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The Impact of Light in Buildings on Human Health

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Light · Health · Buildings · Radiation · Visual system · Circadian system

Abstract
The effects of light on health can be divided into three sections. The first is that of light as radiation. Exposure to the ultraviolet, visible, and infrared radiation produced by light sources can damage both the eye and skin, through both thermal and photochemical mechanisms. Such damage is rare for indoor lighting installations designed for vision but can occur in some situations. The second is light operating through the visual system. Lighting enables us to see but lighting conditions that cause visual discomfort are likely to lead to eyestrain. Anyone who frequently experiences eyestrain is not enjoying the best of health. The lighting conditions that cause visual discomfort in buildings are well known and easily avoided. The third is light operating through the circadian system. This is known to influence sleep patterns and believed to be linked to the development of breast cancer among night shift workers.

There is still much to learn about the impact of light on human health but what is known is enough to ensure that the topic requires the attention of all those concerned with the lighting of buildings.

Introduction

This review is concerned with the impact of light in buildings on human health. From the start, it is necessary to explain what is meant by the terms light, buildings, and health. Light is conventionally defined as electromagnetic radiation in the wavelength range 380–780 nm. However, most light sources used in buildings produce both ultraviolet and infrared radiation as well as visible radiation. In this situation, the simplest approach is to consider light to include these wavelengths as well.

As for buildings, these can take many forms but the ones of interest here are those where people are likely to be present for prolonged periods. Even these can vary widely in the nature of the occupants and the type of lighting provided – from schools to hospitals, from factories to homes, from offices to shops.

Health is defined by the World Health Organization as "a state of complete physical, mental and social well-being and not merely the absence of disease and infirmity". Well-being is defined by Webster's dictionary as "a good or satisfactory condition of existence; a state characterized by health, happiness and prosperity". The problem with such definitions is that they are so wide as to be virtually meaningless. On the basis of these definitions, there are very few events or features of an environment that would not influence health and well-being, lighting being just one of many. Here, health will be more strictly defined as the

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absence of disease or infirmity. Further, the effects on health considered are restricted to those where there is scientific evidence for the importance of light exposure rather than conjecture.

Having defined these terms, it is now necessary to consider two other factors that influence the impact of light on human health. These are the health status of the people exposed and the types of lighting to which they are exposed. In this paper, attention will be given to people who are healthy and to groups of people who have conditions that make them sensitive to light exposure. As for the forms of lighting, those considered here are what might be called the conventional, that is, those designed to enable people to see and that follow the recommendations made by authoritative bodies [1,2]. This excludes some forms of lighting designed to use light as a source of radiation for industrial or medical purposes or for entertainment.

There are three routes whereby exposure to light can influence human health, as radiation on the eye and skin, through the visual system, and through the circadian system. Each is examined in turn.

Light as Radiation

People typically spend many hours in buildings bathed in the ultraviolet, visible, and infrared radiation produced by natural or electric lighting. This radiation can damage tissue regardless of whether or not it affects the visual and circadian systems.

Tissue Damage by Ultraviolet Radiation

Exposure to ultraviolet radiation affects both eye and skin. For the eye, exposure to ultraviolet radiation can produce photokeratitis of the cornea. This is a very unpleasant but temporary condition that can result in severe pain beginning several hours after exposure and persisting for 24 h or longer [3]. The symptoms of photokeratitis are clouding of the cornea, reddening of the eye, tearing, photophobia, twitching of the eyelids, and a feeling of grit in the eye. Typically, all these symptoms clear up within about 48 h. Photokeratitis occurs because of a photochemical reaction to ultraviolet radiation at the cornea, but not all the ultraviolet radiation incident on the eye is absorbed at the cornea; some reaches the lens. The effect of exposing the lens to ultraviolet radiation can be to produce a cataract, an opacity that absorbs and scatters light, thereby severely degrading the retinal image. This can occur over two time-scales: acute, a few hours after exposure; and chronic, after many years of exposure.

Exposure to ultraviolet radiation also has an effect on the skin. Within a few hours of exposure, the skin reddens. This reddening is called erythema. Erythema reaches a maximum about 8–12 h after exposure and fades away after a few days. High-dose exposures may result in edema, pain, blistering, and, after a few days, peeling of the skin, that is, sunburn. Repeated exposure to ultraviolet radiation produces a protective response in the skin in that pigment migration to the surface of the skin occurs and a new darker pigment is formed. Coincident with this, the outer layer of the skin thickens producing a tan. It is just as well this screening process occurs because frequent and prolonged exposure of the skin to ultraviolet radiation is associated with skin aging and increases the risk of developing certain types of skin cancer [4].

Tissue Damage by Visible and Near Infrared Radiation

Electromagnetic radiation in the wavelength range 400–1400 nm can damage the retina of the eye by heating the tissue. This effect goes under the name of chorio-retinal injury. Such injuries have a long history, mostly derived from looking directly at the sun for a prolonged period. The main symptom of chorio-retinal injury is the presence of a "blind spot" or scotoma in the area where the absorption occurred. The location of the injury is important. If it occurs in the fovea, then it severely interferes with vision. If it is small and occurs in the far periphery, it may pass unnoticed. Recovery from chorio-retinal injury is limited or nonexistent.

