

BRE Client Report

Report describing initial literature review on circadian lighting

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Executive Summary

Exposure to light, particularly blue light, has been shown to maintain, or potentially alter the body's circadian clock. The lighting industry has recently started to market circadian lighting, using tuneable (most commonly LED) white light sources that can alter their light colour and intensity. The aim is to help maintain correct timing of the circadian clock of the occupants in a space; to improve their alertness during the day or during working hours, then change to lower brightness, warmer coloured lighting when it is time to relax. However little or no research has been done on the best way to control this tuneable lighting under real-world conditions.

With this in mind, a project jointly funded by CIBSE and the BRE Trust 'Circadian lighting effects on health and wellbeing' has been initiated. The project will investigate when is the best time to have the high intensity, cool coloured lighting, and for how long, and when to turn it down and make it warmer. The project aims to find optimal control strategies for circadian lighting to maximise health and wellbeing benefits.

This report, the first output of the project, provides a review of the existing literature on circadian lighting and how this affects human health and wellbeing. It incorporates findings from a workshop on circadian lighting, held at BRE on 29 September 2016 as part of the project. The workshop was attended by leading professionals from academia, manufacturers, lighting designers and public health institutions.

Much recent research has looked at the effects on wellbeing and health of disruption to the circadian clock. Levels of artificial lighting may be too low during the day, or contain insufficient blue light to maintain circadian rhythms. Conversely, inappropriate exposure to light, particularly light at night in the blue wavelength range, is likely to disrupt the circadian system and lead to a range of disorders and health problems. Daylight gives high levels of blue enriched light and changes in colour and intensity over the day, which makes it ideal for modulating circadian rhythms. Various studies have shown positive effects of daylight on health, stress and mood. In principle, exposure to bright artificial light at the correct times of day could have similar effects.

Various studies have shown that during working hours alertness, mood, performance and productivity can be improved at higher illuminances (at least 1000 lux) and under blue enriched lighting. However, research investigating the effects of circadian, or dynamic, artificial lighting systems on health and wellbeing is still scarce. Some studies in office and school environments have concluded that dynamic lighting conditions tend to help improve concentration, performance and feelings of satisfaction and wellbeing.

Nevertheless, a recent CIE document warns that exploiting the non-visual effects of light for health and wellbeing benefits still needs development. The lighting levels for circadian entrainment recommended by several standards may be very difficult, or even impossible, to achieve in most indoor spaces through traditional electric lighting

Based on the literature review, experimental work is being planned in the next phase of the project to determine subjective occupant reactions, and where possible, measures of wellbeing, under different lighting conditions (illuminance level and colour temperature) at specific times of day.



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Introduction

Lighting is a key aspect of the indoor environment. Current SLL publications set out good practice guidance for lighting based on task requirements, the ability of occupants to move around the building easily and safely, and the overall appearance of the lit space. However lighting has non-visual effects, too. Exposure to bright light during the day is important for people to maintain their daily cycle of waking and sleep. Conversely, light of the wrong colour and intensity at the wrong time can be detrimental, suppressing melatonin, the hormone important for enabling sleep. This can potentially cause health problems (Ticleanu et al 2015), including depression, cardiovascular and digestive problems, and even cancer. It is a particular issue for shift workers or for people working late hours.

Recently some lighting companies have begun to market tuneable lighting which can alter its colour and intensity. This has been marketed as 'circadian lighting', or sometimes as 'human centric lighting'. It aims to improve people's alertness during the day or during working hours using bright light, but to switch to lower brightness, warmer coloured lighting when it is time to relax. However little or no research has been done on the best way to control this tuneable lighting under real-world conditions.

With this in mind, a project jointly funded by CIBSE and the BRE Trust 'Circadian lighting effects on health and wellbeing' has been set up to investigate when is the best time to have the high intensity, cool coloured lighting, and for how long, and when to turn it down and make it warmer. The project aims to find optimal control strategies for circadian lighting to maximise health and wellbeing benefits.

This report, the first output of the project, provides a review of the existing literature on circadian lighting and how this affects human health and wellbeing. It incorporates finding from a workshop on circadian lighting which was held at BRE on 29 September 2016 as part of the project. The workshop was attended by leading professionals from academia, manufacturers, lighting designers and public health institutions.

