Lighting for circadian rhythms

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Abstract

Exposure to light is a key factor in maintaining circadian rhythms. A combination of bright light during the day and darkness at night helps to keep up the daily cycle of waking and sleep. Recently, ‘circadian’ lighting has been marketed which varies in colour and intensity during the day. The aim is to improve alertness during working hours using bright light, but to switch to lower brightness, warmer coloured light before it is time to relax. This report gives the results of an experiment to assess circadian lighting, and provides guidance to building owners and occupiers, lighting designers, lighting manufacturers and installers.

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Introduction

People have circadian rhythms linked to the natural light/dark cycle of the day. These control patterns of alertness and sleep as well as other factors like body temperature and release of various hormones (Figure 1). Light and dark patterns act as the most important signal to entrain (synchronise) the circadian clock to the solar cycle and cause waking and sleeping to occur at consistent times.

As well as the photoreceptor (rod and cone) cells which allow normal sight, the retina contains special cells called intrinsically photosensitive retinal ganglion cells (ipRGCs) (Figure 2). These cells produce a photopigment, melanopsin, which transmits signals to the suprachiasmatic nucleus (SCN) in the brain. The SCN is the body’s master clock, sending signals to cells in the body to synchronise their activities. This includes the release of a hormone, melatonin, which causes sleepiness and may help the body fight various diseases.

Without any light at all, for most people the circadian clock runs for slightly longer than 24 hours, which causes waking and sleeping to occur a little later each day. Blind people often have disrupted circadian rhythms and poor sleep patterns for this reason.

People who spend some of the daytime outdoors or in well daylit spaces are exposed to high levels of light, which help synchronise their circadian rhythms. In principle high levels of electric light can also do this. However, many people work in poorly daylit spaces with relatively low levels of electric light. In these circumstances it may be harder for the body to maintain its circadian rhythms. A US study found workers in well daylit offices slept an average of 46 minutes more per night than those in non-daylit offices. Workers without windows reported poorer scores on quality of life measures related to physical problems and vitality, and poorer outcomes on measures of overall sleep quality and sleep disturbance.

This is also an issue for people (for example the elderly or infirm) who spend all day inside poorly daylit dwellings, or in hospital wards, which are often lit to lower levels than offices. Several studies have reported that patients recovered more quickly in daylit hospital wards. For example in the UK, Joarder and Price found that average patient length of stay was reduced by 7.3 hours per 100 lux increase of daylight inside the investigated rooms.

High levels of electric lighting have been found to have psychological and physiological effects. Smolders et al. 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) white (4000K colour temperature) lighting in non-daylit workplaces. Hubalek et al. showed that increased daily light exposure of office workers led to improved sleep quality during the subsequent night. Light exposures over 1000 and 2500 lux improved sleep quality, implying that bright light is beneficial for circadian entrainment.

However, exposure to artificial light at the wrong times of day can have an adverse effect on circadian rhythms. Light at night time can alter the body clock, suppressing melatonin production and keeping you awake at night, and making you sleepier during the day. In an experiment by Gooley et al., exposure to light levels of more than 200 lux in a room before bedtime was found to have a measurable effect on melatonin levels compared to a group exposed to dim light of less than 3 lux.

Figure 1: Circadian peaks in body functions
Colour of light

The colour of lighting also has an effect, because the ipRGCs in the retina, which help control circadian rhythms, have a particular spectral response. They are most sensitive to blue light. The black line in Figure 3 shows their spectral response, often called the melanopic action spectrum. It peaks at 490nm wavelength which is in the blue region of the spectrum. (Work is still ongoing to determine the exact spectral response, and some authors indicate slightly lower peak wavelengths).

It follows that lighting with a high colour temperature (a ‘colder’, bluer light) ought to have more of an effect on the ipRGCs, and hence on circadian rhythms, compared to warm white (redder) light with a low colour temperature. Figure 3 shows the spectra for warm white (2700K) and ’daylight’ (6500K) LED types. (These were measured in the office used for the experiment described below). The ‘daylight’ LED (blue line in Figure 3) gives more light at the blue end of the spectrum to which the ipRGCs are sensitive, compared to the warm white LED (orange line in Figure 3). In total, the ‘daylight’ LED gives slightly over twice the response of the ipRGCs compared to the warm white LED, for the same visual effect (illuminance or lux level).

