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Considerations for lighting in the built environment: Non-visual effects of light

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Abstract

Light is defined as that part of the electromagnetic spectrum (~380–780 nm) that gives rise to a visual sensation. Lighting in buildings, whether through use of daylight or by artificial means, is designed primarily for the visual needs of the occupants and their expected tasks within a given space. However, solar radiation, and, depending on spectral output of the source, artificial radiation, has other effects on human physiology and behaviour. Blue light affects the circadian rhythm, mood and behaviour; at shorter wavelengths in the ultraviolet (UV) the detriments of photoaging and sunburn are balanced by the benefits of Vitamin D synthesis.

Keywords: Daylighting; Melatonin; Circadian rhythm; Ultraviolet; Vitamin D; Erythema

1. Introduction

Buildings, by their nature, create an artificial environment that differs from the ambient conditions outdoors. They provide shelter from wind and rain and the extremes of heat and cold, and are often equipped to provide controlled comfort levels of heat and humidity. Buildings also have internal lighting, to compensate for the restricted natural light that can penetrate the structure, and to allow the occupants to function at all times of day or night. The primary concern in the lighting of buildings has generally been to allow for vision, suited to the room or building usage. However, light has other implications for our health and well-being which merit consideration in the lighting, and use of daylighting, within buildings.

2. Spectral characteristics of daylight and artificial lighting

The source of daylight is the sun. The extraterrestrial solar radiation, approximated by blackbody radiation at 5800 K, is modified as it passes through the atmosphere, losing the shortest wavelengths so that the spectrum at the ground begins in the UVB region (280–315 nm). There is also loss in other wavebands, especially the infrared, due to absorption by water vapour, carbon dioxide and other atmospheric constituents. Fig. 1 shows a typical ground level solar spectrum, peaking in the visible region (400–700 nm) of the electromagnetic spectrum. This is the natural radiation environment within which we evolved, with vision that is most efficient at wavelengths from blue (400 nm) to red (700 nm), although both shorter, UVA, and longer, infrared, radiation can be detected by the human eye in the right circumstances [2].

The intensity of solar radiation, and its spectral shape (particularly in the UV) varies with solar elevation, controlled by latitude, season and time of day. Solar radiation is far from constant, but the hours of daylight and the diurnal variation are very predictable at any location and season. A secondary influence is the weather since cloud can greatly reduce solar radiation at the surface, albeit in a transient and unpredictable way.

Artificial lighting provides a consistent radiation field that can simply be turned on or off. However, it has rather different spectral characteristics to the sun, directed towards allowing suitable visual performance in a simple and economic fashion [3]. Fig. 2 shows the spectra of some typical indoor light sources, a tungsten filament lamp and fluorescent lamp. Note that the tungsten lamp spectrum increases towards the red end of the spectrum and has a large infrared output as well, while the fluorescent lamp peaks at shorter wavelengths, giving the tungsten filament lamp a softer looking more yellow light when

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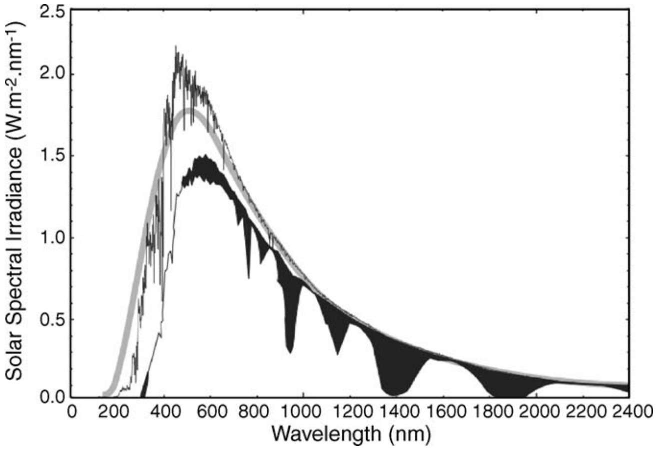

Fig. 1. A blackbody spectrum at 5800 K (grey), extraterrestrial solar spectrum (upper line) and ground level, clear sky solar spectrum (lower line). The shaded area shows absorption regions of atmospheric gases, the general reduction in intensity at the ground is due to Rayleigh scattering. Adapted from Ref. [1].

compared to the fluorescent lamp. Differences in fluorescent lamp spectra are controlled by the mixture of phosphors coating the inside of the lamps, allowing the spectrum to be tuned [4].

