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An Overview of Recent Findings on the Effect of Light on Circulation Rhythms

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Cover Page Footnote

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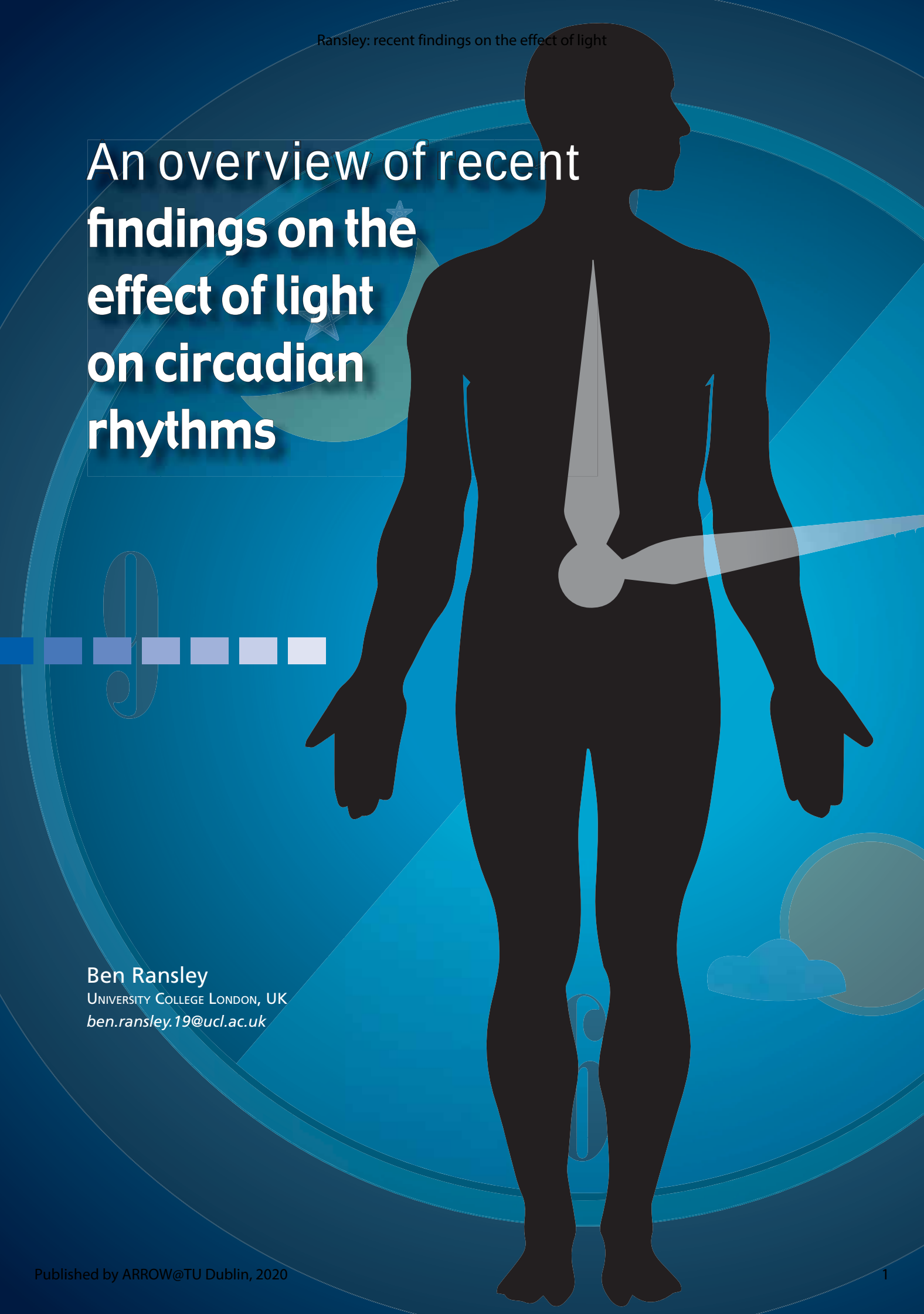
An overview of recent findings on the effect of light on circadian rhythms



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Abstract

Light, traditionally for vision, also has non-visual effects on human physiology. Recent developments in neuroscience have demonstrated that light reaching the retina entrains the human circadian system to the natural light and dark cycle. Studies have shown that exposure to bright light during the day, particularly in the morning, may be as important as avoiding light at night for the healthy functioning of this system. This paper provides a summary of the key experimental studies which have driven understanding of this nascent subject forward. These studies are largely neuroscientific in nature, but their implications relate directly to building services engineering as the emergence of "circadian lighting" is bringing with it new metrics and standards for the environmental design of buildings. Two such metrics, Equivalent Melanopic Lux (EML) and Circadian Stimulus (CS), are examined and compared. It is shown that while care must be taken when adopting incomplete knowledge into practice, it is already becoming clear that much of our current lit environment is inadequate when seen through the lens of non-visual light.

