**Light and Lighting**

 **Part 1: LIGHTING CAN BE A HEALTH RISK But Does Not**

**Reduce Crime Or Road Accidents**

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**Abstract**

Exposure to artificial light at night (ALAN) can affect the body’s melatonin cycle and the body clock that controls circadian rhythms including the sleep-wake cycle, especially when the light has a strong blue component. A review of the literature on the biological effects of ALAN indicates that present levels of ALAN can be harmful to humans and lower life forms.

Historically, people have tended to feel safer in the presence of ALAN and this led to the belief that they are safer. More recently, people felt safer after the introduction of road lighting, again leading to the belief that they are safer and the formulation of lighting standards to ensure the widespread provision of plenty of artificial light. Scientific testing of these beliefs has given mixed results with a trend appearing to favour the beliefs. However, large-scale reductions in lighting have clearly not increased crime or road accidents.

This report indicates that time-of-day and day-by-day variations in crime and road accidents are almost completely independent of the amount of ambient illumination, the exception being that the crime rate appears to reduce substantially as the dimmest conditions are approached. The evidence suggests instead that the variations are caused by social and physiological factors and that lighting effectiveness testing to date has often been marred by conflicts of interest and shortcomings in scientific method.

Lighting standards at present are thus largely based on false beliefs. In conjunction with ill-advised public officials and conflicts of interest, the standards have led to the current gross overprovision of ALAN. The situation is worsening with the displacement of existing blue-poor main road lighting by blue-rich white LED lighting and the promotion of blue-rich lighting in general. Present lighting standards should be withdrawn for extensive correction in accordance with current knowledge. Minimalist night lighting practices can be expected to improve health, wellbeing, personal safety, biodiversity, the environment and the national economy.

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**EXECUTIVE SUMMARY**

Life on Earth evolved in the presence of a daily cycle of light and dark. The neuro-hormone melatonin is present in nearly all living things, and varies in a daily cycle. In mammals, special blue-light receptors in the eye provide the signals for melatonin production at night and its cessation around dawn. Exposure to artificial light at night (ALAN) can affect the mammalian melatonin cycle and the body clock that controls circadian rhythms including the sleep-wake cycle, especially when the light has a strong blue component. A review of the scientific and medical journal literature indicates that present levels of ALAN can be harmful to humans and lower life forms. In humans, there are strong associations between exposure to ALAN and obesity, breast and prostate cancers, type 2 diabetes, heart disease, dementia and more, to the degree that 1200-strong delegate meetings of the American Medical Association have voted overwhelmingly for campaigns against excessive use of blue-rich ALAN.

This topic is raised in the ‘*Roadmap*’ document (IPWEA 2016) about future outdoor lighting prepared for the Australian Department of Energy and Environment. The *Roadmap* is singled out for mention because it has already been widely distributed to authorities responsible for outdoor lighting It promotes a view that the observed adverse biological effects of exposure to ALAN, especially of its blue component, on health, wellbeing and biodiversity are not well enough understood to warrant major changes to the lighting practices that apply in Australia, New Zealand and further afield. In the writer’s view, the lack of understanding lies not with the medical and biological researchers involved but with others who have potential conflicts of interest that may lead them to discount disquieting results of research relevant to present lighting practices.

The ramifications of bad lighting practice are unpleasant and extensive, if not alarming. For instance, it can be shown that almost all existing sports lighting installations have the capability with a single exposure of say two or three hours to trigger a proliferative state in known tiny and seemingly harmless quasi-static breast cancer tumours, quite apart from the contribution that such an exposure would make anyway to the adverse health outcomes of chronic exposure to all sources of artificial blue light at night. Spectators as well as sportspeople are at risk. The problem is greatest with the bright daylight-level lighting of major night-time sporting events and concerts. Given the current state of knowledge, it appears possible to estimate the proportion or number of attendees to a specific event at night who will be diagnosed with breast cancer within say the following twelve months as a direct consequence of exposure to the bioactive blue component of the lighting in use.

The health threats posed by present lighting practices are accompanied by other known or likely adverse effects of ALAN and/or its spectral components on biodiversity and the environment. The environmental effects include loss of night sky visibility which is of concern for unnecessary greenhouse gas emissions, and for losses in aesthetic appreciation, first peoples’ cultural heritage, amateur and professional astronomical observations, and public astronomy for STEM encouragement. Sleep disturbance, sleep duration and sleep quality all stand to be ameliorated or improved as a consequence of improved lighting practices, which may well include substantial reductions of luminous flux, intensity, duration, blue spectral components and unwanted light spill. Considerable economic benefits can be expected to follow from the substantial reductions necessary in the amount of artificial light in use.

Historically, people have tended to feel safer in the presence of ALAN and this led to the belief that they are actually safer, as may be true in the case of campfires as a means of keeping dangerous animals away. More recently, road users felt safer after the introduction of road lighting, again leading to the belief that they are safer. Lighting standards were accordingly formulated on the basis that there should be widespread provision of adequate amounts of ALAN to reduce crime and road accidents. Scientific testing of these beliefs has so far given mixed results but in both cases there has been a tendency for positive findings. However, recent large-scale implementation of lighting reductions has produced no change in crime or road casualties. Regardless, the *Roadmap* uncritically accepted the existing standards. Where it does make grudging acknowledgement of the medical and biological problems, smart lighting controls are seen as having sufficient potential to allow an adequate practical compromise. Instead, the situation should have been assessed as well past the stage at which the Precautionary Principle, already enshrined in Australian law,[[2]](#footnote-2) should have been applied.

This report provides clear evidence for the first time that time-of-day and day-by-day variations in crime and road accidents are almost completely independent of the amount of ambient illumination, the exception being that the crime rate appears to reduce substantially as the dimmest conditions are approached. The evidence also indicates that the variations are caused by social and possibly physiological factors and that lighting effectiveness testing to date has often been marred by conflicts of interest and shortcomings in scientific method.

Lighting standards at present are thus largely based on false beliefs. In conjunction with ill-advised public officials, commercial greed and conflicts of interest the standards have led to the current gross overprovision of ALAN. The situation is rapidly worsening with the displacement of existing blue-poor main road lighting by blue-rich white LED lighting and the promotion of blue-rich lighting in general, sometimes for reasons that have a demonstrable racist basis. Present lighting standards and any erroneous supporting documents such as the *Roadmap* should be withdrawn for extensive correction in accordance with facts rather than beliefs.

The lighting industry now needs to adopt a more rational balance between the great social and commercial benefits of ALAN on the one hand and on the other, the often nasty health, wellbeing and economic costs of ignoring a half-billion years of evolution. The minimalist night lighting practices that should then result can be expected to improve health, wellbeing, personal safety, biodiversity, the environment and the national economy. Failure of the industry to act responsibly and promptly on this matter should invite a legislative approach.

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# INTRODUCTION

The direct adverse effects of artificial light at night (ALAN) on health and wellbeing have become more plainly evident since the end of the twentieth century. What is not helping is the determination of large parts of the lighting industry to press ahead with the lucrative twentieth-century practice of promoting the installation of more and brighter lighting as a supposed way of reducing crime and road accidents, despite highly reliable evidence to the contrary and overwhelming evidence that ALAN, especially its blue light component, also has widespread and serious consequences for life on Earth in general.

Documentary evidence to back these claims amounts to many thousands of peer-reviewed journal papers. In the interests of readability and brevity only a small proportion of this literature is cited specifically here, but many more references can be supplied if necessary.

This document begins with sections relating to natural light levels, effects of ALAN on the environment, native peoples’ cultural heritage, ecology and biodiversity, human health and wellbeing, and safety and security. These sections are followed by a discussion and conclusions.

# NATURAL ILLUMINATION

Illumination is the process in which visible light falls onto a surface. The measure of this illumination is called the illuminance, often represented by E. The SI (metric) unit of illuminance is the lux. In the early days of measuring light (photometry), the standard light source was a carefully specified wax candle. For this reason, an illuminance of one lux is roughly equal to the illumination provided by an ordinary household candle at a flat surface directly facing the candle at a distance of one metre. Illuminance falls off with the square of distance from the light source, so the illuminance at three metres would be 1/9 or 0.111 lux or ~0.1 lux, which is usually the lowest illuminance detectable by ordinary light meters. At 1 lux, good vision will allow newspaper headlines to be read easily but the article text will generally be too difficult.

In the real world, illumination can come from one direction (eg the sun) or from a range of directions, as with light from the sky. It is therefore necessary to specify the plane in which illuminance is measured. The most common orientation used for outdoor lighting measures is horizontal. The total illuminance falling on a horizontal surface is called EH.

The variation of EH over the course of 24 hours is of basic importance. The writer derived a curve for a cloudless equinox day at latitude -37.8º (Melbourne) from a combination of observations and calculations: see Figure 1.

Compared with the variation in EH from the sun and sky during the day, the variation in EH during a moonless clear sky at night tends to be flatter between the end of astronomical twilight in the evening and the beginning of morning astronomical twilight. On the first night of photometric measurements the nearly full moon rose 90 minutes after sunset. It proved possible to separate the contributions of moon and moonless sky and then to calculate the EH values at night for three different conditions, viz, the darkest observed moonless clear sky, the moonless sky with moderate light pollution, and the moderately light polluted sky with the brightest possible full moon (0.267 lux at normal incidence according to Smith, Vingrys, Maddocks and Hely (1994) is used here, although Kyba, Mohar and Posch (2017) found that full moon in the tropics at lunar perigee can contribute as much as 0.36 lux to EH).

With the sun high in the sky, EH may be over 100 000 lux (100 kilolux). By sunset this is down to a few hundred lux. Natural starlight provides less than 0.001 lux (1 millilux).[[3]](#footnote-3) If the illuminance in lux is plotted against time, late twilight and night values would be indistinguishable from zero on the graph, but this is a key region in the present context. The solution is to make the scale logarithmic, such as having it in successive steps of 10. Thus, bright sunlight becomes 5 log10 units, late twilight 1 unit and natural starlight -3 units. An overcast can reduce the illuminance from sunlight, moonlight and starlight by about 1 log unit (eg NOAO 2018).

Another benefit of using a logarithmic scale is that the visual system tends to respond to visual stimuli as a logarithmic detector. Values in lux are additive in the photometric system but adding log 2 (= 0.301) to log EH gives log 2EH, twice the illuminance. Figure 1 illustrates how light pollution beyond the control of individuals can reduce the amplitude of the natural cyclic daily light exposure experienced outdoors.

Figure 1. Three possible forms of horizontal illuminance curve for an equinox day at a latitude of -37.8º (and practically also for +37.8º). The daytime parts of the curves are identical. In summer the midday peak will be a little higher and daytime will be longer than nighttime. In winter, the daytime peak will be a little lower and night will last longer than daytime. These differences would become more pronounced as distance from the equator increases. *However, illumination from the natural dark sky and from any level of artificial skyglow at night does not change appreciably with the seasons unless snow is on the ground.* Rarely will the contribution of the moon be at least as bright as is shown here and mostly the moon will not be visible all night. Most of the time its effect will be small to negligible but lunar light cycles can influence life stages in many species if the signal is not swamped by ALAN.

Key features of Figure 1 are the daytime peak of 5 log units, 2.4 log units at sunrise and sunset, and a natural minimum of -3.5 log units. The natural range following sunset can be as much as 5.9 log units, a factor of nearly a million. Modern lighting deprives us of much of this range. For instance, lighting of televised stage and sports events is typically at 3.2 log units (1500 lux) or more. Spectators are given about a third of that to limit the glare they would otherwise experience. These amounts are well into the daylight range. Even the sports training lights for juniors are around 2.2 log units (150 lux). Commercial lighting can be just as bright; for example 1300 lux on a city footpath as the spill from an outdoor advertising sign, and hundreds of lux in shopping malls. For street lighting, the overall range might start at 0.3 lux in environmentally sensitive areas to 20 lux or more for intersections. A public area may be in the 10 to 100 lux range. Workplace lighting can be as much as 20 kilolux when the most intricate manipulative tasks need to be done.

Skeldon, Phillips and Dijk (2017) showed the upper part of a graph like Figure 1 with an additional curve to represent typical modern light exposure. Its daytime peak (indoors) is at about 200 lux, and the curve then drops to about 60 lux in the evening before dropping steeply at bedtime. We thus tend to be deprived of a couple of log units of light in daytime and about twice as much dark at night.

Modern civilisation could not function effectively without artificial illumination, but present practice tends to come at great costs, as will be seen. Substantial moderation of artificial light at night (ALAN), especially its biologically active components, is well justified and way overdue.

# ENVIRONMENTAL ASPECTS OF ARTIFICIAL LIGHT AT NIGHT (ALAN)

Light from celestial bodies entering Earth’s atmosphere does not all reach the ground. For a light source at the zenith, about 7% is back-scattered into space and another 7% is scattered forwards, ie downwards. In the case of light from the sun, the scattered light appears as the daytime sky. The scattering is stronger for light of shorter wavelengths, which is why the clear sky has a blue tint. When the sun is near the horizon its disk and the light from it takes on a reddish hue as more of its short wavelength violet and blue light is scattered during its longer than usual path through the atmosphere.

Much of the ambient artificial light present outdoors in populated areas at night ends up as a mix of used and unused waste light travelling at or above the horizontal through the atmosphere. Between 7% and 50% of it will also be scattered downwards, adding an artificial component to the permanent faint light (natural skyglow) emitted by atmospheric gases at night. The scattered artificial light is called artificial skyglow, urban skyglow or inaccurately but popularly, light pollution. In urban and suburban areas at night, it often provides an ambient outdoor illumination in the order of 0.1 lux to 1 lux in clear atmospheric conditions, and as much as ten times greater in the presence of cloud (Kyba, Ruhtz, Fischer et al. 2011) Even in populated areas where obstructions such as buildings and trees tend to block direct light from streetlights, the amount of ambient artificial light outdoors is now often several log units brighter than natural darkness at night. This represents a massive change in the night phase of the daily light-dark cycle on Earth that most living things evolved in.

Artificial skyglow is a curse for professional and amateur astronomers alike as it reduces the apparent contrast of celestial objects, making the fainter objects harder or impossible to see and photograph, and adding spurious information to spectroscopic analysis that has been so important in generating knowledge of the universe. Glare from unwanted direct artificial illumination is also an increasing problem. Both forms of light pollution also interfere with the education and knowledge of members of the public who attend public telescope viewing nights. This explains what motivates some of the individuals including the writer who campaign against the environmental and ecological damage being caused by present lighting practices. Other reasons include climate change, sustainability, biodiversity loss and so on.