These common lighting systems provide the necessary light for vision and can be selected or adjusted to provide suitable illumination for any visual task. However, light has other biological effects that influence human physiology, behaviour and mood [5]. Artificial lighting designed to optimise the visual effect of a space does not take account of these non-visual effects, yet designing buildings that make greater use of daylight and recognise the additional benefits of natural light could have great benefits for the occupants.

3. Non-visual effects of light

Before the advent of artificial light periods of activity were largely controlled by the rising and setting of the sun. Dark periods were for sleep when the body was at rest, and light periods were for activity. Many of our daily rhythms are still attuned to what was a natural cycle of light and dark, and patterns such as the sleep/wake cycle, daily patterns of hormone secretion and body temperature cycles are controlled by light.

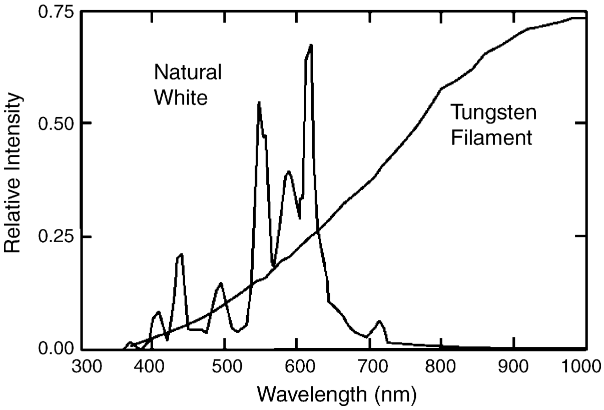

Fig. 2. Spectra of a typical tungsten filament and natural white fluorescent lamp. Data taken from Ref. [4].

The eye remains the portal by which light enters the body for non-visual effects, but it is transmitted by a different system to that which regulates vision [6]. The non-visual light signal goes to the suprachiasmatic nuclei (SCN) that are in the hypothalamus and primarily responsible for regulating daily rhythms through connections to many parts of the central nervous system [7]. One vital and much studied connection is the pathway from the SCN to the pineal gland. The pineal gland synthesises and secretes melatonin in response to the external light–dark cycle, with high levels of melatonin secreted during dark periods (night) and low levels during the day [8]. The circadian rhythm of melatonin secretion becomes entrained to the normal day/night cycle at a location. Significantly changing the external light/dark cycle requires re-entrainment of the circadian rhythm, which takes some days to achieve (one common experience of this is jet lag). Light at night strongly suppresses the expected secretion of melatonin [9], both in humans and many other species.

Since light is observed to elicit powerful non-visual effects it is important to understand which wavelengths of light are responsible for the effects, and how the eye detects these wavelengths—what are the photoreceptors? Primary candidates would be the rods and cones that are active in different aspects of light detection for vision. Studies in mice showed first that mice without rods still maintained circadian rhythms [10], and later that rodless–coneless mice could be phase shifted and have melatonin suppressed by light [11]. Furthermore, in humans melatonin can be suppressed by exposing the eyes to light both in visually blind [12] and colour blind people [13] who have intact neural pathways between eye and SCN. These findings imply that besides the rods and cones for vision the eye has an additional photoreceptor for non-visual effects. Recent studies have identified melanopsin, a light sensitive protein [14–16], found in some retinal ganglion cells and identified in rodent, primate and human retina, as the new photoreceptor. In rodents the responses to light of the melanopsin containing ganglion cells match those for melatonin suppression and light entrainment [17], and the cells have a dendritic network extending to the SCN. Other studies have shown that the rods and cones also have some input to the SCN [18,19]. Thus, the precise roles of rods, cones and melanopsin in the control of circadian cycles remains to be determined, but the additional, non-visual photoreceptor may provide for new methods of lighting to benefit health and well-being.