Keywords

Circadian rhythms; non-visual light; daylight; ipRGCs; circadian stimulus; Equivalent Melanopic Lux.

Acronyms

CS: Circadian stimulus
DLMO: Dim light melatonin onset
EML: Equivalent Melanopic Lux
ipRGC: Intrinsically photosensitive retinal ganglion cell
LAN: Light at night
LRC: Lighting Research Centre
SCN: Suprachiasmatic nucleus

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1. Introduction

> "Our biology and our society seem to be in serious opposition, and it is not clear which force will win. Although it is true that millions of years of natural selection have made us what we are, our problem is that we don't really understand what that is." (Foster & Wulff, 2005, p.413)

That light, health and wellbeing are connected has been known intuitively long before the biological sciences began to discover why. Sunlight exposure at sanatoria situated high in the Swiss Alps was used for the treatment of tuberculosis in the late 19th century, and at the beginning of the 20th century physicians began using artificial light sources to replicate its effects (Wells, 2006). Before the use of antibiotics became widespread, light was considered a significant player in the treatment of disease, and hospitals were built away from dense city centres to avoid the lack of daylight and fresh air (Volf, 2020). Beginning in the 1980s, light began to be used as a treatment for depression (Rosenthal et al., 1984) and seasonal affective disorder gained popular recognition.

However, knowledge of light's relationship with health is shifting away from the treatment of acute cases of illness and towards a broader conception of everyday wellbeing. This is largely due to the discovery of new photoreceptors in the retina known as intrinsically photosensitive retinal ganglion cells (ipRGCs) (Berson et al., 2002), which are crucial in the synchronisation of human circadian rhythms. Circadian clocks are present in almost every cell in the body (Mohawk et al., 2012), and their proper synchronisation, or entrainment, has been linked to lower rates of cancer, obesity, substance addiction and neurodegenerative diseases such as Parkinson's and Alzheimer's (Roenneberg & Merrow, 2016). In industrialised societies where most people spend 90% of their time indoors (Klepeis et al., 2001), it is important that we understand what these non-image-forming effects of light are, and what quality and quantity of light stimulates them.

This paper divides the literature into two main sections. The first covers work that has revealed the mechanisms in the eye and brain that connect light, melatonin production and circadian entrainment (Section 2). The second is focused more on the specific details of what kind of light is required to stimulate this system (Section 3). This includes the colour of light, the quantity needed, the effect of timing and the effect of spatial distribution in the field of view, and is related closely to resultant standards, metrics and practical recommendations.

The paper discusses the types of research that have been conducted, what they are able to tell us, and what their limitations are. It will demonstrate that while many pieces of the puzzle have been put together, the full extent of our relationship with light and the natural environment is still very much incomplete.

2. Light, melatonin and circadian entrainment

The connection between light and circadian entrainment had been suggested well before the discovery of the ipRGCs. Early research in the field of chronobiology had shown that in the absence of any light-dark cycles, a wide variety of organisms ceased to entrain their internal clocks to 24-hour cycles of activity and would instead gradually shift their sleep-wake cycles continually forward or backward over time (Pittendrigh, 1960). This is akin to owning a slightly fast or slightly slow watch which needs adjusting every day – the longer one leaves it unchecked the more out of time, or *phase shifted*, it becomes. In the case of the biological clock, this adjusting is achieved by the rising and setting of the sun.

In the early 1980s, seeking to investigate this effect in humans, Charles Czeisler and his team exposed two young men to a series of lighting conditions over the course of 66 days (Czeisler et al, 1981). At the time, other environmental time cues, or zeitgebers as they were known, were thought to be at least as powerful as the light-dark cycle in the entrainment of humans (Aschoff et al., 1971). These included factors such as knowledge of the time of day (eg. alarm clocks), social interaction and the timing of meals, rest and activities.

However, Czeisler's study showed that even with all these other cues removed, modulation of light by itself was able to properly entrain the subjects (Figure 1). While this finding was significant, and elevated the importance of light in human chronobiology, the study provided no explanation in physiological terms. In other words, light may simply have been acting as another psychological zeitgeber that influenced the subjects' decision to go to bed.

