Human Centred Lighting of a 24-hour Control Room

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SUMMARY

Lighting of Industrial Control Rooms may disrupt natural circadian rhythms, affecting the health and wellbeing of operators. Human Centred Lighting (HCL) is designed to mimic the natural dark/light cycle, maintaining alertness and to reduce adaptation to night work and therefore avoid a phase delay of the circadian rhythm. Research has emphasised the part played by melanopsin in regulating the production and suppression of melatonin which is directly linked to circadian rhythms. Using the refurbishment of a control room as a case study, the implementation of a HCL design to support circadian rhythms and health and wellbeing of control room operators is illustrated.

KEYWORDS

Circadian, lighting, Melanopic Equivalent Daylight Illuminance (MEDI), intrinsically photosensitive retinal ganglion cells (ipRGC), melatonin, night shift, Human Centred

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Introduction

Light from the sun is vital to the existence of most life on our planet and has shaped the evolution of almost every species of flora and fauna. For most of human history the only source of Light at Night (LAN) was provided by moonlight, or fire, candles and lamps which relied on the in-situ combustion of a fuel source. Until 1879 and the invention by Thomas Edison of the light bulb, it was impossible to undertake many of the activities we now take for granted at night. Our working and leisure time are no longer restricted by the natural cycle of sunrise and sunset. We take it for granted that there will be artificial light when we need it. It has changed our lives immeasurably but comes at the cost of disrupting circadian rhythms and contributing to long term adverse health conditions.

In industrial settings, control rooms are an important function to control safety systems especially in a nuclear facility. Some control rooms may require continuous staffing round the clock, as there are many safety systems that must remain operational overnight when the dayshift has gone home. An illuminance survey of one of AWE's control rooms found that the existing lighting met the extant requirements of the Chartered Institute of Building Service Engineers (CIBSE) guidance and was suitable for use in its current configuration (AWE Plc, 2019). However, since commissioning the control room lighting in the 1990's, research into lighting has developed and has emphasised the part played by Non-Image Forming structures of the eye in regulating the production and suppression of melatonin which is directly linked to circadian rhythms (Cajochen, Zeitzer, Czeisler, & Dijk, 2000; Casper & Rahman, 2014; Kayumov, et al., 2005; Lowden & Kecklund, 2021; Lunn, et al., 2017; Provencio, et al., 2000).

This paper refers to the developing research in this area as the basis for a case study of a recent control room refurbishment at AWE. The aim was to consider the potential for modern Human Centred Lighting (HCL) design to support the health, wellbeing and the performance of control room operators. The case study follows an introduction to the research literature on the reaction of the circadian rhythm through melatonin production and suppression, following exposure to light sources.

Light at Night: the effects on human performance

Humans are a diurnal species with circadian rhythms naturally synchronised to the day/night cycle. However, since the invention of the electric light bulb, humans' exposure to the natural light/dark cycle has progressively decreased, while exposure to artificial light has increased. Humans are exposed to less light, including natural daylight, during the day, and less darkness at night as they spend ever more time indoors exposed to artificial illumination (Brown, et al., 2022). It is estimated that "84% of the working population in industrialised societies spend more than 90% of the day indoors" (Lowden & Kecklund, 2021). Large proportions of the population receive an "unnatural exposure to light including irregular light-dark patterns characterised by insufficient light exposure during the day, too much LAN, or a combination of both" (Lunn, et al., 2017).
The synchronization of circadian rhythms is greatly influenced by environmental light cues detected via image forming (rods and cones) and non-image forming (intrinsically photosensitive retinal ganglion cells (ipRGCs)) pathways (Provencio, et al., 2000; de-Kort, 2014). The ipRGCs are photosensitive by means of the photopigment melanopsin (BSI, 2022; Lowden & Kecklund, 2021); They detect the daily cycle of light/dark and inhibit or trigger the production of melatonin (Lunn, et al., 2017; Blask, et al., 2005).