Several action spectra associated with non-visual effects of light have been studied in both humans and animals. They all peak in the wavelength region from 446 to 488 nm [6]. An action spectrum for melatonin suppression in humans is shown in Fig. 3. It has a peak at 464 nm in the blue region of the visible light spectrum. While the action spectra in other animals and for other endpoints do not match this exactly, the consensus of all these studies is that melanopsin is most sensitive to short wavelength visible light [6,20]. This suggests that light optimised for vision (the photopic response peaks around 555 nm) is not necessarily effective for other non-visual effects, and the specification of lighting environments in lux, that is the

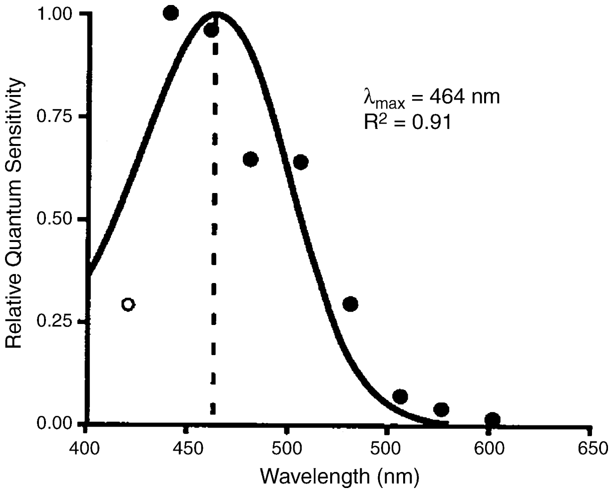

Fig. 3. Data providing the action spectrum for melatonin suppression. From Ref. [6] with permission.

emission spectrum weighted by the photopic response to give a unit of vision-effective radiation, may be inappropriate for other light effects.

The use of light to influence human physiology and behaviour is not yet a priority of general lighting in buildings, but it has been investigated for some specific applications associated with modern lifestyles, and for clinical treatment of disease.

4. Shifts in circadian rhythm

One of the occupational hazards of shift workers is the disruption to their circadian rhythm, both with respect to the ambient day/night cycle, and when shifts change and the personal rhythm must be re-entrained to meet a different schedule. In industrialised nations it is estimated that up to 20% of the workforce are involved in some kind of shift work, and may experience detrimental effects [21]. These include an observed increased risk of accident, higher incidence of cardiovascular disease and gastrointestinal problems, and psychological problems. There is also a potentially increased risk of breast and colon cancer amongst women exposed to light at night, which would include many shift workers [22,23]. Several studies have shown that carefully scheduled periods of exposure to light and dark can help alleviate these problems by assisting workers' circadian systems to adapt to shift patterns [24,25]. However, the application of such a lighting regime is complex [26] and shift patterns, durations and frequency of change vary tremendously from job to job.

Bright lighting has been shown to make people more alert in many (e.g. [27]), but not all [28], studies of this stimulus. Both physiological and behavioural changes were observed by French et al. [29] when they illuminated shift workers on a continuous 30-h shift with bright light (3000 lx compared to the normal 100 lx). Cognitive and behavioural functions were improved and there were significant differences in melatonin and cortisol levels as well as body temperature. The question of whether bright lighting during the day can also improve performance has been addressed in a preliminary study by Noguchi et al. [30] who found that bright lighting in the office (2500 lx compared to 750 lx, provided for 2 h in the morning and one hour after lunch for several weeks) boosted alertness and mood, especially in the afternoon. It also seemed to promote melatonin secretion and fall in body temperature at night, changes that should improve the quality of sleep. Although this work was based on a small number of people and further work is needed, it shows promise for alterations in office lighting in terms of productivity and health of the workers. It is worth noting that temporary lighting levels exceeding 2000 lx are routinely found in typical daylit workplaces (Nabil and Mardaljevic [31]), showing that daylighting can make an important contribution to increased lighting levels for building occupants.

