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CIRCADIAN LIGHT EXPOSURES OF SHIFT WORKING NURSES

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Abstract

Studies have linked adverse health outcomes to work during the body's subjective night. Certain shift schedules result in light exposure profiles that may cause circadian disruption. Previous studies estimated average artificial illuminance to quantify light at night (LAN) at work which limits their validity and scope. However, daylight, shift length, commuting exposures and light during restricted sleep opportunities compete with LAN as causative agents, as do non-photic factors such as social disruption, activity and food intake during the subjective night.

Investigations into the effects of light in shift work should be supported by 24-hour light exposure measurements, *e.g.* to establish dose-response relationships. The purpose of the study was to collect and suggest interpretations of 24-hour exposure data, and investigate both daytime and night-time workers' light cycles in more detail.

Keywords: Shift work, night work, IIL responses, melanopic, non-visual dosimetry, health, time-weighted average dose, 24-hour exposures, circadian rhythms, chronotype, sleep

1 Motivation, specific objective

Exposure to light is the main driver of central circadian clock timing (or "zeitgeber"). Changes in the pattern of light exposure due to night shift work may cause disruption to the circadian clock, or other important physiological markers of circadian rhythms, such as melatonin. Circadian disruption reduces performance and impairs sleep and wellbeing.

Studies have also linked work during the body's subjective night with an increased risk of various long-term adverse outcomes on endocrine, mental, cardiovascular and ontological health (Pan *et al.*, 2011; Gan *et al.*, 2015; Vyas *et al.*, 2012; Marquie *et al.*, 2015; Cordina-Duverger *et al.*, 2018). However, there are mixed findings between different studies, suggesting that there may be limitations within some of these studies.

Mixed results may be due to misunderstanding or over-simplification of the effects of work schedules on circadian rhythms (Erren and Morfeld, 2013), and this may be associated with a lack of data about the light exposures in the majority of retrospective and prospective studies. The measurement and interpretation of light exposures are typically limited by more than one of the following reasons:

- The contribution from daylight is often excluded, which can be inappropriate, *e.g.* in northern European latitudes in summer;
- Measurement timing does not represent 24-hour exposures due to work schedules, and outdoor exposures due to travel to work are routinely excluded;
- Measurement locations (*e.g.* on work surfaces, or devices worn on the wrist) are not representative of the exposure of the eye or the full range of conditions in the workplace;
- Measurement quantities relating to "ipRGC-influenced responses to light (IIL)" are now the subject of an international standard, but typically studies have reported only illuminance and correlated colour temperature of artificial lighting;

- Interpreting circadian exposure timing requires information about the individual's subjective clock state, but chronotype methods are often overlooked, and may need to be adapted to individual shift schedules in the case of shift workers; and
- Time-weighting in dose calculations are not directly relevant to circadian responses, and exposure dose proxies are usually based on time above threshold or hourly averages.

Indoor night and day work not only alter light exposure profiles but also patterns of activity, food intake, social behaviour and sleep. Understanding the role of light in circadian disruption is therefore complex. For example, long shift durations and night work may both result in workers needing more time to recover during their free-time, so the influence of work may modify an individual's behaviour and hence their environment long after the shift. Time spent travelling to/from work at the start and end of shifts often results in substantial light exposures, and there is a possibility that daylight exposure after night work could significantly reduce subsequent sleep quality. A review into the health consequences of shift work and insufficient sleep calls for additional research to investigate whether insufficient sleep is part of a causal pathway that could explain shift work's adverse health effects (Keklund and Axelsson, 2016).

When investigating physiological responses to different patterns of light exposure, it is worthwhile and important to carefully establish the role that can be played by detailed non-visual light measurements. To this end, the present study aims to characterise circadian aspects of 24-hour personal light exposures of shift-working and day-working nurses in the UK and Germany.

