BLUE LIGHT

AOTEAROA

Impacts of artificial blue light on health and the environment

EVIDENCE SUMMARY

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ROYAL SOCIETY TE APĀRANGI

BLUE LIGHT

at night
not so bright

in the morning
stops you yawning

Blue light occurs naturally as part of sunlight and moonlight and, like all living things on Earth, we have evolved to respond to the daily cycle of light and dark. There is growing concern that the increased exposure to artificial sources of blue light from lighting and digital screens is having an effect on our health, wildlife and the night sky.

This paper summarises the latest evidence on this topic and explores what we can do to protect ourselves and the environment from the effects of exposure to artificial blue light outside daylight hours.

TE AO HURIHURI

What has changed?

Artificial light sources are widely used in our everyday lives to illuminate streets and our homes. There has been a change to use more energy efficient technologies such as light emitting diodes (LEDs) and an increase in the use of digital screens. Artificial lights can vary widely in their brightness and colour composition, including how much blue light they emit. These properties, together with the timing and duration of their use, can alter how these light sources may affect health and the environment.

HAUORA

Our health

Specialised cells in the human eye have evolved over millions of years to respond to daylight, particularly blue wavelengths of light, in order to track time and regulate biological functions such as our circadian clock. Daylight is important for vision as well as our health and wellbeing. Adequate exposure to daylight, particularly during the morning, is important for synchronising the circadian body clock, which can affect many processes including sleep, metabolism, immune function and even our mood. However, exposure to blue wavelengths in artificial light outside normal daylight hours can disrupt sleep and the body clock, and have flow-on negative health effects.

TE TAIAO

The environment

The effects of blue light in the environment on wildlife include similar disruption of biological clocks, and may affect plant growth, pollination, reproduction, migration, predation, and communication.

MĀTAI ARORANGI

Astronomy

Blue wavelength light is also more strongly scattered by the night sky, increasing the levels of sky glow at night and reducing visibility of the universe.

HE PUTANGA IHO

Solutions

There are ways to reduce some of the negative impacts of using light at night. Limiting screen time before bed may mitigate effects on the circadian rhythm from exposure to blue light at night from digital devices. Selecting 'warmer' coloured white light sources that emit less blue light and reducing brightness may lessen the potential negative effects associated with using blue light at night.

Well-designed outdoor lighting installations can minimise light pollution and other environmental impacts while still providing adequate light for visibility and to support road safety. Strategies for reducing unwanted effects from lighting include matching lighting levels to changing needs with timers, motion and directional controls, avoiding lighting areas excessively, using light shielding, and by installing warmer coloured light sources.

Overall, we can support our natural circadian rhythm by using daylight in the morning and sleeping in a dark room at night.

TŪĀWHIORANGI KITEA

What is ‘blue’ light?

Light is part of the electromagnetic spectrum that ranges from low-energy radio waves to high-energy gamma rays (Figure 1 – see next page). The human eye perceives visible light, from the Sun or other sources, in the region from around 380 nm to 780 nm of the electromagnetic spectrum.[1,2] Daylight is a white light source composed of the full spectrum of visible light. We can see the spectrum of colours in a rainbow because sunlight refracting through raindrops separates daylight into different wavelengths that the eye perceives as different colours. The Sun emits radiation in the infrared, visible and ultraviolet regions of the electromagnetic spectrum, peaking in the visible region. Daylight is a dynamic light source that varies depending on location, time of day, season and with various weather and atmospheric pollution conditions.[2] Throughout the day ultraviolet radiation and visible light increase in intensity before peaking in early afternoon. These intensities drop significantly by late afternoon (Figure 2).

Blue and violet light are at the shorter wavelength (higher energy) end of the visible spectrum. This blue light component of sunlight gives the sky its blue appearance[3] because it scatters more readily in the atmosphere than most other visible light.* The blue light region of the visible spectrum extends from approximately 424 to 500 nm,[4] although the exact range differs between reference documents.

This paper refers to blue light as a generic term meaning the blue wavelength portion of the light spectrum. Blue light can refer to either saturated blue lights, which emit a monochromatic blue colour, or blue-enriched broad spectrum white light that contains blue wavelengths as part of its light spectrum. This paper focuses on blue wavelengths due to recent concerns about the associated effects on our health and the environment from increasing exposure to artificial light sources emitting blue-enriched white light at night.

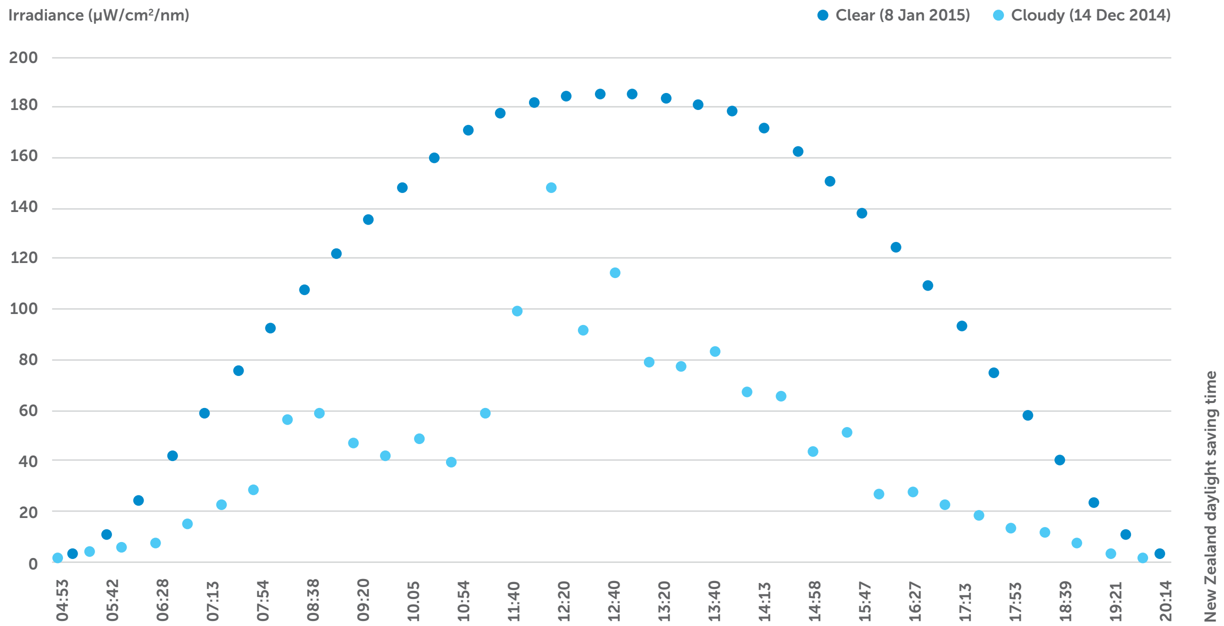


FIGURE 2

Intensity of blue light (480 nm) at the Earth’s surface, measurements taken from Lauder, Central Otago on cloudy and clear summer days. Daylight time is approximately the same for both days due to a similar time interval before and after the summer solstice (22 December). The cloudy day was overcast except for a few times between 12:00 and 13:00 where some direct sunlight was observed. Data provided by the National Institute of Water & Atmospheric Research (NIWA). For detail on solar UV and visible light spectra in New Zealand see **niwa.co.nz/our-services/instruments/instruments/lauder/uvspec**.