A discomfort experienced by many people travelling for business or pleasure is jet lag. Intercontinental travel that involves the crossing of several time zones in a short period of time disrupts the established circadian rhythm that was adjusted to the home cycle of light and dark. The body must readjust its biological clock, a process that takes several days, depending on the initial phase shift (change in time zones) and the direction of travel (whether the biological clock has to advance to catch up with the new time zone, or fall behind its original rhythm) [32]. Providing light at appropriate times to the jet lagged traveller should in principle help the body to readjust and entrain the circadian rhythm to the new location. Exactly how to achieve this in a practical way is still under investigation. It has been shown [33] that a 3-h exposure to bright white light (3000 lx) from a head mounted visor for two evenings accelerated circadian entrainment in travellers from Zurich to New York. Whether such a treatment can be generalised and optimised is not clear.

More exotic journeying into space is another cause of disturbed sleep/wake patterns and circadian rhythms among astronauts. On long space flights the associated decrease in alertness, reduced concentration and performance can all pose a hazard to the safety of the flight. Preliminary trials with both flight and ground crew have indicated that light treatment can help circadian entrainment [34,35]. Current research [36] is exploring how best to minimize circadian disruption during space flight missions through illumination of the living quarters, and attention to sources of sunlight through windows and space visors. The problems, and maybe the solutions, are similar to those encountered by shift workers.

5. Seasonal changes in daylight

At middle to high latitudes the daylength changes considerably with time of year. At the extremes, within the polar circles, there are periods when the sun never rises, and a mid-summer season when the sun never sets. In general, winter is a time of long nights and short days, with the reverse in summer. This means that the daily melatonin cycle in humans, and some animals, changes with time of year, melatonin being elevated for a shorter time during the summer nights than during the prolonged winter nights [8,37]. This annual changing of the melatonin cycle in response to changes in daylight has been suggested as a cause of seasonal affective disorder (SAD). SAD is a type of depression whose symptoms become apparent during the winter months and disappear in the summer when the days become longer. Reports suggest that anything from 0.4% to 9.7% of the population may suffer from SAD, with up to three times that number having some signs of the affliction without being classified as major depression [38,39]. The symptoms are of feeling low, lack of energy and fatigue, low levels on interest and concentration. They may also include a desire for sleep, and food, with carbohydrate cravings leading to increased weight. The suggestion that short winter days and lack of light exposure is behind SAD led to the use of light as a treatment for this depression [37,40]. Light therapy has proved an effective therapeutic treatment for SAD, although exactly how it works is still not clear. Studies showing that there is a delay in the onset of nighttime melatonin secretion in SAD patients has led to the hypothesis that the depression may be caused by a phase delay in the circadian system [41]. The phase could be advanced by light treatment in the morning and further delayed by light treatment in the evening, so the fact that morning treatment has proved the most effective timing for the light therapy supports this hypothesis [40,42]. The standard treatment trial is to illuminate patients for 30–60 min in the morning with bright light of 10,000 lx white fluorescent light [42]. Responses vary from person to person and the timing may be adjusted to suit the patient. Various methods of delivery of the light have been tried, including headsets and light boxes.

The discovery of a new photoreceptor for non-visual effects of light, with an action spectrum that peaks in the blue, suggests that SAD might be better treated with light rich in the blue wavelengths. A recent clinical study [6] used light panels of blue LEDs (468 nm) in comparison to panels of red LEDs (652 nm) when treating SAD patients. Remission of the depression was found in 55% of those using the blue light panels compared to 31% of those using the red lights. Tailoring the wavelength, or spectrum, of the treatment lights would seem to offer improved efficacy of treatment for SAD, and a blue-enriched "white" light would still allow for normal visual tasks during treatment.

