightpollutionmap.info). These provide strong arguments against the excessive use of ALAN with blue-spectral components (Bedrosian 2013, Romeo 2012).

This clinical data does not provide the mechanisms for these impacts, but it is a warning, and should not be ignored while waiting for future research to prove these assertions.

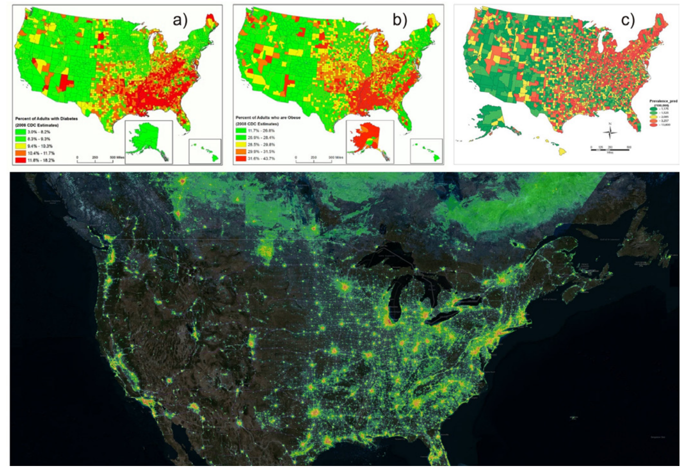

Figure 11 - Correlation between a) Diabetes, b) obesity, and c) Parkinson's disease is normalized and compared to the distribution of urban light pollution. The studies show these diseases primarily affect urban populations. On their own, this suggests a link to light pollution, but other factors may contribute to this trend. For example, light pollution does not correlate equally or consistently with all these ailments. The diffuse (green) skyglow over Canada is due to atmospheric effects. (From CDC 2020, b) Nyguyen 2012, c) Willis, et.al. 2010, and lightpollutionmap.info 2012)

Mesopic Vision and the Sp Ratio

The ratio of the spectral sensitivity of our night (scotopic) vision and our day (photopic) vision (SP ratio) was developed to compare the visual impact of a lamp assuming our rods and cones are working together to form a single image. "*S*" is the normalized scotopic spectrum (maximum sensitivity = 1) convolved with the spectrum of the light source, and similarly "*P*" is the normalized photopic spectrum convolved with the lamp spectrum (Miller 2019).

However, typical urban lighting situations in our photopic range (>5 lux), exceed the bleaching threshold of our scotopic vision. Therefore, in most practical applications, only one of either the rods or the cones is functional, and consideration of the combined scotopic and photopic vision (mesopic vision) is therefore "academic."

Regardless, the SP Ratio is used in the literature and posted on luminaire information sheets. A blue-white coloured lamp will have a *S/P >2*. In contrast, lamps that emit amber light have a very low SP ratio (*S/P* <0.1 for amber LEDs and ~0.2 for HPS lamps).

The SP ratios for several light sources are listed in Table 1 (from LIA 2013). In principle, for a high SP ratio, a designer could use less light for the same visibility, because of the higher sensitivity of our scotopic vision. However, industry lighting guidelines are based on our less-sensitive photopic vision, which underrates the blue light content—leading to brighter lighting.

There are anecdotal comments that low (amber) S/P is 8"promote" the use of white light. So, when engineering the

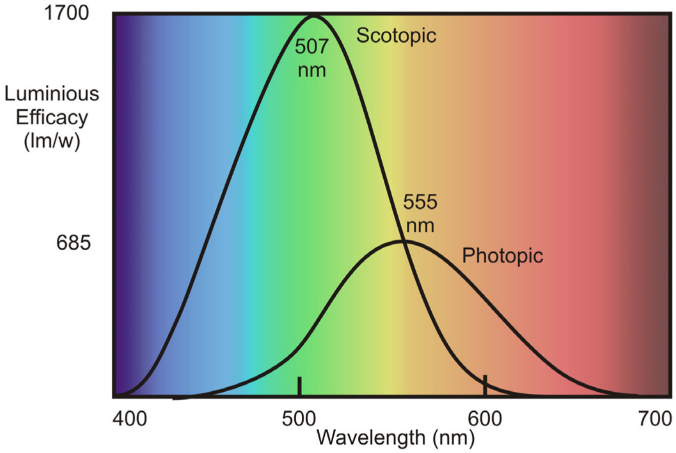

Figure 12 - Luminous efficacy for scotopic and photopic vision. Light with a spectrum of our photopic vision should be 40% of the brightness of light for our scotopic vision if it is to "appear" the same brightness. (Ref. Yao 2018)

lighting system, the illuminance metric, which is based on our photopic vision, is not reduced to reflect our scotopic vision.