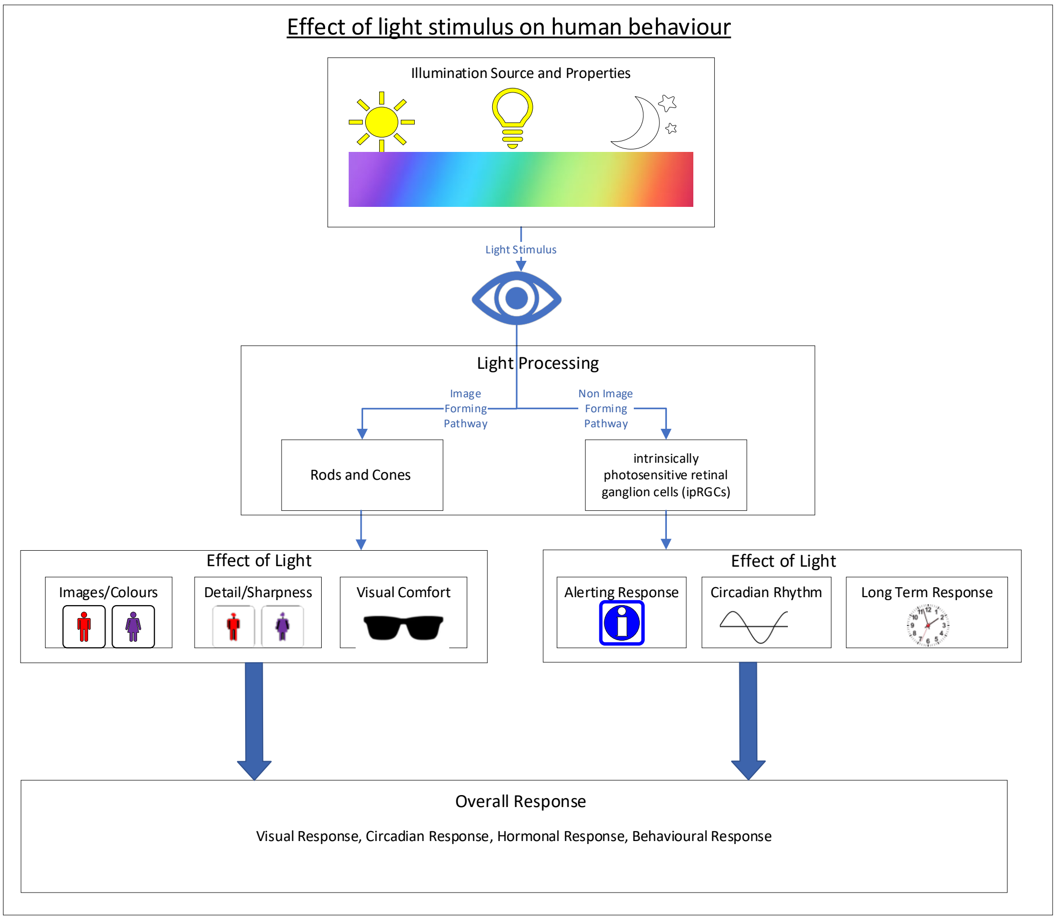

Figure 1: Effect of light on human behaviour.

Melatonin suppression and direct alerting effects

Melatonin is a naturally occurring hormone found in humans and is produced in the pineal gland during dark hours, triggering sleep. It plays a central role in the regulation of circadian rhythms and is the main influencer of the brains central clock.

Blue wavelengths in light (i.e., between 450 nm to 490 nm) suppresses Melatonin production which can induce a phase change in the circadian rhythm. It has been demonstrated that an alertness response and suppression of melatonin production is related to dosage of light with the strongest effects generated by a light > 1000 lx (fluorescent room lighting 4000 K, ≈>760 MEDI). However, in an environment with very little light in the evening, a 50% suppression in Melatonin levels has been observed at <30 lx, (≈<23 MEDI) (Cajochen, Zeitzer, Czeisler, & Dijk, 2000) (Lunn, et al., 2017). This means that by dimming existing lights, night workers are still exposed to light in the range of 450-490 nm which will reduce melatonin suppression, but there will still be an alerting effect from the blue light which may be beneficial for alertness but is still disruptive to the circadian rhythm.