The above discussion was concerned with thermal damage to the retina. Unfortunately, there is also the possibility of rapid photochemical damage of the retina occurring following exposure to visible wavelengths. This is called blue-light hazard or photoretinitis. The exact nature of the chemical process by which photoretinitis occurs is not understood but what is known is that it can occur at radiant energy levels less than those required to cause threshold thermal damage. Photoretinitis is rare in practice because normal aversion to very bright lights causes people to shield their eyes or to look away before damage can occur. However, if exposure is sufficient to cause photo-retinitis, the damage is not usually apparent until about 12 h later. Some recovery is possible.

Tissue Damage from Infrared Radiation beyond 1400 nm

Longer wavelength infrared radiation is absorbed in the cornea, aqueous humor, and lens of the eye. The absorbed energy raises the temperature of the tissue where it is absorbed and may, by conduction, raise the temperature of adjacent areas. Fortunately, extremely high corneal irradiances, of the order of $100\,W\,cm^{-2}$, are necessary for changes in the lens to occur within the time taken for the common aversive reaction to occur. Further, only $10\,W\,cm^{-2}$ absorbed in the cornea will produce a powerful sensation of pain that should trigger the aversive response.

As for the skin, the effect of visible and infrared radiation is simply to raise the temperature. If the temperature elevation is sufficient, then burns will be produced. It is important to realise that the focusing process of the eye makes it much more sensitive than the skin to such injury for visible radiation and near infrared radiation. However, the skin and eye are equally at risk from radiation beyond 1400 nm because the ocular media are virtually opaque for these wavelengths and the mechanism for acute damage is thermal. The efficiency with which a given irradiance raises the temperature of the skin depends on the exposed area, the reflectance of the skin, and the duration of exposure. The threshold irradiance for thermal injury of the skin is greater than $1\,W\,cm^{-2}$. Such irradiances are very unlikely to be produced by sunlight or conventional lighting of interiors; so, such sources are unlikely to produce any degree of thermal injury to the skin by radiation. In any case, for anything other than very short exposure times, considerations of heat stress become relevant before thermal damage can occur.

Threshold Limit Values

Given the potential for tissue damage by ultraviolet, visible, and infrared radiation, it should not be too surprising that there are recommended limits to exposure to such radiation [5–7]. These threshold limit values are levels of exposure and conditions under which it is believed, based on the best available scientific evidence, that nearly all healthy workers may be repeatedly exposed, day after day, without adverse health effects [8]. The threshold limiting values take various forms depending on the size of the source of radiation and the exposure time. For some situations, the threshold limit values are based on total irradiance at the eye, while for others they are based on the spectral irradiance at the eye or the spectral radiance of the source, multiplied by a weighting function based on the action spectrum of the damage being controlled.

Hazardous Light Sources

The Illuminating Engineering Society of North America Recommended Practice 27 [7] sets out a system for classifying light sources according to the level of radiation risk they represent. This system has four classes: exempt, and risk groups 1, 2, and 3. Exempt light sources are those that do not pose an ultraviolet hazard for 8 h of exposure, nor a near ultraviolet hazard, nor an infrared cornea/lens hazard within 1000; nor a retinal thermal hazard within 10 s, nor a blue-light hazard within 10,000 s. For light sources where sound assumptions about typical use can be made, the radiometric measurements necessary to evaluate the light source against these criteria are made at a location where the light source is producing 500 lx, or at 200 mm from the light source if the distance at which 500 lx is achieved is less than 200 mm. For light sources where sound assumptions about use cannot be made, the necessary radiometric measurements are made at a distance of 200 mm. Any light source that is assigned to risk groups 1, 2, or 3 must exceed one or more of the criteria used for the Exempt Group. The philosophical basis for risk group 1 (low risk) is that light sources in this group exceed the limits set for the exempt group, but do not pose a hazard due to normal behavioral limitations on exposure. The philosophical basis for risk group 2 (moderate risk) is that light sources in this group exceed the limits set for the exempt group and risk group 1, but do not pose a hazard due to aversive response to very bright light or to thermal discomfort. Any light source in risk group 3 (high risk) is believed to pose a hazard, even for momentary exposures. The criteria defining risk groups 1, 2, and 3 are the same as those for the exempt group but the permitted exposure times are reduced. Lamps falling into any of the risk groups should carry a warning label, indicating the nature of the hazard and suggested precautions that should be taken.

Measurements of incandescent and fluorescent lamps commonly used for the lighting of homes show that such light sources fall into the exempt category and therefore are not a hazard for tissue damage in normal conditions of use [9]. This comprehensive evaluation is consistent with the conclusions of other, more limited, studies of incandescent and fluorescent lamps for ultraviolet radiation [10,11] and for photoretinitis [12]. Table 1 shows the classification of a wider range of light sources used for general lighting [13]. Again, both linear and compact fluorescent lamps fall into the exempt group for all criteria. The 85 W tungsten halogen is also in the exempt group for all criteria but the 500 W tungsten halogen is not, probably because the radiation was measured at only 200 mm from the lamp. This may seem unrealistic but as the lamp falls into risk group 3 on two criteria, the lamp does represent a hazard to people doing maintenance work on the luminaire. Other light sources commonly used for lighting industrial and commercial buildings, such as high wattage high pressure sodium, metal