Based on the literature review, experimental work is being planned in the next phase of the project to determine subjective occupant reactions, and where possible, measures of wellbeing, under different lighting conditions (illuminance level and colour temperature) at specific times of day.



Literature review on circadian lighting

Human circadian system

Nearly all plants and animals have circadian rhythms (Karatsoreos et al, 2011). In humans the circadian clock, or body clock, regulates the body's internal processes to the time of day. This controls not just sleep and alertness, but core body temperature, metabolism, hormone secretion, cardiac function and ageing (Kondratova and Kondratov, 2012).

The master clock, or pacemaker, is located in the Suprachiasmatic Nucleus (SCN) of the brain's hypothalamus (Czeisler, 2013). Additional clocks in the brain and the liver serve important co-ordinating functions (Albrecht, 2012).

Most research suggests that light exposure is the key driver affecting circadian rhythms driven by the SCN (Eisenstein, 2013). In addition to the photoreceptor (rod and cone) cells which allow normal sight, the retina contains special cells, intrinsically photosensitive retinal ganglion cells (ipRGCs). ipRGCs produce a photopigment, melanopsin, which transmits signals to the SCN. These signals enable light resetting (entrainment) of the circadian clock to adjust it to the solar cycle, and to synchronise individual cell clocks. Therefore, light exposure is widely accepted as the major time cue, or 'zeitgeber', to synchronise the circadian system (Kantermann, 2013).

Melatonin is a key hormone linked with the 24-hour light-dark cycle that is produced by the pituitary gland of the brain when it is dark, to regulate sleep-wake patterns. Hence the body's level of melatonin is frequently used as a biological marker for circadian impact. Melatonin is also believed to influence regulation of digestive functions (Amaral et al, 2014), and to inhibit breast cancer development (Fonken and Nelson, 2011).

Circadian clocks run differently between individuals (Holzman, 2010). Some people (early chronotypes) get up and go to bed earlier than others (late chronotypes) (Roenneberg et al, 2003). A person's chronotype can be assessed using the Munich Chronotype Questionnaire (LMUM, no date) which considers individual sleep pattern, working hours and lifestyle.

In the complete absence of light, circadian clocks run slightly longer than 24 hours a day for any chronotype, which causes a daily slight delay in waking and sleeping (Rea et al, 2008). A consistent pattern of light and dark enables synchronisation of circadian clocks to the solar day so that waking and sleeping can occur at consistent times (Wright et al, 2013). However, modern lifestyles where people may have limited access to outdoor conditions and increased exposure to electric light, particularly in the evening, can disrupt circadian rhythms and associated sleep patterns.

Impact of light spectrum on circadian rhythms and performance

The spectral composition of a light source affects the degree to which it might affect circadian rhythms and sleep patterns. The retinal ipRGC cells are most sensitive to light at 460 to 480 nm, and melatonin suppression occurs most strongly between 446 and 477 nm (West et al, 2011), which is in the blue light area of the spectrum.

Whereas blue light can improve cognitive performance and alertness, outperforming caffeine in some circumstances (Beaven and Ekström, 2013), blue light at night can be particularly disruptive to the circadian system (Bedrosian et al, 2013). Filtering blue light before sleep has been found to improve sleep quality and mood (Burkhart and Phelps, 2009). Shift workers wearing blue-filtering glasses during night shifts tend to have better performance and sleep quality (Rahman et al, 2013).



Red light appears to be less likely to suppress melatonin and stimulate wakefulness (Eisenstein, 2013). However, Sahin et al (2014) suggest that red light can be used to increase short term performance during the daytime, and other research (Window, 2016) found that red light can improve reaction time in the short term, with no short term benefit from blue light.

The spectrum of daylight is broad but changes over the course of the day. In the middle of the day, the daylight spectrum contains more blue light compared to the late afternoon, when the proportion of red light increases.