Waste light in the atmosphere tends to be proportional to the total amount of light generated electrically, although the constant of proportionality varies from place to place depending on spectral power distribution of the various lamps in use, the shielding and aiming of their luminaires and the albedo (total reflectance) of the terrain. Much of the electricity used currently involves fossil fuel burning. Overlighting and other poor lighting practices result in unnecessary emissions of greenhouse gases and the contribution of this to anthropogenic climate change.

Many of the seriously adverse effects of ALAN have only come to attention within the last two decades. In that time there has been a revolution in vision science. For well over a century the presence of rod and cone light receptors in the eye has been known and their functions are now reasonably well understood. So the discovery of a third type of light receptor in mammalian eyes in 2002 has led to substantial further research and uncovered much detail about how exposure to the blue component of ALAN is a risk factor for some serious ill-health conditions such as breast and prostate cancers, obesity, dementia, heart disease, and type 2 diabetes (eg Blask, Brainard, Gibbons et al 2012). The mechanisms by which ALAN also has adverse effects on quality and quantity of sleep should not be overlooked either: some details are given at the end of this section.

The third kind of light receptors are the 5% or so of the retinal ganglion cells that contain melanopsin, a substance (photopigment) that is sensitive to light. These cells are called *intrinsically photosensitive retinal ganglion cells* (ipRGCs). They respond to a narrow range of wavelengths in the blue part of the visible spectrum with a peak at about 460 nm. Their output is not image forming; instead, their combined signal is like the output of a light meter: it affects pupil size, provides the synchronising signal for the body’s circadian rhythms and controls the release of the neuro-hormone melatonin that is a precursor to several other important biochemicals, a part of the sleep-wakefulness system, a powerful antioxidant and the body’s primary defence against breast cancer.

Most life forms on Earth, even fungi and algae, include melatonin. It was present from the earliest stages of evolution. In mammals, even the nocturnal ones, melatonin is secreted by the pineal only in dim and dark conditions, ie only at night in the natural world. Bright blue light, which of course tends to be plentiful in daytime, usefully suppresses the secretion of melatonin then. Bacteria in the gut are the main generators of melatonin. In this, they act in synchrony with the pineal.

Campfires produce very little blue light so that exposures to campfire light at night did not produce much evolutionary pressure on humans over the last hundred thousand years or more since humans began to employ fire. Gas light had hardly more effect when it came into use. It has only been since the introduction of practical electric lighting in the 1880s and its subsequent widespread adoption that there has been enough blue light at night to cause large-scale interference with the health of exposed humans and lower order life forms.

With human exposures to environmental pollution such as asbestos, heavy metals, tobacco smoke, some modern organo-chemicals and ionising radiation, some time, even many years, may elapse between exposure and adverse health outcomes. Ill health resulting from exposure to ALAN also tends to have a long latency, but acute exposures can quickly trigger bad outcomes in some circumstances. This is of particular concern in relation to modern blue-rich sports lighting and similarly intense light sources such as illuminated billboards and outdoor video screens.

Poor sleep can arise for numerous reasons, one of which is exposure to ALAN. Self-report of poor sleep (worse subjective sleep quality, more sleep problems and daytime somnolence) was associated with greater Alzheimer’s-disease-related pathology in cognitively healthy adults at risk for AD. Effective strategies exist for improving sleep; therefore sleep health may be a tractable target for early intervention to attenuate AD pathogenesis (Sprecher, Koscik, Carlsson et al. 2017).

# ABORIGINAL CULTURAL HERITAGE EFFECTS OF ALAN

A person with good eyesight can see about 2700 stars in the natural clear night sky. In central Melbourne the number of stars visible to the unaided eye may be as small as ten and the iconic Southern Cross is seen only as a triangle, which is bad news for tourism. The Milky Way, Magellanic Clouds and other faint features are completely blotted out by the urban skyglow. But these are major features in the natural night sky and illustrate and assist perpetuation of the Dreamtime stories that have provided tribal law, survival knowledge and social order for Aborigines (and also Torres Strait Islanders) over many millennia. Obscuration of these features continues to interfere with the shrinking collective memory of the stories over much of the populated areas of Australia.

Many organisations in Australia make a public show of paying respects to traditional land custodians and past, present and future Aboriginal elders while ALAN under the control of these organisations is often released carelessly into the outdoor environment and thereby continues to contribute to irreversible losses of Aboriginal cultural heritage. It is also common but particularly incongruous to find a forest of sky-unfriendly artificial lights at and near Aboriginal cultural centres, memorials and sacred sites, Uluru being a prime example.

In countries outside Australia, the link between features of the night sky and the cultural heritage of other first peoples may be as strong as or lesser than is the case in Australia, the point being that it is a world-wide problem.

# ECOLOGY AND BIODIVERSITY EFFECTS OF ALAN

There is a vast literature on this topic. Much of the earlier work about effects of ALAN on plants and animals is summarised by Rich and Longcore (2006). They found that the effects were often different from those that affected humans and accordingly proposed a new term to make the distinction, viz ecological light pollution. Here just a few of the many important scientific papers in this area are discussed, most of them newer than 2006.

Bishop (1969) found that when the incident light at the surface of an artificial stream was above a threshold in the range of 1 to 10 mlux, aquatic insect activity measured as drift decreased.[[4]](#footnote-4) Below that threshold the activity increased. Preliminary experiments showed variations in wavelength to have little effect on insect activity patterns. This paper is cited in at least twenty others since then about such effects. Aquatic insects are often highly sensitive to minute levels of ALAN (often less than 1% of full-moon light) but many variations have been found between species in wavelength sensitivity. A common feature of aquatic life (and marine life also) is the cyclic vertical migration towards the surface after sunset and the subsequent descent before sunrise (the diel migration). The highest level reached in the ascent at night is lowered markedly by ALAN. This lowering inhibits feeding by the affected organisms but also reduces their vulnerability to predation. This can result in major interference to early stages in the food chain and the adverse effects can extend to higher life forms. Such ecological disturbances typically favour some species at the expense of others and can lead to downwards pressures and losses in biodiversity. In the present context, aquatic environments are of relevance given the frequent presence of rivers, creeks, lakes, and ponds near and within cities and towns.

There are many papers on the adverse effects of ALAN on the navigation of marine turtle hatchlings (eg Salmon 2003). This is certainly an issue in the coastal areas of countries including Australia where marine turtles lay eggs. In the different case of Little Penguins, [Rodríguez](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Rodr%C3%ADguez%2C+Airam), [Holmberg](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Holmberg%2C+Ross), [Dann](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Dann%2C+Peter) and [Chiaradia](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Chiaradia%2C+Andr%C3%A9) (2018) studied their behaviour in coastal areas where they nest not far from Melbourne. Introducing ALAN at ecotourism venues did not affect colony attendance behaviour of the penguins but they did prefer lit areas in crossing the beach and following paths to their nests in the sand dunes. Dim red light of limited duration was chosen as standard for all venues. Whether this would have adverse effects on penguin health was not studied.

A comprehensive study of invertebrates and ALAN is given in the ‘Buglife’ study by Bruce-White & Shardlow (2011). ALAN clearly has many adverse effects in this area.

Gaston, Duffy, Gaston et al. (2014) reported that biological effects have been observed in natural conditions (eg forest floor, caves, in deep water) where the light levels are as low as 2 microlux. To put this into perspective, outdoor sports and public events lighting may provide as much as 2000 lux. Adverse biological effects can therefore be expected when sports lighting is operated near rivers, creeks, lakes and ponds.[[5]](#footnote-5) Australian and New Zealand Standard AS/NZS 4282: 2019, *Control of the obtrusive effects of outdoor lighting*, may be one of very few constraints that could be applied in any attempt to limit light spill under these circumstances as its definition of environmentally sensitive areas appears to accept the reality that such areas can be present within towns and cities and the maximum allowable spill at the boundary can be as low as 0.1 lux in curfew hours. This is a substantial improvement over the previous (1997) version of the Standard that followed the CIE system of lighting zones in which only rural areas could be regarded as environmentally sensitive and acceptable light spill at the zone boundary could be as much as 10 lux in pre-curfew hours.

Longcore, Aldern, Eggers et al. (2015) took advantage of LEDs that create a ‘full-spectrum’ light through use of RGB diodes in conjunction with conventional white diodes to allow spectral adjustment in ways intended to minimise insect attraction to ALAN. They used indices based on existing insect attraction curves as a function of wavelength to develop custom LED configurations for indoor use. They noted that outdoor installations usually do not require full-spectrum lighting, and lower colour temperatures and filters to avoid sensitive wavelengths would be environmentally preferable. Spectrally tailored ALAN also has potential for attraction and trapping of disease vectors, so lighting engineers may be persuaded to follow a new paradigm that would extend beyond display, price and durability, to improve ecological and human health outcomes and reduce skyglow.

[Longcore](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Longcore%2C+Travis), [Rodríguez](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Rodr%C3%ADguez%2C+Airam), [Witherington](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Witherington%2C+Blair) et al. (2018)described methods forrapid assessment of lamp spectra to quantify ecological effects of light at night. Although spectral content of the light is important, they emphasised that *any approach to reduce ecological effects of lights must first keep intensity to a minimum and tuning of the spectrum used can perhaps then further reduce adverse effects*.[[6]](#footnote-6)

Bennie, Davies, Cruse and Gaston (2016) studied ecological effects of ALAN on plants. They found that roadside plants exposed to vehicle headlights can receive as much as 3000 lux and tree canopies can have peak illuminances of about 2000 lux from streetlights. Grass verges can be lit by streetlights to 50 lux. Away from these extremes, artificial illumination becomes progressively weaker but it applies over increasingly larger areas and adds to all natural sources down to the lowest levels of starlight. In so doing, it amplifies and distorts the effects of natural light sources on plants as well as animals. City skyglow can affect biota over thousands of square kilometres of the surrounding countryside. ALAN can interfere with many of the known interactions of plants with light. The effects may be beneficial, neutral or adverse for plants, affecting germination, growth, development, shade avoidance, DNA repair, phototropism (movement according to light direction) and photoperiodic effects. For instance, exposure to light as weak as 0.1 lux from white LED streetlights was enough to affect budburst date of lime trees. Overall, exposure to ALAN may affect a plant’s health, survival and reproduction. Periods of darkness may be essential for repair and recovery from environmental stresses, but the presence of ALAN might hinder or prevent this.

Exposure to ALAN can also affect fauna that interact with plants for useful outcomes for one or both species. Some of these interactions can be extremely complex. Much is yet to be learnt about such processes; meanwhile, some of the effects of anthropogenic environmental stressors such as ALAN may be contributing to undesirable results such as the dispersal of non-native species (Bennie, Davies, Cruse and Gaston 2016). The lesson appears to be that if we don’t know what ALAN is doing to important aspects of our environment, we should be wary of making things worse with more and brighter lighting, especially when the lights have spectral power distributions already suspected or known to have adverse effects on living things.

Schroer and Hölker (2017) addressed both the perception of light by various organisms and the impact of ALAN on flora and fauna. The increasing use of ALAN with high intensities in the blue part of the spectrum, eg from fluorescent lamps and LEDs, is a critical trend. Blue light is a major circadian signal in higher vertebrates and can also substantially impact numerous insect species and other invertebrates. Signaling thresholds in flora and fauna at night are often several log units below present streetlighting levels. Contemporary outdoor lighting can markedly degrade habitat and biodiversity and aspects of its sustainability must therefore be considered unacceptable. The need for broad-scale protection of humans and lower species must also be considered. In the small number of cases where blue-rich outdoor lighting is necessary or desirable its undesirable effects can be reduced by simple technical measures such as reducing the number, intensity and hours of use of such sources in and near populated areas, parklands and wildlife reserves, aquatic and riverine environs, farmlands, watersheds, grasslands and forests.

Newspapers are already carrying complaints by bee-keepers about diminishing bee populations and consequent substantial reductions in honey production. Knop, Zoller, Ryser et al. (2017) demonstrated that ALAN is a far-reaching threat to nocturnal pollination and predicted that the effect would propagate to the diurnal community and aggravate its decline also. This human-induced decline in pollinators and their ecosystem service is already well under way. This is an issue that is starting to affect everyone.

Sanders, Kehoe, Cruse, van Veen et al. (2018) found that low levels of ALAN from white LEDs strengthen top-down control in an insect food web. In a field experiment with [insect communities](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/insect-communities) of wasps and aphids, they determined the impact of artificial light ranging from 0.1 to 100 [lux](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/lux) on different [trophic levels](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/trophic-levels)[[7]](#footnote-7) and interactions between species. The strongest impact was at low levels of [artificial lighting](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/artificial-lighting) (0.1 to 5 lux), which led to a 1.8 times overall reduction in [aphid](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/aphid) densities. Artificial light at night increased the efficiency of [parasitoid](https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/parasitoid) wasps in attacking aphids, with twice the [parasitism](https://www.sciencedirect.com/topics/biochemistry-genetics-and-molecular-biology/parasitism) rate under low light levels compared to unlit controls. However, at higher light levels, parasitoid wasps spent longer away from the aphid [host plants](https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/host-plants), diminishing this increased efficiency. Aphids thus reached higher densities under increased light intensity as compared to low levels of lighting, where they were limited by higher parasitoid efficiency. This study highlights the importance of different intensities of artificial light in driving the strength of species interactions and ecosystem functions.

Macgregor, Pocock, Fox and Evans (2019) found that in comparison with unlit controls, full-night lighting appeared to be better than part-night lighting in terms of insect visitations to a nocturnally pollinated plant, but other interactions between LEDs and HPS lamps and lamp distance affected seed numbers and mass to the extent that part-night lighting was concluded to be the better option. The work demonstrated the potential for ALAN to disrupt pollination systems across the community of plants, disproportionately strengthening some interactions and weakening others.

In case it might be thought that the ecological case for minimisation of ALAN has been overstated here, see Grubisic, van Grunsven, [Kyba](https://onlinelibrary.wiley.com/action/doSearch?ContribAuthorStored=Kyba%2C+CCM) et al. (2018). They raise the issue of drastic and widespread declines in insect populations, ‘Ecological Armageddon’, which has recently gained attention in the scientific community. One example is a 75% reduction in flying insect biomass in Germany in the last three decades. These declines are commonly attributed to large‐scale factors such as land‐use changes, pesticides, climate change and habitat fragmentation but Grubisic et al. make a strong case that ALAN is a pervasive major global factor that strongly impacts insects and biodiversity, placing at risk important ecosystem services such as natural pest control, pollination, conservation of soil structure and fertility and nutrient cycling.