2 Methods

Reusable data relating to the melanopic irradiance time-series close to the eye were collected* (CIE, 2018). Approximately 40 nurses were recruited in each of Kings College Hospital (London, UK) and Klinikum Dortmund (Germany). The two population centres have the same latitude (51,5°) and a 7,5° difference in longitude; on average sunrises and sunsets take place half-an-hour earlier in Dortmund in Coordinated Universal Time, but half-an-hour later using local clocks.

Participants completed a demographic and basic health questionnaire plus a brief workplace and home lighting questionnaire. Participants were studied during three separate weeks in January, April and June 2015 ("winter", "spring" and "summer"), completing day-work and shift-work chronotype questionnaires (MCTQ and MCTQ^{Shift}) prior to each week (Juda et al., 2013). Daylight saving time applied in April and June.

24-hour melanopic light exposure data were recorded by a commercial research actimeter, the Actiwatch Spectrum (AWS, Fig. 1a) (Actiwatch Spectrum, Philips Respironics). The AWS includes three solid-state photosensors (silicon photodiodes with distinct optical filters). The R-, G- and B-photosensors detect irradiance (expressed in $\mu W \cdot cm^{-2}$) in different wavelength regions of the visible spectrum, between 350 nm and 750 nm (Fig. 1b). The AWS devices were individually characterised and calibrated in optical laboratories of the Public Health England and the Federal Institute for Occupational Safety and Health (Price *et al.*, 2013; Udovicic *et al.*, 2016). As shown in Figure 1c, the measured spectral sensitivities for the G- and B- sensors, were combined according to the equation $C(\lambda) = c_1 B(\lambda) + c_2 G(\lambda)$, to create a data series with the optimal spectral match to the melanopic action spectrum, $s_{mel}(\lambda)$. The remaining spectral mismatch, $_p f_1$, (Price et al., 2017a), for each individual AWS device was between 12% and 18%, lower than any other available actimeter at the time.

* Melanopic Equivalent Daylight (D65) Illuminance (melanopic EDI), in lx, is used here for presentational purposes. Melanopic EDI of 1 lx = Melanopic irradiance of 1,3262 $mW.m^{-2}$. For the initial data from Germany, the weighted irradiance from the B-sensor is shown in $\mu W.cm^{-2}$, reflecting the native format of the AWS output.