The ratio between the peak spectral sensitivity of our scotopic and photopic vision is 1700 lm/w / 685 lm/, or 2.5. Therefore, as a first approximation, the illuminance of white photopic light should be reduced to 40% if it is to appear at approximately the same brightness for our scotopic vision. Based on the de Boer Scale for Glare (Bullough 2009, De Boer 1967), this reduces the perception of glare from "just permissible" to "satisfactory."

Melatonin Suppression Index

In a similar fashion to the SP ratio, a biological sensitivity parameter has been developed called the Melatonin Suppression Index or MSI (Aubé 2013). This is a biological metric whereas the SP Ratio is a vision metric. Lower values of MSI have a lower impact on the natural melatonin levels. Table 1 lists the MSI for a number of light sources with their Colour Rendering Index (CRI - ability to reveal true colours). The CIE D65 is the standard for "daylight." Lamps that emit minimal blue light (<500 nm), such as amber LEDs, have very little impact on the concentration of melatonin in our blood, whereas lamps with higher correlated colour temperatures have a greater effect.

Summary

The colour of ALAN is more than aesthetically pleasing. It changes the natural environment that would normally "inform" our biology. It also changes the natural colour of the landscape, which distracts and confuses the behaviour of animals that do not understand its artificial nature.

Our colour perception adapts to changes with the illumination level—our brain automatically "white balances" the scene. However, our spectral sensitivity to ALAN does not adapt. It extends our biological perception of daylight and delays critical processes that occur as we sleep. This affects human physical and mental health and also that of other animals.

Lamp	CRI**	S/P**	MSI**
Low-Pressure Sodium	-47	0.25	0.017
Amber LEDs*	47	0.07	0.043
High-Pressure Sodium (70W)	19	0.21	0.118
Incandescent	93	1.36	0.255
4000K LED	90	1.6	0.452
Metal Halide	48	2.4	0.624
CIE D65 Spectrum	100	~2.18	1.000

** Nichia Corporation   ** all values are sensitive to specific lamp spectrum*

Table 1 — Comparison of Melatonin Index of Different Light Sources.

Our understanding of how the spectrum of ALAN affects biology and behaviour provides us with a fourth "tool" we can use to reduce its impact. The next paper will discuss the scheduling of the light and how it affects the behaviour of wildlife. ✷

Endnotes

1 L-XXX is the FAA designation and the CL-XXX is the Transport Canada Designation, CAR 2019

References

Apogee Instruments, www.apogeeinstruments.com/conversion-ppfd-to-foot-candles, Accessed 2020 May 29
Aubé, M., Roby, J., Kocifaj, M., (2013) Evaluating Potential Spectral Impacts of Various Artificial Lights on Melatonin Suppression, Photosynthesis, and Star Visibility, *PLoS ONE 8*(7): e67798. doi:10.1371/journal.pone.0067798, Accessed 2020 June 24
Barghini, A., and Bruno A. S. de Medeiros, B.A.S.,(2010) Artificial Lighting as a Vector Attractant and Cause of Disease Diffusion, Environmental Health Perspectives, *National Institute of Health*, doi: 10.1289/ehp.1002115 (available at http://dx.doi.org/) Accessed 2020 June 24
Bedrosian, T. and Nelson, R., (2013) Influence of the Modern Light Environment on Mood, *Molecular Psychiatry (2013) 18*, 751–757
Bennie, J., et.al, (2016) Ecological Effects of ALAN on Wild Plants, *Journal of Ecology, Vol. 104*, pp 611–620, 2016
Bullough, J.D., (2009) Spectral Sensitivity for Extrafoveal Discomfort Glare, *Journal of Modern Optics, Vol. 56, No. 13*, 1518–1522 Accessed 2009 July 20
Brainard, G., et.al., (1988) Dose-Response Relationship between Light Irradiance and the Suppression of Plasma Melatonin in Human Volunteers, *Brain Research, 454* (1988) pp. 212–218
Bunning, E., (1979) Circadian Rhythms, Light, and Photoperiodism: A Re-Evaluation, *Botany Magazine, No. 92*, pp. 89–103
Cajochen, C., et.al., 2006, High Sensitivity of Human Melatonin, Alertness, Thermoregulation, and Heart Rate to Short Wavelength Light, *Journal of Clinical Endocrinology & Metabolism 90 (3)*, pp. 1311–1316
Calkins, D. (2001) Seeing with S Cones, *Progress in Retinal and Eye Research, Vol.20, No. 3*, pp. 255–287, 2001
CAR (2019), CAR Standard 621, www.tc.gc.ca/en/transport-canada/corporate/acts-regulations/regulations/sor-96-433/standard-621.html, Accessed 2020 May 12