On top of these problems, farmers, food processors and distributors are also increasingly being affected by climate-change-induced drought. If we care about the health of our parks and gardens and the productivity of farming we are increasingly faced with worries that are in part exacerbated by the failure of our society to deal thoroughly with the ALAN problem.

This section could hardly be considered complete if it did not mention the severe effects that ALAN can have on birdlife. These include the catastrophic disruption of navigation in bird migrations, trapping of birds in circular flight around upwardly floodlit buildings and structures, and fatal impacts of birds with illuminated tall buildings and structures at night (eg Rich and Longcore 2006).

The following section deals with effects of ALAN on human health, but first it is useful to note that its connections with the present section are bridged by Aulsebrook, Jones, Mulder and Lesku (2018), in which impacts of ALAN on sleep are reviewed comprehensively for humans as well as wildlife. They point out that natural cycles of light and darkness govern the timing of most aspects of animal behaviour and physiology. ALAN can mask natural photoperiodic cues and interfere with biological rhythms. One such rhythm vulnerable to perturbation is the sleep-wake cycle. ALAN may greatly affect sleep in humans and wildlife, particularly in diurnal animals (ie those that that sleep predominantly at night). There is good evidence for impacts of ALAN on sleep, but critical questions remain. Some of these can be addressed by adopting approaches already established in sleep research. Meanwhile, there is sufficient biological evidence to warrant strategic minimisation of ALAN to reduce its harmful impacts on humans. This will also be of benefit to many other species, pets and wildlife alike, in urban and surrounding environments.

# HEALTH AND WELLBEING EFFECTS OF ALAN

ALAN has well-defined and at least in some cases well-understood effects, mostly adverse, on human health and wellbeing. Cho, Ryu, Lee et al. (2015) reviewed 85 papers on the topic. Several studies concluded that outdoor ALAN levels are a risk factor for breast cancer, with indoor light levels and individual lighting habits relevant to this risk. Exposure to bright artificial light during evening twilight and at night tends to suppress melatonin secretion, increases sleep onset latency (SOL) and increases alertness. Circadian misalignment caused by chronic ALAN exposure may have negative effects on the psychological, cardiovascular and/or metabolic functions. ALAN can also cause circadian phase disruption, which increases with longer duration of exposure and with exposure later in the evening. Visible light with wavelengths in the blue and violet parts of the spectrum at night is particularly potent in interfering with melatonin secretion and can cause circadian phase shifts, even if the light is dim.

Life on Earth evolved over billions of years in a daily cycle of light and dark that currently covers a maximum range of about 8.5 log10 units. Modern lighting and electronic image screens tend to reduce the amount of time that humans are exposed to the lowest 5 log units in this natural range. This, along with much time spent indoors during daytime, tends to limit the daily amplitude in the cycle of luminance (the psychophysical correlate of brightness) experienced by most of the population.

The ipRGCs mentioned in Section 3 above originate the neural signals that synchronise the body clock with the external cues provided by the rapidly changing light levels around sunrise and sunset. Jet lag is a relatively mild example of the circadian dysrhythmia that can result when the body clock is not synchronised with the perceived phase of natural light.

Short sleep can result from work and social pressures, excessive time spent on pastimes and entertainment, and/or excessive exposure to ALAN. Taheri, Lin, Austin et al. (2004) showed that short sleep duration is associated with elevated levels of the hormone ghrelin, reduced levels of the hormone leptin, and increased Body Mass Index. ALAN thus increases the hunger signal produced by ghrelin and suppresses the leptin signal that apparently controls satiety, that enough food has been eaten. The connection between ALAN and obesity has also been demonstrated in a worldwide epidemiological study: satellite images of night time illumination were combined with country-level data on female and male overweight and obesity prevalence rates, reported by the WHO. The study aimed to identify and measure the strength of association between ALAN and country-wide overweight and obesity rates, controlling for *per capita* GDP, level of urbanization, birth rate, food consumption and regional differences. ALAN was a statistically significant and positive predictor of overweight and obesity (*t*>1.97; *P*<0.05), helping to explain, together with other factors, about 70% of the observed variation of overweight and obesity prevalence rates among females and males in more than 80 countries worldwide (Rybnikova, Haim and Portnov 2016). It is no wonder that the obesity treatment industries based on diet or exercise or both have failed to control the modern obesity epidemic, insofar as they ignore a fundamental cause of the problem.[[8]](#footnote-8)

Humans are remarkably adaptable and can usually tolerate circadian dysrhythmia resulting from late nights, shift work etc but this does not mean adaptation to such changes in the sense of evolutionary adaptation.

A link between breast cancer and exposure to ALAN was first proposed by a medical researcher (Richard Stevens) in 1987. He was ridiculed to some extent then but the connection is now firmly established (eg Blask, Brainard, Gibbons et al. 2012; Haim & Portnov 2013). Direct experiments on cancer in humans are ethically unacceptable so researchers have to work around the issues by growing human breast cancer tumours on laboratory rats and mice, even to the extent of supplying human blood as the sole source of nutrition for those tumours. This has allowed the role of melatonin in controlling breast cancer to be understood in considerable detail. For example, Blask, Dauchy, Brainard et al. (2009) found that tiny quasi-static human breast cancer tumours are common and can exist for a long time, growing during the day and shrinking at night under the action of melatonin. If there is insufficient melatonin for any reason including exposure to ALAN at a level of just 0.2 lux or more in a rat model (but more in humans), a tumour can begin to proliferate. Even if the normal amount of melatonin is then restored after daytime growth it is unlikely to be able to keep the tumour in check.

James, Bertrand, Hart et al. (2017) used satellite photometric data across the contiguous United States to obtain objective measures of ambient illumination at the known addresses of nearly 100 000 female participants in the Nurse’s Health Study II and found that women living in areas with high levels of outdoor ALAN may be at higher risk of breast cancer even after accounting for individual and area-level risk factors for breast cancer. The risk was greatest for premenopausal women and smokers.

Exposure to ALAN is now known to be a risk factor for a range of other serious medical conditions. Using lung cancer as a control, Haim and Portnov (2013) found reliable worldwide correlations between ALAN and prostate cancer as well as breast cancer. McFadden, Jones, Schoemaker et al. (2014) found in a study of 100 000 women that chronic exposure to small amounts of light in the bedroom at night is associated reliably with higher levels of obesity. Analysis by the writer indicated that the effective light levels were as low as 0.01 lux, just 5% of the illuminance typically provided by light from a full moon. Given that ordinary drapes and blinds allow about a tenth of the light outside a window to enter the room, this sets the upper barely safe limit for the total allowable ALAN incident on the window to be just 0.1 lux. Existing widely used specifications for maximum spill light at bedroom windows range from 5 lux or more to 1 lux, and this usually applies to single sources of spill even though multiple sources of spill light tend to shine on individual windows simultaneously in practice and they add linearly in making up the total amount of light. Especially in high-rise apartments, many bedroom windows are not fitted with any form of curtains or shading so that the maximum allowable spill could justifiably be revised down to 0.01 lux as the total for all contributing sources. This might upset the lighting industry as a departure from long established practice but understanding of the situation has changed dramatically and the industry needs to start putting the health and wellbeing of the population ahead of its own benefits and beliefs.

The American Medical Association has been campaigning against excessive ALAN and its blue light component for over a decade. Its most recent press release (AMA 2016a,b) and committee report on the topic (Kraus 2016)[[9]](#footnote-9) list the following outcomes: eye fatigue, disability glare, reduced sleep times, dissatisfaction with sleep quality, excessive daytime sleepiness, nighttime awakenings, impaired daytime functioning, and increasing long-term risk of cancer, obesity, type 2 diabetes[[10]](#footnote-10) and cardiovascular disease. An earlier publication (Blask, Brainard, Gibbons et al. 2012) also mentions depression and mood disorders, and reproductive problems. Other journal literature indicates that ALAN appears to be a risk factor for sleep disorders (eg Min and Min 2018). None of these conditions is likely to improve sleep quality and quantity. Poor sleep itself is associated with amyloid pathology in normal adults, a potential risk factor for Alzheimer’s disease (Speech, Koscik, Carlsson et al. 2017).

In practical application of such knowledge, it is important to quantify the amount of melatonin-suppressing light in the circumstances of interest. Duration of luminous exposure during the night is straightforward and cumulative. Intensity, luminance or illuminance data are readily available, but the fraction of the total light that is melatonin-suppressing requires a wavelength-by-wavelength summation using data that might be difficult to obtain or handle (eg Clark 2009). Instead, a fairly crude proxy has come into popular use- the Correlated Colour Temperature (CCT) of the light source in degrees absolute (Kelvin). Some examples of CCT are given in Table 1 below.

Light sources with relatively high CCTs have as much as ten times the melatonin-suppressing[[11]](#footnote-11) blue light output compared with equally bright (photopic) low CCT sources such as high pressure sodium lamps.[[12]](#footnote-12) The ratios are smaller if the comparisons are for equal scotopic brightness. This is why there have been several journal papers warning of the health risks of using electronic screen devices (from smart phones to TV and computer screens) after dark and before going to bed. For example, Green, Dagan and Haim (2018) studied the effects of digital media screen use in 280 Israeli men and women. Smartphones were the most used digital media device in the evening and after bedtime (hereafter described apparently more accurately as getting into bed), followed by TV, computers, and tablets.

**TABLE 1. Apparent colour and Correlated Colour Temperature of light sources**

|  |  |  |
| --- | --- | --- |
| **Source** | **Approximate Correlated Colour Temperature, degrees K** | **Apparent Colour****(but subject to colour constancy)**  |
| Match flame | 1700 | Orange |
| Candle | 1850 | Orange to amber |
| Sodium vapour lamps | 1700 to 2100 | Amber to yellow |
| Light globe | 2400 to 3000 | Yellow to cream |
| Warm white fluorescent lamp | 2700 to 3100 | Yellow to cream |
| Moonlight | 4000 | Creamy-white |
| White fluorescent lamp | 4000 to 5000 | Creamy-white to white  |
| Direct sunlight | 5500 | White |
| Daylight | 6500 | Bluish-white |
| Cool white fluorescent lamp, metal halide sports lamp | 5500 to 7000 | White to bluish- white |
| Screens of computers tablets, telephones, TVs | 5000 to 9000 | White through bluish-white to blue-white |
| LED phosphor lamp varieties | 1800 to 10 000 | Amber to blue-white |
| Clear blue sky | 15 000 to 27 000 | Blue-white to pastel-blue |

Smartphones tended to be used for about 30 min and TV for about 15 min after getting into bed. Significant positive correlations were found between time to fall asleep (sleep latency) and the use of TV after getting into bed, and using smartphones in the evening and after getting into bed. Using digital media screens in the evening and at night is associated with sleep difficulties and, presumably as an outcome in the following morning, greater sleepiness and attention/concentration dysfunction. Note that the factory setting of digital media screens appears to be in the range from 5000 K to 6500 K. Major manufacturers of mobile phones and computers now offer ‘blue light reduction’ for their screens at night “to reduce eye strain”, which is ‘spin’ by any measure.[[13]](#footnote-13)

Replacing high-pressure sodium street lamps of about 2100 K by 4000 K LEDs of similar photopic intensity increases the melatonin-suppression signal by about 4 to 5 times. The operating and capital savings claimed for such replacements generally do not factor in the costs associated with increased incidences of diseases such as breast and prostate cancer, let alone all the other possible diseases, disorders and ecological disruptions. The supposed savings may be wildly illusory.

Australia-wide, suburban streetlights are mostly being fitted with LED lamps with a CCT of 4000 K to 4200 K instead of a much lower value desirable on health grounds. This is also a sad illustration of how some influential members of the lighting industry are prepared to advocate such values of CCT for reasons such as claimed slightly greater energy efficacy or ‘that’s the CCT of moonlight’ while ignoring or discounting the published work of medical, biological and physical scientists on the adverse health and environmental effects of ALAN, especially in the case of higher values of CCT.

The International Dark-Sky Association (IDA 2018a) currently recommends that all outdoor lighting should have a CCT of <3000 K. IDA (2018b) anticipates that as LED technology advances it is only a matter of time before 2700 K or lower becomes the new norm. At least in Melbourne, for several years one of Australia’s major supermarket chains has been stocking 2700 K LEDs for domestic lighting.[[14]](#footnote-14) Several LED manufacturers already include LEDs with CCTs as low as 1800 K in their streetlighting catalogues.

#  SAFETY AND SECURITY EFFECTS OF ALAN

There is excellent evidence that as the ambient lighting increases, fear of crime at night tends to reduce to an asymptote dependent on location. The asymptote is effectively reached when the illuminance is between about 20 to 40 lux (Boyce, Eklund, Hamilton et al. 2000).

Prior to the late 1980s, studies generally presented no conclusive evidence to support the use of brighter lighting to prevent actual crime, contrary to popular belief and a century of lighting industry propaganda that conflated the roles of light in influencing fear of crime and possibly influencing actual crime. The confusion was reinforced by a series of publications by Painter, Farrington and Welsh in which the results supported the popular belief of lighting for crime prevention and were lauded by the lighting industry. Key aspects of those publications have been criticised by Clark (2002; 2003; 2009; 2018) mainly on the grounds of rationality and by Marchant (eg 2004; 2005a; 2005b; 2006; 2017; 2018) on the grounds of scientific method and statistical analysis. Some of the objections by Marchant were summarised and rejected by Welsh and Farrington (2008), who appeared then to be unaware of any adverse effects of streetlighting beyond the effect of light pollution in making stars harder to see. Accordingly, most of the lighting industry continues to install more and brighter lighting in the belief that this will reduce crime as well as reduce the fear of crime.

In discussing real-world trials and epidemiological studies on lighting and crime, it is important to be mindful of the difficulties and deficiencies in data collection and analysis that affect reliability of crime datasets as a function of type of crime, place and time (eg Mosher, Miethe and Phillips 2002).

## 7.1 Field Trials by Painter

Painter began her research with a series of small-scale field trials on outdoor lighting and crime in England. The treatment areas were regarded as ‘crime prone’ with a tendency to have an initial crime rate higher than the chosen control area.[[15]](#footnote-15) Support from a lighting industrialist allowed Painter to undertake larger-scale trials in Stoke-on-Trent and Dudley (towns in England), which were reported in her PhD thesis (Painter 1995). The treatment areas in both trials had already been selected by the local councils for relighting because of complaints from residents about the low level of lighting there, possibly spurred by the fear of crime. In Stoke-on-Trent these rates were significantly higher initially than in the respective control area. It would have been justifiable to abandon that trial at the outset as inappropriate for the intended scientific analysis.