* Blue light scatters less than violet; however, more blue light passes through our atmosphere and our eyes are more sensitive to blue than violet.[2]

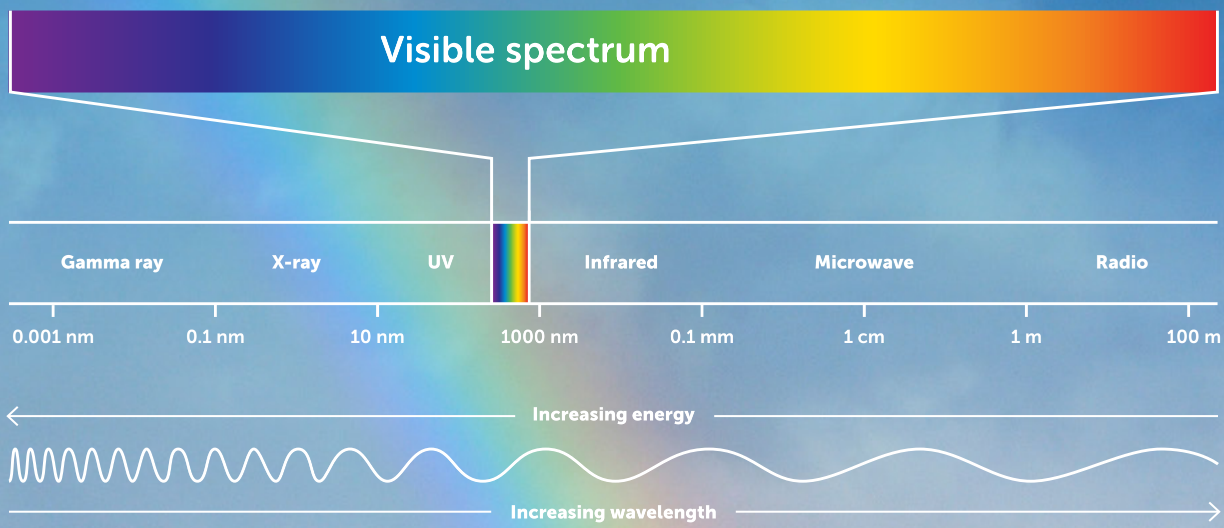


FIGURE 1

Visible light is part of the electromagnetic spectrum. Blue wavelengths are at the shorter (higher energy) end of the visible spectrum.

TŪĀWHIORANGI KITEA

Artificial sources containing blue light

Artificial light sources are widely used in our everyday lives. Broad-spectrum light sources are those that span the visible spectrum producing a resulting white light rather than a coloured light produced from a narrow range of wavelengths. Advanced broad-spectrum lighting technologies have a wide range of applications in lighting systems and digital displays. The reach of these technologies is evident in household lighting, computer and phone screens, televisions, security, architectural and street lighting.

Different broad-spectrum white light sources vary in their colour appearance, generally perceived as ranging from warmer red-yellowish-white light to cooler/brighter blueish-white light.[5] As a rough indicative measure, the lighting industry uses correlated colour temperature (CCT), measured in kelvin,* to describe the perceived colour of a broad-spectrum light source (Figure 3). Low CCT generally, but not always, corresponds to a relatively low proportion of blue wavelengths in the visible spectrum. As CCT increases, the appearance becomes a cooler blueish-white colour. Incandescent lamps, which also include halogens, produce a warm light, weighted towards the yellow/red end of the visible spectrum. More energy efficient technologies than incandescent lamps, including compact fluorescent lamps (CFLs) and light emitting diodes (LEDs), are available in a range of warm or cool coloured lighting.

A more informative gauge of lighting is to measure the spectrum of light emitted; this is known as Spectral Power Distribution (SPD). These spectra can differ significantly between various lighting technologies such as incandescent, high-intensity discharge lamps, CFLs and LEDs (Figure 4). Researchers can use these spectra to calculate the proportion of blue wavelengths across the visible spectrum. Higher correlated colour temperatures often, but not always, correlate with a higher proportion of blue light (Figure 4 and Table 1). At a given CCT, even within a given light source technology, the proportion of blue wavelengths, and the shape and position of peaks in the visible spectrum can be quite variable.[4]

FIGURE 3

The correlated colour temperature scale. Some light sources come in a range of correlated colour temperatures from the warm-white of traditional incandescent bulbs to the cool/bright-white light of some CFLs and LEDs. Source: Adapted from **lightingschool.eu/portfolio/understanding-the-light**.[5]

* The kelvin scale (K) used to describe the colour of a light source is equivalent to the temperature required to heat an ideal blackbody radiator to give the particular hue of light.