Table 1. Tissue damage classifications for a number of lamps used for general lighting (E = Exempt Group; RG1 = Risk Group 1; RG2 = Risk Group 2; RG3 = Risk Group 3). All lamps except the 500 W tungsten halogen were measured at the distance at which they produced 500 lx. The 500 W tungsten halogen lamp was measured at 200 mm [13]

Hazard	85 W tungsten halogen	500 W tungsten halogen	37 W linear fluorescent	36 W compact florescent	400 W mercury	360 W high pressure sodium	150 W compact metal halide
UV for eye and skin	E	RG3	E	E	E	E	RG3
UV-A for eye	E	E	E	E	E	E	E
Chorioretinal burn	E	E	E	E	E	E	E
Retinal blue light	E	RG1	E	E	RG1	RG1	RG1
Infrared eye hazard	E	RG2	E	E	E	E	E
Infrared eye hazard with weak visual stimulus	E	RG3	E	E	E	E	E
Thermal damage to skin	E	E	E	E	E	E	E

halide, and mercury discharge lamps, all fall into risk group 1 or 3 on one or more hazard criteria.

It is important to appreciate that these observations about the potential for tissue damage posed by various light sources are generalisations. They should not be taken to apply to all lamps of a given type. For example, while fluorescent lamps used for general lighting fall into the exempt group, there are fluorescent lamps used for sunbeds and for germicidal purposes that are designed to emit considerable ultra-violet radiation and that are not exempt. The safest principle to follow when evaluating the potential for tissue damage from any specific light source is to assume that the source is hazardous unless information suggesting otherwise is available. This is particularly true for light emitting diodes (LEDs), a solid state light source that is viewed by many as the future of lighting in buildings. LEDs that produce the white light required for lighting in buildings are almost always a combination of a blue LED and a yellow phosphor giving a two-peaked spectrum (Figure 1). The problem is that the blue peak falls close to the peak of the action spectrum for photoretinitis. The hazard posed by LEDs used for lighting in buildings can be assessed using the photobiological safety standard issued by the Commission Internationale de l'Eclairage (CIE) [6].

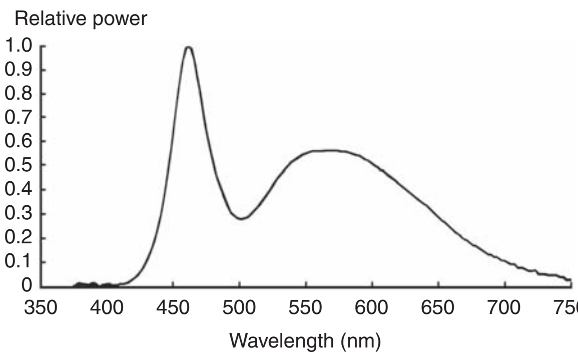

Fig. 1. The relative spectral power distribution of a white LED. This is basically a blue LED with an integral phosphor.

Practical Considerations

The key word in the above discussion of the hazards posed by different light sources is ‘‘potential’’. Whether the potential for tissue damage turns into actual damage depends on how the light source is used. The classification of a light source hazard used [7] assumes a bare lamp viewed directly for a defined time. Light sources are normally used in luminaires, and are rarely viewed directly for an extended period of time. Placing the light source in a luminaire may dramatically change the spectrum of the radiation received by the viewer. For example, the ultraviolet radiation emitted by tungsten halogen lamps can be much reduced by using a glass cover. Dichroic reflectors can be used to transmit infrared radiation while reflecting visible radiation. Different plastics and glasses have very different ultraviolet transmittances. Another factor that will change the spectrum of the radiation received by the viewer is what proportion of the radiation incident comes directly from the light source. The larger the proportion of radiation received after reflection, the more likely it is that the spectral content will be changed, because there is no guarantee that the reflecting surface reflects ultraviolet, visible, and infrared radiation equally. What this implies is that where there is doubt about the risk of tissue damage by radiation from light sources, field measurements of the actual spectral radiance or irradiance are essential.

Aging Effects

In addition to the hazards of exposure to ultraviolet, visible, and infrared radiation discussed above, there are also possible effects of such exposure on the rate at which aging progresses. One example is the possibility of a link between the total light exposure over life and the likelihood of retinal damage. The proposed mechanism is that exposure to light causes damage to the retina. This damage can be repaired but the repair mechanisms become less effective with age, resulting in damage that accumulates more rapidly with greater retinal exposure to light [14,15]. There is no doubt that the probability of retinal deterioration increases with age, and there are close similarities between the changes induced in the retina as a result of the aging process and those elicited by exposure to high levels of illumination [16], but whether it is really exposure to light that is responsible for the aging process in the retina remains open to question.

Risk of Exceeding Limits Using Task Lights

Although many of the effects of light as radiation on human health are well established, the extent to which they occur in buildings is limited. The filtering of sunlight through glass or plastic removes most of the ultraviolet radiation and some of the infrared radiation, the exact amount depending on the chemical composition of the materials. The electric light sources used in buildings produce little by way of hazardous radiation and when they do, they tend to be placed in luminaires far above the places where humans are to be found. Even when humans move close to such light sources, the aversion response to visual and thermal discomfort is usually sufficient to ensure that exposure is limited. The one common form of lighting where light as radiation has been identified as a hazard is the task light. Following measurements of ultraviolet radiation from task lights fitted with tungsten halogen or compact fluorescent light sources, the UK Health and Safety Executive recommend that the use of task lights fitted with unfiltered tungsten halogen lamps for more than 2 h a day should be discouraged when the lights are within 0.6 m of the user. Similarly, it is recommended that the use of task lights fitted with single encapsulated compact fluorescent light bulbs should not be allowed for longer than 1 h at distances of less than 0.3 m.