It was a contemporaneous study by Lewy et al. (1980) that first connected light exposure to acute human melatonin suppression. Melatonin is a hormone produced in the pineal gland at night-time by both diurnal and nocturnal animals and is hence often referred to as the "darkness hormone" (Arendt, 1998). Production of melatonin is regulated by the suprachiasmatic nucleus (SCN) in the brain, which is the master clock responsible for keeping circadian time. The SCN is in turn connected via the retinohypothalamic tract to the retina of the eye, a pathway which in many mammals is used for the transmission of light-dark signals for entrainment (or *photoentrainment*).

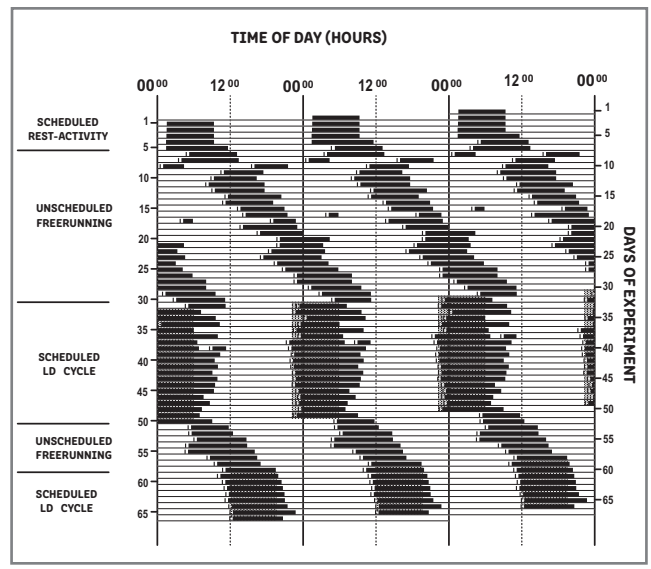

Figure 1 – Triple plotted data showing the rest-activity cycle of one of Czeisler's subjects. Sleep periods shown with black bars. Ethically questionable by today's standards, the chart shows the subject spent 66 days living in an environment with no knowledge of time and limited social interaction. Between the unscheduled and scheduled conditions (labelled left), the only environmental factor changed was the cycle of light and dark. Triple plotting allows the phase shifting patterns to be more easily seen. Adapted from Czeisler et al. (1981).

However, as already discussed, doubt surrounded the mechanism by which humans were being entrained, as previous studies had failed to detect melatonin suppression after light exposure. As a result it was proposed that while other mammals are entrained by light, humans have different, unique pathways derived from social cues, thereby elevating them above other species (Perlow et al., 1980). Lewy's study, which employed higher light levels than previous studies, completely dispelled this theory. Blood melatonin concentration was measured after night-time exposure to illuminances of 500, 1500 and 2500 lux at the eye.

The result was a clearly measurable suppression of the hormone, thereby drawing a direct connection between light exposure and melatonin suppression. Melatonin suppression is, however, only a proxy measure for circadian impact, and what the results did not show was evidence of actual sleep-wake phase shifting. Taken together though, the Lewy study and the Czeisler study (which did show phase shifting) provide evidence that the human SCN and the control of melatonin production is directly connected to light exposure.

While this evidence was important, the real paradigm shift came as a result of a series of neuroscientific discoveries that connected specific cells in the retina to the SCN. Around the beginning of the 21st century, a third photoreceptor in the eye was uncovered in addition to the classical rods and cones. Despite the ethically questionable nature of such practices, research undertaken by genetically engineering rodless and coneless mice have been particularly important to this process (Foster & Hankins, 2002; Lucas et al., 1999). Lucas et al. showed that these mice could still photoentrain despite a complete lack of rods or cones, and that mice with their eyes fully removed could not, a result that pointed positively towards the existence of a novel non-rod, non-cone photoreceptor in the eye.

However, doubts still remained due to a lack of anatomical evidence (Rea et al., 2002). A study published in 2002 began to provide this evidence (Berson et al., 2002), confirming the photosensitivity of the ipRGCs in the eye. By bathing a rat retina in chemicals that prevented any activity from the rods and cones, researchers in the Berson study could still detect electrical signals that projected to the SCN.

In a second phase of the experiment in which the ipRGCs were entirely physically isolated from the retina, there was still a detectable signal in response to light, thereby demonstrating their intrinsically-photosensitive nature. By then exposing the cells to a series of narrow band light sources, the same study went on to determine that the ipRGCs respond most to light of around 484nm, towards the blue end of the light spectrum. This latter point indicated that melanopsin was the most likely candidate photopigment, one which had already been detected by others in frogs as well as the human retina (Provencio et al., 1998, 2000). This was confirmed in subsequent studies that involved the removal of the specific melanopsin-producing gene from rodents, with the result of desensitising the ipRGCs, thereby proving that melanopsin is the photopigment responsible for the ipRGC light response (Lucas et al., 2003; Panda et al., 2002).