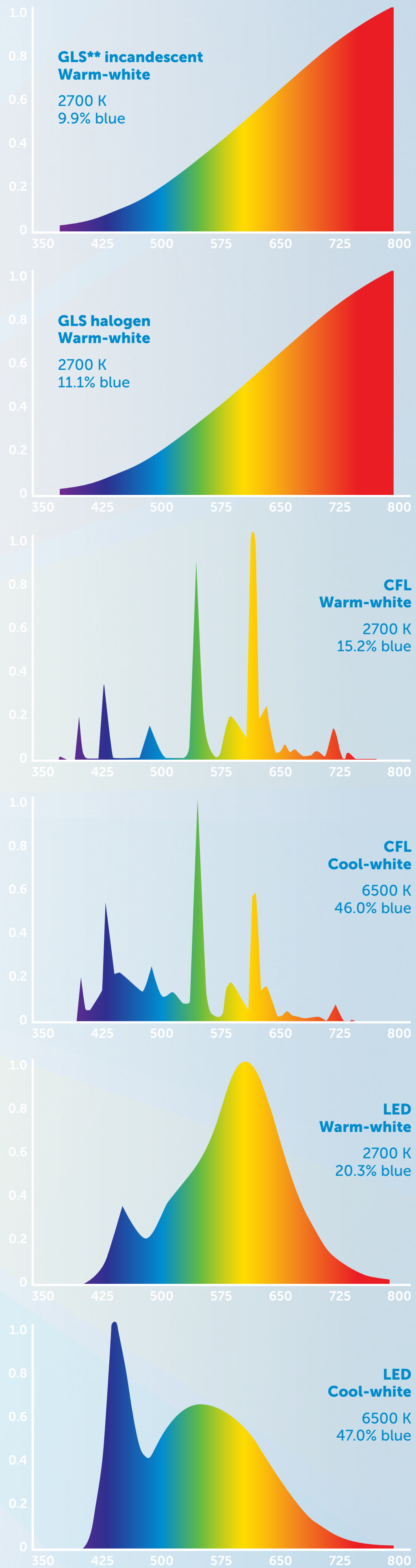


FIGURE 4

Spectra from a few domestic lamps available in the New Zealand market.* The x-axis is wavelength (nm). The y-axis is relative intensity, where 1.0 represents the highest peak in the spectrum. Spectra provided by the School of Engineering and Advanced Technology, Massey University.[6]

* The percentage of blue content is determined using the formula provided by the Lamp Spectral Power Distribution Database,[7] which uses a very broad definition of blue light ranging from violet (405 nm) to green (530 nm). The calculation for blue light uses 380 to 780 nm as the visible light range to make these calculations consistent with those provided by the United States Department of Energy.[4, 8]

** GLS: General Lighting Service – standard bulb shape.

Light source	CCT (K)	% Blue*
Narrowband Amber LED	1606	0%
Low-Pressure Sodium	1718	0%
PC Amber LED†	1872	1%
High-Pressure Sodium	2041	10%
PC White LED† (2700 K)	2700	15% – 21%
PC White LED† (3000 K)	3000	18% – 25%
PC White LED† (4000 K)	4000	26% – 33%
Metal Halide	4002	33%
Mercury Vapour	6924	36%
PC White LED† (5000 K)	5000	35% – 40%

TABLE 1: Blue light in a selection of outdoor lighting sources at equivalent lumen output (luminous flux 1000 lm)** [8]

At home, people may be exposed to blue light through domestic lighting, and through the use of light-emitting screens, including computers, televisions, smartphones, tablets and light emitting eReaders.[9] Residential lighting has changed dramatically over the past century from traditional incandescent to modern LEDs.[9] The main sources of residential lighting in New Zealand are CFL, incandescent, halogen and LED lighting.[10] Light emitting diodes are predicted to make up over 70% of the global residential lighting market by 2020.[11] Display technologies are also found in many aspects of modern life in the form of computer monitors, data projectors, smartphones, tablets and televisions.[12] A substantial amount of our time is spent using smartphones, which often peaks during the day, but for some users this peaks at night.[13]

The use of digital display technologies throughout the day and into the night can expose us to relatively high amounts of blue light outside normal daylight hours.[9]

Streetlights are another potential source of blue light exposure. In New Zealand, and worldwide, many streetlights are being switched to LEDs because they are energy efficient to run, long lasting, allow good colour rendition*** and give precise optical and electronic optimisation of light delivery. White LED streetlights have a higher proportion of blue wavelengths than the yellow-orange high-pressure sodium streetlights that were New Zealand's dominant streetlight in 2014.[14] By the mid-2020s the percentage of LED streetlights in New Zealand is expected to pass 60%.[15]

* The percentages of blue light are provided by the United States Department of Energy, using 405 nm to 530 nm for blue light, and 380 to 780 nm as for the visible spectrum.[4, 8] This definition is the same as the Lamp Spectral Power Distribution Database.[7] It is a broad definition of blue light ranging from violet (405 nm) to green (530 nm), which have been selected to cover the region most strongly influencing the disruption of the circadian rhythm in human health.

** Adapted from the **United States Department of Energy website**.[8]

*** Colour rendition describes how accurately a given light source reveals the colour of objects compared with an ideal light source such as the colours observed for the same objects in daylight.

† PC White LED or PC Amber LED are phosphor-converted white or amber light emitting diodes respectively. Phosphor-converted white LEDs are the most common method for forming white LEDs. In this process, a yellow phosphor coats a blue LED to convert some of the short blue wavelengths into longer wavelengths; these combine with the blue wavelengths to give a white light.

TE HAUORA

Human health and blue light

Light detection in the eye

The eye detects light and sends information about the environment to the brain through both visual and non-visual processes.[16] Rods and cones are specialised cells in the eye that contribute to image formation. Humans detect colours with three different types of cells – S, M and L cones. These cones have maximum sensitivities in the blue (S cones), green (M cones) and red (L cones) regions of the colour spectrum, (Figure 5) corresponding to peak maxima of approximately 420 nm, 530 nm and 560 nm respectively.[16] Black and white, or monochromatic, vision is undertaken using another type of cell, rods, which can detect light between about 400 and 600 nm (Figure 5).

For more than a century, rods and cones were thought to be the eye's only light detectors. However, in 2002, another cell type, called 'Intrinsically Photosensitive Retinal Ganglion Cells' (ipRGCs), was identified.[18, 19] These cells drive non-image forming responses to light including aligning when we feel sleepy or alert with the time of day, and controlling pupil constriction.[18, 20] These cells directly respond to light via a blue light sensitive chemical called melanopsin, which has a peak sensitivity of around 480 nm (Figure 5).[20, 21] These cells also receive information from other wavelengths indirectly through interconnections with rods and cones.[16, 22, 23] Rather than forming and tracking images, ipRGCs directly signal the hypothalamus, affecting processes including circadian rhythms and neuroendocrine regulation (the interaction between the nervous system and the hormones of the endocrine glands). The variety of biological functions that ipRGCs are known to modulate has expanded steadily since their discovery in 2002.[22]

As people age, their eyes will transmit less light to the back of the retina because of the yellowing of the eye's lens.[1, 24, 25] The eye becomes less responsive to all wavelengths of light with age, with shorter wavelengths in the blue and violet regions of the visible spectrum more prominently affected.[25, 26]