The thesis is remarkable for displaying an extraordinary amount of enthusiasm for lighting as a means of reducing crime, hardly the dispassionate and even-handed approach expected in scientific research at any level. The possibility that lighting could do the opposite and increase crime is barely mentioned. As a result, Painter applied one-tailed statistical tests and obtained significant positive results in circumstances where two-tailed tests were more appropriate but would have provided results of lesser or no significance. Other breaches of scientific method occurred, including intervention in the form of extra police patrols and police ‘pep talks’ about home and personal security favouring the treated areas. Painter attended at least some of these talks and was introduced to residents as the researcher. No mention was made of these factors as possible reasons for the apparently favourable results.[[16]](#footnote-16)

Not least of the problems with the Stoke-on-Trent and Dudley results is that nighttime crimes did not decrease more than daytime crimes! Instead of interpreting this as a sign that something is wrong with the overall method when daytime crime is claimed to be reduced by streetlights that remain switched off all day, it was claimed that a theory focusing on the role of street lighting in increasing community pride was more plausible than a theory focusing on increased surveillance. Instead, however, it would appear more reasonable to suppose that something such as social factors were overwhelming any apparent effect of light on crime.

Painter’s thesis was passed regardless but embargoed against online access for ten years at the University of Cambridge, of all places. Meanwhile, journal papers on the Stoke-on-Trent and Dudley trials were published, eg Painter and Farrington (1997; 1999a,b), all exhibiting bias towards the belief that lighting prevents crime. Additional papers by Painter and Farrington (2001a,b) continued the apparent bias and they build on results that appear to be unreliable because the size of the effects claimed for a given lighting change is unreasonably large.

See Sections 4.1, 4.2 and 4.3 in Clark (2002) and Chapters 4 and 5 in Clark (2003) for more details. A draft of the 2002 report was sent to Farrington before its online publication. He kindly responded at length with some useful criticisms and explanations, copies of relevant papers, and agreed to inclusion of his name in the Acknowledgements, but did not accept that the Dudley and Stoke-on-Trent papers exhibited a pro-lighting bias.

## 7.2 The Farrington and Welsh Meta-Analysis

Meta-analysis is a powerful technique often used for pooling results of independent individual trials of a particular possible cause and effect. The numbers of events such as crimes a, b, c and d observed in the experimental and control areas before and after treatment are defined by:

 Before After

 Experimental a b

 Control c d

A common basis for comparisons between experiments is given by a Relative Effects Size: [[17]](#footnote-17) RES = a\*d/b\*c

The RES represents the proportional change in crime in the control area compared with that in the treatment area. It allows for extraneous influences that affect the crime levels in the experimental and control areas equally during either the ‘before’ or ‘after’ periods or both. An RES of 1 means that the intervention had no net effect either way on crime. A greater value represents a beneficial result of more lighting, and less than 1 indicates a counterproductive effect. The process tends to reduce the uncertainty caused by random effects in individual trials but it is also has the shortcoming that it is highly effective at propagating systematic error (bias) common to more two or more trials.

In order to collect data for a meta-analysis, Farrington and Welsh (2000; 2001; 2002) did a literature search for what they considered were reliable experiments on lighting and crime and found three with RESs less than one and ten more with RESs greater than 1.[[18]](#footnote-18) The RESs for the 13 studies ranged from 0.75 to 3.82. The overall RES was 1.25 (since slightly revised), with a 95% confidence interval of 1.18 to 1.32. This implies that a well-designed and conducted ‘standard’ lighting intervention would most likely result in a 20% reduction of total crime (1–1/1.25 = 0.2) in the relit area as a beneficial outcome. This result is incomplete, however, as it is also important to know what the initial value of illuminance is as well as how much of an increase in light is necessary to get this improvement.

Of the 13 experiments selected by Farrington and Welsh for their meta-analysis (see Table 2 in Welsh and Farrington (2008)) only eight provided any indication of the numerical increase in lighting. All of the estimates were single digit integers ranging from 2 to an unusually high 7, with a mean of 3.375. The log of this is 0.53, so that two representative lighting treatments sum approximately to one log unit on the illuminance scale in Figure 1. These values must be regarded as over-estimates of the actual treatment size as urban skyglow and light spill from outside the treated area would add to the illuminances provided by both the existing and the new streetlighting. None of the trials reports provided sufficient photometric information to allow calculation of the actual dose.

Ideally each RES should have been divided by the associated individual dose to allow the individual response/dose ratio to be found or estimated for eight data sets, allowing a mean to be derived. The five data sets without dose information should have been discarded. Instead the mean RES for 13 trials was divided by the mean of the seven multipliers, 3.375x. The overall result then was that an overestimated lighting increase of 3.375 times applied to the unknown mean starting illuminance produced a 20% reduction in crime. Confidence limits for the overall RES were calculated apparently without consideration of the extra uncertainty or variability that must have been introduced by the poor and missing photometric data.

Note that the actual size of the dose is also required in assessing the reasonableness of the response observed: see Reasonable Benefit Limits in Clark (2002).

Regardless of all these problems, the published results were enthusiastically and uncritically adopted by the crime prevention and lighting industries. However, Marchant (2004; 2005a,b; 2006) unearthed shortcomings in the scientific method and statistical methods in the individual trials and in the meta-analysis. Some of these objections were partly or fully answered by Farrington and Welsh (2004; 2006) or Welsh and Farrington (2006; 2007; 2008), but others were not. Farrington and Welsh have continued to maintain that a meta-analysis of controlled trials is an effective way of detecting reliable effects in the presence of confounding factors. However, meta-analysis compounds effects of systematic bias such as that from higher-crime areas tending to be those chosen for relighting treatment, and when local authorities and police apply non-lighting anti-crime measures such as improved natural and CCTV surveillance, security campaigns and extra police patrols preferentially to higher crime areas.

At least three of the 13 trials were so biased, confounded or otherwise suspect (viz the Birmingham markets trial (Poyner and Webb 1987) and the Dudley and Stoke-on-Trent trials (Painter and Farrington, loc. cit.) it is argued both in Clark (2002) and here that they should have been excluded from the meta-analysis. These three just happen to have had the three largest RESs.

Unlike the other twelve trials, the Birmingham markets trial involved a mix of indoor and outdoor lighting, only in daytime. Most of the crimes occurred in the early afternoon, especially during summer, and there were none at night because the markets were not open then. No before and after photometric information about the natural and artificial components of the lighting was given but indoor daytime commercial illuminances are likely to have been two or more log units brighter than typical streetlighting at night and thus closer to or within the photopic plateau where variation in the amount of light is unlikely to have much if any effect on visual performance that might affect crime one way or the other.

The market lighting change was one of several interventions variously applied in the experimental and supposed control areas and intended to deal with pickpocketing, thefts from shopping bags and other thefts involving jostling or stealth. Security staff introduced wider aisles between stalls and claimed that the reduction in congestion had successfully increased the difficulty of committing such thefts. Eck (1997) considered only aisle widening as the cause of theft reduction and did not mention lighting at all as a factor in this case. Regardless, the unusually large reduction in crime experienced (74%) in the markets trial was ascribed by Poyner and Webb (1997) *solely* to the unstated change in the artificial component of the lighting during daytime, and the meta-analysis includes this assumption.

Painter’s thesis and the papers on the Dudley and Stoke-on-Trent trials thus have many serious faults. Mostly they acknowledge the financial assistance provided by a lighting industrialist. They do not mention the additional potential conflict of interest attached to Painter’s subsequently admitted relationship with that person (Private Eye 2005). This adds to doubt already raised about the reliability of the results from Dudley and Stoke-on-Trent and is further justification for the removal of those results from the meta-analysis.

Removing the Birmingham, Dudley and Stoke-on-Trent results from the meta-analysis reduces the RES from 1.27 to about 1.20.

Even the latest version of the meta analysis (Welsh and Farrington 2008) does not take into account the carefully planned and well executed Chicago alley relighting trial (Morrow and Hutton (2000) in which a 2.78 times increase in electrical power of the lighting was accompanied by a 21% *increase* in crime. Adding this result to the meta-analysis produces a further drop in the MES to about 1.15, with a confidence interval of about 0.98 to 1.32, which includes the no-effect value of 1.0.

Welsh and Farrington (2008) actually considered the possibility that the confidence interval could be revised and reach below 1.0 and claimed that a municipal authority would be taking a large financial risk if it accordingly withheld expenditure for more and brighter lighting. This argument depends completely on the validity of the claim that increased lighting provides economic benefits from subsequent crime reduction (Painter and Farrington 2001b). The evidence presented in this report indicates that this claimed benefit is erroneous. The claim that ignoring the supposed benefit would be financially risky is scaremongering.

Availability of reliable before-and-after photometric data in the treatment and control areas should have been a prerequisite for inclusion of each trial included in the meta-analysis but it seems that this basic essential is universally missing. This gives an impression that the researchers generally had an inadequate understanding of the lighting and vision part of their lighting and crime studies. For this and other good reasons, removal of more studies from the meta-analysis could be justified. Not even a meta-analysis can produce a good output from biased or otherwise low-quality input data.

In the individual studies and in the meta-analysis there seems to have been no discussion about the generality of the results, insofar as if one lighting treatment produces a certain change in crime, then repeated treatments should continue giving similar changes until the environment has become sufficiently different to affect the size or even the sign of the change. No evidence for any such variations in the effect is presented in any of the meta-analysis papers. If the beneficial effect of increased lighting in suppressing crime found in the meta-analysis is true it can therefore be expected that the crime measure would compound to greater values if the ambient lighting were *dimmed* repeatedly by a factor such as 3.375. Supposing that a mean for the starting illuminance of all 13 trials was about 0.5 log units, about the middle of the streetlighting range, about 7.6 successive treatments of the factor 3.375 (ie 3.3757.6 or 10 350) would be expected to reduce the ambient illuminance by just over 4 log units to the level of cloudless and moonless natural darkness (shown as -3.6 log units in Figure 1). According to the results of the meta-analysis, those 7.6 negative treatments would also produce a compounded crime level of 1.27.6 or 4.0 times the starting value. Allowing for the presence of some ambient light (eg from artificial skyglow generated elsewhere) as well as streetlighting would make this result even larger and more ridiculous.

Introducing streetlighting to a previously unlit area does not appear from elsewhere in the literature to have resulted in an observed reliable reduction of crime by anything like a factor of four, nor does it appear that a total power blackout in an area normally provided with streetlighting has been reported as producing anything like a fourfold increase in crime. In fact the available evidence suggests the opposite- that crime at night uncoupled from confounding effects such as social factors decreases with less lighting and increases with more lighting. This is why the writer’s second report on the subject (Clark 2003) was given the subtitle ‘Coupled growth’.

After its initial publication by the UK Home Office in 2002, the meta-analysis should not have been republished at all in the journal literature without a valid explanation of why its results fly in the face of such simple and powerful checks of its veracity and reasonableness. Nor should others in a position to make their own scientific assessments have adopted the meta-analysis results so uncritically.

Note that the Welsh and Farrington (2008) version of the meta-analysis includes a statement attributed to the anonymous reviewers that “[Streetlighting] has few negative effects and clear benefits for law-abiding citizens.” Even eleven years ago the severity and extent of the adverse effects of streetlighting on the environment, native cultural heritage, ecology, biodiversity and health were already clear in the scientific literature (eg Clark 2009).

The meta-analysis also indicated that nighttime crimes did not decrease more than daytime crimes did. The reviewers also accepted the explanation of Welsh and Farrington for this, viz that increased streetlighting is supposed to signal community investment in the area, which is supposed to increase community pride, community cohesiveness, and informal social control, which are then supposed to decrease crime during both daytime and nighttime. These claims compound stretches in credulity. If switched-off streetlights are responsible for a decrease in crime by day, why would they need to be switched on at all at night, let alone need to be made brighter? It could be argued that if the ‘pride’ theory is true, the treatment was merely the installation of new streetlights and it would not have mattered if they had been kept switched off, perhaps after a brief demonstration. For every trial in which crime did decrease both for night and day, the proper scientific action would be to regard the results as subject to substantial confounding of unknown origin and sufficiently unreliable to justify their removal from the analysis.

As will be seen below, the Welsh and Farrington claims are also at variance with overriding new scientific evidence.

## 7.3 Crime by Time of Day

If an increase of streetlighting by a factor of 3.375 does indeed produce a questionably large (20%) reduction in crime as claimed by Farrington and Welsh, the daily 7 to 10 log unit change in outdoor illumination, or at least the twilight and night part of that range, should result in a great increase in crime at night. Nothing like this actually happens. Worldwide a modest preponderance in the night/day proportion of crime at night appears to be typical, in the order of 60:40. A majority of residential burglaries occur during the daylight hours but two thirds of the less frequent nonresidential burglaries happen at night (Mosher, Miethe and Phillips 2002, p 80). This suggests that some massive confounding effect or effects overwhelm the true effect or effects of lighting on crime, if any. There are clues as to what these confounding effects may be.

Figure 2 shows violent crime as a function of time of day on schooldays according to a large and reliable US database. The curve for under-18 offenders shows peaks corresponding with times for start, lunch and end of school. The curve for under-18s on weekends (not shown) is more like the smoother curve shown for older offenders. Curves for other crimes (eg OJJDP 2018) and for different places show substantial variations in peak times for crime between cities in the USA (eg Felson and Poulsen 2003), but the basic features of a pre-sunrise minimum and an afternoon or evening peak are usually present.



Figure 2. US violent crime data including murder, violent sexual assault, robbery, aggravated assault and simple assault. Data are from law enforcement agencies in 37 states and the District of Columbia (OJJDP 2018). The black curve is for offenders under 18 years of age on school days and the brown curve is for offenders aged 18 and over. The vertical scale is ‘Offenders per 1000 violent crime offenders in the age group’. The curves have been shifted to the left by a half hour as the original data came in 1-hour blocks labelled with the hour at the start of the block.

What is clear from Figure 2 is that apart from both curves being daily cycles, there is no obvious connection between the daily illumination cycle (such as in Figure 1) and the daily pattern of crimes generally. In particular, it should be noted that apart from the brightest and faintest parts of the illumination curve, all other values on the curve are experienced twice in every twenty-four hours, sometimes close together but mostly hours apart. If there were a general connection between lighting and crime, it could therefore be expected that crime curves such as those in Figure 2 would show a clear indication of symmetry about noon and about midnight. There is hardly any evidence for such symmetry in Figure 2. Indeed, the 18+ curve in Figure 2 clearly looks to be rather antisymmetric. Social and possibly other factors clearly dominate the daily crime cycle.