The spectra in Figure 3 show that the fit is not perfect. The peak of the ‘daylight’ LED is at a shorter wavelength (around 450 nm) than the peak response of the ipRGCs. The ‘daylight’ LED spectrum actually has a dip close to the peak response wavelength of the ipRGCs. Conversely, the warm white LED does have a small peak in the blue end of its spectrum which could act to stimulate the ipRGCs.

In the future it should be possible to develop LED lamps which give a better fit to the melanopic action spectrum and a maximum stimulus to the ipRGCs; and different LEDs with very low outputs at the peak of the melanopic action spectrum and minimum stimulus to the ipRGCs. This has to be balanced against the colour quality of the light for visual tasks. For example, an LED lamp that exactly reproduced the melanopic action spectrum would have little or no red light, and make it impossible to distinguish the colour of red objects.

Viola et al. found significant increases in sleep quality, sleep duration, alertness and performance of office workers in winter under blue-enriched (17000K) compared to conventional white (4000K) fluorescent light, even though the blue light gave lower illuminances. 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. who compared existing warm white lighting (2900K) to blue-enriched 17000K of the same illuminance.

Lighting with a colour temperature as high as 17000K is rare in typical indoor environments. Chellappa et al. compared a 6500K fluorescent light source to a 2500K fluorescent source and a 3000K incandescent source, all with an illuminance of only 40 lux. The study was conducted with 25 participants during the evening, as opposed to in a workplace. Nevertheless, the results show how choice of low output domestic light sources can stimulate a biological effect. Melatonin levels were nearly 40% lower with the 6500K fluorescent source when compared to the incandescent source. Alertness and cognitive performance were increased, and sleepiness reduced following exposure to the blue 6500K light source.

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Dynamic lighting: previous studies

Research on the effects of dynamic, changing lighting systems on health and wellbeing is still limited. In 2006-2007 BRE assessed the potential impacts of a dynamic fluorescent lighting system installed in a school in Manchester. The study included physical monitoring of environmental conditions over all four seasons, questionnaires, and reaction time tests to assess student performance. No effects were found on reaction time, but under the dynamic lighting system students and teachers had an increased perceived wellbeing, and a better rating of the classroom environment. Attendance also increased in the dynamic lighting condition.

Barkmann et al. also investigated the effect of variable lighting in a school environment. Seven lighting programmes varied from 275 lux and 3500K for ‘extreme relax’ (no reading or writing being performed) to 1060 lux and 5800K for ‘concentrate’. 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 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 4700K, and was compared with static lighting delivering 500 lux at desk level with a colour temperature of 3000K. 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.

Figure 2: ipRGC cells in the retina send signals to the brain that help control circadian rhythms. The most sensitive ipRGCs are located in the rear and lower part of the eye, so light from above should have a bigger impact on them.
Existing recommendations

Various parameters have been developed to quantify how different types of lighting affect circadian rhythms. Typically these involve taking the spectrum of the light source and weighting it by the response of the ipRGC cells (the black curve in Figure 3). This has resulted in quantities like effective circadian stimulus and spectrally-weighted irradiance. One of the more widely used quantities is Equivalent Melanopic Lux (EML). This takes the spectral radiation falling on a surface, and instead of multiplying it by the visual response of the eye to get a visual illuminance in lux, it multiplies it by the response of the ipRGCs to get EML.

EML has been adopted by the WELL Building Standard. The initial version 1 recommended at least 250 EML (which may incorporate daylight) measured vertically at 1.2m above floor level at 75% or more of workplaces for at least 4 hours every day of the year; however, the target value was later reduced to 200 EML for at least the hours of 9am to 1pm for every day of the year if daylight is included. At least 150 EML is recommended in version 2 of WELL for electric lighting alone, and for maximum credits 240 EML; Table 2 shows some examples of EML levels for different light sources.