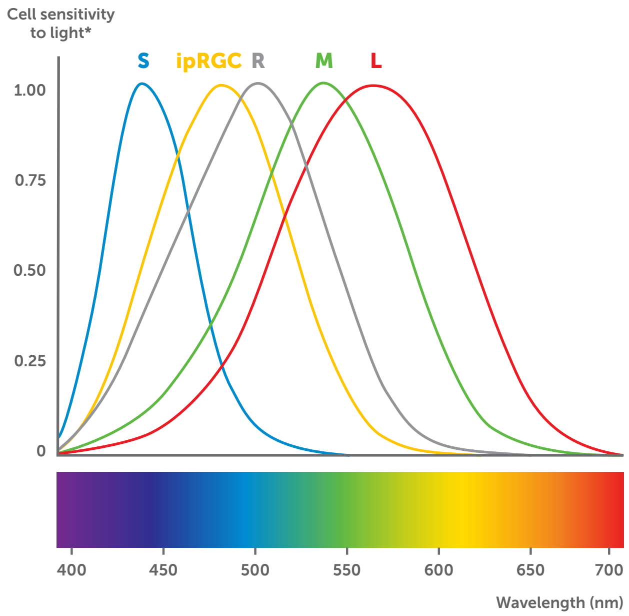


FIGURE 5

Spectral sensitivities to light by photoreceptor cells in the human eye.

	Cell type	Peak maximum
S	Short cones	~420 nm
ipRGC	Intrinsically Photosensitive (light detecting) Retinal Ganglion Cells	~480 nm
R	Rods	~500 nm
M	Medium cones	~530 nm
L	Long cones	~560 nm

Figure adapted from Cao and Barrionuevo, 2015.[17]

* The y-axis is relative to the peak maximum (adjusted to 1) for each cell type, not absolute values.

Effects of blue light on circadian rhythm

Humans use environmental cues from light to synchronise the body's internal daily rhythms to the external day/night cycle.[2, 27] How light affects the human body depends on timing and duration of exposure to light, the brightness, as well as its spectral content.[28, 29] The master circadian clock, a pacemaker in the hypothalamus region of the brain, synchronises daily rhythms at the organ and cellular level. It influences vital processes including metabolism, immune function, sleep, and many aspects of behaviour and mood.[22, 30, 31] The circadian clock mechanism involves a core group of genes that regulate a protein production loop controlling cell metabolism in cycles ('circadian rhythms') of about 24 hours.[29, 32-34] The circadian clock receives light information exclusively from ipRGCs in the eye.[22, 35, 36] These cells are predominantly influenced by blue light at high intensities,[37, 38] although they also receive information from other wavelengths via interconnections with cones and rods.[16, 22, 23]

Exposure to light, particularly blue wavelengths, at an inappropriate circadian phase leads to circadian disruption and related health and behavioural consequences. Our increasingly 24/7 lifestyle alters our patterns of exposure to blue light and directly challenges our circadian drive for sleep at night. Exposure to blue wavelengths in the evening, including from domestic lighting and light emitting screens, delays the circadian clock. This interference makes it harder to fall asleep at night, to wake up in the morning, and impedes attention abilities the next morning.[39-42] Shift work also results in people sleeping and working at sub-optimal times of the day, leading to poorer sleep[43] and health,[43, 44] reduced productivity, and increased risk of errors and accidents.[45-47] In contrast, people experience jetlag as the circadian clock adjusts to the solar cycle of a new time zone and, given enough time, it will adapt completely.[48] Social jetlag, the difference between weekend and weekday sleep patterns, can also lead to circadian misalignment with the solar cycle because the body is receiving inconsistent exposure to daylight and light at night.[49, 50]

Reinforcing circadian rhythms with blue-enriched white light at the right time in the circadian cycle can improve alertness, performance, mood and sleep quality.[51] Natural exposure to blue light from the sky during the day is much greater than that received at night from many artificial sources.[52, 53] Exposure to blue light from the sky is greatest around midday.[9] Exposure to blue light in the morning advances the circadian clock, so may help people who want to move their sleep to an earlier time. Outdoor activities, including camping under natural light conditions, can increase exposure to high intensity light during the day and re-calibrate the circadian rhythm.[52] Exposure to bright daylight may also reduce the sensitivity of the circadian system to light exposure at night compared to those experiencing dim daytime light with minimal outdoor light contact.[54] As mentioned above, as people grow older less blue light is transmitted to the retina and this lower level of transmission during the day is thought to negatively affect sleep for some elderly people.[24]

Our increasingly 24/7 lifestyle alters our patterns of exposure to blue light and directly challenges our circadian drive for sleep at night.

Clinically administered exposure to light therapy with carefully selected intensity, wavelength and exposure of light can treat some conditions associated with sleep and behaviour. Repeated flashes of saturated blue light (480 nm) during the circadian night, even delivered through closed eyelids, has been shown to shift the human circadian clock.[55] Professionally administered bright light therapy is used to treat some mood disorders (see the section Behaviour on page 13). Preliminary evidence in honeybees, used as a model for anaesthesia in humans, shows that administering bright white light (fluorescent source, 10 000 Lux) alongside the general anaesthetic isoflurane can counteract the circadian shift caused by the anaesthetic.[56, 57]

Preliminary evidence suggests that high levels of light exposure at night, particularly when enriched in blue wavelengths, may contribute to the development of some cancers and other health problems.[58-66] Possible mechanisms proposed include sleep and circadian disruption via melatonin suppression or disruption of the immune system.[66] White light sources that are enriched in blue wavelengths, particularly around 460 nm, are more potent at suppressing normal night-time production of the hormone melatonin, which is also regulated by the circadian body clock.[38, 67] Mice prone to developing breast cancer have an increased risk of forming tumours under repeated light/dark cycle changes simulating shift work.[68] In humans, there is research supporting the impact that the disruption of normal circadian rhythms has on mood disorders, such as depression, as well as cognitive dysfunction,[59] increased risk of obesity[58] and some types of cancer.[60-62, 65] Preliminary evidence provides a possible association of blue-enriched, white outdoor lighting with breast cancer and prostate cancer.[69] However, although blue wavelength light potentially contributes to health problems associated with circadian disruption, research has not conclusively demonstrated that blue wavelength light exposure at night causes an increase in these health risks.[63, 64, 70] More research is required into potential mechanisms that light at night might contribute to certain cancer risks, such as disrupting circadian clock genes or by directly suppressing melatonin synthesis.[66] Further research is also needed to investigate potential long-term health effects caused by the increasing use of blue light enriched sources in many aspects of our daily lives.[9]