The ipRGCs and their connection to the SCN are not an entirely isolated system. Research has demonstrated that while the ipRGCs have an intrinsic response to light which they pass downstream to the SCN, they also receive extrinsic upstream input from the rods and cones, a property common to other ganglion cells in the eye (Belenky et al., 2003; Dacey et al., 2005; Perez-Leon et al., 2006). Experiments in genetically-engineered mice have shown that this input can influence circadian functioning (Hattar et al., 2003). With the photosensitive element of the ipRGCs disabled, Hattar et al. showed that mice were still able to entrain to light-dark cycles, albeit to a lesser extent. When those ipRGCs were killed entirely, however, the entrainment ceased altogether (Güler et al., 2008). This shows that this newly-discovered rod and cone input to the circadian system operates solely through the ipRGC cells.

As discussed in the next section, these findings may complicate the determination of spectral efficiency functions for circadian lighting, in that circadian stimulation cannot simply be equated with the intrinsic response of the ipRGCs. Similarly, the connection between the ipRGCs and the brain is not limited to the SCN and not limited to the function of circadian entrainment (Schmidt et al., 2011). There exist at least five sub-types of ipRGC found to be responsible for functions such as the regulation of pupil size (Lucas et al., 2003), contrast detection (Schmidt et al., 2014) and exacerbation of migraine intensity (Noseda et al., 2010). This further complicates the idea of circadian-specific lighting in that circadian effects cannot be manipulated by light independently of other brain functions.

3. Characteristics of circadian light

3.1 Spectral characteristics

Light of any kind is distinct from radiant power in that it is defined according to the sensitivity of the human eye. To translate radiant power into light, it is necessary to apply a weighting system, or luminous efficiency function. Using such a function, wavelengths to which the eye has a greater sensitivity contribute more to the quantity of light than others, and vice versa. This weighting is usually done according to one of two models of the visual system: photopic or scotopic vision (though additional models exist).

Photopic vision, and its associated efficiency function $V(\lambda)$, is based on relatively bright lighting conditions. Under these conditions the brain primarily uses the three cone photoreceptor types to see, and this is the conventional characterisation of light upon which the candela and lux metrics are based.

In scotopic conditions, such as under moonlight, the brain primarily uses the rod photoreceptors to see. Rods have a different spectral sensitivity to the cones and so a different efficiency function is used $V'(\lambda)$, though scotopic units are relatively uncommon in practice. These two abilities of the eye – seeing in the day and seeing in the night – are now accompanied by a third, non-visual one: entraining the circadian clock. As such, a new efficiency function is needed.

Two early landmark experiments (Brainard et al., 2001; Thapan et al., 2001) sought to solve this problem. Both studies exposed their subjects to multiple discreet narrow band light sources at multiple intensities at night via a full visual field device known as a Ganzfeld dome. They measured the resulting drop in melatonin in the blood for each wavelength and intensity. Despite there being differences between the two studies (in the Brainard study, subjects were

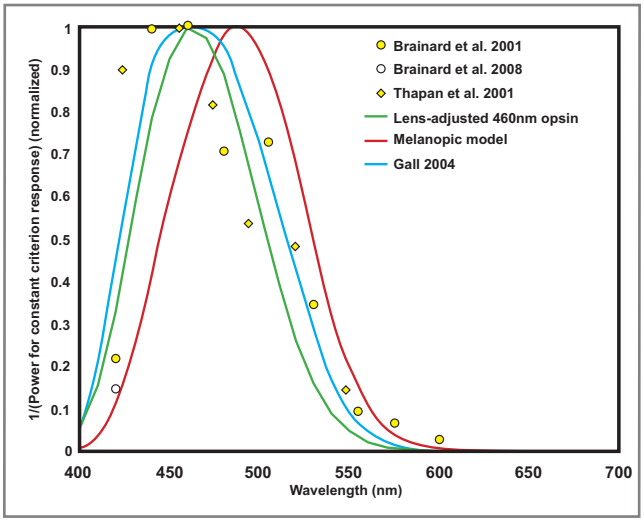

Figure 2 — Data from the Brainard et al. (2001) and Thapan et al. (2001) studies plotted together with efficiency functions for EML (labelled "Melanopic model") and Gall and Bieske (2004). Also shown is an early function (labelled "Lens-adjusted 460nm ospin") which was based on a hypothetical photopigment with peak sensivity at 460nm. The Brainard et al. study from 2008 plotted here measured only responses to light at 420nm. Adapted from Rea et al. (2012). Colourised by the author.

irradiated for 90 minutes as opposed to 30, and in the Thapan study the subjects had two control days before exposure whereas in the Brainard they had none), the resulting data from the two studies correlated well and the authors concluded with similar proposed ranges for peak melatonin suppression (446-477nm in Brainard et al. and 457-462nm in Thapan et al. – both blue as perceived by the photopic system).