Figures 7 and 8 in Jochelson (1994) show for the years 1990 to 1992 that the total of recorded offences on trains per 100 000 passengers is about 3 times higher at night than by day. This suggests that the problem could be fixed by increasing the carriage lighting to daylight levels. But the graphs also allow the offences to be tallied for weekdays and weekends. This shows that the crime rate between 1 am and 6 am on the weekends is double the total rate for all other times and days. In this and doubtless many other circumstances, crime is clearly a social problem, possibly compounded by physiological factors, rather than a lighting problem.

## 7.4 Crime in Reduced Illumination and Near-Darkness

The disconnect between crime and illumination is hardly surprising given that over more than half of the daily range in illumination, performance of the human visual system is high and near constant, the so-called photopic plateau. If there is any substantial effect of illumination on crime it would appear more likely in conditions where visual performance does show a large dependence on illumination, as in the mesopic (< 10 to 0.1 lux) and especially the scotopic (< 0.1 lux) ranges of vision. But the increased difficulty of seeing in dim conditions could reasonably be expected to hinder as well as assist the commission of crime to some extent. In the case of violent crimes against another person, resistance/avoidance and calls for help by the victim could be expected to be assisted as well as hindered somewhat by the dim lighting, again tending to reduce or minimise any overall effect of lighting one way or another.

Crime reductions in the New York blackouts of 1965 and 1977,[[19]](#footnote-19) Auckland in 1998 (Clark 2003) and the August 2003 blackout of the north-east of North America (Clark 2009), among several others, indicate overwhelmingly that darkness tends to diminish crime in general.[[20]](#footnote-20)

A lesser effect but still in the same direction occurs when lighting reductions are smaller, such as:

1. In the LED relighting of Los Angeles, in one part of a presentation on the project (BSLLA 2013) the relighting with mostly 4000 K LEDs (and others around 3000 K) for economic reasons resulted in about a one-third reduction in (photopic) illuminance in most places. Glare complaints increased with higher colour temperatures. Later in the presentation, credit is claimed for the project as producing a reduction in crime, with no mention that it occurred in association with a substantial reduction in lighting. Crime reduction in the 7 pm to 7 am interval from 2009 to 2011 was 13.6% in vehicle theft; 7.8% in burglary, robbery and theft; and 10.9% in vandalism. Overall crime reduction was 10.5% for the one-third *reduction* in lighting. This result seems to be too large from the point of view of Reasonable Benefit Levels.
2. More non-violent crimes took place in the parts of streets in Houston, Texas, where the lights are more closely spaced along the roadway. Areas with higher densities of lights experienced 60 percent more non-violent crimes on average than areas with low concentrations of streetlights (fewer than 9 streetlights per km of roadway). In 2015, the number of lights per km varied from less than 0.6 to 29, with an average of about 9. The total number of streetlights was 173 000. There was no clear evidence that lighting density had any effect on violent crime rates, but the non-violent crime rate was highest in the areas with no ethnic majority (O’Connell 2017; O’Connell and Shedler 2017).

Steinbach, Perkins, Tompson et al. (2015) tested whether reduced illumination by streetlighting at night had any effect on crime. They surveyed 126 UK municipalities that have stopped streetlighting outright, stopped streetlighting after midnight or 1 am, dimmed all-night streetlighting or substituted white or LED lighting (presumably replacing amber high pressure sodium lamps) over several years for reasons of economy and reduction of greenhouse gas emissions. Sixty-two municipalities responded with acceptably complete data. The same data set was subjected to a different analytical method by Perkins, Steinbach, Tompson et al. (2015). Both studies found weak evidence for reductions in crime associated with dimming and with white light, but no effect of switching off for part or all of the night.[[21]](#footnote-21) These results rebuff the claims of the minority of ratepayers in England who objected publicly to these streetlighting reductions on grounds of safety, security, modernity and governance. It terms of the immediate context of the present document, the results are consistent with an explanation below in this section, especially if other light sources contributed significantly to the before and after light levels involved or the levels were relatively close to the photopic plateau or both.

There are some issues with the two Steinbach and Perkins studies. One is that the response rate of municipalities to the survey was 49%, which seems lower than could be expected for a non-commercial survey about something of community interest. The most likely reason for the non-response could well be a form of publication bias. Ratepayers generally have been exposed to a lifetime of lighting industry propaganda on security and safety and would therefore tend to expect increased crime from lighting reductions. They might well interpret zero change or a reduction in crime as a chance result of some sort of council or researcher incompetence or conspiracy. Staff of individual councils may have been unaware of the trend in the overall survey results and may therefore have feared ridicule if their result stood out as zero change or a decrease in crime. Thus there would probably be a non-response bias against participation in the survey by some municipalities when their particular result was not an increase in crime.

Another issue with the survey is that it contains no photometric data about the lighting changes or the baseline outdoor illuminance. Most places in England are understood to be subject to noticeable artificial skyglow, much if not most of which arises from escaping indoor artificial light plus all forms of outdoor lighting such as commercial, decorative and sports lighting and vehicle headlighting as well as public lighting and streetlighting. Furthermore, at and near the latitude of London, for most of the year astronomical twilight ends about two hours after sunset and starts again about two hours before sunrise, but for over two months during summer astronomical twilight lasts all night (BAA 2019). These effects become more pronounced for higher latitudes. Thus even with the streetlights switched completely off at night, the total ambient illuminance outdoors can still be well above natural darkness. This would be especially so in cloudy conditions, which are understood to be common in England.

Other evidence is clear that the crime rate tends to be lowest in the dimmest illumination conditions. The writer hypothesised in Clark (2003, Figure 6) that in the absence of confounding influences, the crime rate *increases* from the lowest light levels along a sigmoidal curve to an asymptote as lighting is increased towards daylight levels. Figure 3 is a revision of the original figure, the improvement being possible because of the mass of evidence now available that overall crime is consistently low in the dimmest conditions. The vertical scale for crime is linear but otherwise relative, and social/behavioural factors that appear to confound the impact of lighting on actual crime are not represented in the curve shown. As shown in Figure 2, these factors can sometimes be quite large and easily misinterpreted as lighting-related because they also follow a 24-hour cycle. The horizontal line that passes through 1.0 on the vertical scale in Figure 3 would represent a condition in which lighting changes have no effect at all on crime. This appears to be true in the medium and high parts of the photopic range but as the light level falls through the low parts of the photopic range the crime rate may begin to follow the sigmoidal curve.[[22]](#footnote-22)

The upper curve in Figure 3 illustrates how fear of crime for adult subjects changes with illuminance (Boyce, Eklund, Hamilton et al. 2000, Figure 7). Unfortunately the illuminance scale used by Boyce et al. was linear, so that results from as much as about four or five log units of dim lighting are crammed into the leftmost 0 to 1 lux span of the scale. Accordingly there is no apparent indication about what shape the fear curve takes as light levels continue to diminish. However, there must be a finite upper limit to fear, say, when a subject is terrified to incoherence or maybe even frightened to death, so that the situation for fear of crime in given circumstances would seem more likely to be represented by a sigmoidal curve above the daylight line, with a vertical scale to suit. Sigmoidal curves are monotonic and their gradients may be zero but nowhere do they change sign.

What is not known with any certainty is the vertical scale value for the darkness asymptote of the lower curve. It is unlikely to be a single value for different kinds of crime. Some kinds may become totally impracticable but other crimes could still take place in total darkness even if their motivation changed and committing them would be hindered. As an example for discussion, the dim light asymptote for the lower curve in Figure 3 was chosen to be at about 0.1 on the vertical scale as a realistic overall value. As drawn, the gradient of the long middle part of the curve varies somewhat around 0.2 per log unit.

On this basis, any properly controlled lighting and crime trial with a typical lighting increase of less than a log unit in scotopic conditions should be regarded with suspicion if it has a result outside the range of say a 0 to 20% *increase* in crime. In mesopic to low photopic conditions a limiting range of say 0 to 10% increase per log unit may be more appropriate.

Purely for illustrative purposes, in Figure 3 the marked point on the lower (sigmoidal) curve at 0.5 log unit has already dropped to 0.898 on the vertical scale. If this represents the starting point for a lighting treatment of say a 0.5 log unit increase and no assumptions are made about the direction of any change in crime, the three possibilities are an increase of crime of 0.062 or 6.9%, zero, and a decrease of 9.4%. For brighter starting points, the corresponding changes in crime would become vanishingly small around low photopic light levels where it may be no coincidence that the fear of crime cannot be further lowered appreciably by lighting increases. For dimmer starting points, the reduction in actual crime is likely to remain in the order of 10% per 0.5 log unit treatment through most of the light levels that can occur in modern suburbs even when the streetlights are off for any reason at night. One outcome of all this is that if the field experiments reported so far had been more robust in their rejection of confounding factors, they might not have had enough statistical power to detect any small genuine changes expected at lower photopic levels.



Figure 3. A sketched sigmoidal curve for actual crime as a function of ambient illuminance, redrawn from Figure 6 in Clark (2003) and a sketched curve for fear of crime based on Figure 7 in Boyce, Eklund, Hamilton et al. (2000). The linear vertical crime scale is notional. The illuminance at which either curve reaches to within say 0.1% of the drawn horizontal asymptote is here uncertain by about ± 0.5 log unit.

So far this discussion has added to some of the reasons outlined in Clark (2002; 2003) for why many of the experiments on lighting and crime have produced discordant results. But there is one more explanation now available. Farrington and Welsh’s result is that a lighting increase of 3.375 times will produce a 20% decrease in crime over an unspecified range of light levels at night. Look at Figure 2 again: at 5 am, an hour before sunrise around the equinox, the crime rate value shown for people aged 18 and over is 16%. At or around 7 pm, an hour after sunset, the light level *will be the same* on average but the crime rate value then is 60%, a factor of 3.75 times higher. For under-18s the factor is 8.5 times higher, but only on school days!

Controlled trials and meta-analyses are good at teasing out genuine effects in the presence of random confounding factors but when the ‘noise’ is over forty times the signal or even more for brighter conditions, and systematic errors such as preferential treatment of the experimental area and publication bias are present, vastly better experimental design, execution and analysis than so far displayed are necessary but not sufficient for genuinely reliable results. Meanwhile, crime reduction by more and brighter lighting has to be regarded as a thoroughly discredited myth.

Some further consideration can now be given to the nil effect of streetlighting reductions on crime in the Steinbach and Perkins dual studies. Some representative photometric data needs to be collected to determine what the initial level and treatment size actually has been. If the levels are typically high to begin with, ie in the photopic range, and the drop caused by the lighting reduction is small enough then the apparent discrepancy in the effect on crime may well become insignificant.

## 7.5 Costly Outcomes of Believing that More and Brighter Lighting Will Reduce Crime

Sections of the lighting industry in England moved quickly to promote the supposed value of more and brighter lighting for crime reduction according to the work of Painter, Farrington and Welsh. By 2004, the UK government had been convinced by industry bodies to spend £300 million on streetlighting upgrades primarily to reduce crime (eg Cozens, Neale, Whitaker et al. 2003), and the cost subsequently grew to over £1 billion. Obviously, this massive program proved highly profitable for the lighting industry. Unfortunately, and inexplicably, neither the lighting industry nor the UK government capitalised on the golden opportunity to use the relighting program in a way that would use randomised controlled trials to quantify the observed benefits, so the only way of gauging the effectiveness was by simple observations of the crime rate over time. Crime in England and Wales fell steadily from a peak in 1995 to a shallow minimum at the end of 2004 and then rose slightly in 2005 before resuming the slow fall (Nicholas, Kershaw and Walker 2007). There was no sign of the substantial decreases that should have taken place according to Farrington and Welsh (2002) but the small rise in 2005 was in the order of the few percent that might be expected according to Clark (2003). Despite this outcome, for many years the Home Office kept on promoting the claim that more and brighter lighting would prevent crime.

Chalfin, Hanson, Parker and Lerner (2017) described a study that sought to determine whether additional outdoor lighting at public housing sites would reduce crime. Temporary generator-powered portable light towers were distributed in a random selection of 39 New York City Housing Authority (NYCHA) complexes with the remaining 38 complexes as controls. The test sites were given a random allotment of light towers averaging 10, but ranging from as few as one or two. A graph in the report shows greatest effect for a single tower, less for a second tower and little for a third tower. Results for all additional towers are omitted!

This temporary lighting cost $30 million USD and existing lighting was left in place. The study was set up as randomised controlled trials but the statistical analysis used was inappropriate for such trials (Marchant 2018). Furthermore, the study report has no data on pre-treatment crime rates or the actual illuminances present in the treated and control areas, and ignores the existing lighting in the treated areas. The derived results indicated as much as a 39% reduction in nighttime index crimes (includes murder, robbery and aggravated assault, as well as certain property crimes). On this basis, over 300 new lights at a cost of $80 million USD were installed subsequently at the NYCHA complexes in 2016, replacing the existing and temporary lighting in the treated areas and apparently also the existing lighting in the control areas. The changes to the control areas will greatly increase the difficulty in quantifying any actual change in crime from the permanent relighting. Dubbed “safety lights”, the new lights are part of the Mayor’s Action Plan for Neighborhood Safety, which assumes that increased lighting will decrease violent crime in public housing. This large permanent increase in lighting has certainly not reproduced the impressive results claimed in the earlier trial; instead, it is difficult to discern any changes at all (Bittle and Craven 2018). Dechesne (2018) independently examined this case and concluded that the noisy and obtrusive generator-powered light towers used in the initial trial probably reminded potential criminals that the area was part of a crime study, thus changing their behaviour and explaining the observed initial crime reduction of as much as 39%, which can now be seen as an improbably large result that should have been discounted at the outset.

Overall, the project has cost $110M USD and doubtless will turn out to be a health and environmental fiasco as well: all of this because of the depth of belief in the myth of lighting for crime prevention.

## 7.6 Lighting and Road Accidents

This matter is discussed in Section 7.3 of Clark (2003), part of which is reproduced here.

Traffic safety people often express a desire for more road lighting as an accident countermeasure. Present lighting levels and extent of coverage are largely limited by capital and running costs. The case for street lighting has often been bolstered by claims that it adds security, but that claim can now be dismissed as counterproductive or at least ineffective in the case of actual crime.