Incandescent light bulbs are also a full spectrum light source, but they are much richer in red light and hence impact less on circadian rhythms. The spectra of other types of light source, including fluorescent and LED lamps, tend to be more concentrated in particular wavelengths compared to incandescent bulbs or daylight. The output from white LEDs is typically rich in blue light, and night-time exposure to white LEDs is more likely to cause disruption to circadian rhythms, melatonin production and sleep patterns (Czeisler, 2013). However, blue light at the correct times during the day can also be used to synchronise circadian rhythms, correct disrupted sleep or increase alertness (Arendt, 2012; West et al, 2011).

An adjustable light spectrum can either be used to help preserve normal circadian rhythms where light at night cannot be avoided, or change or reinforce those rhythms to achieve alertness when needed. Since white LED modules are now available which allow dynamic adjustment of the colour temperature by varying the intensity of each individual LED (IET, 2014). Such technology could be an ideal light source for circadian lighting systems.

Circadian disruption and impacts on human health

The wrong light at the wrong time can affect health through melatonin suppression. The amount of light that causes a change in melatonin production is still being studied. Gooley et al (2011) found measurable effects on melatonin levels from exposure to over 200 lux before bedtime compared to dim light of less than 3 lux, whereas Rea et al (2014) suggest that 30 minutes exposure to 30 lux of white light at the eye would be a reasonable and conservative threshold for light to suppress melatonin at night. However, this threshold would vary with the spectral composition of the light source.

The widespread use of electric lighting has led to a shorter night period, resulting in reduced melatonin production in general populations exposed to electric light, and reduced effects of melatonin in preventing formation of cancer cells (Fonken and Nelson, 2011). Kloog et al (2009; 2010) found a positive association between light at night and prostate and breast cancer. A growing body of evidence has associated various cancers with shift work, particularly where schedules include night work. Consequently the International Agency for Research in Cancer classified shift work which involves circadian disruption as potentially carcinogenic in 2007 (IARC, 2010). Circadian disruption is one of the factors raised, alongside others that include smoking, diet, fatigue, and sleep quality.

Whilst breast cancer has been associated with shift working groups such as nurses (Hansen and Lassen, 2012; Knutsson et al, 2013; Schernhammer et al, 2001), other studies have not found the same correlation. Moreover, Knutsson et al (2013) found that only women working shifts that include night work presented an increased risk of breast cancer, but not those who did not do night shifts.

Increased Body Mass Index and obesity have also been linked to circadian disruption (Roenneberg et al, 2012; Young and Bray, 2007).

The retinal ipRGC cells also send signals to the limbic system of the brain, which supports emotion and behaviour, and thus light may also affect mood and cognition. Research has found that exposure to light at night influences behaviour by an alternative route to that of circadian rhythm (Bedrosian et al, 2013), and the disruption of circadian rhythms may lead to various mood disorders, most notably depression (Salgado-Delgado et al, 2011). Moreover, the circadian system is the key target in some treatments for depression, including light therapy.



Besides exposure to artificial light at night, lack of outdoor light in the built environment also affects synchronisation to the solar day (Wright et al, 2013). Daily life schedules and internal circadian rhythms fail to coincide (Eisenstein, 2013; Kantermann and Roenneberg, 2009), which leads to chronic sleep problems that can negatively affect work performance through tiredness and poor concentration. Lack of light during the day means that individuals become more vulnerable to circadian disruption from light at night, for example from light pollution (Kantermann, 2013).

With no light cues to entrain the circadian clock, such as in the case of complete blindness, sleep difficulties are very common (Skene, 2003; Barion and Zee, 2007). Although exposure to bright morning light can be used to ameliorate circadian rhythm sleep disorders (Barion and Zee, 2007; Okawa and Uchiyama, 2007), evening light before bedtime can affect sleep onset and sleep quality (Kantermann, 2013).

Exposure to light at sleep times can also cause direct disturbance, even when it does not affect the body clock. This is can be the case of night workers and shift workers who need to sleep during the day, but also for people who are not able to experience true darkness at night, for example in a hospital environment or due to obtrusive light received through a window. Both circadian disruption and direct impacts of light on sleep can contribute to metabolic disorders and other health problems. However, research data are still limited and the comparative and cumulative effects of poor sleep quality, melatonin suppression and circadian disruption have not been fully separated from each other (Stevens et al, 2013).