Gall and Bieske used the Brainard and Thapan melatonin suppression data to attempt to define a circadian metric (Gall & Bieske, 2004). They compiled the results from the two studies and interpolated an efficiency function for light-induced melatonin suppression using a best-fit methodology, with a resulting peak sensitivity at around 460nm (Figure 2). In the paper, Gall and Bieske go on to suggest the modification of existing light meters as approximate methods of measuring their new metric. The Gall and Bieske function would go on to be used in the German pre-standard DIN V 5031-100 (2009) (now withdrawn). However, this early effort to create a circadian efficiency function is limited in accuracy in that it does not account for a key feature of the Brainard and Thapan data – a distinctive spike in spectral sensitivity at around 500nm (Figure 2).

3.1.1 Equivalent Melanopic Lux (EML)

Another notable circadian metric that has entered into building standards, but which nevertheless has its own limitations, is Equivalent Melanopic Lux (EML). EML is based on the spectral sensitivity function for melanopsin operating in isolation and does not take into account the upstream influence of the rods and cones (Lucas et al., 2014). The melanopic efficiency function was introduced by Al Enezi et al. (2011), who demonstrated that in mice lacking rods and cones, light tuned to the sensitivity range of melanopsin was most effective in altering their circadian rhythms. Adjustments were later made to account for variations between human and rodent pre-receptoral light filtration (Lucas et al., 2014).

Melanopic lux and the EML metric is therefore a measure of the impact of light on human circadian rhythms in the absence of rods and cones. As a result, its spectral range (peak sensitivity: 480nm, Figure 2) differs from that of empirical melatonin suppression responses in normal humans as per Brainard (2001) and Thapan (2001) (peak sensitivity: ~460nm). This apparent mistuning was not by mistake. The authors of the 2014 Lucas paper published sensitivity functions for all five photoreceptors independently, without claiming the ability to predict precisely how they might interact with each other and what signal they might eventually send to the brain. They wrote "it is not yet possible to predict the non-image-forming impact of a given illuminant based on its intensity and spectral composition" (Lucas et al., 2014, p. 7).

Nevertheless, EML was adopted by the WELL Building Standard v1.0 in 2015 as a measure of circadian effectiveness (International WELL Building Institute, 2015). In the context of design and engineering, it could be argued that EML is "accurate enough" in that it would not lead to drastically inappropriate decisions. Light sources biased towards longer wavelengths will avoid circadian disruption at night and vice versa. For the purpose of a design guideline it may be sufficient. However, as a standard unit to measure circadian light it must be subject to greater scrutiny.

3.1.2 Circadian Stimulus (CS)

Since 2005, researchers from the Lighting Research Centre (LRC) at Rensselaer Polytechnic Institute in New York have been developing their own metric dubbed Circadian Stimulus (CS) (Rea et al., 2005, 2010, 2012; Rea & Figueiro, 2018). What sets CS apart from EML is principally the modelling of rod and cone input to the ipRGCs, a mechanism which is complex partly because it involves sub-additive brightness perception. In an additive model such as EML or the photopic luminous efficiency function V(λ), light of different wavelengths delivered simultaneously to the eye simply add together in the perception of brightness.

However, the opponent system of colour vision means that within one opponent channel (blue-yellow or red-green), light of one wavelength range can serve to cancel out its opponent wavelengths when delivered simultaneously, resulting in a sub-additive output from that channel as a whole. In the circadian system, research suggests the ipRGCs are reliant on input from the blue-yellow opponent channel (Dacey et al., 2005; Figueiro et al., 2004). The blue-yellow channel balances stimulation signals from the S (blue) cones against the combined M (green) and L (red) cones so that in the case of polychromatic light sources there is the possibility of spectral opponency.

In the CS model, this means that the relative spectral power when all photoreceptors are considered can dip below zero for wavelengths of light towards the red and green area of the spectrum (Figure 3, next page). Rods are also implicated in that they control the sensitivity of the cones. The integration of rod and cone input in the CS model results in a closer fit to the Brainard and Thapan data than provided by other metrics (Rea et al., 2012). Rea et al. (2012) found a mean residual error for CS of 0.06 compared with 0.12 for the Gall and Bieske function, and 0.23 for EML when compared with the Brainard and Thapan data.