Light Operating through the Visual System

With light we can see – without it, we cannot. Light is a necessity for the visual system to operate but if provided in the wrong way, it can be injurious to health.

Eyestrain

The most common effect of lighting on health due to the operation of the visual system is colloquially known as eyestrain. The symptoms of eyestrain are irritation of the eyes, evident as inflammation of the eyes and lids; breakdown of vision, evident as blurring or double vision; and referred effects, usually in the form of headaches, indigestion, giddiness, etc.

The symptoms of eyestrain are likely to appear whenever the viewer experiences

- Visual task difficulty, in which it is difficult to extract the required information from the task,
- Under- or overstimulation, in which the visual environment is such that it presents too little or too much information,
- Distraction, in which the observer's attention is drawn to objects that do not contain the information being sought,
- Perceptual confusion, in which the pattern of illuminance can be confused with the pattern of reflectance in the visual environment.

These problems can be brought about either by poor lighting, the inherent features of the task and its surroundings, inadequacies in the individual's visual system, or some combination of these factors. There are two mechanisms by which eyestrain can be caused, one physiological and one perceptual. The physiological is muscular strain occurring in the muscle systems that control the fixation, accommodation, convergence, and pupil size of the eyes. The perceptual is the stress that is felt when the visual system has difficulty in achieving its primary aim, to make sense of the world around us. Conditions that require the eye to be held in a fixed position for a long time or to make frequent movements of the same type are likely to produce eyestrain through muscular exhaustion. Conditions that make it difficult to see what needs to be seen or which distract attention from what needs to be seen are likely to produce eyestrain through stress. Such conditions are likely to be described as uncomfortable. The aspects of lighting that can cause visual discomfort and hence eyestrain are too little light, too much light, too much variation in illuminance between and across working surfaces, disability glare, discomfort glare, veiling reflections, shadows, and flicker [17]. Despite this list, it is important to appreciate that in conditions where the task is visually easy and free from visual discomfort, the visual system can function for many hours without eyestrain. Carmichael and Dearborn [18] measured the eye movement patterns of people continuously reading books printed in high contrast, 10-point print, for 6 h, at an illuminance of 160 lx, expecting to find signs of eyestrain. No such signs were found. Apparently the visual system is perfectly capable of prolonged activity without strain in the right conditions. Even when the conditions are not right, vision does not fail. Rather it protests, but will rapidly recover with rest.

There is a lot of guidance published on what are the right conditions for electric lighting in buildings [1,2]. Some of this advice is qualitative, for example, for avoiding shadows and minimising flicker, while other advice is quantitative, for example, limiting values for discomfort glare and luminance ratios. There is rather less advice published for daylighting in building [19], visual discomfort from windows being dealt with by obstruction of the sun or sky through the use of external shields or canopies or internal light shelves or blinds.

Migraine

Everyone is likely to experience eyestrain in poor lighting conditions but there are some groups of people who are particularly sensitive to lighting conditions. One such group is made up of those who suffer from migraines. A migraine attack is much more than a severe headache. Nausea, vomiting, intolerance of smells, and photophobia are all part of a migraine attack. People who suffer from migraine are more sensitive to light than people who do not, even when they are headache-free [20]. This means people who suffer from migraines are much more likely to experience glare from luminaires and to complain about high light levels. In addition, they are likely to be hypersensitive to visual instability, no matter whether it is produced by fluctuations in light output from a light source, or by large area, regular patterns of very different reflectances [21,22]. The presence of large area, high contrast, regular patterns in an environment is usually the responsibility of the architect or interior designer, but the presence of light output fluctuations is the responsibility of the lighting designer. One way to ensure that light output fluctuations do not cause trouble is either to use light sources that are inherently low in modulation, such as the incandescent lamp, or, if high modulation discharge light sources are to be used, to operate them from high frequency control gear. Wilkins et al. [23] carried out a field study in an office of the effect of replacing magnetic control gear operating from a 50 Hz electricity supply with electronic control gear operating at 32 kHz, on the frequency of headaches and eyestrain. The fluorescent lighting operating from the magnetic control gear had a modulation of about 45% at a fundamental frequency of 100 Hz. The same lamps operating from the electronic control gear had a modulation of less than 7% at 100 Hz. Figure 2 shows the percentage of the occupants experiencing various frequencies of headaches per week when working under the two types of fluorescent lighting. The distribution of headaches per week is strongly skewed. This implies that everybody in the office gets a headache now and again, for all sorts of reasons, but there are a few people who experience headaches two or three times a week. Figure 2 demonstrates that changing from magnetic to electronic control gear does little for the mass of people but does help the people who frequently have headaches. With the electronic control gear, nobody had a headache more frequently than 1.3 times per week. A similar change occurred in the distribution of the frequency of eyestrain per week. Kuller and Laike [24] report a similar pattern in that individuals who had a high critical flicker frequency showed an increased arousal of the central nervous system