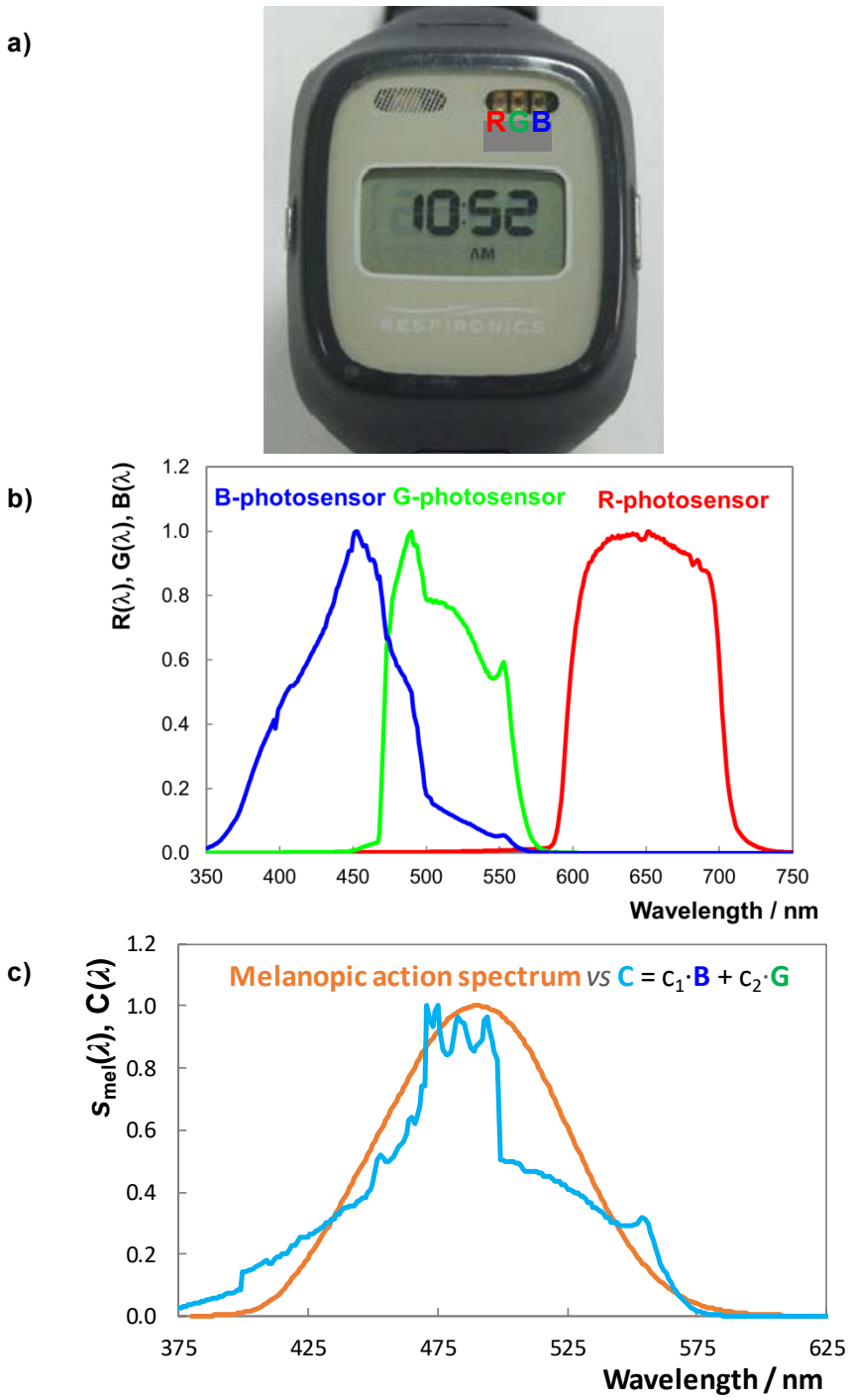


Figure 1 – The Philips Respironics Actiwatch Spectrum actimeter

a) Showing the location of the R-, G- and B-photosensors for the red (R), green (G) and blue (B) portions of the visible spectrum

b) The spectral sensitivity the three photosensors (measurement data reproduced from Udovicic et al., 2016)

c) The match of the combined spectral sensitivity of the G- and B-photosensors $C(\lambda)$ to the melanopic action spectrum $s_{mel}(\lambda)$

In addition to hourly averages, a duration response model was applied to the melanopic EDI to estimate the effective “non-visual dose” due to the light exposure up to any point in time. This model can be generally applied to melanopic time-series, and was shown to closely predict the dose-response relationship for phase-delaying due to late evening exposure to bright light in laboratory experiments (Price, 2014; Chang et al., 2013).

Information about the study was provided in advance. Participants gave written consent, and were free to withdraw at any time. Data were stored and processed securely and anonymously, and no identifiable individual data were available to employers or third parties.

3 Results

Recruitment was largely successful, and withdrawal rates were low. As already presented elsewhere, difficulties with questionnaires and diaries were greater than were predicted, and related compliance rates were lower than predicted based on similar published studies and related methods validation studies; data relating to the questionnaire-based chronotype adjustment did not appear to be suited to the different types of shift arrangements:

- London shifts ran from 07:30 to 20:00 (long day shift) and 19:30 to 08:00 (long night shift), with the day-work only hours being approximately 09:00 to 17:00; and
- Dortmund shifts from 06:30 to 14:30 (early shift), 14:30 to 22:30 (late shift) and 22:30 to 06:30 (night shift).