Specific design recommendations are also given in the German standard DIN SPEC 67600. It recommends a vertical illuminance at the observer’s 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 the eye at no more than 2.700K in the evening. Guidance on calculating these illuminances for different light sources is given in DIN SPEC 5031-100, and Table 2 shows some examples of illuminances adjusted for different light sources.

As an alternative, an SLL-erate report and the CIE standard S 026/E:2018 recommend using melanopic equivalent daylight illuminance (MEDI). This is the daylight illuminance needed to produce a similar circadian stimulation to the light source considered. Corresponding values of MEDI are shown in Tables 1 and 2 for daylight D65.

The standard also gives factors for calculating EML values for different colours of light. Using this method, equivalent visual lux levels can be determined for different spectra and correlated colour temperatures of typical light sources, as shown in Table 1.

Table 1 Examples of vertical visual lux levels equivalent to 240 EML, 200 EML and 150 EML for different correlated colour temperature (derived from the WELL Building Standard).

<table>
<thead>
<tr>
<th>Light source</th>
<th>Correlated colour temperature</th>
<th>Visual lux for 240 EML</th>
<th>Visual lux for 200 EML</th>
<th>Visual lux for 150 EML</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent</td>
<td>3000K</td>
<td>533 lux</td>
<td>444 lux</td>
<td>333 lux</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>4000K</td>
<td>414 lux</td>
<td>345 lux</td>
<td>258 lux</td>
</tr>
<tr>
<td>LED</td>
<td>4000K</td>
<td>316 lux</td>
<td>263 lux</td>
<td>198 lux</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>6500K</td>
<td>235 lux</td>
<td>196 lux</td>
<td>147 lux</td>
</tr>
<tr>
<td>Daylight D65</td>
<td>6500K</td>
<td>218 lux*</td>
<td>182 lux*</td>
<td>136 lux*</td>
</tr>
</tbody>
</table>

*This represents melanopic equivalent daylight illuminance (MEDI)

Table 2 Examples of vertical illuminance of 250 lux at 8000K adjusted for other typical light sources of different correlated colour temperature (derived from DIN SPEC 5031-100).

<table>
<thead>
<tr>
<th>Light source</th>
<th>Correlated colour temperature</th>
<th>Adjusted illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent</td>
<td>3000K</td>
<td>592 lux</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>4000K</td>
<td>425 lux</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>5000K</td>
<td>350 lux</td>
</tr>
<tr>
<td>LED</td>
<td>3075K</td>
<td>560 lux</td>
</tr>
<tr>
<td>LED</td>
<td>4250K</td>
<td>324 lux</td>
</tr>
<tr>
<td>LED</td>
<td>5400K</td>
<td>304 lux</td>
</tr>
<tr>
<td>LED</td>
<td>6535K</td>
<td>299 lux</td>
</tr>
<tr>
<td>Daylight D65</td>
<td>6500K</td>
<td>239 lux*</td>
</tr>
</tbody>
</table>

*This represents melanopic equivalent daylight illuminance (MEDI)

Most of the values shown in Tables 1 and 2 are well above those normally recommended for visual (non-circadian) purposes. In most spaces lit from above, the horizontal illuminance on the desk is around double the average vertical illuminance at eye level. A typical office might have a horizontal illuminance of 300–500 lux and an average vertical illuminance of 150–250 lux. BS EN 12464-1:2011 recommends a minimum maintained mean cylindrical illuminance (average vertical plane illuminance) of 50 lux in regular indoor areas. For offices, the minimum value recommended is 150 lux. For education spaces, the SLL ‘Lighting Guide 5: Lighting for education’ also recommends a maintained mean cylindrical illuminance of at least 150 lux at 1.2m above floor level in teaching areas. Compared to these recommendations, the adjusted illuminance levels shown in Tables 1 and 2 are significantly higher, except for very cool colour sources. This can result in a potential conflict, because high levels of light reaching the eye can cause glare, especially if people are using computer screens. A study by Zhang et al found that above a vertical illuminance of 340 lux on the eye, people tended to find the lighting glaring. In practice glare will depend on other factors too; if most of the light comes by reflection from the walls and ceiling, people may be more tolerant of glare than if it comes directly from small light sources.
An experiment to assess variable lighting

Lighting in the space

BRE undertook an experiment to assess the effects of variable lighting, and its timing, on human subjective assessments, activity and reported sleep in an open plan office space in Norwich, UK. There was limited daylight penetration in the office space; the windows were small and heavily obstructed by overhangs and nearby buildings; 36 people worked in the space and 23 of them (19 women and four men) opted into the experiment.