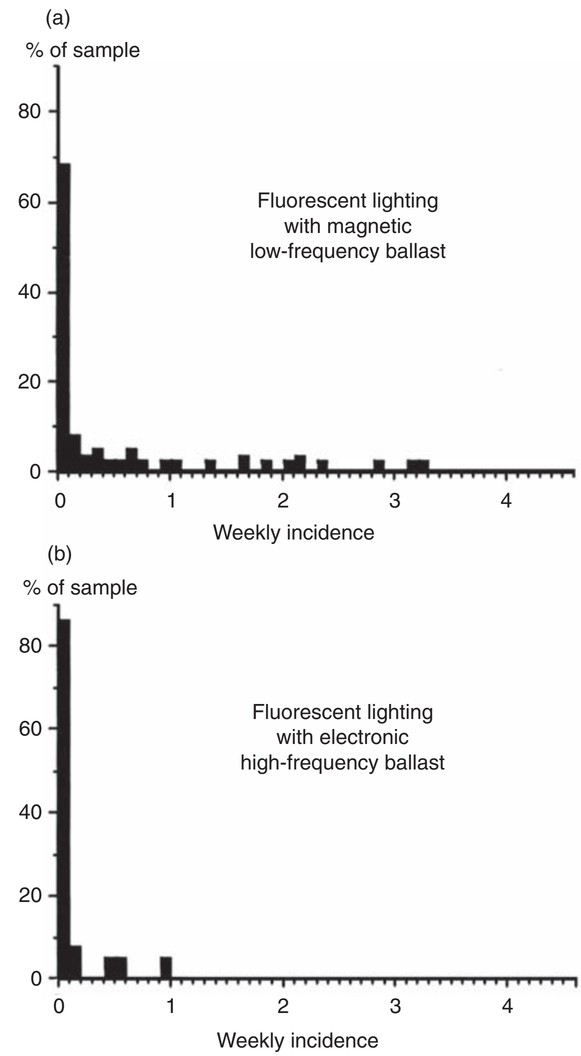

Fig. 2. Percentage of a sample of office workers experiencing different frequencies of headaches per week, while working under fluorescent lighting operated on magnetic (50 Hz) control gear and electronic (32 kHz) control gear (after 23).

when working under lighting controlled from conventional 50 Hz control gear.

Autism

Another group who can be expected to be sensitive to fluctuations in light output is the autistic. Autism is a neurological disorder that affects the ability to communicate, understand language, and relate to others. Symptoms are repetitive activities, stereotyped movements, resistance to changes in the environment, and the daily routine and unusual responses to sensory experiences. The level of arousal of autistic children is chronically high and repetitive behaviours are believed to be a way to regulate it [25]. This implies that an increase in environmental stimulation will generate an increase in repetitive behavior and regular fluctuations in light output can be regarded as a form of environmental stimulation. Observations of autistic children have demonstrated that repetitive behaviour does occur more frequently under fluorescent lighting than under incandescent lighting [26,27]. This suggests that autistics too would benefit from the use of electronic control gear for fluorescent lamps. Care should also be taken to avoid lighting control systems that change light levels suddenly.

Visual Comfort and Human Variability

There have been many years of experience in designing lighting in buildings for the comfortable operation of the visual system. This has resulted in numerous recommendations being published to ensure that lighting does not cause visual discomfort [1,2]. If these recommendations are followed, the vast majority of people will not experience eyestrain. However, even if these recommendations are followed, eyestrain may still occur. The reason is that eyestrain is caused by the visual environment and while lighting is a contributor to the visual environment it is not the whole picture. The colors and reflectances of the surfaces illuminated by the lighting are also important. It is also necessary to appreciate that while the above is true for most people, there are groups of people with enhanced sensitivity to some aspects of lighting. Where these people are likely to be present, the recommendations made may need to be strengthened.

Light Operating through the Circadian System

Circadian rhythms are a basic part of life and can be found in virtually all plants and animals, including humans. The human circadian system involves three components: an internal oscillator, located in the suprachiasmatic nucleus in the brain; a number of external oscillators that can reset (entrain) the internal oscillator; and a messenger hormone, melatonin, which carries the internal "time" information to all parts of the body through the bloodstream. In the absence of light, and other cues, the internal oscillator continues to operate but with a period longer than 24 h. External stimuli are necessary to entrain the internal oscillator to a 24-h period and to adjust for the seasons. The light–dark cycle is one of the most potent of these external stimuli.