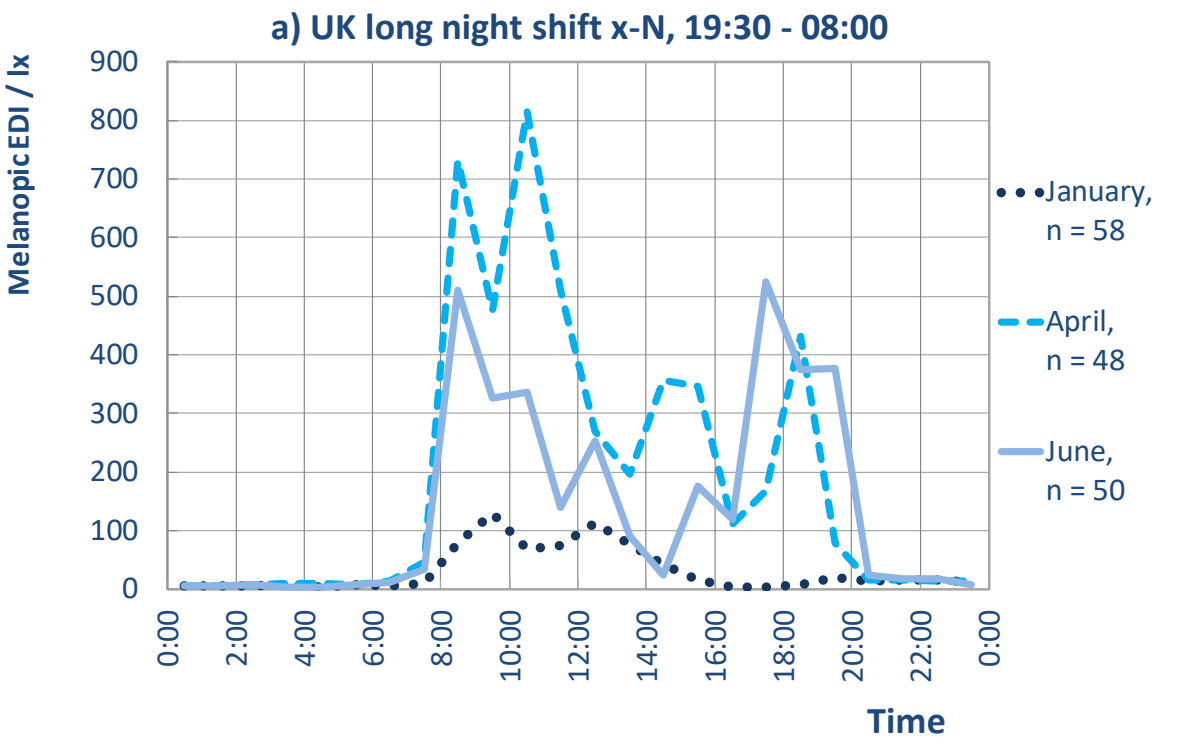
To establish compliance with the actimetry protocol (*i.e.* correct use of the devices), inactivity was looked for. As smooth light exposures can also indicate when the light sensor has been removed, these were also used and the data compared to diaries. Missing data periods of up to an hour whilst at home were permitted, but days or part days containing long periods of missing data were excluded.

In the duration response model, prior missing data introduce minimal influence on subsequent dose levels when the missing exposure levels and exposure dose levels are both low. This is typically only the case following extended sleep at night, or after a significant period of compliant daytime exposure. Consequently, selected periods of actimetry compliance starting during extended sleep at night were identified for further analysis:

- For daytime, morning or evening work, 24 hours of compliant data; and
- For night work, including consecutive nights at work, multiples of 24 hours, from which a representative 24-hour period can then be selected.

Results for the night shifts in UK and Germany are presented in Figures 2 and 3, respectively. The upper panels represent average hourly melanopic EDI (B-sensor irradiance data for Germany), and the lower panels show the resulting duration response dose plots. The hourly averaged winter exposure values were lower than spring or summer. The UK night shift spring and summer exposures appeared to follow different daytime profiles (Fig 2a), whereas Germany’s night shift spring and summer values were more alike (Fig 3a). Figures 2b and 3b show the duration response model; elevated dose values are an indication of the zeitgeber for daytime, and without imposed behaviours (e.g. work) sleep would naturally occur during the night-time period of low dose levels.