Initially (February 2018) the space had constant fluorescent lighting (Condition 1, see Figure 4). Most of the lighting was 4000K (white) but some luminaires had 3000K (warm white) replacement lamps. Some of the tubes had been removed when the occupants complained that the lighting was too bright. So the lighting was non-uniform; the mean horizontal illuminance was 377 lux, in line with the 300 lux recommendation for computer users in offices, but the minimum illuminance on a desk was only 129 lux and the maximum 1017 lux. The median illuminance was 267 lux, so more than half the desks had illuminances below the recommended value.

The light reaching people’s eyes varied too. Vertical EML values ranged from 50 to 246, with a mean of 101 and median of 70 EML. 18 of the 23 participants received less than the lower recommendation of 150 EML in the WELL standard.

After two weeks of monitoring the existing lighting, at the start of March 2018 it was replaced with LED lighting. For the first week the new lighting was maintained at constant light output and colour to allow participants to adapt to the appearance of the new lighting. Then the LED lighting was programmed to change dynamically (Condition 2, see Figure 5 and 6) and there was a further two weeks monitoring. Figure 6 shows how the average EML varied with time of day. In the early morning the lighting became brighter and bluer from 3500K and 30% output at 0800 until 1030 when it was at its coolest setting (6500K) and at 80% output. From 1230 onwards the colour started to change again to be a standard white (4000K and 40% output) from 1400. At 1600 it started to become dimmer and redder, with 2700K colour temperature and 50% output by 1830. Light output was different for the various settings of correlated colour temperature; for an equal dimming percentage, light output was highest at 4000K and lowest for 2700K.

Most of the change in EML over the day was due to the change in colour of the lighting. Visual illuminances did not vary as much, with mean horizontal illuminances ranging from just over 350 lux at the beginning and end of the day, up to 488 lux in late morning. The aim was to give people an appropriate level of light to work by at all times. Even though the new lighting appeared more uniform and all the LED lamps were working, there were still big differences in the amount of light reaching different people’s eyes. Under the 6500K (late morning) setting, EML values ranged from 142 to 413. All but two people received the WELL standard’s minimum of 150 EML, but some received considerably more.

This has important implications for using lighting to influence circadian rhythms. In multi-occupant spaces with conventional ceiling lighting, it is very difficult to achieve a standard ‘dose’ of light for everyone. If people are facing the walls, or, as in this case, near a walkway, they will have less light reaching their eyes than people with their backs to the wall facing into a brightly lit space.

Additional variable lighting conditions were administered in the second phase of the project during November-December 2018. 20 participants took part in this phase after four participants withdrew from the experiment and a new one opted in.

Before these latter tests, the desks had been replaced. The occupants of the space had complained about too much light being reflected from the initial white desk’s (0.84 visible light reflectance). To avoid unwanted glare effects, the initial desks were replaced during the summer with similar desks in a light oak finish (0.35 visible light reflectance).

For the first two weeks of monitoring (Condition 2), the LED lighting was programmed to change dynamically (see Figure 7) throughout the day. A similar variation to that used in Condition 2 was implemented but higher EML values were targeted. Figure 8 shows how the mean EML (averaged across all 20 participants’ seating positions) varied with time of day. In the early morning the lighting became brighter from 50% output at 0800 to 100% output at 1030 at a constant colour temperature of 4000K. This setting was maintained until 1130 when the lighting started to become cooler in colour, until at 1200 it was at its coolest setting (6500K) and 100% output. At 1600 it started to become yellower, with 2700K colour temperature and 100% output by 1830.