The amount of light required to form the light part of the light–dark cycle is measured by the effect of light exposure on melatonin concentration. The spectral sensitivity revealed is different from those of the visual system, having a peak sensitivity at about 470 nm. This difference is due to the fact that the effect of light on the circadian system is primarily mediated through a newly discovered photoreceptor located in the ganglion level of the retina [28,29], although the cone photoreceptors used by the visual system are also involved. Rea et al. [30] have created a model of human phototransduction that enables the percentage melatonin suppression due to the illuminance at the eye from a light source with a known spectral power distribution to be calculated. Figure 3 shows the predicted percentage nocturnal melatonin suppression achieved by exposure to different illuminances from incandescent and D65 daylight[1] for periods of 30 and 60 min using this model. Based on such data, Figueiro et al. [31] have suggested that an exposure of 30 lx at the eye for 30 min should be taken as the threshold for white light to impact

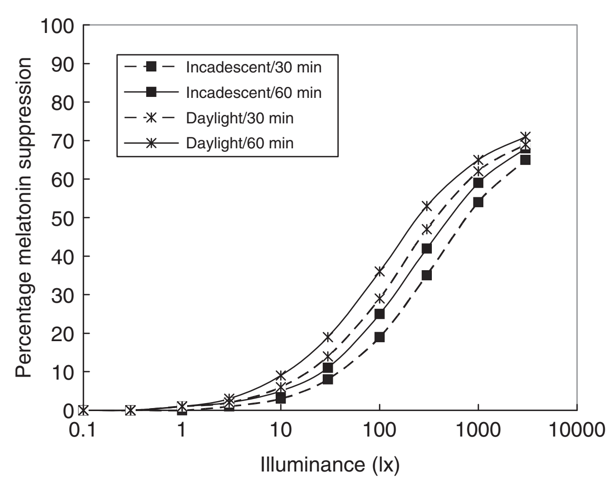

Fig. 3. Predicted percentage human nocturnal melatonin suppression produced by incandescent and daylight illuminances (lx) measured at the eye provided for 30 and 60 min (after [31]).

the circadian system. Of course, this is a gross simplification, the actual threshold varying for individuals depending on their previous history of light exposure and age [32,33]. Nonetheless, as a working hypothesis, it has some interesting implications. For a start, when compared with measurements of vertical illuminances in a range of building types in the USA [31], it suggests that most commercial and industrial lighting is sufficient to act as the light component of the light–dark cycle. Second, it suggests that much residential lighting is insufficient for the purpose of stimulating the circadian system and people who are confined to such interiors may effectively be living in biological darkness. More importantly, it implies that people working night shifts in conventionally lit industrial or commercial buildings and whose circadian system is not fully adjusted to working at night will have their melatonin concentration reduced at the wrong time. There are at least three consequences from such a reduction. First, there is an immediate alerting effect that leads to better task performance [34]. Second, there is the delayed effect of shifting the phase of the circadian rhythm. Depending on when the light exposure occurs, the phase can be advanced or delayed [17]. Third, there is concern that the incidence and rate of development of breast and other forms of cancer are increased when melatonin suppression occurs night after night for a prolonged period [31].

The circadian system operates at a very fundamental level of human physiology. In consequence, it can carry the effects far beyond those normally associated with light. Some of those that have been extensively investigated are discussed below.

Sleep

The sleep/wake cycle is one of the most obvious and important of the circadian rhythms. People whose sleep is disturbed frequently feel permanently tired. There are a number of common sleep disorders. Those susceptible to treatment with light are concerned with the timing and duration of sleep. Those associated with timing are delayed and advanced sleep phase disorders. Delayed-phase sleep disorder is characterised by late sleep onset and late awakening, and is predominantly experienced by the young. Advanced phase sleep disorder is characterised by early sleep onset and early morning awakening and is predominantly experienced by the elderly.

Exposure to light has been shown to be an effective treatment for these sleep disorders. Czeisler et al. [35] have demonstrated that exposure to 10,000 lx at appropriate times, would result in significant phase advances for people with delayed sleep phase disorder and significant phase delay for those with advanced sleep phase disorder. The appropriate times are immediately on awakening for the delayed sleep phase disorder and in the evening for the advanced sleep phase disorder. Campbell et al. [36], in a study of elderly patients with advanced sleep phase disorder, showed not only a phase delay following exposure to 4000 lx in the evening but also an improvement in sleep quality.

As for sleep duration disorders, the classic problems are sleep onset insomnia with normal awakening and normal sleep onset with sleep maintenance insomnia. Both these disorders are common in the elderly [37]. It has also been shown that exposure to bright light in the evening produces longer and better quality sleep for people who were experiencing sleep maintenance insomnia [38,39].

There can be little doubt that exposure to enough light at the right time is helpful in promoting sleep, but what is enough light and what spectrum should the light have? Unfortunately, there are no proven answers to these questions. A wide range of illuminances, from 2500–10,000 lx and a wide range of spectra, from fluorescent lamps to sunlight, have been shown to be effective in the treatment of sleep disorders [40]. Such high illuminances are unrealistic for conventional building lighting but may well be the result of a desire to guarantee a beneficial effect rather than necessary. Given that what is required is to provide an effective light stimulus to the circadian system, it seems reasonable to suppose that by matching the spectral emission of the light source to the spectral sensitivity of the circadian system, a much lower illuminance could be used. Table 2 shows the calculated ratio of circadian efficacy to luminous efficacy for a number of commercially available light sources [31]. The use of blue LEDs would allow the lowest illuminance to be used although the risk of photoretinitis would need to be checked. If white light is required for reasons of user

Table 2. The ratio of circadian to visual efficacies for a number of commercially available light sources, the ratio being scaled so that the ratio for incandescent light source is unity [61]

Light source	Circadian/Visual ratio
4100K Fluorescent	0.72
2700K Fluorescent	0.73
Incandescent	1.00
3000K Fluorescent	1.08
6500K Daylight	2.07
8000K Fluorescent	2.11
7900K Metal halide	2.22
17,000K Fluorescent	3.84
Blue LED	17.60

acceptability, then either daylight or one of the very high colour temperature discharge light sources would be most effective.