Are the traffic safety people right? Their belief in the value of more light does have a rational basis in that visual performance at night is lower than by day and it generally improves with increased artificial lighting, even when accompanied by glare from semi-cutoff luminaires. Furthermore, the International Commission on Illumination (CIE) has examined the problem and pronounced that street lighting is an accident countermeasure (CIE 1992). Reasons given for this are:

* The rate and severity of traffic accidents at night are reliably greater than by day.
* Visual performance degradation by low light levels is considered to be the main reason.[[23]](#footnote-23)
* Statistically significant reductions in traffic accidents at night usually occur after street lighting is installed or increased.
* In round figures, up to a third of the accidents at night on unlit roads are considered to have been avoidable by the installation of street lighting.

Such reasons would appear to put the issue beyond contention, but the matter is not straightforward. There are some parallels with the lighting and crime situation. Firstly, there are non-light-related differences between day and night. In the driving case, these include practices that could also have some tangible adverse effect on driver performance, eg people appear more likely to consume alcoholic drinks after the end of their daytime work, in the evening and at night. Conditions at night, not only dim light but low periods in relevant circadian rhythms, tend to be conducive to reduced alertness, drowsiness and falling asleep.

Secondly, field evaluations of increased lighting with poor experimental design or funding by vested interests, or both, may have had undue influence in assessing the degree to which road lighting is a night traffic accident countermeasure. For example, the installation of brighter lighting at accident-prone sections of roads without adequate experimental controls invites false beneficial results because of the effect of regression to the mean. Many of the existing lighting and accident studies would appear to have a low rating on the Marylands Scientific Methods Scale (eg Madaleno and Waights 2015), meaning they were of poor design and questionable reliability. Although about 85% of the studies investigated by the CIE claimed lighting to be beneficial, only a third of these had statistical significance.

Thirdly, it is hard to have confidence in the claim that lighting has a beneficial effect on traffic safety while sections of the motor vehicle industry persist in claiming that the use of large windshield rake angles and all-over tinting[[24]](#footnote-24) along with other tinted glazing has no effect on the accident rate. As windshield transmittance specifications typically set a minimum of 70 or 75% at normal incidence, the light transmitted in practice by a typical clean original-equipment tinted windshield with a large rake angle can be as small as 50%, compared with up to 92% for a clean untinted windshield at a small rake angle (Clark 1995). The combined effect of tinting and large rake angle can thus be equivalent to as much as a 45% reduction in road lighting and vehicle headlighting. The presence of water or dirt or both on the glass may make the relative loss even larger. In effect, the pro-tinting case is tantamount to claiming that halving street lighting *and headlighting* would not increase the night accident rate. That claim does not appear to have been adequately countered, maybe because the loss actually caused is near zero or at least smaller than that claimed by the pro-lighting camp.

Given the disproportionately large rate of traffic accidents at night, it appears to be undesirable that the respective proponents of tinted glazing and more street lighting are allowed to continue the standoff that sees both sides continuing to have their own way at what is possibly a terrible net cost to the public.

Van Bommel (2015) demonstrated how blue-rich light sources such as high-CCT (ie blue-rich) LEDs can improve visual task performance compared with blue-poor light sources such as High Pressure Sodium (HPS), which is commonly used for main road lighting in Australia and elsewhere. This result is consistent with findings of lighting research laboratories in Europe, UK and USA that driver reaction times are faster when high-CCT LEDs are used for road lighting. The laboratories use this argument to justify road lighting change from HPS to high-CCT LEDs. However, Van Bommel pointed out a serious flaw in this conclusion, insofar as the well-known yellowing with age of the crystalline lens in the human eye results in substantial apparent dimming of the bluer source when observed by older drivers, negating the apparent advantage. In his view, such changeovers are therefore not justified by the research on reaction times. It should be noted that van Bommel has been a leading contributor to the CIE for several decades.[[25]](#footnote-25)

The CIE still maintains that road lighting is beneficial in helping to reduce the number and severity of road accidents at night. Few researchers in the field would dispute the notion that road lighting produces a useful improvement of visibility for drivers at distances and lateral positions outside the useful range produced by headlights. However, differences of opinion still arise as to how much and where roadlighting is required in practice.

Assum, Bjørnskau, Foss et al. (1999) showed that increased road lighting led some drivers to drive faster and reduce concentration on the driving task. They suggested that the effect of this in increasing the accident rate tends to be hidden by the present increase in the population proportions of elderly people and of women, who tend to drive more slowly.

Plainis, Murray and Pallikaris (2006) pointed out that a disproportionately large number of fatal road accident injuries occur after dark. Probably because of the poor temporal response characteristics of rod photoreceptors, low luminance is believed to play a major role in this effect. Processing information based on targets with low luminance and low contrast is much slower than that for high contrast bright targets. Simple visual reaction times were measured under typical low visibility conditions encountered on non-lit roads and were found to be substantially longer than under optimal conditions. Longer reaction times translate into significantly increased stopping distances. Introducing road lighting leads to an approximate three times decrease in the severity of injuries both in the UK and Greece, despite the fact that these countries have dramatically different injury rates.

The Steinbach-Perkins studies mentioned in Section 7.4 above also tested for effects of lighting reductions on road traffic injuries as well as crime in many parts of England and Wales. The interventions were complete switch-off, part-night switch off, dimming and replacement of HPS lamps by white lamps or LEDs. The data were road traffic injuries for 13 years and crime for 3 years in 62 English municipalities. Both studies found little evidence of changes resulting from the interventions in relation to road traffic injuries, showing that factors other than visual performance controlled the relation between road accidents and time of day. This casts doubt on the claims of Plainis, Murray and Pallikaris (2006) and mirrors the situation in the case of crime in Section 7.4 above.

Jacket and Frith (2013) used the ratio of nighttime to daytime road accidents in New Zealand as a measure of the effect of adding lighting. They found a 19% to 56% reduction in night crashes for every 0.5 cd/m2 increase in lighting. Making allowance for the mean reflectance of the terrain, say 40%, the illuminance equivalent of this increase is approximately 4 lux. Starting from an illuminance of say 8 lux, each increase of 4 lux is expected to result in a reduction of road accidents to between 0.81 and 0.44 of the initial value. Four successive increases, say, to 24 lux (added here rather than compounded) should therefore reduce the accident rate at what was an 8 lux location to between 43% and 4%, so that increasing lighting to early twilight conditions could be much less dangerous than full daylight! Worse, starting from 8 lux, two successive reductions of 4 lux would result in total darkness. This method of justifying and designing road lighting can thus lead to wildly excessive predicted benefits or some other nonsense result, but it was accepted uncritically by the *Roadmap* (IPWEA 2016).

This result prompts an examination of the method used by Jacket and Frith, viz relation methodology. Basically, CIE light technical measures (eg luminance, uniformity etc) were measured at a variety of road locations. The results were matched with five years of crash history to provide a quantitative measure of the night-to-day crash ratio for each variable. This allows the reduction in crash ratio to be calculated for a given increase in lighting, or the increase in crash ratio if lighting is reduced for reasons of economy or greenhouse gas emissions reduction. The method depends on the unsupported and untested assumption that the crash rate is actually dependent on lighting characteristics rather than these two factors having independent or nearly independent 24-hour cycles.

Figure 4 is for all road casualties per hour in Great Britain averaged over time of day for Mondays to Thursdays in 2017. Its maxima at 9 am and 6 pm coincide with the morning and evening travel peaks. The curves for Friday, Saturday and Sunday are somewhat different in the daytime and evening, showing how social factors including traffic volume have a large effect. There is no apparent connection between the casualty curve in Figure 4 and the illumination curve in Figure 1, even when account is taken of the daily variation in traffic density. Presuming that the daily course of crime in the UK is more-or-less like that in the US,[[26]](#footnote-26) these results are fully consistent with the almost complete absence of any effect of lighting on the crime rate and on road casualties found in the two Steinbach-Perkins papers.

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Figure 4. Number of all types of reported road casualties per hour in Great Britain averaged over Mondays to Thursdays in 2017 (Gov.UK 2019a,b)

# KEY ISSUES FOR FUTURE ARTIFICIAL LIGHTING

## 8.1 Maximum Colour Temperature

The *Roadmap* (2016) explains that the present widespread adoption of 4000 K LED streetlights in Australia stems from a 2014 decision by Standards Australia when suitable LEDs with lower CCTs were not readily available. By 2016 there were increasing numbers of commercially available LEDs of 3000 K or less. Now (2019) because of the growing global demand for blue-poor lighting they are available down to 1800 K. In considering evidence regarding choice of CCT, the *Roadmap* quotes the then-new policies adopted by the American Medical Association (Kraus 2016):

1. That our AMA support the proper conversion to community-based Light Emitting Diode (LED) lighting, which reduces energy consumption and decreases the use of fossil fuels.

2. That our AMA encourage minimizing and controlling blue-rich environmental lighting by using the lowest emission of blue light possible to reduce glare.

3. That our AMA encourage the use of 3000 K or lower lighting for outdoor installations such as roadways. All LED lighting should be properly shielded to minimize glare and detrimental human and environmental effects, and consideration should be given to utilize the ability of LED lighting to be dimmed for off-peak time periods.

The *Roadmap* also summarises US Department of Energy (DoE) responses (Brodrick 2016; Kinzey 2016) to the AMA:

* Colour temperature does not accurately provide the measure of blueness attributed to the potentially harmful aspects of lighting (the melanopic content)[[27]](#footnote-27). Light Spectral Power Distribution (SPD) provides the best scientific measure,
* Using SPD, it is clear that almost all street lighting has some blue light content with these potentially harmful lights including yellow HPS lighting,
* The potential for harm to humans is highly dependent on the intensity of the light source and the time exposed to the light. Neither of these important issues were identified in the AMA report.

As the US DoE is then quoted, “The ‘raw’ melanopic content produced by a light source is only one contributor to any ensuing environmental health impacts actually realised. Focusing exclusively on a single measure ignores the various means of offsetting the increased melanopic content of white light sources, and particularly those that are enabled by LED technology such as improved photometric distribution, dimming capability etc.”

The US DoE does not appear to understand that a truly safe ecological and human health and wellbeing level of ALAN is much lower than can be provided by any practical light distribution, dimming and duration of 4000 K streetlights. Using Table 1 in Kinzey (2016),[[28]](#footnote-28) changing from 4000 K LED to 3000 K LED would reduce the melanopic content of the light by about one fifth. The problem with the AMA argument is that it was limited by LED availability to 3000 K at the time, giving just a one-fifth reduction in melanopic light compared with an equally (scotopic) bright 4000 K LED. Even dropping to 2700 K gives only a one-third reduction. But a reduction by two-thirds can be gained by using a 2100 K LED. On this basis, replacing the 2040 K HPS streetlights commonly used on Australian main roads at present by LEDs with higher CCTs appears likely to result in increases in the breast cancer rate and in the rates for the other ailments already mentioned.

Note that the Board of the Illuminating Engineering Society also disagreed with some aspects of the AMA’s 2016 statement (IES Board 2017). It did not mention the apparent conflict of interest that arises from the connection between the installation of more and brighter lighting and the income of its members. This is in stark contrast to the AMA’s altruistic efforts to improve health and wellbeing.

The acceptable proportion of blue light emission by street and other outdoor lighting was considered at length in November 2009 by the UK Royal Commission on Environmental Pollution (RCEP). It found that light pollution, light spill and glare should be reduced greatly and recommended, inter alia, that unless and until supported by further biological studies, replacement streetlights should not use lamps that emit more blue light than the low levels produced by existing high pressure sodium lamps (with matching illumination implied) (UK RCEP 2009). No progress on this topic is mentioned in the UK Government’s 2013 report on implementation of the RCEP findings, so the recommendation presumably still applies. Note that an international working group of experts in Spain in 2007 had already recommended unequivocally that “Lamps that emit more energy in the blue than standard high-pressure sodium lamps should not be installed outdoors”. It is regrettable that neither the AMA nor the US DoE cited UK RCEP (2009), particularly as its recommendation is cast in terms of spectral power distribution.

The final mention of CCT in *Roadmap* is in connection with financial modelling. When the modelling was done, commercial catalogue prices were more favourable for LEDs with CCTs of 4000 K and above. Furthermore, moonlight is also about 4000 K, so the specification adopted for future LED installations in Australia has been 4000 K for some years. This should not be taken by readers as endorsing or legitimising the ongoing use of 4000 K LEDs.

So far this discussion of appropriate choice of CCT has related to fixed outdoor lighting. But vehicle headlighting produces a substantial contribution to the overall amount of ALAN, which suggests that limits also need to be applied to headlighting. This case is bolstered by the increasing use of high-CCT headlights and the substantial glare they cause for oncoming drivers, particularly those who are older.

Of all the diseases for which journal papers have found evidence for a causal connection with ALAN, breast cancer is probably top of the list in terms of scientific understanding of the relevant physiological processes. Furthermore, studies of blind, partially blind and sighted women indicate that women with no perception of light have less than half the breast cancer rate of all adult women (OR = 0.43) (Flynn-Evans, Stevens, Tabandeh et al. 2009). In other words, *light is a risk factor in at least half of all breast cancer cases*. Exposure to unnecessarily blue-rich ALAN might therefore be proposed as a proximate cause of the illness, opening a way for victims to seek compensation from individuals or organisations involved in specifying, installing or operating such lights. Of course, the legal aspects of the situation would be a matter for legal experts, one of whom has described how Australian law relating to such actions is open to various interpretations (Stapleton 2011). Regardless, it would not be a pleasant position for anyone to find themselves or their organisation targeted in a legal action relating to a breast cancer case, let alone a class action on behalf of numerous breast cancer victims. Being a victim would be even worse, of course.

Chellappa, Steiner, Oelhafen et al. (2013 investigated sleep structure and ECG characteristics of 30 healthy young participants following 2 h of evening light exposure to 30 lux polychromatic light at each of 2500 K, 3000 K and 6500 K. Exposure to 6500 K light reduced frontal non-rapid eye movement ECG power density and slow wave activity, suggesting that such exposure impacts upon homeostatic sleep regulation. The writer is unaware of whether this is good, immaterial or undesirable. Issues like this can be expected to continue arising.

## 8.2 Colour Rendering

There is a further issue related to CCT: colour rendering. Lighting industry literature often mentions the importance of keeping the CCT high as a way of ensuring that outdoor lighting has a good Colour Rendering Index, CRI. This is of dubious value for most of the tasks performed under such lighting, which was once the near-monochromatic yellow of low pressure sodium (LPS) lamps. Its CRI is effectively zero, but finding one’s car at night in a car park can usually be done under LPS lighting. Individuals with deficient colour vision might be similarly handicapped if relying on colour recognition under high-CRI lighting. To allow better colour recognition, limits were set for the CRI value, which can be as high as 100 with a broad spectrum light source. Somehow this became a reason for the promotion of outdoor lighting with a high CCT. But this is at odds with the fact that the first CIE standard light source, Illuminant A, a 2854 K incandescent lamp, has a CRI of 100!