Mean horizontal illuminances varied from around 600 lux at the beginning of the day to around 1120 lux in late morning and then back down to around 670 lux at the end of the day. Similar to Condition 2, big differences were recorded in the amount of light reaching different people’s eyes. For example, EML values ranged from 216 to 606 under the 4000K (late morning) setting. All participants received the WELL standard minimum of 150 EML under 4000K and 6500K at full output, but some received more than double. Most of them (14 out of 20) also received the minimum of 150 EML under 4000K at 50% output at the start of the day.

Compared to Condition 2, the higher EML values were due to the higher light output. However, the change in EML over the day was mainly due to the change in colour of the lighting. For example, mean horizontal illuminance and mean vertical illuminance were relatively similar between the 6500K and the 2700K full output settings: 664 lux and 671 lux, and 252 lux and 257 lux, respectively. Despite this, the mean EML value was approximately double for the 6500K setting, 277 compared to 132 for the 2700K setting. This shows the important impact that the light spectrum has on the ipRGCs, and hence potentially on circadian rhythms.

Once the monitoring for Condition 3 was finished, the LED lighting was set to a constant light output (40%) and colour (4000K) to replicate typical office lighting whilst achieving a minimum horizontal desk illuminance of around 300 lux. This was maintained for a week to allow participants to adapt and then for another two weeks of monitoring for Condition 4. The mean horizontal illuminance was 480 lux, with a minimum of 284 lux and a maximum of 633 lux. Thus the lighting was more uniform in Condition 4 compared to Condition 1. All but one desk had a horizontal illuminance above 300 lux, and more than half of the desks had illuminances above 500 lux too.

In Condition 4 vertical EML values varied from 77 to 272, with a mean of 149 and median of 133 EML. 15 of the 20 participants received less than the lower recommendation of 150 EML in the WELL standard.
Results

The participants provided subjective assessments of the space after each condition, and responses in the morning and afternoon on two days a week to assess subjective alertness, reaction time and concentration. Subjective alertness was assessed using the 9-point Karolinska Sleepiness Scale (KSS). With the new dynamic LED system (Condition 2), the average scores for subjective alertness, both in the afternoon and averaged across the day, were significantly better than with the old constant fluorescent lighting (Condition 1). However, there were no statistically significant correlations between the increases in circadian-weighted lighting metrics (such as EML) and the variations in subjective alertness. When comparing the LED system set up to provide dynamic (Condition 2) and constant (Condition 4) lighting, no statistically significant differences were found in the average scores for subjective alertness. Also, there were no statistically significant correlations between the higher values for circadian-weighted lighting metrics (such as EML) and the variations in subjective alertness.

Figure 8 shows the results. It shows that most people felt more alert under the dynamic LED lighting in Condition 2 compared to the constant fluorescent lighting in Condition 1, but this also happened for the small number of people who received less light in Condition 2. The increase in alertness did not depend significantly on how much extra light people had with the LEDs.

All participants received more light in Condition 3 compared to Condition 4, and the increase in light level was much more uniform across participants compared to the first conditions. However, the higher light levels in Condition 3 did not lead to higher scores, on average, for subjective alertness; only half of the participants felt more alert under the dynamic LED lighting (Condition 3). Participants also undertook computer tests to assess their reaction time and concentration. Reaction time scores were significantly better with the new dynamic LED system (Condition 2) than with the old constant fluorescent lighting (Condition 1), both in the morning and across the entire day. However, there were no statistically significant correlations between these variations and the increases in circadian-weighted lighting metrics. There were no statistically significant differences in reaction time scores between Conditions 3 and 4, nor in concentration scores between the two conditions tested in each phase of the project. Around half of the participants agreed to wear an Actiwatch device to monitor their activity and sleep patterns; there were negligible differences in sleep and circadian rhythm indicators between the two conditions tested in each phase of the project.

In each phase, participants were asked whether they would prefer dynamic or constant lighting. On average, just over half of them preferred dynamic lighting for their office, typically brighter in the morning and following the variation of natural light outdoors throughout the day. Just under one third preferred the constant lighting.

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Discussion

Amount of light

From the literature review undertaken as part of this project, it is clear that exposure to brighter, blue light during the day can improve subjective alertness, help maintain circadian rhythms and improve sleep quality. A pathway has been discovered to demonstrate how light reaching the eyes can affect circadian systems, through the ipRGCs releasing melanopsin and sending signals to the suprachiasmatic nucleus (SCN) in the brain.