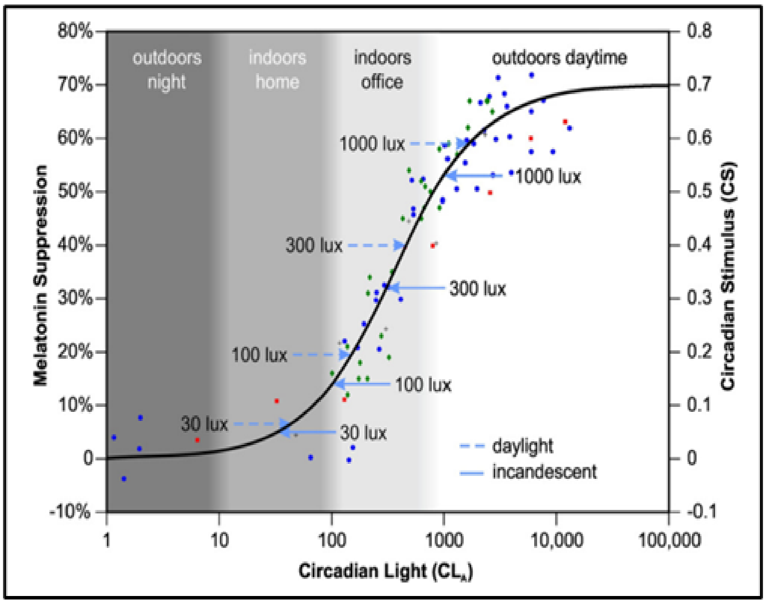

Figure 2: Nocturnal melatonin suppression for different light spectra plotted as a function of light level, where the spectral power distributions of various light sources used in previous published studies are weighted according to the CLA (x-axis). CLA is irradiance at the cornea weighted to reflect the spectral sensitivity of the human circadian system as measured by acute melatonin suppression and is measured in units of spectrally weighted flux per unit area. The right ordinate (y-axis), labelled "circadian stimulus" (CS), is scaled to be proportional to the left ordinate, representing the relative amount of melatonin suppressed after exposure of the retina for 1 h, ranging from 0.0 (no suppression) to a maximum of 0.7 (70% suppression). (Lunn, et al., 2017) Reproduced under Elsevier licence 5723651389783.

Human Centred Lighting

HCL is designed to mimic the natural dark/light cycle. The literature proves the concept that removing or filtering short-wavelength light exposure between 460 and 480 nm at night, results in natural melatonin secretion and surprisingly has no effect on alertness, fatigue, or sleepiness (Kayumov, et al., 2005; Casper & Rahman, 2014). Counterintuitively, supporting the health and well-being of control room operators on night shift involves reinforcing the natural circadian rhythm and facilitating the production of melatonin. In rapidly rotating shift schedules, a minimum suppression of melatonin is preferrable as well as an alerting lighting. Rather than dimming lighting at night, but instead changing the intensity and wavelength of the light provided, the natural dark/light cycle can be replicated inside the control room. It is recommended that lighting at night should be close to the longer wavelength of light, >490 nm, and that blue light from computer screens is filtered out. The general light level should be kept low but individual workstations should be provided with high MEDI lighting to support personnel with reading, writing and other visual needs, and to maintain alertness (Lowden & Kecklund, 2021). Consequently, alertness is maintained, adaptation to night work is reduced, and a phase delay of the circadian rhythm is avoided. This is preferable in rapidly rotating shift systems with no more than three night shifts in a row.

Unnatural exposure to LAN can lead to the circadian rhythm being out of synchronization with the internal circadian-clock and working hours, sleep deprivation, and suppression of melatonin from the alerting effect of short wavelength light. Links are made to increased risk of cardiovascular disease, breast and colorectal cancer, stroke, type 2 diabetes, obesity, digestive problems, depression, and increased accidents and injuries (Lowden & Kecklund, 2021; Lunn, et al., 2017; Kayumov, et al., 2005).

Melanopic Equivalent Daylight Illuminance

Traditional measurement of illuminance doesn't capture the human non-visual system response to light because the photopic luminous efficiency functions of commercially available light meters do not represent the full spectral response of the human circadian system. New measures are needed to quantify and assess responses of the non-visual system to light, and the effect on melanopsin contained in the ipRGC's. This has led to the development of the Melanopic Equivalent Daylight Illuminance (MEDI) which is measured at the eye of the user rather than illuminance which is measured at the surface being illuminated. In daytime, the recommended minimal MEDI level throughout the day would be 250lx at the eye, measured in the vertical plane about 1.2m (eye level when seated) above the floor (Lowden & Kecklund, 2021).

Case Study

The Control Room is staffed 24/7 on a rapidly rotating shift pattern with a mixture of 8-hour shifts on weekdays and 12-hour shifts at weekends, plus rest/admin days. The room is windowless, so there is no sense of the passing of the day and is entirely artificially illuminated. The main lighting is not adjustable but local task lighting is dimmable where available.

A survey was undertaken to capture data on the experiences of the 17 control room operators and managers, achieving a response rate of 65%. The user population were aged between 25 and 65 years. More than half of the respondents have worked in the control room for more than ten years. Nearly three quarters of respondents considered the lighting to be bright or too bright; with more than half disagreeing with the statement "After night shift I am able to sleep well during the day". Responses to open questions confirmed that adjustment of the main lights was not possible, only a few spotlights could be adjusted. The prevailing opinion was that the lighting was too bright.

Operators were asked an optional question "Do you have, or have you ever suffered from any of the following health conditions? Heart Disease, Stroke, Type 2 Diabetes, Obesity". The question was designed to find out if the data reported in the literature was reflected by the operators in this small sample. One operator reported that they were living with long term health conditions consistent with long term exposure to rapidly rotating shift patterns.