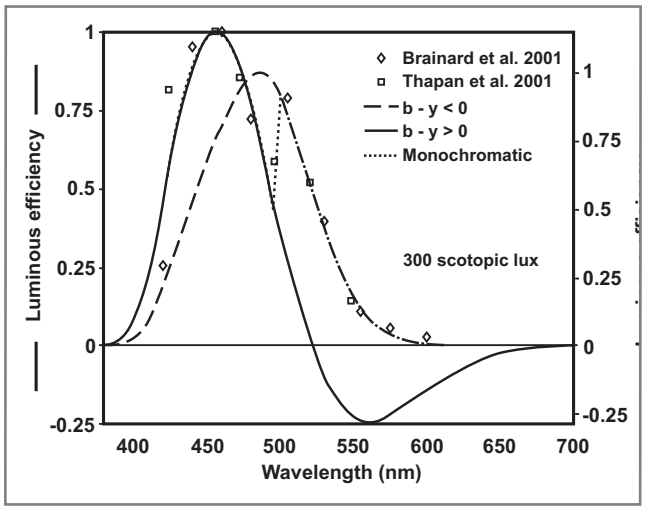

Figure 3 – Three spectral weighting functions used for calculation of Circadian Stimulus. B-y<0 (dashed line) applies to polychromatic light sources with a warm appearance, while b-y>0 (solid line) corresponds to a cool appearance. Under the cool lighting condition, the circadian response exhibits spectral opponency, causing luminous efficiency to dip below zero around 560nm. Also shown is the response to monochromatic illuminants (dotted line). This curve fits the Brainard and Thapan data closely as those experiments were carried out under monochromatic lighting conditions. 300 scotopic lux is the illuminance at the eye. Adapted from Rea et al. (2018).

3.1.3 EML versus CS

Research into the interaction between ipRGCs and other photoreceptors is still incomplete (Spitschan et al., 2017), and very recent research has even shown that one subtype of ipRGC has an inhibitory, dampening effect on circadian phase shifting in mammals (Sonoda et al., 2020). The neurological pathways responsible for circadian entrainment are still in the process of being gradually unearthed, something which casts doubt on the validity of the CS model.

In addition, the CS metric is more complex than others. In order to model the opponent colour channels in the retina, the CS algorithm requires the input of full spectral power distribution information and the selection of one of two efficiency functions, one for warm sources and one for cool sources. A more recent version has also indicated that illuminance levels further modify these functions (Rea & Figueiro, 2018). In contrast, EML could in theory be measured using a conventional photometer modified with a curve matching filter appropriate to the melanopic sensitivity function.

Another potential problem with CS (as well as Gall and Bieske's metric) is that it is based on nocturnal melatonin suppression and not circadian phase shifting. While these two things are very closely related, there is mounting evidence suggesting melatonin suppression and circadian phase shifting are not inseparable in their spectral or temporal response (Gooley et al., 2010; Najjar & Zeitzer, 2016; Rahman et al., 2018). CS is not perfect, and the state of neuroscience research is by definition never complete, but the metric has gained traction in lighting research (Chen et al., 2020; Leslie et al., 2012; van Creveld & Mansfield, 2020) and the question of whether it is suitable for implementation in lighting practice is still in discussion (Ashdown, 2019; Soler, 2019).

3.2 Intensity and timing

Aside from concerns for the spectral qualities of circadian effective light, the amount of light and the timing of that light have also been the subject of extensive research. Estimates have reduced over time. An early study showed that for a 60-minute exposure to light at night (LAN), minimum light levels for acute melatonin suppression were 350 lux at the eye (McIntyre et al., 1989). Another study, using longer exposures of 120 minutes, found that levels of just 285 lux were sufficient (Aoki et al., 1998).

However, these studies measured only acute melatonin suppression rather than any subsequent phase shifting effects. To determine the effect on phase shifting, it is necessary to expose subjects to LAN and then subsequently measure the shift in circadian phase. One way to do this is to measure the difference in dim light melatonin onset (DLMO) between a control night and the night immediately after the LAN intervention. Employing this methodology, one study found that LAN as low as 100 lux for 6.5 hours was capable of delaying DLMO as well as acutely suppressing melatonin (Zeitzer et al., 2000).

More recently, research has suggested that a level of 30 lux for only 30 minutes (Figueiro et al., 2006) or 0.05 CS (Figueiro & Rea, 2013) is a safe working threshold for LAN. These levels are below those emitted to the retina by self-luminous displays like PCs, tablets and e-readers, and are not sufficiently mitigated by the use of apps that shift the spectral composition of those displays (Nagare et al., 2019). One study found that outdoor LAN in the business districts of Shanghai and Hong Kong was found to exceed the 0.05 CS threshold in 47% and 86% of tested viewpoints respectively (Chen et al., 2020).