What is not clear is how much light is required, particularly in the situation where light is being used to reinforce the normal circadian pattern of alertness during the day and sleep at night. The studies that have shown an increase in daytime alertness or performance have either been with those with unusually high light levels (around 1000 lux horizontal)10,11, or those with unusually blue light (1700K colour temperature)12,13,14.

In addition, most of the existing studies do not take into account the potential variation of light exposure for different individuals within a space. Some were undertaken in spaces with a significant amount of daylight, which would vary with time of day and location within the space.

Most report a single illuminance figure, usually horizontal illuminance. However, different types of lighting design can give different levels of light at the eyes (vertical illuminances) for the same horizontal illuminance. Typically, direct downlighting from ceiling mounted luminaires intended for rooms with computer use gives relatively low vertical illuminances. Lighting that results in a lot of reflected light, including suspended luminaires that direct light onto the ceiling and ‘wall washing’ luminaires, tends to give higher vertical illuminance and more light in the eyes.

As the BRE study has shown, even in a space with relatively uniform lighting the amount of light reaching someone’s eyes can vary considerably. In an office, someone facing a wall may receive much less light than another person facing into the space. It is difficult to achieve the same ‘dose’ of light for everyone.

In addition, the amount of light people need to reset their circadian rhythms will vary from individual to individual. It will depend on age: for elderly people, and especially those with some forms of partial sight, a higher proportion of light, particularly blue light, is absorbed as it passes through the eye before reaching the retina. So elderly people would need to have the same effect36. Rea et al37 suggest that a reasonable and conservative working threshold for suppressing melatonin by light at night would be to have less than 0.5 lux at the eye.

Timing of light

To reinforce normal circadian rhythms, bright light during the day is beneficial. However, the required duration for this bright light is not clear. The WELL standard states four hours, while the DIN standard suggests several hours. The WELL standard v1 specifies 9am–1pm38 if daylight is included, whereas WELL v2 specifies the same time interval also for electric lighting alone39. WELL v2 also introduces the possibility of reducing the EML values after 8pm but does not give a clear recommendation in this respect. DIN 67600 gives examples40 for different applications but these are not specific recommendations. For offices, the example is: 250 lux and 8000K at the eye between 8am-10am and 1pm-2pm, 200 lux and 3000K at the eye between 12pm-1pm and 6pm-8pm, and an illuminance corresponding to the requirements of the visual task for the rest of the day/night.

The optimum timing for dynamic lighting may vary between individuals, because their circadian clocks run differently41. Some people (early chronotypes) get up and go to bed earlier than others (late chronotypes)42. For late chronotypes, bright light in the morning may help reset circadian rhythms. However, this will be less beneficial for early chronotypes.

In a normal workplace with typical daytime working hours (say between 0800 and 1700) there may be little advantage in having a dynamic lighting system compared to one that delivers good levels of light all day. However, in workplaces where people work upwards into the evening or night, or in residential environments like old people’s homes, there may be significant advantages in a dynamic system that gives low levels of light, at a lower colour temperature, in the evening.

Significant circadian disruption can occur if people are exposed to light late in the evening or at night43. Light at night suppresses melatonin, the hormone that causes sleepiness. Even quite low levels of light can do this if they have a significant blue component. For example, the amount of light generated by a self-luminous tablet computer over two hours is enough to trigger a change in melatonin levels, although this depends upon the type of task being performed by the tablet, as illuminances can range from 5 to over 50 lux depending on task44. Light from a television was not found to have the same effect45, but it is suggested that a reasonable and conservative working threshold for suppressing melatonin by light at night would be about 30 minutes exposure to 30 lux at the eye for a white light source. However, the threshold value would depend on the colour of the light.