CDC (2020) Centre for Disease Control, National Diabetes Statistics Report 2020, www.cdc.gov/diabetes/pdfs/data/statistics/national-diabetes-statistics-report.pdf, Figure 3. Accessed 2020 March 30

De Boer, J.B. (1967) *Public Lighting*; Philips Technical Library: Eindhoven, 1967

Dick, R., (2020a) The Biological Basis for the Canadian Guideline for Outdoor Lighting 1—General Scotobiology, *JRASC*, June 2020

Dick, R., (2020b) The Biological Basis for the Canadian Guideline for Outdoor Lighting 2—Impact of the Brightness of Light, *JRASC*, October 2020

Dick, R. (2020c) The Biological Basis for the Canadian Guideline for Outdoor Lighting 3—Impact of the Extent of Lighting, *JRASC*, December 2020

Do, M., et.al. (2009) Photon Capture and Signalling by Melanopsin Retinal Ganglion Cells, *Nature, Vol. 457*, 2009 January 15, doi:10.1038/nature07682

Duarte, R., Flores, A., Stevens, M., (2017) Camouflage through colour change: mechanisms, adaptive value and ecological significance, *Philosophical Transactions, Royal Society B, Biological Sciences, 372(1724)*: 2017 July 5; 20160342, Available at: www.ncbi.nlm.nih.gov/pmc/articles/PMC5444063, Accessed 2020 May 24

FAA (2016) AC 70 7460-1L – Obstruction Marking and Lighting – Change 2, www.faa.gov/documentLibrary/media/Advisory_Circular/AC_70_7460-1L_-_Obstuction_Marking_and_Lighting_-_Change_2.pdf, Accessed 2020 May 12

FAA (2019) AC 150/5345-43H, Specification for Obstruction Lighting Equipment, Table 3-4, Accessed 2020 May 24

Gehring, J., Kerlinger, P., and Manville, A., (2009) Communication Towers, Lights, and Birds: Successful Methods of Reducing the Frequency of Avian Collisions, *Ecological Applications, 19(2)*, 2009, pp. 505–514

Hart, N., (2001) The Visual Ecology of Avian Photoreceptors, *Progress in Retinal and Eye Research Vol. 20, No. 5*, pp. 675–703, 2001

Hillman, W., (1973) Light, Time, and the Signals of the Year, *BioScience 1973, Vol. 23 No. 2*, pp. 81–86

Koukkari, W. and Sothern, R., (2006) *Introducing Biological Rhythms*, Springer Science, 2006

Miller, N., (2019) M/P ratios – Can we agree on how to calculate them?, IES, Nov. 2019, www.ies.org/fires/m-p-ratios-can-we-agree-on-how-to-calculate-them/, Accessed, 2020 April 17

Karasek, M., (2004) Melatonin, Human Aging, and Age-Related Diseases, *Experimental Gerontology 39*, 1723–1729 (2004)

Larkum, A. and Kuhl. M., (2005), Chlorophylld: The Puzzle Resolved *Trends in Plant Science, Vol. 10, No. 8*, August 2005

Lee Jr., R. and Hernandez-Andres, J., (2003) Measuring and Modeling Twilight's Purple Light, *Applied Optics, Vol. 42, No. 3*, 2020 January 20