These low thresholds suggest that the effects of our urban environment could be at serious odds with circadian health. Two studies conducted at the University of Colorado provide compelling evidence for this by directly comparing the influence of electric and natural lighting environments on melatonin timing (Stothard et al., 2017; Wright et al., 2013). Participants in the studies spent one week of a two-week protocol in their normal urban environment and the second week on camping trips in the Rocky Mountains, with one study taking place in winter (Stothard et al., 2017) and one in summer (Wright et al., 2013). In the natural light condition participants experienced average daytime illuminances up to thirteen times that of the artificial condition, and LAN was restricted to a campfire.

Melatonin onset and offset were measured before and after the week-long camping trip in lab conditions. Both the summer and winter studies showed that the natural light environment resulted in significantly earlier phase timing (Figure 4, next page). The studies had a particularly marked influence on subjects who habitually wake up and go to bed later (known as late chronotypes). These subjects experienced greater phase shifting effects as a result of exposure to natural light, such that their sleep-wake phase was closer to that of the other participants.

This is significant in that late chronotypes are particularly likely to suffer from a problem known as "social jetlag" (Wittmann et al., 2006). Social jetlag occurs when people fail to adjust their circadian timing to the demands of society (usually work or school), a problem which is exacerbated when they sleep in during the weekends. This in turn leads to greater negative health outcomes such as daytime

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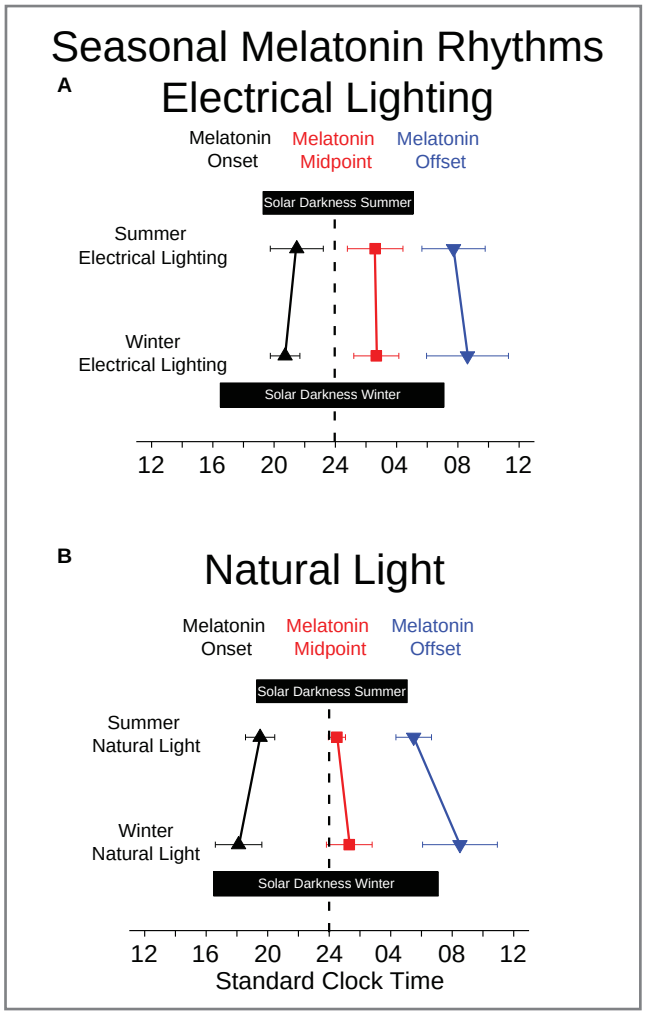

Figure 4 – 24-hour plot of melatonin phase during summer and winter relative to solar darkness. Subjects were exposed to one week of either normal natural and electrical lighting in an urban environment (A) or one week of natural lighting while camping (B). Timing of solar darkness is represented by the black bars. Closer correlation between melatonin on- and off-set and the solar cycle is shown in the natural condition. Note also that subjects adapted to the seasons, experiencing longer melatonin duration in the winter compared with the summer. Adapted from Stothard et al. (2017).

sleepiness, diabetes, mood disorders, substance addiction and obesity (Stothard et al., 2017). By promoting a later circadian cycle, modern artificial lighting environments may be a significant contributor to this problem.