6. Beyond visible light

Fig. 1 illustrates that daylight consists of radiation at wavelengths other than the visible. About half the solar energy is in the visible part of the spectrum. The other half is ultraviolet (~10%) and infrared. Infrared radiation is experienced as heat, and may be considered a by-product of lighting, especially with tungsten lamps (see Fig. 2). Indeed, lights are sometimes used for the purpose of heat as in incubators, or canteens. At the short wavelength end of the spectrum, the ultraviolet, the biological consequences of the radiation become less benign.

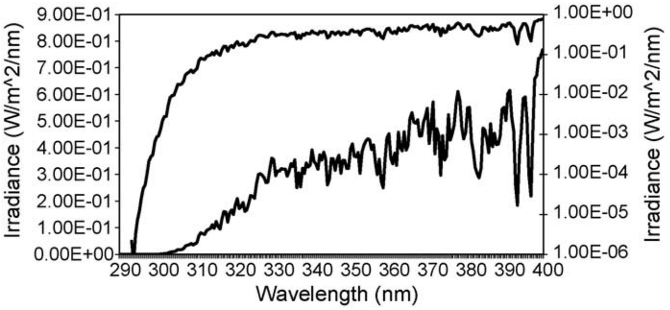

Fig. 4. The UV end of solar spectrum measured at noon in September, SE England, shown on both a logarithmic scale (right axis and top line), linear scale (left axis and bottom line).

Solar ultraviolet radiation at the surface covers the UVA (315–400 nm) and UVB (280–315 nm) wavebands. Ozone in the stratosphere prevents the shortest UVB wavelengths reaching the surface, and results in a very sharp edge to the short wavelength end of the solar spectrum (Fig. 4). The most common experience of (over) exposure to UV radiation is sunburn (erythema). As shown by the CIE action spectrum for erythema [43] in Fig. 5, the UVB wavelengths are most effective at damaging the skin in this way, but UVA wavelengths also have some effect, and are in far greater abundance in sunlight than the UVB. Erythema and cumulative exposure to UV radiation are linked with skin cancers, including the life threatening malignant melanoma [44]. Other undesirable effects of UV radiation include photoaging of the skin, DNA damage and eye damage, e.g. cataracts (cumulative exposure) and snow blindness (acute exposure) [45]. There are also positive effects of exposure to UV radiation. The major benefit is the cutaneous synthesis of Vitamin D, initiated by exposure to UVB radiation (Fig. 5) [46]. Vitamin D has long been recognised as necessary for calcium metabolism and hence a healthy skeleton [47]. More recently there have been claims that Vitamin D can provide a series of other benefits including a protective effect against some cancers (e.g. of colon, breast and prostate) [48–50], a lowering of blood pressure [51], and may also play a role in preventing the onset of some autoimmune diseases such as multiple sclerosis [52] and type 1 diabetes [53]. With mounting evidence, both epidemiological and experimental, to support these claims for Vitamin D, the recommendations for Vitamin D status are being reviewed [54]. As the vast majority of the population get their Vitamin D from exposing their skin to sunlight, rather

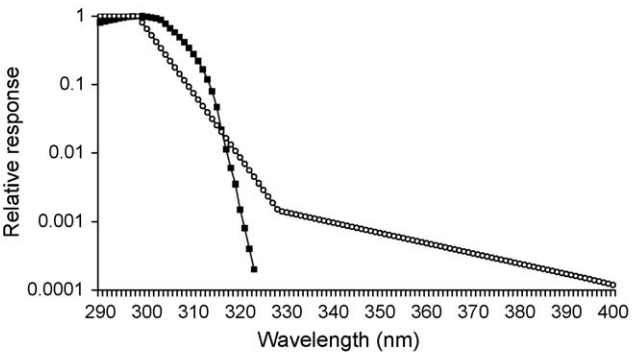

Fig. 5. CIE erythemal action spectrum, open circles [42], and action spectrum for the formation of previtamin D_3 in human skin, squares, taken from Ref. [45] and extrapolated at wavelengths greater than 315 nm.

than diet or vitamin supplements, this has implications for advice on sun exposure.