One of the early but still current requirements for outdoor lighting to have a relatively high CRI relates to specifications for pedestrian lighting. If such requirements relate to a desire for recognition of facial features or skin colour they may be based unwittingly or deliberately on racist notions. Pro-racist specifications need to be expunged from public documents.

## 8.3 Adaptive Roadway Lighting

The *Roadmap* includes a discussion on adaptive roadway lighting. A good deal of notice is taken of Gibbons, Guo, Medina et al. (2014), whose reasoning indicated that that existing CIE-based illuminance specifications for road lighting could be reduced substantially in periods of reduced traffic and potential conflict while maintaining the overall level of road safety. This reasoning is based on the assumption that crashes increase as visual performance decreases with diminishing light levels. However, their Figure 26 showing crash rate as a function of time of day between 1700 hours through midnight to 0700 hours shows a peak at 0200 hours. Accordingly they acknowledged that “some level of crashes will occur regardless of the presence of lighting and may be related to fatigue, alcohol and other factors.” They did not discuss the possibility that “some level of” should have been omitted. If their findings are implemented, it appears highly probable that the accident rate will not change significantly and the project would then be regarded as a success. But the experiment has already been done in the 62 municipalities in England and Wales: the accident rate did not change with dimmed lighting or switched off lighting. The recommendations of Gibbons, Guo, Medina et al. (2014) appear to be of no value because they are based on false assumptions.

The *Roadmap* itself concludes:

The design criteria defined in this report provide the basis for development of a method for selecting lighting level in the roadway based on time and traffic as well as for the implementation of adaptive lighting. These criteria are based on the analysis of safety in the roadway based on the lighting level. General conclusions are as follows:

This research verified a strong relationship between safety and the presence of lighting.

The relationship of the actual lighting level to safety was not as strong as the no-lighting condition. This provides flexibility in the selection of lighting based on design criteria while maintaining the safety level.

The current lighting levels may be higher than required for safety on the roadway. For interstates and freeways, there is a potential to reduce the lighting level by as much as 50 percent from the current recommended practices.

A method was developed, based on previous work, to provide both lighting level selection criteria and a method for adaptive lighting selection.

These conclusions are seriously erroneous. Any subsequent document that relies on it may well end up with a similar judgement. This is not to say that all of the *Roadmap* is bad, but the bad bits need to be eradicated before republication.

## 8.4 Existing and Proposed Lighting Practices

The Australian Standards on road and public lighting (AS/NZS 1158 series) and on controlling obtrusiveness of other outdoor lighting (AS 4282) are the responsibility of a committee whose members and/or their institutions mostly have connections with the lighting industry. The standards make it clear that they were formulated on the basis that outdoor lighting should be provided primarily as a crime and road accident prevention measure, and the recommended minimum illumination for various purposes is set higher as the estimated risks of crime and accidents become greater. The lighting industry in general appears to have ignored, refused to consider or dismissed the contrary evidence and has resisted calls for lighting standards to be rewritten accordingly.

The two Australian standards mentioned are the ones intended to have most relevance to the safety of individuals as it may be affected by visible light at night. Both were revised and the drafts circulated in 2018 for public comment. The final versions were issued in early 2019. Statements about more lighting being needed when the risk of crime is estimated to be high have been moderated somewhat from those in the existing standards but the minimum lighting levels set still appear to be influenced by what the present writer regards as faulty analyses by Painter, Farrington and Welsh. The CIE’s belief in the use of lighting as a road accident countermeasure also appears to have been followed closely in setting light levels in the two standards.

In general, the *Roadmap* appears to be reasonably consistent with the two Australian standards in their current form. However, its content is primarily about the benefits that might accrue from ensuring that future ‘Smart Lighting’ should be provided with integrated ‘Smart Controls’ to enable the road and public lighting networks to be controlled and monitored with ease in terms of being readily able to change or adapt the intensity and other characteristics of all or selected luminaires in particular areas. This makes good sense in terms of being able to provide dimming, switch-offs and other desirable states as may be advantageous, but, like the two standards, it relies on beliefs that now stand thoroughly discredited.

The present document also generates concern that the *Roadmap* includes content that will unwittingly mislead Australian industry and governments by understating the adverse effects of exposure to the blue component of ALAN on human health and on the ecology of much of the Australian terrain.  Apart from the evidence provided above as a basis for this judgement, there is far greater amount of congruent evidence in scientific journals to back up this statement.

As sponsor of the *Roadmap*, the Australian Government has a duty of care to act now to ensure that the *Roadmap* is fully withdrawn, copy by copy if necessary, for far-reaching revision. As it stands, the *Roadmap* has doubtless already helped set up circumstances that must lead to more ill-health in the population, greatly increased Australian Government expenditure on avoidable medical treatment and on futile attempts to overcome an alarmingly increasing rate of biodiversity loss. All Australian governments are wasting an enormous amount of money on lighting for security when the scientific evidence is clear that lighting is not only ineffective for crime prevention (including graffiti) but may actually be counterproductive in some circumstances.  Comparable problems arise from the extensive but futile use of more and brighter road lighting as a supposed road accident countermeasure.

## 8.5 Getting the Amount of Light Right at Night

This work in no way suggests that ALAN should be abandoned outright. Modern society simply could not function without it. The World War 2 blackout in Great Britain showed just how dangerous life could be in the absence of enough light to walk about safely and find one’s way- many were injured by falls and collisions, or drowned in ponds and waterways (eg Clark 2002, p 2). But, misled by myths and racism, encouraged by the genuine effect of a moderate amount of light in reducing the fear of crime, and boosted by commercial and architectural excesses, modern lighting practice has developed somewhat haphazardly if not irrationally to its present stage of gross overuse of ALAN. More and brighter outdoor lighting is a relatively low cost option for politicians seeking voter support. Official safety advice for pedestrians is to choose well-lit streets and places. Lighting is often extended into usually darker areas such as parks and gardens as part of misguided attempts by politicians and others to promote a 24/7 lifestyle in the face of much evidence about the overriding importance of circadian rhythms.

In recent years in Melbourne several young women have been raped and murdered at night while walking home in illuminated but isolated, secluded or deserted places.[[29]](#footnote-29) In each case the attacks had different perpetrators but were all preceded by stalking and they did not take place in or near the darkest part of the victim’s track.[[30]](#footnote-30) Subsequent outpourings of public grief have generally been followed by the local council’s implementation of an enhanced public lighting program in the area or even the whole municipality. Herein lies the problem- lighting can provide a false sense of security and tends to encourage potential victims to make a risky choice and to press on rather than seek some safer alternative. In many instances it would be safer to have less, minimal or even no outdoor lighting rather than more. Responsible authorities also need to be watchful that lighting for pedestrians has not been specified with characteristics intended to facilitate recognition of facial skin colour, a racist criterion.

The term ‘security lighting’ can now be seen as an oxymoron and misleading. Its further use should be strongly discouraged. The term is mentioned in Victorian planning law as providing freedom from appeals against local councils for installing security lighting at heritage properties. Such laws should be discarded, along with the practice of floodlighting the grounds and exteriors of buildings and structures whether of heritage value or not.

Not least of the problems of present outdoor light and lighting is the reliance of the CIE on the value of evolved lighting practices and the compulsion to perpetuate such practices, particularly that of having city centres brightly lit. Many years ago the CIE devised a system of lighting zones ranging from the central city zone as the brightest, through intermediate suburban zones to the rural and environmentally sensitive zones as the dimmest. There is no doubt that retail commerce does well out of bright lighting. Against this advantage, all in the population have a right to darkness at night for health and other reasons. The same may be said for the rest of life on Earth. On the basis of evidence in this document, there is now no advantage to be claimed for bright lighting over minimally sufficient pedestrian lighting in terms of road safety or crime prevention. There is thus no compelling reason for continuance of the CIE system of lighting zones, but there are particularly compelling reasons for at-most minimal outdoor lighting. Lighting zones are still used in the 2019 versions of the Australian/New Zealand outdoor lighting standards but they are more reasonable and useful than the CIE-based lighting zones, and can be considered as transitional improvements.

At best, graffiti is a nuisance. At worst, it promotes intolerance and inequality, can distress property owners and residents and is generally difficult and costly to remove. It is facilitated by outdoor lighting and suppressed by darkness (Clark 2003, p 22), but many local government candidates still campaign with promises to light up graffiti problem places. Such calls need to be exposed as counterproductive and indicative of ill-informed candidates.

Crime is a social and possibly physiological problem, not a lighting problem. If we want to feel safer in a particular place, crime needs to be reduced significantly by dealing intelligently and effectively with the fundamental causes of crime. Much the same can now be said for road accidents.

Not least of the benefits to be gained from this minimalist and evidence-based lighting approach are the improvements and economic benefits it will also bring in reducing anthropogenic emissions of greenhouse gases.

## 8.6 UK and French Approaches to Control of Light Pollution

*United Kingdom*

Apart from the many municipal councils in the UK that have imposed reductions or switch-offs in road lighting in the small hours as a greenhouse gas reduction measure, since 2012 the UK has national legislation that includes light pollution alongside noise and noxious odours as statutory nuisances under the UK Environment Protection Act 1970 (Gov.UK 2019c). Anyone who believes that a light unreasonably and substantially interferes with the use or enjoyment of a home or other premises or injures health or is likely to injure health can lodge a complaint with the local council. The council has to treat the complaint as a prima facie statutory nuisance. If this is upheld the council has to issue a notice of abatement to the owner or operator of the light.

 Artificial light nuisances can be caused by security, sports and decorative lighting and by laser shows and light art if the lighting is abused or I not selected or maintained properly. Light nuisance laws do not apply to airports, harbours, railway and tram premises, bus stations, public transport and goods vehicle operating centres, lighthouses, prisons, military bases and streetlights, most of which tend to be prolific sources of obtrusive effects. Interestingly, there are no set photometric levels for light to be considered a statutory nuisance, which saves local councilors and staff and legal practitioners from the need to struggle with photometric concepts. On the other hand, arbitrary quantitative limits are commonly set for compliance in other fields such as mass limits for building lifts or manual lifting, or limits for road vehicle speeds. This is because quantitative limits are generally much more precise than qualitative limits when an alleged offence is being tested in a court or tribunal.

*France*

The French approach also involves legislation (French Gov 2019) about ‘nuisances lumineuses’, which Google translates as ‘light pollution’. The law covers lighting for transport but not signal, safety, inland security or tunnel lights. It also covers lighting of heritage places, parks and gardens open to the public, outdoor car parks, the built environment and temporary lights used for artistic performances, culture, commerce, sport and leisure. In general, all such non-exempt lighting has to be switched off at 1 am.

Commercial outdoor lighting has to cease within 1 hour of the end of the commercial activity, but storefront lighting can remain on until 1 am or later. Variations are possible in specific cases, such as when the lights are sensor-activated. The maximum colour temperature of outdoor lighting is 3000 K except in nature reserves where it is no more than 2700 K. Excessively intrusive (obtrusive?) light is not permitted in (to enter into?) homes regardless of the source of light. No direct emission of light above the horizontal is permitted in areas around astronomical observation sites and nature reserves. Direct illumination of the water surface is not permitted at lakes, ponds, rivers and sea and the associated public domains except where necessary for safety. The maximum permitted value of illuminance (presumably EH) is as much as 35 lux in urban areas and some circumstances and as little as 10 lux in non-urban areas. In most cases the law will come into force on 1 January 2019. Where exact details are required the official version of the law should be consulted.

*Comment*

Each of the respective governments appear to have framed their approaches around beliefs that lighting is important for crime prevention, security, traffic accident prevention and mobility safety and wayfinding. No distinction appears to be made between the very different effects of lighting on actual crime and fear of crime. Indeed, the French illuminance maxima given all tend to be near the upper end of the range over which lighting can be effective in reducing fear of crime (Boyce, Eklund, Hamilton et al. 2000). Both governments appear to have some awareness of the adverse effects of ALAN on health, wellbeing and biodiversity conservation. But the main driver in both cases appears to be the adverse effects of unnecessary ALAN on the environment, particularly the unnecessary use of electric energy involved and the associated excessive emissions of greenhouse gases.

To date, the Australian approach has largely been set by the lighting industry via its influence on the Australian Standards for artificial lighting. A majority of the population now agrees with the overwhelming view of climate scientists that the present global warming is largely anthropogenic and that mitigation of the effect by substantial reduction of greenhouse gas emissions is urgent. The present Australian Government does not accept these views, however, and argues instead for all available resources to go into growing the Australian economy. Applied to lighting, this approach tends to foster the view that more and brighter lighting is the way to go, turning night into day and enabling a ‘vibrant’ 24/7 lifestyle.

Application of Australian Standards for lighting is largely in the hands of local government, which has a poor record in particular for its efforts in dealing with AS 4282-1997, *Control of the obtrusive effects of outdoor lighting*. It is too early to say whether the revised version, AS/NZS 4282: 2019, will be treated better. In the first nine months since its issue, there have been several instances known to the writer where local councils have refused to act on obtrusive lighting complaints on the grounds that there is no legal requirement to do so. The irony is that the councils themselves have the power to make local laws, including obligations to comply with specific Australian Standards. In the past, more often than not the nuisance involved in complaints about light pollution was seen by council staff as the complainant rather than the offending light. It might take some time before a more rational approach prevails.

# CONCLUDING REMARKS

Parts of the material in this submission overlap topics contained in two documents by others, viz the *Roadmap* (IPWEA 2016) prepared for the Australian Department of Energy and Environment and RSNZ (2018) prepared for the advice of New Zealanders about the issues surrounding artificial blue light in the environment. Some of the journal papers and technical reports cited in those two documents and this one are common to two or all three but most are not, primarily because there is such an extensive literature to draw on. The main differences in the approach are that the *Roadmap* is very much a lighting status quo work based on dogma, bad science and unfounded belief that ALAN reduces crime and road accidents and that the adverse effects of ALAN, especially of its blue component, on health and wellbeing are not well enough understood to warrant major changes to the lighting standards and practices that apply in Australia and New Zealand.