Control Room Refurbishment Project

The Project engaged the AWE HF team to consult on the control room lighting during the refurbishment. The proposed lighting design which had been accepted by the project required a Correlated Colour Temperature (CCT) of 4000K providing 3800 lumens (lm). The specification met the requirement, and the design incorporated sufficient luminaires spread uniformly across the room to provide adequate lighting of the area. The design met the requirements of the extant standard for Light and lighting in the work place of BS EN 12464-1:2021 (BSI, 2021), but the survey feedback on the experiences of the control room operators and managers strongly suggested that the replacement lighting scheme needed to be more innovative.

BS EN 12464-1:2021 provides the following guidance:

> "The choice of colour appearance of the light is a matter of psychology, aesthetics and what is preferred. The choice will depend on illuminance level, colours of the room and furniture, surrounding climate and the application. (BSI, 2021).

Given the enduring nature of the facility a flexible approach was adopted. There was a small window of opportunity to modify the lighting scheme to support control room staff immediately, which could then be easily modified if required. The project procured multiple spectrum adjustable lights, allowing the scheme to be modified cost effectively in the future once improved guidance is available. Control room operators will require training on the use of lighting to ensure that lighting regime is implemented correctly. HF team will gather User Experience (UX) data from the control room personnel to understand the efficacy of the lighting and any psychological or physiological effects.

HF reviewed the lighting design and provided guidance on the preferred wavelengths for illuminating the Control Room. As the day progresses the intensity and temperature of the light decreases, shifting from the short wavelength blue end of the spectrum to the long wavelength amber end.

Table 1: Preferred Illumination Wavelengths (Lowden & Kecklund, 2021)

Shift	MEDI	CCT
Morning	250lx	5200 K
Afternoon	100lx	4000 K
Night	70Lx	3000 K

Future Work

AWE is currently in the process of upgrading a significant part of its existing ageing infrastructure. During concept design, the proposed shift patterns required during the operational phase of a new facility must be understood and disseminated via the Target Audience Description to assist designers.

Following on from this paper, a follow-up paper will be developed to report on users' experiences of the new lighting scheme. Depending on the results, the HF team will feed the results into AWE's internal Engineering Mandatory Elements on Workplace Lighting, and Human Factors Design Guide to provide designers with clear guidance.

Standards vs Research

Standards are catching up with the research. CIE published its System for metrology of optical radiation for ipRGC-influenced responses to light in 2018 (CIE, 2018); BSI published PD ISO/CIE TR 21783 Light and lighting - Integrative lighting - non-visual effects in 2022. However, CIBSE guidance for control room lighting states; “The main room lighting should be under central management control to avoid [control] room night-shift staff changing the lighting to more ‘restful’, dimmer ‘night’ lighting. Lower lighting levels at night will only contribute to reduction in operative alertness and response times” (CIBSE, 2022). If the basis of this statement is that Spectral Power Distribution (SPD) of the control room lighting contains light in the range 460 and 480 nm then dimming the lights will reduce the intensity of the light in that range, not the SPD. This will result in melatonin suppression and does not take account of the findings of Lunn et al. 2017, Kayumov et al. 2015, unlike the BSI guidance (BSI, 2021) which supports the use of dynamic adjustment of colour temperature. This indicates that there is a gap between the research and the extant guidance.

Conclusion

There is good evidence that Circadian Lighting can synchronise and support the human circadian system by establishing a strong daily light-dark pattern (BSI, 2022). Full spectrum lighting at night will result in maximum suppression of melatonin. However, where rapidly rotating shift patterns are in effect, circadian rhythm should be supported by providing longer wavelength illumination that facilitates natural production of melatonin. Individual workstations should be provided with high MEDI task lighting to permit reading, as well as an alerting lighting. Display screens should be provided which filter out the blue wavelength light.

In contrast, it observed that workplace illumination during the day generally falls below natural daylight levels. There is likely to be a shortfall in operators’ exposure to light when working during the day. Therefore, during daylight hours short wavelength illumination incorporating the blue part of the spectrum, representative of the colour temperature and intensity of natural daylight should be provided. This lighting should transition towards the longer wavelength as the day progresses.

The way that the working environment is illuminated has a direct physiological and psychological effect on employees. Designers and HF professionals working on new-build and refurbishment projects are in a unique position to influence the lighting design of control rooms to support the long-term health and well-being of operators. Specification of Circadian Lighting schemes in HF Requirements for control room environments should become the norm rather than the exception.

There is an opportunity for the AWE HF Team to influence lighting policy across the sites as a major construction program gets underway to replace the ageing infrastructure and facilities in the nuclear and conventional estate. HCL can become the standard for all AWE facilities, not just in one control rooms, thus leveraging the positive psychological and health effects of lighting on the entire workforce.

The control room in the case study has not yet received its replacement multi-spectral luminaires so the operators are still exposed to short wavelength blue LAN. Further work is required following their installation to collect user experience data and determine the effectiveness of the solution.

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