The increasing use of electric light has paralleled a rise in sleep deficiency. The average adult sleep duration in the UK was found to be 6 hours 35 minutes (Sleep Council, 2013), with 33% of adults sleeping between 5 and 6 hours and 7% sleeping less than 5 hours. Sleeping either less or more than 7-8 hours in a 24-hour period is associated with risk factors for cardiovascular disease and diabetes, depression, accidents, learning and memory problems, and excess mortality (Krueger and Friedman, 2009). The online Great British Sleep Survey (Sleepio, 2012) identified light levels as being fifth in the list of physical factors that kept the respondents awake.

Exposure to daylight in buildings

Providing daylight in buildings helps achieve the benefits of daytime light in regulating circadian rhythms, which results in improved health and mood (Boyce et al, 2003).

Various studies report healing effects of daylight (Aries et al, 2013; Rashid and Zimring, 2008). Walch et al (2005) studied hospital patients with spinal injuries. Those in bright unobstructed rooms reported less pain and significantly less stress at discharge, and needed significantly less pain medication, compared with patients in dim rooms with an obstructed view. High indoor levels of daylight were found to reduce the patient's average length of stay (ALOS) in a hospital in Korea (Choi et al, 2012). In a similar study in Canada, overall mortality rates in a cardiac intensive care unit were found to be lower in sunny south-facing rooms than in dim north-facing rooms (Beauchemin and Hays, 1998). Patients in a ward having a view of trees were found to recover more quickly than those in a ward with a view of a brick wall (Ulrich, 1984). Using daylight measurements in hospital rooms, Joarder and Price (2013) showed that coronary patients' average length of stay was reduced by 7.3 hours per 100 lux increase of daylight inside their rooms.

Boubekri et al (2013) found that occupants of windowless indoor spaces receive less light overall and report a lower amount and quality of sleep compared with occupants of daylit spaces. Studying young adults in a school in North Carolina, Figueiro and Rea (2010) determined that the onset of melatonin can be delayed by removing short-wavelength light during the morning. Delayed melatonin onset can reduce the amount of sleep in adolescents that need to wake up early for a fixed school schedule, which in turn may lead to poorer academic performance. Randler and Frech (2006) found that school students who naturally wake up earlier tend to perform better academically. Additionally, exposure to bright daylight as children grow has also been found to reduce the risk of them developing myopia (short sightedness) (Lougheed, 2014; Morgan et al, 2012; Wu et al, 2013).



Mood and depression are affected by exposure to bright light. Whilst daylight has mood-enhancing effects, the general preference is for sunny and bright environments (Beute and de Kort, 2013a). Daytime exposure to bright light can improve performance and reduce subjective sleepiness (Kaida et al, 2007; Phipps-Nelson et al, 2003). Also, there is a direct and immediate interaction between bright light and serotonin (aan het Rot et al, 2008a), which is a hormone that influences mood. Thus exposure to bright daylight can improve mood and pleasantness (aan het Rot et al 2008b; Kaida et al, 2007) and mood in general is better in summer than in winter (aan het Rot et al, 2008b). Evans and Ferguson (2011) found that patients with serious depressive symptoms can recover faster if hospitalised in rooms with higher levels of natural light.

Daylight also influences production of the stress hormone cortisol (Beute and de Kort, 2013b). Studies suggest that exposure to bright daylight (> 10,000 lux) can decrease cortisol levels in humans (Jung et al, 2010), and that exposure to daylight for at least three hours a day can reduce work stress and dissatisfaction (Alimoglu and Donmez, 2005).

However, the levels of daylight available to occupants of typical buildings may not be sufficient. A recent study (Acosta et al, 2015) shows how the level of biological stimulation for occupants is impacted by daylight penetration into buildings with deep plan spaces with windows on a single façade. The study confirmed that circadian stimulation levels are highest in areas near the windows, and decrease progressively away from the windows. Electric light of similar characteristics to those of daylight would be required in areas where daylight levels are thought to be insufficient for circadian entrainment.

In a study on people working in a three-storey building designed for daylight maximisation, Figueiro and Rea (2016) found that personal light exposures and circadian stimulation levels were higher during the summer and during the working day, which coincided with significant increases in sleep quantity and quality. However, reliance on daylight for interior workplaces is not always possible, and thus appropriate artificial lighting is needed to provide circadian light exposure.