Lee, R. (2011), Atmospheric Ozone and Colors of the Antarctic Twilight Sky, *Applied Optics, Vol. 50, No. 28*, 2011 October 1

LIA (2013), SP Ratios and Mesopic Vision, *Lighting Industry Association* 2013, www.thelia.org, Accessed 2020 April 17

Lieshout-van Dala, E., Snaphaan, L., and Bongers, I., (2019) Biodynamic Lighting Effects on the Sleep Pattern of People with Dementia, *Building and Environment, 150* 245–253 (2019)

Mainster, M. and Turner, P. (2014) Glare's Causes, Consequences, and Clinical Challenges After a Century of Ophthalmic Study, *American Journal of Ophthalmology*, April 2012

McFadden, E., et.al., (2014) The Relationship Between Obesity and Exposure to Light at Night: Cross-Sectional Analyses of Over 100,000 Women in the Breakthrough Generations Study, *American Journal of Epidemiology* 2014 May 29, DOI:10.1093/aje/kwu117

Morel, A., et.al., (2007) Optical Properties of the "Clearest" Natural Waters *Limnology and Oceanography, 52(1)*, 217–229, (2007)

Nguyen, T. (2012) Does driving make you fat? From www.zdnet.com/article/does-driving-make-you-fat-infographic/ Accessed 2020 February 10

Onaolapo, A. and Onaolapo, O., (2018) Circadian Dysrhythmia-linked Diabetes Mellitus: Examining Melatonin's Roles in Prophylaxis and Management, *World Journal of Diabetes, Vol. 9 (7)*; 2018 Jul 15, PMC6068738

Reiter, R., (1995) The Pineal Gland and Melatonin in Relation to Aging, *Experimental Gerontology, Vol. 30, Nos. 3/4*, pp. 199–212, 1995

Romeo, S., et.al, (2012) Bright Light Exposure Reduces TH-Positive Dopamine Neurons: Implications of Light Pollution in Parkinson's Disease Epidemiology, *Scientific Reports, 2012, 3*:1395, DOI:10.1038/srep01395

Schweikert, L., et.al. (2018), Variation in rod spectral sensitivity of fishes, *Journal of Experimental Biology, 95*:179–185, 2019

Smith, H., ed. (1978) *The Molecular Biology of Plant Cells, Chapter 14—Phytochrome Action*, University of California Press 1978

Stevens, R., et.al., (2013) Adverse Health Effects of Nighttime Lighting: Comments on American Medical Association Policy Statement, *American Journal of Preventative Medicine, 45 (3)*: pp. 343–346, 2013

Thomas, B. and Vince-Prue, D., (1997) *Photoperiodism in Plants*, Ed.2, Academic Press, 1997

Tincker, M.A.H. (1924), Effect of Length of Day on Flowering and Growth, *Nature,* 1924 September 6, pp. 350–351

vanHoof, J., et.al., (2008) Ambient Bright Light in Dementia: Effects on Behaviour and Circadian Rhythmicity, *Building and Environment* (2008), doi:10.1016/j.buildenv.2008.02.005

Walton, J., Weil, Z., and Nelson, R., (2010) Influence of Photo Period on Hormones, Behavior, and Immune Function, *Frontiers in Neuroendocrinology*, (2010), doi:10.1016/j.yfrne.2010.12.003

Wikipedea, https://en.wikipedia.org/wiki/Secchi_disk, Accessed 2020 May 12

Willis, A., et.al., (2010) Geographic and Ethnic Variation in Parkinson Disease: A Population-Based Study of US Medicare Beneficiaries, *Neuroepidemiology 2010; 34*:143–151, DOI: 10.1159/000275491

Witherington, B. and Bjorndal, K., (1991) Influences of Wavelength and Intensity on Hatchling Sea Turtle Phototaxis: Implications for Sea-Finding Behavior, *Copeia, 1991,(4)*, pp. 1060–1069

Withrow, R. and Benedict, H., (1936) Photoperiodic Responses of Certain Greenhouse Annuals as Influenced by Intensity and Wavelength of Artificial Light used to lengthen the Daylight Period, *Plant Physiology, 11(2)*, pp. 225–249, April 1936

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