Lighting, and daylighting, in buildings is generally perceived to exclude significant UV radiation. Common window glass is highly transmissive in the visible but the transmission decreases rapidly across the UV, although the precise transmission spectrum depends on the type of glass and any coatings that have been applied. Sitting in direct sunlight behind a window may provide some UV(A) load, but daylight penetrating further into the room contains little UV and being indoors is usually considered a safe UV environment.

Light sources for general lighting are not usually thought of as UV sources, though Fig. 2 indicates that there is a small UV output from common light sources. Quartz halogen lamps are known to emit UV wavelengths and should be filtered to remove harmful radiation [55,56]. Sayre et al. [57] recently measured the output of a range of common household light sources, in an unfiltered, uncovered state and at a distance of 20 cm (much closer than one would normally come to a light bulb, unless working close to a desk lamp). They found small but measurable output of UVA and UVB radiation from most lamps, including fluorescent lamps, tungsten filament lamps (Fig. 6) and quartz halogen lamps. The shortest wavelength UVB radiation was greater than that in sunlight in some cases (Fig. 7). The work was done in the context of safe lighting for xeroderma pigmentosum patients, who are exquisitely sensitive to UV radiation. The authors conclude that while common lighting may be a risk factor for these patients, for the general public the risks from inadequately shielded, filtered or covered light sources remains very low. In fact, common indoor lighting, used as intended, provides a UV dose that is neither useful (in terms of Vitamin D production) nor harmful (with respect to sunburn and skin cancers) to the normal person. Figs. 6 and 7 show that for wavelengths longer than about 300 nm sunlight exceeds the irradiance from lamps by 2–3 orders of magnitude. At shorter wavelengths the irradiances are anyway very small, and in normal use would be significantly less as the distance between lamp and skin is generally far greater than the 20 cm used for these measurements.

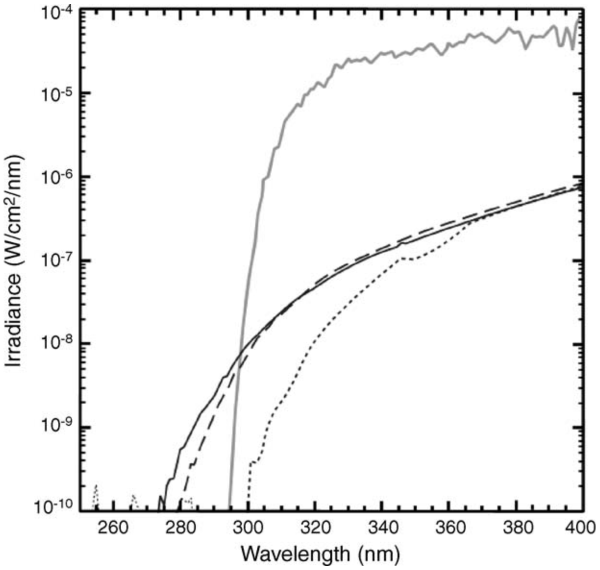

Fig. 6. Comparison of sunlight with selected tungsten filament lamps. Reference solar spectral irradiance (thick grey line), ASTM G173-03 air mass 1.5; the lamps were all 60 W, (—) Wal-Mart Great Value Soft White, (- -) GE crystal clear brilliant decorative and (. . .) GE Reveal. Data taken from Ref. [56].