Effects of bright artificial lighting

Smolders et al (2012) found higher alertness and physiological arousal, as well as better performance, faster response times and greater accuracy under high illuminance (1000 lux) compared with low illuminance (200 lux) cool white (4000K) lighting in non-daylit workplaces. Preference for high levels of artificial light (980 lux), particularly when combined with cooler white light appearance (4000K), was also found by another study on office lighting (Van der Zande, 2016). Subjects perceive the lighting as more comfortable and resembling daylight, which contributed to lower stress and fatigue levels and to higher alertness levels.

Research on lighting for education has also found improvements in alertness, performance and mood at higher illuminance or under blue enriched lighting. Sleegers et al (2013) observed increased concentration and performance at 1000 lux / 6500K compared with 600 lux / 4000K, 380 lux / 3000K and 300 lux / 3000-4000K. Mott et al (2012) found better oral reading fluency and motivation under 1000 lux / 6500K compared with 500 lux / 3500K in classrooms with reduced daylight penetration. Keis et al (2014) also found that blue enriched lighting can also increase concentration and speed of cognitive performance, and lower inaccuracy. However, Macchi and Bruce (2004) point out that prolonged exposure to bright light may have negative impacts due to the effect on the circadian rhythm through cortisol secretion, including higher level of agitation and disturbance during classes.

Hubalek et al (2010) showed that increased daily light exposure of office workers led to improved sleep quality during the subsequent night. It also showed that light exposures over 1000 and 2500 lux improved sleep quality, implying that bright light is beneficial for circadian entrainment.

Viola et al (2008) found notable increases in sleep quality, sleep duration, alertness and performance of office workers during winter months under blue-enriched (17000K) compared to conventional white (4000K) fluorescent light. Participants also reported feeling less tired in the evenings, and less tired more



generally, after working under the blue-enriched light. Similar results were found by Mills et al (2007) when comparing existing lighting of 2900K to blue-enriched 17000K. Another study (Iskra-Golec et al, 2012), in which office workers were exposed to 4000K and 17000K lighting scenarios, determined that the blue-enriched light had the most pronounced effect on 'energetic arousal' (self-reported mood assessment) of workers during the first half of the working day. In the afternoon, energetic arousal decreased under both lighting scenarios, but was generally higher under the blue-enriched light.

Lighting with a colour temperature as high as 17000K is rare in typical work environments. Chellappa et al (2011) found evidence of biological effects when comparing a 6500K fluorescent light source to a 2500K fluorescent source and a 3000 K incandescent source, all with an illuminance of only 40 lux. The study highlights that biological response to light is wavelength dependent, with exposure to the 6500K light source leading to increases in alertness and cognitive performance. In common applications, circadian lighting systems would need to provide a suitable light stimulus through a combination of intensity and spectral distribution. In this respect, Boyce (2010) suggests that for light sources with a high content of blue light in the circadian 'action spectrum' a lower illuminance may be used. Therefore circadian effectiveness may not necessarily need overly high illuminances.

Using electric lighting to assist circadian entrainment may improve the health and wellbeing of building occupants, primarily through better and longer sleep. Evidence suggests that people prefer the dynamic nature of daylight as opposed to a constant illumination afforded by traditional lighting designs. Therefore, a dynamic, or circadian, electric lighting system could be preferable in spaces with limited daylight penetration.

Existing research on circadian/dynamic/variable lighting

Van Bommel and Van Den Beld (2004) pointed out that lighting that satisfies occupants' visual and biological needs is beneficial for both workers and employers, since it offers health benefits as well as increased productivity and reduced absenteeism. For areas with insufficient levels of daylight, they also recommended using 'dynamic' electric lighting that resembles variable daylight by changing illuminance and colour temperature throughout the day with the aim of positively influencing mood and stimulation.

However, research on the effects of circadian, or dynamic, lighting systems on health and wellbeing is still limited. This is also acknowledged by a SSL-erate report (2014), which emphasises the importance of daylight and recommends that daylight properties be mimicked by additional electric lighting where insufficient daylight is available. The report also considers that modern LED light sources and lighting control systems offer new opportunities for dynamic lighting, through sophisticated modulation of light intensity and spectrum.