Similar to the negative influence of LAN, research has also shown the positive influence of bright light during the daytime for robust sleep cycles, something which is likely to have been a contributing factor in the Colorado experiments. One study measured the morning light levels experienced by a large subject group in an office environment (Figueiro et al., 2017). The aim of the study was to determine how exposure to relatively bright morning light affected sleep and mental health outcomes. Instead of using brief light interventions as in most LAN studies, the emphasis was on measuring existing light conditions via the use of a wearable light meter throughout the day. The results showed that subjects who experienced bright light in the mornings were less likely to report depression and experienced lower sleep onset latency and better self-reported sleep quality.

Bright light in the study was defined as light reaching the LRC's recommended CS value of 0.3 or over (roughly equivalent to daylight of 180 lux or 200 EML measured vertically at the eye). This is still relatively dim when compared with an overcast day (approx. 1000 to 10,000 lux) and supports the application of the WELL standard's higher recommendation of 240 EML from 9am to 1pm (though not necessarily the lower 150 EML option). However, one study using similar EML targets for artificial lighting found no significant effect on sleep and circadian phase outcomes (Ticleanu & Littlefair, 2020). More research in real world scenarios is needed to confirm the effects of applying daytime circadian light exposure recommendations.

Prior exposure to bright light in the day may also have positive circadian effects by reducing subsequent sensitivity to LAN (Hébert et al., 2002; Kozaki et al., 2016). Early studies on people working in Antarctica found that during winter, when the sun does not rise for months and ambient light reaches a maximum of 500 lux, it took significantly less light to suppress melatonin at night when compared with a summer condition, in which ambient light was often at 100,000 lux during the day (Owen & Arendt, 2002). These effects have been shown in less extreme conditions, with studies taking place over the course of weeks (Hébert et al. 2002) and even a 24-hour period (Kozaki et al., 2016).

It has also been shown that blue-enriched light in the morning reduces the phase-delaying effects of LAN (Münch et al., 2017). This has implications for the validity of recommendations made regarding LAN in that sensitivity is dependent on individual prior light history. Broadly, the studies indicate that exposure to bright light during the day, particularly in the morning, is as important as avoiding LAN for circadian entrainment.

3.3 Other characteristics of circadian light

As has been covered in this section, spectral composition, quantity and timing are all variables that need to be taken into account when discussing circadian light. However, more variables are emerging. The ipRGCs have been described by the LRC as "blue sky detectors" for their sensitivity to blue light (LRC, 2006), but this term may be accurate not only in terms of colour but also in terms of vertical distribution in the visual field. Glickman et al. (2003) found that by exposing only the upper retina, which is responsible for seeing below the horizon, to 200 lux at night, melatonin suppression was not significantly different from an entirely dark condition. The implication here is that circadian disruption will be significantly reduced if designers keep LAN to the lower half of the visual field.

Interestingly, this resonates with lighting designer Richard Kelly's assertion in the 1950s that light above eye level is "formal" while below eye level it is "informal or cozy" (Kelly, 1952, p.30). This echoes the polarity between high bright sky light in the day and low dim firelight in the evening, and it could be argued in this case that research is catching up with design intuition.

4. Conclusion

There is a need in modern society to introduce light into otherwise dark environments. In industrialised countries, more and more people around the world have moved their lives indoors, into light that is orders of magnitude less than it is outdoors. Added to this, there is a

need to extend the solar day into the night, to accommodate working and social lives. The problem is that thus far, this light has been for one purpose: vision. As discussed in this paper, recent science is beginning to reveal that humans use light for purposes other than vision. Developments in neuroscience have been instrumental in understanding the circadian effects of light on the eye and brain, as have attempts to quantify the spectral and temporal response of the circadian system. We now know that light towards the blue end of the spectrum is most effective, and that bright light during the day should be combined with lower levels of light at night for robust circadian entrainment.

While the research is far from conclusive, and metrics and standards are still up for debate, incorporating these principles into daily life would have a significant impact on health and wellbeing. However, in the time of the COVID-19 pandemic, "daily life" has changed dramatically for many people, as varying degrees of lockdown have become the "new normal". As people spend less time in offices or commuting and more time at home, they may become less likely to go outside.

In May 2020, the LRC surveyed around 600 people who worked from home during lockdown and found that subjects who described their indoor environment as bright or spent time outside during the morning experienced less anxiety, less daytime sleepiness and better sleep quality (LRC, 2020). This could mean that while people work from home, raising awareness of light exposure and encouraging light-seeking behaviour is an important factor in promoting resilience and health. Beyond lockdown, the potential for buildings to be considered either beneficial or detrimental to our health provides a greater incentive than ever for building owners, designers and engineers to be attentive to light and circadian rhythms.

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