Colour of light

The effect of colour of light on the ipRGCs in the eye, and hence on circadian rhythms, has been questioned. Although there is still some degree of uncertainty, the black curve in Figure 3 is widely accepted to give a good approximation to the spectral response of the ipRGCs. This peaks sharply at the blue end of the spectrum. Current high colour temperature light sources such as LEDs and some types of fluorescent light, give high outputs of blue light. There is still scope to tailor their spectra further in the future to fit the peak response of the ipRGCs and maximise their circadian impact. Conversely there is future scope to alter the spectrum of existing LEDs to give very low circadian stimulus in the evening or at night. Even warm white LEDs often have a small peak of blue light which can stimulate the ipRGCs.

Timing of light

Dynamic lighting requires effective controls that work reliably, and exactly as programmed. One of the potential installations for BRE’s monitoring study had advanced colour changing LEDs, but the controls did not work properly and the building managers changed the system to work at a static light level.

To avoid disturbing the occupants, it is recommended to vary illuminances and colour slowly. It is best to explain to them what is happening and the purpose of varying the lighting.

People vary in their preferences for lighting; conventional good practice is to offer individual control46 but this can negate the circadian effects. There is no obvious way round this.

This has important implications for people who work at night47. Studies of night shift workers indicate that they sleep over two hours less than day workers, and can be more prone to cancer, and digestive and circulatory problems48.

Thus, although exposure to high levels of light at night could, in the short term at least, improve alertness by suppressing melatonin production, this may cause health problems, particularly in those on short term or rotating night shifts. For these people it would be better to have lower levels of light, especially with reduced blue light, to reduce circadian impacts. Bright light at night might be considered for those on long term night shifts in an attempt to synchronise their circadian rhythms to night time working, though this can cause problems at weekends and holiday times when they attempt to revert to a normal cycle of being awake during the day. More research is needed on the health issues arising from this.

Control of lighting

Dynamic lighting requires effective controls that work reliably, and exactly as programmed. One of the potential installations for BRE’s monitoring study had advanced colour changing LEDs, but the controls did not work properly and the building managers changed the system to work at a static light level.

To avoid disturbing the occupants, it is recommended to vary illuminances and colour slowly. It is best to explain to them what is happening and the purpose of varying the lighting.

People vary in their preferences for lighting; conventional good practice is to offer individual control46 but this can negate the circadian effects. There is no obvious way round this.

This has important implications for people who work at night. Studies of night shift workers indicate that they sleep over two hours less than day workers, and can be more prone to cancer, and digestive and circulatory problems48.

Thus, although exposure to high levels of light at night could, in the short term at least, improve alertness by suppressing melatonin production, this may cause health problems, particularly in those on short term or rotating night shifts. For these people it would be better to have lower levels of light, especially with reduced blue light, to reduce circadian impacts. Bright light at night might be considered for those on long term night shifts in an attempt to synchronise their circadian rhythms to night time working, though this can cause problems at weekends and holiday times when they attempt to revert to a normal cycle of being awake during the day. More research is needed on the health issues arising from this.

Conclusions and recommendations

Recent international research work has shown that light can affect circadian rhythms. Exposure to bright light during the day can help reinforce the natural daily pattern of waking and sleeping. Blue light is known to be particularly important because the ipRGC cells in the eye that initiate this process are particularly sensitive to the blue end of the spectrum. Current LED technology allows the colour and intensity of lighting to change during the day, and there is scope to tailor this further to the spectral response of the ipRGCs.

However, there is still considerable uncertainty about how much light is required. People vary in their normal daily routines and how much daylight they are exposed to. In addition, even in a space with uniform electric lighting some people may receive significantly more light into their eyes than others, depending which way they face.

Based on the research carried out to date, the following recommendations are tentatively suggested:

– From mid morning until early afternoon, use higher than normal levels of light with high colour temperature (increased blue light).

– Towards the end of the day, dim the lighting down (while retaining enough light to meet visual task recommendations) and lower its colour temperature (‘warmer’, redder light similar to a domestic setting).

– Maximise reflected light from room surfaces using light fittings with an upward light component, and ‘wall washing’ to illuminate the walls directly. This will give more light to people facing away from windows.

– As light levels will be higher than normal for part of the day, use high quality fittings to minimise glare and avoid all flicker. Have a balanced visual environment, for example by avoiding very light coloured desks.

– Vary the lighting gradually. Controls need to be reliable.

– Explain to the occupants what the lighting system is doing and why.
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