In 2006-2007 BRE assessed the potential impacts of a dynamic electric lighting system installed in a school in Manchester. The study included physical monitoring of environmental conditions over all four seasons, questionnaires to capture students' and teachers' experience, and reaction time tests to assess student performance. Whilst no effects were found on reaction time, the study showed that the dynamic lighting system allowed both students and teachers to have an increased overall wellbeing and a better perception of the classroom environment overall and of other children. Attendance also increased in the dynamic lighting condition.

Barkmann et al (2012) also investigated the effect of variable lighting in a school environment. It was implemented in seven lighting programmes varying from 275 lux and 3500K for 'extreme relax' (no reading or writing being performed) to 1060 lux and 5800K for 'concentrate' and 675 lux and 11000K for 'activate'; standard lighting was a constant 300 lux and 4000K. Whilst the study found increased student performance under 'concentrate' variable lighting compared with standard settings, no changes were detected in student achievement motivation. Both teachers and students associated variable lighting with a positive experience.



De Kort and Smolders (2010) assessed the effects of dynamic lighting in an office workplace for three weeks during the winter months. The dynamic lighting altered its illuminance between 500 and 700 lux and colour temperature between 3000 and 4700 K, and was compared with static lighting delivering 500 lux at desk level with a colour temperature of 3000 K. Daylight dimming was incorporated in both lighting conditions. Whilst participants felt more 'satisfied' in the dynamic lighting condition, no significant differences were found between the static and dynamic lighting conditions on self-reported measures of wellbeing and performance, including sleep quality.

Begemann et al (1997) carried out a one-year field experiment to investigate the visual and biological responses to variable fluorescent lighting in individual offices. Each office had daylight from a north-facing window and occupants could change the illuminance (200 to 2000 lux) and colour temperature (2800K to 5000K) throughout the day according to their preference. The study found that occupants preferred the illuminance and colour temperature to follow a daylight cycle, as opposed to constant lighting conditions. Moreover, occupants added on average 800 lux of artificial lighting level over that provided by daylight alone, which was significantly higher than standard recommendations for office lighting.

Measures of circadian lighting

Recent guidance suggests that the absence or deficiency of natural daylight in indoor spaces can be compensated through the use of variable electric lighting to stimulate the circadian system (CIBSE, 2015). The WELL Building Standard (Delos, 2015) also recognises the circadian effects of electric lighting; it requires indoor lighting to satisfy visual tasks but also to minimise disruption to circadian rhythms.

However, the International Commission on Illumination (CIE, 2015a) highlights that knowledge of the use of non-visual effects of light for human health and wellbeing benefits is still being developed. Likewise, research (Rea et al, 2002) has recommended that lighting industry pay considerable attention to fundamental characteristics of the light used in the built environment, including illuminance, spectral composition, spatial distribution, timing and duration, to support circadian entrainment as well as visual functions.

Various metrics have been proposed by researchers to address the response of the human circadian system to electric light sources. Quantitative measures have been developed to represent the effective circadian stimulus. Circadian light is represented by a spectrally weighted irradiance specific to the human circadian system, as opposed to the visual system (Rea et al, 2010; Figueiro and Rea, 2016). Rea (2015) also proposed replacing the photopic spectral luminous efficiency function $V(\lambda)$ with the universal luminous efficiency function $U(\lambda)$, which is a broader luminous efficiency function meant to represent the full range of retinal sensitivity to electromagnetic radiation associated with all photoreceptor types in the retina (S-cones, M-cones, L-cones, rods, and ipRGCs). Lucas et al (2014) developed a weighting function (action spectrum) for the ipRGCs and a tool for light measurement that uses photoreceptor sensitivity weighted illuminances expressed in α -opic lux such as, for example, melanopic lux for the melanopsin containing ipRGCs. However, CIE (2015b) recommends using quantities of the form α -opic spectrally-weighted irradiance expressed in W/m^2 , rather than α -opic lux, in order to accord with SI units.