Seasonally Affective Disorder

Depression is one of the most common psychiatric conditions in patients visiting a doctor, with a lifetime prevalence of about 17% [41]. Seasonally affective disorder (SAD) is a subtype of major depression that is identified by a regular relationship between the onset of depression and the time of year; full remission of depression at another time of year; the pattern of onset and remission of depression at specific times of the year repeated over the previous 2 years; no nonseasonal depression over the previous 2 years; and episodes of seasonal depression substantially outnumbering nonseasonal depression over the individual's lifetime [42]. Winter SAD is the most common form and can be recognised by the increase in feelings of depression and a reduced interest in all or most activities, typical of depression, together with such atypical symptoms as increased sleep, increased irritability, and increased appetite with carbohydrate cravings and consequent weight gain. These symptoms disappear in summer. Winter SAD is experienced by about 5% of the population and about 10–20% have sub-syndromal symptoms, the percentages increasing with an increase in latitude [43,44]. Winter SAD is more common in females than males. Its prevalence increases with age until about the sixth decade, after which it declines dramatically.

The cause of winter SAD is unknown. Explanations based on disturbances to the circadian system and regulation of the hormone serotonin have been proposed but none have been proven. While the cause of winter SAD is unclear, what is clear is that exposure to bright light is often an effective treatment [45–47]. What is meant by "bright light" is usually exposure for 1 or 2 h to a light box that produces an illuminance at the eye of between 2500 lx and 10,000 lx provided by fluorescent lamps. Again, such high illuminances make it unrealistic to provide the necessary stimulation through conventional building lighting apart from the provision of areas primarily lit by daylight. Where this is not possible, it may be that by using light sources that are effective in stimulating the circadian system, lower illuminances could be used. General guidance on the use of light in the treatment of SAD is available from a number of sources [48,49].

Alzheimer's Disease

Alzheimer's disease is a degenerative disease of the brain and is the most common cause of dementia. Lighting can influence the abilities and behaviour of people with Alzheimer's disease, operating through both the visual system and the circadian system. Alzheimer's patients show a reduced visual contrast sensitivity function relative to healthy people of the same age [50]. This pattern of change is consistent with the reports of cell loss at both retinal and cortical level in Alzheimer's disease [51,52]. It has been argued that such reduced visual capabilities may exacerbate the effects of other cognitive losses in Alzheimer's patients, tending to increase confusion and social isolation. This suggests that enhancing the luminance contrast of the stimulus would improve the functioning of Alzheimer's patients. Gilmore et al. [53] have shown that increasing the luminance contrast does increase the speed of letter recognition by Alzheimer's patients. This finding, suggesting as it does that Alzheimer's patients are struggling to make sense of the world with diminished visual and cognitive capabilities, raises the intriguing possibility that building lighting designed to enhance the capabilities of people with low vision might also be effective in helping people with Alzheimer's disease [17,54].

As for the circadian system, people with Alzheimer's disease and other forms of dementia often demonstrate fragmented rest/activity patterns throughout the day and night [55,56]. This makes such patients difficult to care for and is one of the main reasons for having them institutionalised. Degeneration is evident in the suprachiasmatic nucleus of people with Alzheimer's disease [57] and such patients are less likely to be exposed to bright light [58]. This suggests that exposing Alzheimer's patients to bright light during the day and little light at night, thereby increasing the signal strength for entrainment, would help make their rest activity patterns more stable. Studies using light boxes of the type used for the treatment of SAD [59], a general increase in room lighting [56], and localised blue LED lighting [60] have shown the truth of this suggestion.

Recently, Figueiro [61] has proposed a 24-h lighting scheme for older adults, particularly those suffering from Alzheimer's disease. The aims of this scheme are to provide high circadian stimulation during the day and low circadian stimulation during the night, good visual conditions during waking hours and nightlights that are safe for movement but that minimise sleep disruption. The high circadian stimulation requires at least 400 lx to the eye provided by a white light source rich in short wavelength light, such as daylight or fluorescent lamps with a correlated color temperature of 6500 K or higher. The low circadian stimulation requires less than 100 lx at the eye from light sources with little short wavelength light such as incandescents or 2700 K fluorescents. Good visual conditions can be ensured by following the recommendations made by many bodies to avoid glare, shadows, veiling reflections, and flicker. As for nightlight, this should provide no more than 5 lx at the cornea provided by a light source with little short wavelength light as well as perceptual information that enables people to orient themselves relative to the vertical and horizontal planes. Such information has been shown to improve postural stability [62].

Cancer

So far, all the examples of how light operating through the circadian system influences human health have been positive but there is one that is undoubtedly negative. This is the concern that exposure to light at night is involved with the incidence and development of breast cancer. The incidence of breast cancer has increased continuously since the turn of the twentieth century in industrialised societies [63]. In 1987, it was suggested that the increase could be at least partly ascribed to the suppression of melatonin following exposure to light at night [64]. Support for this hypothesis comes in two forms. The first is a series of epidemiological studies that have shown that night shift work is associated with an increase in breast cancer risk [65,66] and that blind women are at a lower risk of breast cancer than sighted women [67]. The second is the finding that melatonin-depleted blood increases the rate of growth of breast cancer tumors [68]. There is little doubt that repeated exposure to sufficient light to suppress melatonin from its normal concentration has some role to play in the incidence and development of breast cancer but there may be other necessary conditions yet to be established [31,69].