Other health effects of blue light

Behaviour

Regions of the brain involved in attention, alertness, and emotional processes can be stimulated by exposure of the eyes' ipRGCs to blue light (470–480 nm).[59, 71-73] This effect is even present in some visually blind individuals.[74] Professionally administered light therapy has been found to be an effective treatment for mood disorders, such as seasonal affective disorder.[75, 76] and other major depressive disorders.[76, 77] Bright light therapy containing blue wavelength light is more effective than other wavelengths for treating some sleep and mood disorders, including seasonal affective disorder.[59, 78, 79] Increasing exposure to blue light from natural daylight may also enhance patient recovery for some depressive disorders. Preliminary evidence suggests patients with depressive disorders who are exposed to more daylight in the morning, in addition to the conventional treatment by their psychiatrist, may require, on average, shorter stays in hospital.[80] Similar research found that the length of hospital stays decreased for bipolar patients, but not unipolar depressed patients, in rooms receiving direct sunlight in the morning.[81]

Road safety

Street lighting aims to reduce accident rates by improving visibility at night[82] and can be an effective road safety measure.[82-84] Advances in lighting technologies have also enhanced the ability to tune the spectrum of LED streetlights and to dynamically adapt light levels compared with older, high pressure sodium or mercury vapour lighting technologies.[85]

The use of white light at night, at low illumination levels, may improve visibility and safety. Streetlights with blue-enriched white light, including metal halide lights and some LEDs, may improve some aspects of peripheral vision,[86-89] which is important in lower-speed residential roads that have low illuminance lighting levels. On highways and other higher speed roads the visual benefits of white light are less apparent.[86] Reaction times are faster at low light intensities of white light than at low intensities of yellower high-pressure sodium streetlamps.[86, 88] While headlights with a higher proportion of blue wavelengths can improve visibility, they also can increase disability glare[*] when viewed directly.[90] Studies in the US have found that both drivers and pedestrians perceived better visibility, safety, security and colour rendering with whiter street lighting containing a higher proportion of blue light[**] than high-pressure sodium lamps.[87, 91]

Further research is required to demonstrate substantial road safety effects for selecting white LED street lighting over high pressure sodium.[85, 92] Street lighting is a complex issue, with safety, road use and driving behaviour, visibility and environmental impacts to consider when choosing lighting options. Factors other than colour temperature, such as lighting levels, uniformity, glare, waste light, energy consumption, reliability, maintainability and costs need to be considered.[93]

Eye damage

Even momentary exposure to high intensity light sources can result in severe and permanent damage to the retina, such as found in solar retinopathy, an injury commonly associated with gazing directly at the sun or a solar eclipse. Examples of high intensity blue light sources where this is an issue include arc welding or high-powered blue coloured lasers.[1, 24, 95] Recent animal studies provide evidence that filtering very high-intensity blue light partially protects photoreceptors from damage.[96] The blue light levels used to induce this damage are usually much higher than the human retina would experience under normal circumstances[97] and not applicable to artificial light sources for general purpose lighting.

Artificial light sources on the market must meet certain requirements including assessment for the potential hazard caused to the retina for sources that contain a significant portion of blue light wavelengths.[1, 98] The health risks from direct viewing of light sources enriched in blue wavelengths, as found in white LED sources, vary depending on the duration of exposure, strength of the light, and distance from the source. For example, under acute, direct viewing conditions of selected LEDs at 200 lumens, the cold-white LEDs (above 5000 K) fell into the moderate risk category (Risk Group 2).[1] Under the same conditions, the neutral-white (4000 K) and warm-white (3000 K) LEDs were classified as low risk or exempt, respectively.[1] Any lamps that are classified as moderate risk (Risk Group 2) must be labelled with a warning not to stare at the lamp during operation because it may be harmful to the retina.[98] Light emitted from typical settings on computer and mobile device screens has been shown to be well below the threshold luminance to cause retinal damage, such as that seen in macular degeneration.[53] There is some concern about the effect of blue light on young children, since their retina receives relatively more blue wavelength light than adults.[1, 97] Further research is required to establish whether long-term, low-level exposure to artificial light enriched in blue wavelengths is a risk factor for macular degeneration.[1, 24, 97]

* Loss of visibility of an object due to stray light scatter within the eye.

** The New Zealand Transport Agency prefers 4000 K LED streetlights, in accordance with the current road lighting standards.[93] Consideration is given for warmer lighting in special circumstances including around Dark Skies reserves or areas of high pedestrian use where additional measures have been taken to mitigate accidents between vehicles and pedestrians.[94]

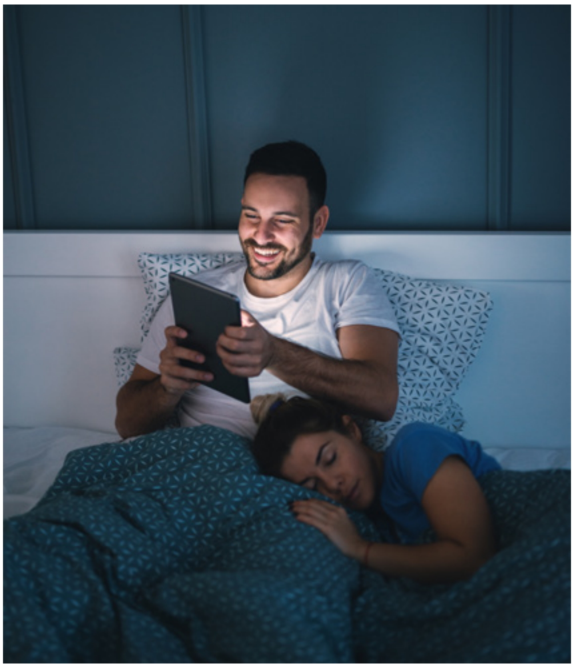
Mitigating the harmful health effects of blue light at night

Humans have evolved to use daylight and darkness to regulate circadian rhythms, which is important for our health and wellbeing.[2, 27] Increasing exposure to natural daylight, particularly in the morning, can help synchronise the body clock with the solar day.[52, 54] Limiting the amount of light at night is also important for circadian health.