The approach of Lucas et al (2014) was also adopted by the WELL Building Standard (Delos, 2015) which gives recommendations in Equivalent Melanopic Lux (EML). This is an alternative metric, weighted to the spectral response of the ipRGCs, which quantifies the biological effects of light. Among other things it recommends at least 250 EML (which may include daylight) measured vertically at 1.2m above floor level at 75% of more of workplaces for at least 4 hours every day of the year. The standard also gives guidance on calculating EML values for different colour temperatures and spectral power distributions.

The recent German standard DIN SPEC 67600 (DIN, 2013) also gives specific design recommendations for biologically effective electric lighting that mimics the natural changes in daylight. It recommends a vertical illuminance at the eye of at least 250 lux at a colour temperature of 8000K for several hours (preferably in the morning), and at most 50 lux at no more than 2700K in the evening. DIN SPEC 5031-



100 (DIN, 2015) gives guidance on calculating the melanopic action factor of different light sources and adjusting these illuminance values for other colour temperatures.

DIN SPEC 5031-100 (DIN, 2015) and the recent SSL-erate report (2016) also give recommendations for daylight equivalent illuminance. This is the daylight illuminance needed to produce a similar stimulation to the light source considered. Daylight is assumed to have the spectrum of the CIE standard illuminant D65. A method is provided to determine the melanopic daylight equivalent illuminance expressed in lux for any light source, based on melanopic action factors.

According to the SSL-erate report (2016), subjective alertness and nocturnal melatonin suppression correlate better with melanopic irradiance (and melanopic daylight equivalent illuminance) than the normal (photopic) measure of illuminance. The report highlights that good quality sleep and circadian entrainment are facilitated by dynamic lighting that delivers a high melanopic irradiance (or melanopic daylight equivalent illuminance) during the day, predominantly in the morning, and a low enough melanopic irradiance during the last 2 hours before bedtime and at night.

However, the illuminances recommended by both the WELL Building Standard and the German DIN standards for circadian entrainment may be very difficult, or even impossible, to achieve in most indoor spaces through traditional electric lighting, since this is guided by standards and codes centred upon lower values of vertical illuminance that are recommended to meet visual (non-circadian) needs.

High illuminances at the eye may cause glare. Zhang et al (2014) found a linear variation of perceived glare with vertical illuminance at the eye, concluding that over 70% of the subjects found the lighting comfortable for vertical illuminances at the eye between 130 and 340 lux. Furthermore, bright light sources or high contrasts in the visual field can cause migraine (Boyce 2010). Therefore, lighting and solar control schemes should be designed so that glare is prevented.

Additionally, research is still required to investigate how best to control tuneable white lighting under real-world conditions and when is the best time to have the high intensity, cool coloured lighting, and for how long, and when to turn it down and make it warmer. Therefore the current research project, jointly funded by CIBSE and the BRE Trust, aims to investigate the effects of circadian lighting on occupants' health and wellbeing and identify optimal control strategies for circadian lighting to maximise health and wellbeing benefits.



Circadian lighting workshop

A workshop was held at BRE on 29 September 2016 to discuss latest research and current thinking on circadian lighting. The workshop was attended by leading professionals from academia, manufacturers, lighting designers and public health institutions. The workshop agenda is enclosed in Appendix A.

The workshop provided a constructive framework for exploration and exchange of ideas, and allowed various key findings to be drawn as follows:

- Human centric lighting is not just circadian, but also covers visual, biological and psychological needs.
- Wellbeing influences productivity.
- Photoreceptors in the retina are sensitive both to light intensity and wavelength.
- Prior light exposure affects the results of experiments on circadian lighting.
- Blue light may not have visible benefits in the short term, but rather in the longer term. However, red light may actually have more effect in the short term.
- Bright light tends to be better tolerated by people in a state of pleasure e.g. relaxing or being outdoors. There is less tolerance to bright light when performing visual tasks indoors.
- Sufficient light levels are required for undertaking visual tasks.
- There is no single solution to satisfy subjective preferences of occupants.
- The human factors (e.g. staff feeling more motivated or feeling better) should be considered when assessing return on investment for lighting systems. Education (i.e. of landlords, agents and users) is equally important.
- The amplitude of the light-dark cycle and melatonin suppression levels vary between individuals and with age, hence they need to be investigated for each individual.
- Daylight is the best light source. However, it may not always be best to mimic the daylight available outdoors at any point in time, since the amount of daylight may be insufficient for circadian entrainment when it is cloudy, raining or dark outside.
- Daylight should not be replaced. Sufficient daylight should still be allowed within indoor spaces, and people should be encouraged to go out more during the day.
- Research is still needed to provide evidence and inform recommendations for circadian lighting.