The implications of what we know so far about the effect of light exposure on breast cancer for the lighting of buildings are rather limited. Given that melatonin suppression is necessary for any adverse effects to occur and the threshold for melatonin suppression is about 30 lx at the eye for 30 min [31], the amount of light present when people are trying to sleep or when briefly visiting the bathroom at night is not a problem. However, the illuminances provided in commercial and industrial premises for visual purposes where people are working whose circadian rhythm is not fully adapted are likely to be a cause for concern. One possible solution to the dilemma of providing sufficient light to enable the visual system to operate effectively while avoiding melatonin suppression would be to use light with a spectrum rich in long wavelength light and deficient in short wavelength light, that is, mismatched to the spectral sensitivity of melatonin suppression. Such an approach would be a wise course to take for the lighting of night shift work until the role of light at night on breast cancer and possible other forms of cancer is clarified.

Future Studies

Unlike the visual system where the impact of light is immediate and obvious, the effect of light on the circadian system has a long time constant and is a relatively recent area of study [70]. As a result, there are several important questions that remain to be answered before light operating through the circadian system can be deliberately used in the lighting of buildings [71]. Among them are the relative sensitivity of different parts of the visual field; whether it is the ratio of the light to dark periods that matter; and, most importantly, what effect does light exposure have, if any, on the health of those who live a conventional diurnal life? There is some evidence that variations in the amount and spectrum of light exposure during the day can increase the alertness and feelings of vitality of people living a normal diurnal life [72,73] but what mechanism is involved and how such feelings might impact health in the long term is not yet known.

Implications

Exposure to light can have both positive and negative impacts on human health, impacts that can become evident soon after exposure or only after many years. The luminous conditions likely to be negative for health from light as radiation and from light operating through the visual system are well established. As a consequence, standards have been written to minimise the probability of harm occurring and lighting practice takes them into account. The same cannot be said for light operating through the circadian system. That exposure to light does influence the operation of the circadian system is undeniable but the suprachiasmatic nucleus is connected to many other parts of the brain (Figure 4). These regulate the production of many hormones so that light may have an impact on aspects of human physiology beyond the circadian system [74]. There is also a positive effect of light as radiation. Vitamin D is synthesized in the body by exposure to ultraviolet radiation. Insufficient vitamin D is known to be linked to bone disorders but it is also associated with a higher risk of such scourges as

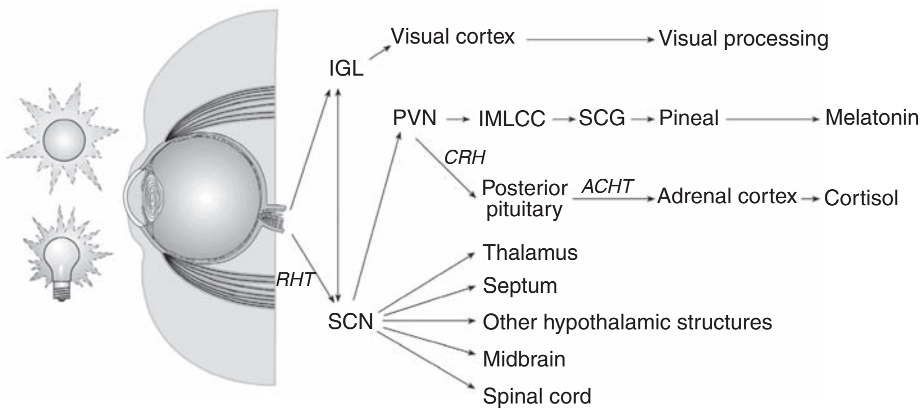

Fig. 4. Schematic diagram of eye-brain pathways. Light received by the eye is converted to neural signals that pass via the optic nerve to two pathways, one visual and one nonvisual. RHT = Retino-hypothalamic tract; IGL = Intergeniculate leaflet; SCN = Suprachiasmatic nucleus of the hypothalamus; PVN = Paraventricular nucleus of the hypothalamus; IMLCC = Intermediolateral cell column; SCG = Superior cervical ganglion; CRH = Corticotropic releasing hormone; ACTH = Adrenocorticotropic hormone. Reproduced with kind permission from the CIE [70].

multiple sclerosis, diabetes, tuberculosis, and many forms of cancer [75].

Clearly, there is still much to learn about the nonvisual effects of light exposure [70,76]. Nonetheless, it is already possible to identify two general implications for the lighting of buildings. The first is that the lighting of buildings should no longer be considered solely in terms of the effects on visual capabilities. The second is that the spectral content of daylight is well suited to stimulate both the visual and the nonvisual systems. Both the visual system and the nonvisual systems have evolved under daylight. The alternative electric light sources have only been available for about a 100 years, a very short time in evolutionary terms. It may be that the main impact of a greater understanding of the role of light exposure in human health will be to return attention to the better daylighting of buildings.

Note

1. Illuminant standard defined by the International Commission on Illumination. D65 corresponds roughly to a mid-day sun in Western Europe/Northern Europe, hence it is also called a daylight illuminant.

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