Advances in lighting technology have provided possible ways of reducing adverse lighting effects and enhancing other desired effects. Compared with earlier lighting technologies, LEDs provide precise optical control and more opportunity to change and tune their spectral distribution, allowing lighting designers to reduce obtrusive effects from light scattering into unintended areas.[85] Consumers can make some decisions about the brightness and blue light specifications in their personal use, including smartphones, laptops, televisions, and household lighting. In contrast, local governing bodies are responsible for decisions relating to broader community and local environment, including street lighting.

Light limiting technologies are also available that reduce exposure to blue light and its potentially adverse effects in the evening. These technologies, designed to block blue light from suppressing melatonin, include blue light blocking glasses[99-103] or applications to lower blue light spectral content and backlight intensities (brightness) of digital screens at night.[100, 104] While these technologies may reduce the blue light effects on circadian health, there is currently a lack of high quality evidence regarding the overall benefits of installing filters or using blue light blocking glasses with regard to long-term macular health.[105]

Other steps to mitigate the harmful effects of blue light at night include using light bulbs with warmer hues and using dimmers to reduce the intensity of exposure to light at night. In addition to using the light limiting technologies above, limiting the amount of screen time on electronic devices at night and reading from a book or from a non-light emitting eReader instead of a device with a backlit digital screen can also reduce exposure.[41] Darkness is beneficial for sleep; rooms can become darker by blocking light from outside with curtains, and turning off lights.



ACTIONS WE CAN TAKE TO

Reduce harmful effects of blue light on our health

1. Be exposed to daylight in the morning and darkness at night for better circadian health and wellbeing.
2. Limit blue light exposure from digital screens including smartphones, televisions and computers at night by reducing screen brightness, using night-time apps that lower blue light output or turning devices off.
3. Replace cooler/brighter blueish-white lightbulbs with warmer coloured yellowish-white lightbulbs.

TE TAIAO

Blue light and the environment

The role of blue light in nature

Plants, animals and many microorganisms have adapted to use and respond to light. The ability to sense blue light (400–500 nm) is widespread throughout the plant and animal kingdoms. This ability works through specialised light-sensitive structures including cryptochromes, blue/UV-A photoreceptors,[106, 107] and short-wavelength sensitive cone cells in the eye.[108] Response to light depends on many factors including timing, duration, intensity, spectral content and spatial distribution.[109-111] Different spectral colours of light have been shown to have a range of effects on plants and animals.[112] Light-associated biological processes, including photosynthesis, vision and circadian rhythms, have evolved to respond more to some wavelengths over others.[113]

Potential effects of artificial blue light on the ecosystem

Circadian regulation

Like humans, plants and animals possess a circadian clock that regulates aspects of their activity and physiology on a cycle that usually approximates 24 hours.[110, 114] Light is generally the most important time cue to synchronise circadian rhythms to the day/night cycle. Exposure at night may disrupt melatonin production in many animals including fish, birds and mammals.[110] Chronic circadian clock disruption caused by experiments inducing jetlag has been shown to accelerate malignant cancer grown in mice;[115-117] and to suppress immune responses in Siberian hamsters,[118] rats,[119] chickens[120] and Japanese quail.[121]

Blue light has been shown to play a role in regulating circadian clocks in plants and animals.[106, 107, 122] For example blue/green light disruption of the light/dark cycle has been shown to reduce both male caterpillar and pupal mass, and reduce the duration of pupation in both sexes in the European cabbage moth.[123]

Plants

Cryptochromes, photoreceptors for blue light and UV-A radiation, play an important role in how plants react to light.[107] Blue (400–500 nm) and red (650–700 nm) light are the primary wavelengths that activate chlorophyll, the main light absorbing pigment in plants.[124] The blue light photoreceptor, phototropin, controls plant behaviours such as growing towards a light source.[111] Blue light has been shown to affect plant greening,[125, 126] budburst,[127] photoperiodic flowering,[128] stomatal opening,[129, 130] the inhibition of warm temperature-induced growth,[131] circadian activity,[132] and root development,[133] and is indicated in the inhibition of spore germination in ferns.[134] Red light also plays a role in controlling flowering and shoot elongation in plants.[135, 136]

Blue light has been shown to play a role in regulating circadian clocks in plants and animals.

Blue light also has the potential to influence plant-animal interactions. For example, blue/green light has been shown to reduce activity and mating in the European winter moth (*Operophtera brumata*).[137] These moths typically show strong synchrony in egg hatching with spring budburst in host trees such as oak.[138] Disruption of seasonal light cues by artificial light, population level changes or aggregation of individuals could modify interactions including herbivory, seed dispersal and pollination.[111, 139]

Animals

Animals have adapted to perceive wavelengths of light in different areas of the electromagnetic spectrum,[112] some at much lower light intensities than humans can see. Artificial light can sometimes enhance or detract from an animal's vision, changing behaviour such as foraging, navigation and reproductive behaviour.[113] At an ecosystems level, light can also change how species interact, for example by altering competitive advantage under different light conditions at night. Different wavelengths can also trigger responses in some species but not in others, for example ultraviolet radiation, violet and blue light are particularly attractive to bees and some other insects.[140, 141]

While much is known about the negative effects of artificial light at night on animal physiology and behaviour, few studies have looked at the emerging issue of blue light wavelengths from streetlights on animals.[142] A New Zealand study showed that flying insects were more attracted to white LED (48% more trapped) than to traditional high-pressure sodium streetlights.[143] These white LEDs contain a higher proportion of blue light than the predominantly orange light from high-pressure sodium lamps. The attraction to light was dependent on the type of insect, with strong effects observed for Lepidoptera* and Diptera**, whereas other dominant taxa showed no significant increase seen from the dark control.

* Lepidoptera is the order that contains moths and butterflies.
** Diptera is the order that contains true flies.

Even warmer coloured LED lights (2700 and 3000 K) affected these insects. There was no significant difference observed for the number of insects trapped as colour temperature increased from 2700 K to 6500 K LED lights.[143] In Germany, white mercury lamps were shown to attract more than twice the number of insects as high-pressure sodium streetlights.[144] This increase is probably associated with both the blue light and UV wavelengths of the mercury lamps. LED streetlights do not radiate UV.