Conclusion

Exposure to bright light during the day is important for people to maintain their daily cycle of waking and sleep. Conversely, light of the wrong colour and intensity at the wrong time can be detrimental and can potentially cause health problems, including depression, cardiovascular and digestive problems, and even cancer. It is a particular issue for shift workers or people working late hours.

Research reveals extensive effects of circadian disruption on health and wellbeing. Human systems have evolved to run on a 24-hour cycle and respond to environmental light as 'zeitgeber' to synchronise with the solar day. Melatonin is a key hormone associated with the light-dark cycle; it regulates sleep-wake patterns and is essential in the way light affects health. Bright light suppresses melatonin production, and the wrong light at the wrong time (late in the evening or at night) may lead to illness through melatonin suppression.

Daylight is ideal for circadian entrainment through its high levels of blue light and dynamic changes in colour and intensity. Providing daylight in buildings helps achieve the benefits of daytime light in regulating circadian rhythms. Various studies have found benefits of daylight for human health, mood and wellbeing.

In principle, exposure to bright artificial light at the correct times of day could have similar effects. However typical electric lighting may provide insufficient light levels at daytime or too much light in the evening or at night, or the spectral composition of the emitted light may not be adequate for circadian entrainment.

Various authors assert the need to increase circadian light exposure within buildings. Where access to daylight is limited, dynamic electric lighting would be preferable to that which provides a constant level of illumination. Dynamic changes in light level and spectrum are believed to provide benefits such as health benefits associated with correct circadian entrainment, increased productivity and reduced absenteeism.

Increasing consideration is being given to circadian lighting, most commonly by using tuneable white LED sources that can alter their colour and intensity. Alertness, mood, performance and productivity appear to improve at higher illuminances (at least 1000 lux) during working hours and under blue enriched lighting, as well as under dynamic lighting conditions. However, research investigating the effects of circadian, or dynamic, artificial lighting on health and wellbeing is still needed. Additionally, a recent CIE document warns that exploiting the non-visual effects of light for health and wellbeing benefits still needs development.

Metrics have been proposed to quantify the human circadian response to electric lighting, and there are some recommendations in DIN standards and the international WELL standard. However, the light levels recommended for circadian entrainment may be very difficult, or even impossible, to achieve using traditional electric lighting practice, which is centred upon lower values of vertical illuminance for visual (non-circadian) needs.

Additionally, research is still required to investigate how best to control tuneable white lighting under real-world conditions and when is the best time to have the high intensity, cool coloured lighting, and for how long, and when to turn it down and make it warmer. Therefore the current research project, jointly funded by CIBSE and the BRE Trust, aims to investigate the effects of circadian lighting on occupants' health and wellbeing, and identify optimal control strategies for circadian lighting.

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Appendix A **Circadian lighting workshop: Agenda**

Date: Thursday 29 September 2016
Time: 1.30 pm – 4:30 pm
Venue: BRE Garston, Innovation Park, Visitor Centre

- 1:30 – 1:45 Coffee and registration
- 1:45 – 1:55 **Welcome and introduction**
Dr Paul Littlefair, BRE
- 1:55 – 2:20 **Human centric lighting in offices**
Dr Bianca van der Zande, Philips Lighting
- 2:20 – 2:45 **Investigation into the effects of short wavelength light on human alertness in the immediate to short term**
Scott Window, Fowler Martin
- 2:45 – 3:00 Break
- 3:00 – 3:25 **New measurement toolkit and SI-compliant photoreceptor weighted light intensities**
Dr Katharina Wulff, Oxford University
- 3:25 – 3:45 **Preliminary findings of literature review on circadian lighting**
Dr Cosmin Ticleanu, BRE
- 3:45 – 4:30 Discussion
- 4:30 Close