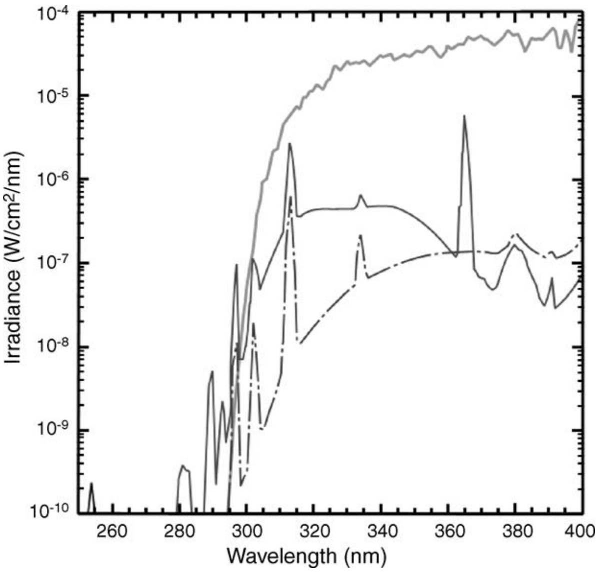

Fig. 7. Comparison of sunlight with selected fluorescent lamps. Reference solar spectral irradiance (thick grey line), ASTM G173-03 air mass 1.5; the lamps were measured at 20 cm, (—) Philips T8 F32T8/TL741 fluorescent lamp and (–·–) Damar Energy Saving Daylight 6400 K compact fluorescent. Data taken from Ref. [56].

Given the risks and benefits of UV radiation it would seem prudent to maintain the indoor lighting situation that has little if any UV radiation from either natural or artificial sources. UVB enhanced lighting has been suggested as a means to increase the Vitamin D status of homebound elderly people who cannot achieve even the brief sunlight exposure that would provide for a healthy Vitamin D status. This raises questions about the safety for carers and nurses if used in a general lighting situation. Boosting Vitamin D status by artificial UVB radiation is possible both for the housebound and for those at high latitudes where for several months of the year there is insufficient UVB in sunlight to enable Vitamin D synthesis [58,59]. However, any such treatments should be given in a carefully controlled situation to maximize the benefits and minimize the risks of UV exposure. In sunlight, sufficient Vitamin D can be made in short exposures at the right time of year, at an overall UV dose that is very much less than that required to get a minimum erythema dose [54,60]. The same should be true of any artificial source considered for the purpose.

7. Conclusion

Solar radiation, daylight, has a range of influences on the human. In addition to vision it controls the circadian rhythm of hormone secretions and body temperature with implications for sleep/wake states, alertness, mood and behaviour (for more in depth cover of these issues see for example [61]). Symptoms of the disruption of these cycles through changes to the natural light/dark cycle can range from temporary jet lag to severe depression. Vision and circadian rhythms are mediated through three photoreceptors in the eye. The skin also responds to incident radiation, synthesising Vitamin D that is necessary for calcium metabolism and a healthy skeleton, plus a range of other potential benefits. Solar radiation can also cause photoaging of the skin, and in excess will result in sunburn and increased risk of skin cancer.

All these non-visual effects have action spectra that differ from that of vision. Mood seems to be most responsive to blue light, while the effects on the skin are the result of UV radiation. Thus, measures of light for vision using a photopic weighting of the incident spectrum (i.e. using a luxmeter) will not provide any indication of the efficacy of the radiation for any non-visual effects. Solar radiation is naturally rich in the short wavelength (blue) radiation that regulates the circadian system, so returning buildings to a more natural light environment through additional use of daylighting would be an energy efficient way to address the current imbalance towards vision. The increased use of daylight and careful tailoring of the lighted environment has potential for both health benefits and increased safety and productivity. However, consideration must be given to the full spectrum of the radiation in the environment, and a delineation made between clinical or therapeutic lighting (e.g. with significant levels of biologically effective UV) and lighting for general purposes. For example, daylighting design can be used to promote occupant alertness during the working day through well timed periods of high light levels, but that does not make it a treatment for SAD for which brighter lights and different timing are required.

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