Blue/green outdoor lighting has been shown to affect the foraging of various European bat species, increasing the activity of some, and reducing it in others.[145, 146] Blue/green light has been shown to help birds align in direction during migration, while red light has been shown to disrupt this orientation,[147, 148] with the potential to increase the risk of birds striking communication towers.[149] Leatherback turtles are more sensitive to shorter wavelengths than other colours, moving towards blue or white light even on moonlit nights.[150] Most frogs also exhibit a blue light preference, and move towards blue light,[151] whereas migrating toads avoid areas of road illuminated with white or green light.[152]

Bioluminescence signals are used in sexual communication by marine species and fireflies, and operate at the 470 nm blue wavelength.[153] Artificial lighting with this spectrum could disrupt mating behaviour in these species.[154]

Mitigating the harmful ecological effects of artificial blue light

A review of the impact of artificial light at night proposed several management strategies to reduce the harmful effects on ecosystems.[109] These strategies include avoiding use altogether, reducing the duration of use, limiting light scattering directed into unintended areas, dimming light intensities and altering the spectral composition through light source selection and filters.[109] However, the effectiveness of many of these strategies to reduce the biological effects of blue light has not been extensively studied.[155] A study in the UK investigated how light intensity, use of timers, and changing the spectral composition affected spiders and beetles in grassland communities. The combination of lower intensity light and turning off the lights between midnight and 4 am had the most potential, but did not completely mitigate the environmental impacts.[155] Further research, with expertise from both ecologists and lighting engineers, is needed to develop lighting that is fit for purpose and which minimises harm to the ecosystem.[143] Some of this research is already underway as part of the Australian Federal Government project on developing 'Light Pollution Guidelines for Marine Turtles, Seabirds and Migratory Shorebirds'.[156]

ACTIONS WE CAN TAKE TO

Reduce harmful effects of blue light on plants and wildlife

1. Be aware that plants and animals are also sensitive to light; some are strongly affected by blue wavelengths whereas others may be more strongly affected by other colours.
2. Use outdoor lighting only when and where needed and ensure light does not spill into unintended areas.
3. Change the colour of outdoor light by filtering or by changing the light source if it will benefit species in your area.

Artificial blue light and the night sky

Artificial sky brightness

Enhancement of sky brightness due to artificial lighting is known as artificial sky glow.[157] Even some locations with pristine dark skies above them can experience significant artificial sky glow at the horizon.[158, 159] The majority of light pollution comes from road-associated lighting including street lighting, vehicle lights, and roadside advertisements.[160] Design standards in New Zealand and Australia set significantly lower road lighting levels than Europe and the USA.[92, 93] A snapshot of artificial sky glow on a cloudless* night in Wellington suggested that artificial sky glow varies during the night as various light sources are turned off.[161] In the late evening, 28% of sky glow could be attributed to variable sources including domestic, commercial and vehicle lighting, and by early morning this contribution had reduced to around 4%. Static sources accounted for the majority of sky glow. The relative contributions of discrete static sources including street lighting, industrial lighting (port and rail), architectural and security lighting, were not quantified.[161]

When observing the night sky, the brightness of artificial sky glow is strongly affected by the spectral distribution of the light sources causing it, and by air clarity and cloud cover.[157, 159, 162] While any light contributes to this issue, blue light easily scatters, which increases light pollution.[163] When the sky is clear, blue-rich white LED and metal halide sources produce up to 3x brighter visual sky brightness than high-pressure sodium lamps, owing to the stronger scattering of blue light in the atmosphere.[162] However, cloudy conditions can substantially increase the relative back-scattering of all wavelengths of light, particularly at the red end of the spectrum.[164] There has been a global movement to replace traditional yellow–orange sodium streetlights (both low and high-pressure) with more energy-efficient LED streetlights. Historically, New Zealand, like many other countries, installed predominantly high-pressure sodium lamps[165] but many are now being replaced with LED streetlights.[15] In comparison with high-pressure sodium lights, 4000 K LED streetlights could cause a 2.5x increase in sky brightness, if other aspects of the lamp design are not improved with the retrofit.[158] In New Zealand, to reduce the impact on sky brightness, design standards restrict the amount of upwards light[93] and guidelines recommend only streetlights with less than 1% direct upward waste light emissions are installed.[166]

Astronomical observations

Any increase in sky brightness has implications for optical astronomical observations as dark skies are required to detect the faint light from objects in outer space.[163] Blue light is of particular concern as it scatters more readily, exacerbating loss of night sky visibility.[162, 163] Māori use of astronomy is also fundamental to many traditional practices including agriculture, architecture and navigation and is entwined in many aspects of Māori culture and beliefs.[167] In New Zealand, 53% of the country is estimated to experience a pristine night sky (See figure 6 on page 20), but only 3% of New Zealand's population is predicted to live under this pristine dark sky.[158] It is estimated that 56% of New Zealand's population lives under a sky where, due to light pollution, the Milky Way is no longer clearly visible.[158]

Light pollution makes ground-based optical astronomical observations more difficult to perform, particularly when the spectral interference from the light pollution overlaps with wavelengths for spectra investigated in astronomy.[168] For example, the blue wavelengths observed in optical astronomy are often characteristic in emerging new stars and galaxies.[163] Blue wavelengths found in some white streetlamps can interfere with these astronomical observations.[163] The wavelength of light used to identify a form of oxygen found in interstellar dust clouds (436.3 nm) is nearly identical to the wavelength of light from fluorescent (low-pressure mercury vapour) streetlamps (435.8 nm).[168] Low-pressure sodium lights produce nearly monochromatic yellow light (589 nm) which is easy to filter out by astronomers.[169] Fluorescent and low-pressure sodium streetlamps are now outdated technology; however, the blue wavelengths of modern, broad-spectrum, white LEDs also cause issues for optical astronomy.[163] Narrow-spectrum amber LEDs may be more suitable than white LEDs around observatories.[163]

* A thin layer of high cloud was detected after 1 am, this was taken into account in the study.[161]

Any increase in sky brightness has implications for optical astronomical observations as dark skies are required to detect the faint lights from objects in outer space.