The primary lack of understanding lies not with the medical and scientific researchers involved but others from outside the field who discount the disquieting results of the research, especially when financial conflicts of interest are also involved. Where grudging acknowledgement is made of the medical and biological problems, smart controls are seen as allowing an adequate compromise. But compelling scientific evidence to the contrary exists and the situation is well past the point at which the Precautionary Principle, already enshrined in Australian law,[[31]](#footnote-31) should have been applied. The future success of smart controls will be better ensured if their introduction is based on a more rational balance by the lighting industry between the great social and commercial benefits of ALAN on the one hand and on the other, the often nasty health, wellbeing, environmental and economic costs of ignoring a half-billion years of evolution in a world that has almost always had its bright days interspersed with dark nights.

The ramifications of bad lighting reach further than might be expected. For instance, existing sports lighting installations typically have the capability, with a single exposure of say two or three hours, to trigger the proliferation of otherwise harmless and tiny quasi-static breast cancer tumours, quite apart from the contribution that such an exposure would make anyway to the adverse health outcomes of chronic exposure to all forms of irradiation by artificial sources of blue light at night. The problem is greatest with the bright daylight-level lighting used at night for major sporting events and concerts. Given the current state of knowledge, it appears possible to be able to calculate upper and lower limits for the proportion or number of attendees to a specific event at night who will be diagnosed with breast cancer or other serious outcomes within the following twelve months as a direct consequence of exposure to the blue component of the sports or stage lighting used. Graphs of odds ratios for risks of breast cancer or other maladies as a function of peak overnight melatonin levels[[32]](#footnote-32) are given in the literature. Such graphs could usefully reduce the number of assumptions required in making the calculations.

A solution would be to restrict such events to twilight and to use commercially available yellow-emitting lamps with the small residual amount of blue light output filtered out with long-pass optical filters. The necessarily poor colour rendition would be a problem for some competing sports teams if they have coloured uniforms that look similar under blue-deficient lighting. An alternative would be simply to prohibit all public events including sport and music concerts under bright lights after the end of evening civil twilight, but this would unfairly penalise organisers who do manage to arrange for lighting with minimal adverse biological action.

There is a further issue, this time relating to aged care. Some years ago in the USA bright blue-LEDs were used in a trial to illuminate walkways and doorway surrounds at night in an aged care facility. This would appear to have been hazardous to health and unethical given the state of scientific knowledge at the time. The hazard is now known to be even worse, given its potential as a risk factor for Alzheimer’s disease (eg Sprecher, Koscik, Carlsson et al. 2017). Nothing like this should be allowed to happen in Australia, but well-meaning care givers may already be doing it, judging by the approbation currently accorded to such use of ALAN in popular online literature about aged-care practice.

The rationale for including adverse non-sleep-related consequences of exposure to ALAN in this submission should now be evident. It is a practical issue. By itself, the collective adverse effect of ALAN on sleep alone might not appear sufficient to hold back the flood of ALAN that will keep coming if the *Roadmap’s* ill-advised findings about ALAN and ill-health, crime and road accidents in particular are allowed to go unchallenged. The Australian Department of Energy and Environment needs to be persuaded to withdraw its support for the *Roadmap* report pending a substantial rewrite of its content in line with post-2000 advances of scientific knowledge relating to the nil or adverse effects of ALAN and/or its spectral components on crime, road safety, health, wellbeing, ecology and the environment. The environmental effects include loss of night sky visibility which is of concern for losses in aesthetic appreciation, aboriginal cultural heritage, amateur, professional and public astronomical observations, and STEM encouragement. Sleep disturbance, sleep duration and sleep quality all stand to be ameliorated or improved as a consequence of improved lighting practices, which may well include substantial reductions of intensity, duration, spectral components and unwanted light spill.

Fortunately, RSNZ (2018) is not beset by many of the faults that exist in *Roadmap* (2016). The way is now open for its shortcomings to be addressed in a revised version.

Parts and extensions of the content of this document are being prepared for publication in learned journals.

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# ****APPENDIX 1: Illuminance by time of day at an equinox****

**Method of deriving 24-hour outdoor illuminance curves for latitude -37.8º at an equinox**

Twenty-five observations of EH were made at intervals over the course of 24 hours from the writer’s backyard at Viewbank, a suburb 13 km northeast of the Melbourne CBD in the Australian State of Victoria. The total population of Melbourne is about 4 million. The photometric equipment used down to 0.1 lux was a Hagner EC2 illuminance meter and for 17 lux and below, a Unihedron (2019) Sky Quality Meter (SQM). The SQM indicates stellar magnitudes per square arc second (MPAS), which is convenient for astronomers. Conversion to sky luminance in cd/m2 is given by 10 800 \* 10(0.4\*MPAS) and multiplication by π gives the equivalent EH in lux. The readings from the two instruments were consistent in the overlap region.

The day of the measurements was 24 December 2018, just two days after the southern hemisphere summer solstice, at lunar perigee and 1.5 day past full moon. It was in the middle of several consecutive cloudless days, so that two long intervals between particular data points were reduced by two supplementary observations made on the following two nights. At the solstices and equinoxes, the illuminance curves should be symmetrical about local observed noon. Accordingly, all observations were used in constructing the am curve and a mirror image of this provided the curve for the remaining 12 hours. The curve was then extended for another 6 hours using am data so that the visual impression of the sunset-to-sunrise part of the curve was not affected by a discontinuity at midnight. The daytime data points were reduced in illuminance to allow for the reduced peak altitude of the sun at the equinox and shifted in time so that sunset for the transformed data occurred at 6 pm and sunrise at 6 am. A time shift was applied to allow for Melbourne not being at the centre of the standard time zone but no account was taken of ellipticity of Earth’s orbit. A new data set for describing the curve was read from the curve for integer hours.

Because the moon rose 90 minutes after sunset on 24 December (coincidently, this was about the end of evening astronomical twilight), the measured nighttime portion of the EH curve was asymmetric. The initial part of the curve followed the usual trajectory for a clear cloudless night at the observation site. The sky in its moonless dark phase at this site has been monitored by the writer using the SQM over the past 15 years. In that time there has been a slight trend towards a darker sky, with the trend line for 2019 at 19.15 MPAS. It was thus possible to reconstruct the night part of the curve in Figure 1 to represent the case of a moonless moderately light-polluted sky. As the clear moonless night sky in the sparsely populated parts of Australia and elsewhere can be as dark as 22.4 MPAS, this value was used as the minimum in another reconstructed curve representing a natural dark sky. A third curve was then generated to show a combination of moderate light pollution and the brightest possible full moon. The three alternative curve sections for the night part of the light curve thus represent the sky in three circumstances: one about as dim as possible anywhere, another in its usual moderately light polluted state, and the third is the brightest extreme in which the brightest possible full moon acts together with the usual moderate level of urban skyglow. These curves will assist in helping the reader to understand the effect of adding outdoor lighting in these three environmental conditions.

1. BSc, MAppSc, PhD, DipMechEng [↑](#footnote-ref-1)
2. For example, in the Public Health and Wellbeing Act 2008 (Vic) - Section 6, Precautionary principle: “If a public health risk poses a serious threat, lack of full scientific certainty should not be used as a reason for postponing measures to prevent or control the public health risk.” [↑](#footnote-ref-2)
3. The absolute visual threshold for human vision is even lower, eg Luria (1960). [↑](#footnote-ref-3)
4. Drift here refers to when the insects in question are detached from the floor of the body of water and move with the flow of water. [↑](#footnote-ref-4)
5. Using the relationship E = I/d2 where E is the illuminance produced at distance d by a light source of intensity I, suppose performers on stage are lit to EV = 2000 lux by a lamp 10 m away. If the light found its way instead to a surface where EV is only 2 lux, the distance would be 320 m, and if the illuminance is only 2 millilux it would be 10 km away. This illustrates the surprisingly severe constraints that should be applied to spill from light sources near inland water bodies. [↑](#footnote-ref-5)
6. This could be of some importance in applications of adaptive lighting. [↑](#footnote-ref-6)
7. The trophic level of an organism is the number of steps it is from the start of the food chain it is in. [↑](#footnote-ref-7)
8. Of course, other factors such as a genetic predisposition also play a part in the occurrence of obesity, or indeed in the cases of any other ill-health condition mentioned in this document. [↑](#footnote-ref-8)
9. Kraus (2016) includes the statement “The excessive blue spectrum also is environmentally disruptive for many nocturnal species”. However, it is clear from the literature that ‘nocturnal species’ should read ‘nocturnal as well as diurnal species’. [↑](#footnote-ref-9)
10. See the odds ratio graph by Obayashi et al. (2014) or its reproduction by Moore-Ede and Platika (2019). [↑](#footnote-ref-10)
11. The term ‘melatonin suppression ratio’ was first devised and published by the writer in 2006 (Clark 2009). [↑](#footnote-ref-11)
12. Exceptions are possible, however, by careful optical engineering in which violet, blue, and blue-green light well away in wavelength from the peak of the action spectrum for melanopsin are used to bolster the amount of short wavelength visible light required for good colour perception and colour rendering after melanopic light has been removed by filtration or other suitable means. It is then possible to have two light sources with identical or comparable CCTs and light output but great disparities in their output of melanopic light (eg Moore-Ede and Platika 2019). [↑](#footnote-ref-12)
13. Perhaps it is understandable that companies are not prepared to state the blunt truth that using their screens at night can contribute to the risk factors for serious illnesses such as breast and prostate cancers. But this is hardly any different from the way that asbestos, chemical and tobacco companies avoided, downplayed or only indirectly raised toxicity issues with buyers of their products. Note that the reduced-blue software for night-time screen use currently offered to Windows operating system users is more honestly stated to be in the interests of better sleep, although ‘less compromised’ might be even more honestly stated than ‘better’. [↑](#footnote-ref-13)
14. The writer’s own house lighting is all at 2700 K as a result of a state government-funded free program to replace incandescent lamps by compact fluorescents. [↑](#footnote-ref-14)
15. Marchant (2005) pointed out that the phenomenon of regression to the mean would tend to favour an outcome in which a brighter lighting treatment coincided with an unconnected reduction in crime. Farrington (2004, 2006) carried out various analyses of regression to the mean and concluded that it could cause a 4% per year decrease in crimes in experimental areas, too small to explain the observed effects. [↑](#footnote-ref-15)
16. Related situations arose in later studies by others in which attempts were made to explain ‘mixed’ (ie negative as well as positive) results by claims along the lines that ‘more lighting does reduce crime, but it needs to be used in conjunction with other anti-crime actions such as extra police patrols and improvements in lines of sight for natural surveillance’. [↑](#footnote-ref-16)
17. Intially, Farrington and Welsh called this quantity an Odds Ratio. [↑](#footnote-ref-17)
18. This could be at least partly a consequence of publication bias in which positive results were favoured. [↑](#footnote-ref-18)
19. Severe looting regardless of time of day or night took place in the poorest areas of New York City during the 1977 power failure but the looting characteristics were those of race riots rather than of natural catastrophes (eg Clark 2003, p 29). In the rest of New York City, it appears that crime was reduced by far more than could have resulted from the increase in numbers of police on duty during the emergency. [↑](#footnote-ref-19)
20. If there is any question about the types of crime described collectively as crime in this document, the ‘index crimes’ referred to by the US Federal Bureau of Investigation are the default. They include murder and non-negligent manslaughter, forcible rape, robbery, aggravated assault, larceny over $50, motor vehicle theft and arson. Somewhat different definitions may apply in all-crime reports from countries other than the USA. [↑](#footnote-ref-20)
21. Davies and Farrington (2018) investigated just one area (Maldon) where streetlights had been switched off and found that the switch-off had not caused any increase in the cost of crime. They surmised that this was the result of people being deterred from going out at night. [↑](#footnote-ref-21)
22. Plotting a precise sigmoidal curve such as a logistic function in Figure 3 would have provided some advantages in precision of coordinates and gradients along the curve but such precision could be of little advantage or even misleading at this stage of development of the topic, so the curve was sketched by hand instead. [↑](#footnote-ref-22)
23. Driver reaction times to visual stimuli certainly increase as light is dimmed (eg Clark 1995; Plainis, Murray and Charman 2002). [↑](#footnote-ref-23)
24. This is not about the tint band at the top of windshields. Few people are aware that because of harmonisation of specifications affecting international trade, nearly all original equipment motor vehicle glazing, including windshields, in the last two decades has deliberately introduced light absorption throughout. The resulting light loss and coloration can be more readily seen with pieces of white paper or card held parallel and side-by-side, one on each side of the glass. [↑](#footnote-ref-24)
25. Van Bommel appears to be among the earliest investigators to have set pedestrian lighting standards on the basis of practical trials. Such trials have been repeated many times since, often with reference to the Colour Rendering Index of the various light sources tried. Some of the researchers describe the purpose of such experiments as determining the amount of light required for facial recognition of oncoming pedestrians. In some cases the explanation has gone further and revealed the desire for correct identification of facial skin colour. This, of course, exposes racial stereotyping (or racial profiling according to Mosher, Miethe and Phillips (2002, p 103)). [↑](#footnote-ref-25)
26. Unfortunately, the UK government crime data for time of day found had all been rendered useless for the present purpose because it had been consolidated into 6-hour blocks, as recommended by Felson and Poulsen (2003) to reduce the amount of data stored. This is a classic case of ‘throwing out the baby with the bathwater’. [↑](#footnote-ref-26)
27. The term ‘melanopic’ is derived from the blue-sensitive melanopsin photopigment in the ipRGCs. [↑](#footnote-ref-27)
28. That table depends on the technique of using the ratio of melanopic light from a given lamp to that for an equally bright (scotopic or photopic) 150-W HPS lamp. This method was devised by the writer and first published in 2006 (Clark 2009). Kinzey and others have since used this method without acknowledgement, presumably unwittingly and independently. [↑](#footnote-ref-28)
29. There is no suggestion that Melbourne is more afflicted by such crimes than are other large cities. [↑](#footnote-ref-29)
30. Indeed, in another case a sexual assault victim told the writer that the attack took place about five metres from a solitary street light (an 80-W mercury-vapour ‘flowerpot’), in the brightest part of the whole isolated area. Unfortunately, such key details are usually withheld from public access for privacy reasons. [↑](#footnote-ref-30)
31. For example, in the Public Health and Wellbeing Act 2008 (Vic) - Sect 6, Precautionary principle: “If a public health risk poses a serious threat, lack of full scientific certainty should not be used as a reason for postponing measures to prevent or control the public health risk.” [↑](#footnote-ref-31)
32. For example, see the odds ratio (OR) graphs by Schernhammer and Hankinson (2009) and Obayashi et al. (2014) or the reproductions by Moore-Ede and Platika (2019). [↑](#footnote-ref-32)