Photo credit: Mark Gee

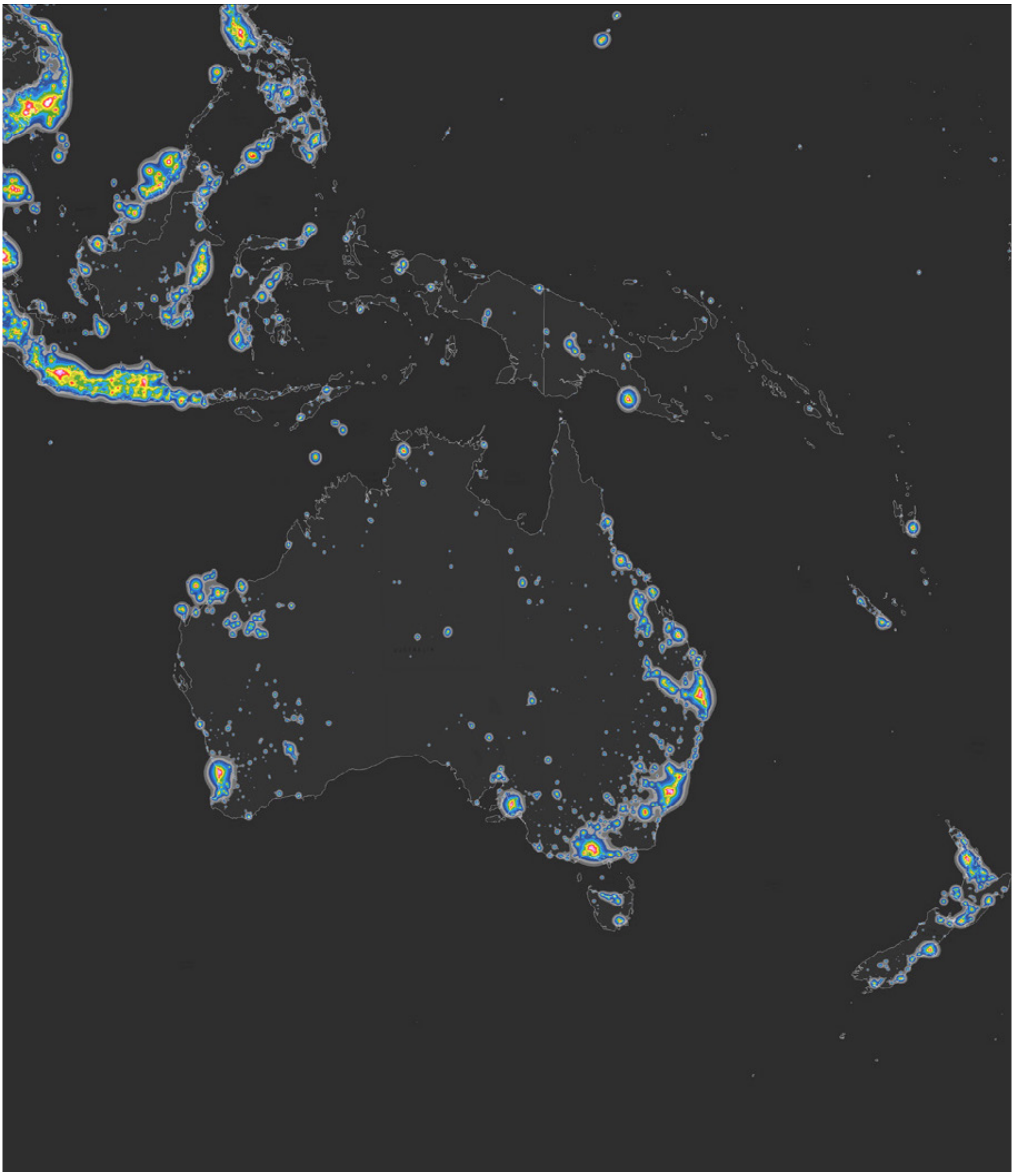


FIGURE 6

Estimated artificial sky brightness for Australia, Indonesia, and New Zealand when viewing the night sky at the zenith (directly above).[158] The colours notate the lighting levels compared to natural background light. Black and grey regions have very low levels of artificial light (<2% natural background). The blue coloured regions (above 8% natural background) are considered polluted from an astronomical perspective. Yellow regions (128–256% natural background) are the level at which the Milky Way can no longer be observed in winter. Red through white (above 512% natural background) are regions that never experience true night as the light levels are at least as bright as natural twilight. The satellite data for mapping the artificial sky brightness in these images were collected over six months in 2014.[158]

Mitigating the impact of artificial blue light on the night sky

The International Astronomical Union[163] and the International Dark-Sky Association[170] suggest measures for effectively reducing light pollution. These recommendations include only lighting areas when and where required, reducing the use of light with dimmers, timers and motion sensors, and avoiding over-lighting.[163, 170] Recommendations also include selecting fully-shielded fixtures that do not emit light upwards, and selecting lamps with lower blue emissions, such as those with a CCT of 3000 K or less.[163, 170] LED technology gives much finer control over tuning and adapting light levels that was not available with previous technology.[85] Smart controls can be installed which can assist in reducing wasteful and unnecessary lamp operation during off-peak traffic periods.[92]

The International Dark-Sky Association certifies communities, parks, reserves and sanctuaries around the world which meet international specifications for their Dark Sky Places Program.[171] The Aoraki Mackenzie International Dark Sky Reserve was designated New Zealand's first International Dark Sky Reserve in 2012. Great Barrier Island received certification as an International Dark Sky Sanctuary in 2017. There is a current proposal underway for Martinborough to become a Dark Sky Reserve.[172] Stewart Island, Waiheke Island and Naseby are also working towards accreditation as Dark Sky Places.[173-176] Martinborough and Naseby are the first two places in New Zealand to be recognised by the International Dark-Sky Association for providing 3000 K street lighting.[177]

ACTIONS WE CAN TAKE TO

Reduce harmful effects of blue light on the night sky

1. Be aware that light pollution reduces our ability to see features in the night sky.
2. Reduce light pollution by using outdoor lighting only when and where needed; ensure light does not spill upwards or into unintended areas; and select amber or warm white sources over those with higher blue emissions.
3. Modify the lighting of communities, parks, reserves and sanctuaries so that they meet international standards for good outdoor lighting practice set out in the Dark Sky Places Program.

Research gaps

Further peer-reviewed research on the impact of artificial blue light exposure, and how rapidly advancing lighting technologies may mitigate any negative effects of exposure, is required. Examples include:

- Investigating long-term health-related impacts of exposure, including for shift workers;[63, 64, 70, 97]
- The changing effects of blue light on circadian rhythms and eye health across different life stages;[1, 9, 24, 26, 97]
- The impact of long-term, low-level retinal exposure to blue wavelengths from common white light sources;[1, 9, 24, 97]
- The impact of exposure from outdoor lighting on ecosystems, including flora and fauna unique to Aotearoa New Zealand;[110, 111, 113, 143, 178, 179]
- How to best mitigate the health and environmental impacts of lighting while still maintaining demonstrable benefits from using artificial light at night.[64, 85, 92, 109, 110, 143, 158, 179]

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