Elevated light exposures were observed at the end of the night shifts in spring and summer ending in the morning, which persisted long after the end of the shift (Fig 2a and Fig 3a). Sleep in the morning may therefore have coincided with high dose levels (Fig 2b and Fig 3b). This was true especially in the UK, although not all workers slept in the late morning. Those preferring to sleep in the afternoon were exposed to daylight for a few hours after the shift. The UK night shift workers also appeared to have had periods of sleep at work, approximately during the hours of 03:00 to 05:00 (not clearly shown when averaged between participants at this scale). Hour-by-hour comparisons of daytime exposures of early and late shift workers (not shown) in Germany showed much lower daylight exposure levels at work. Late shift workers travelled home in the hours of darkness, and German night shift workers travelled home 2 hours earlier by the solar clock than those in the UK.



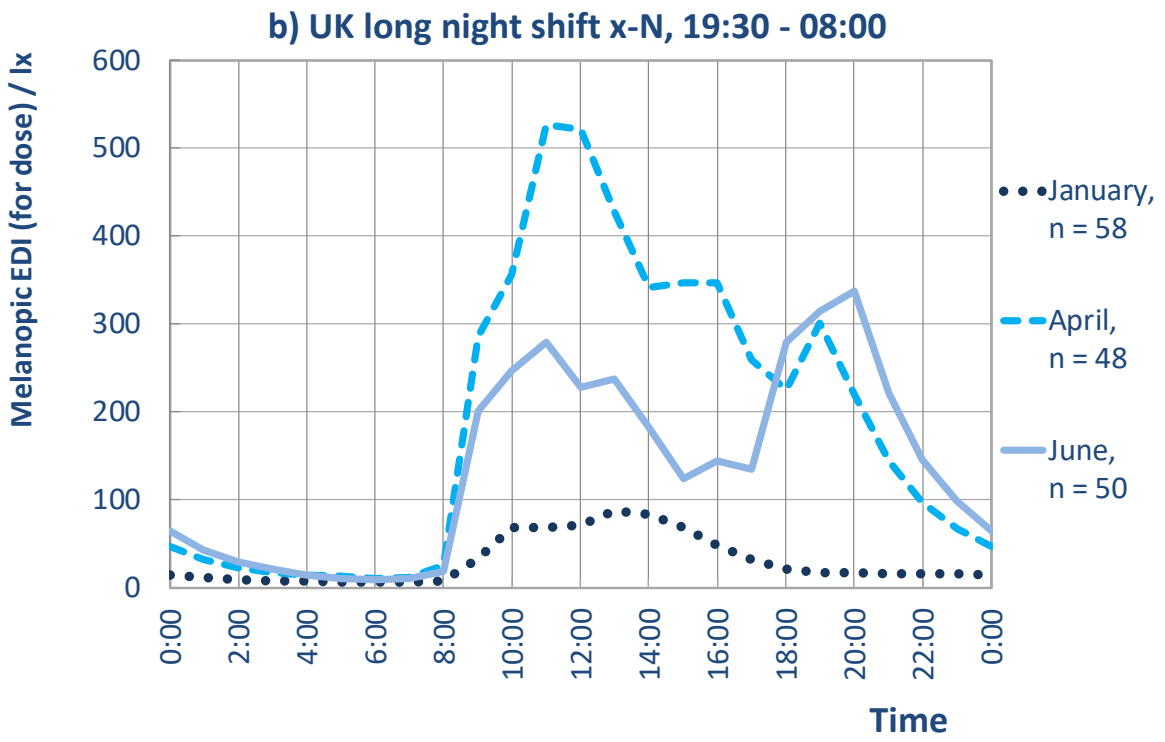
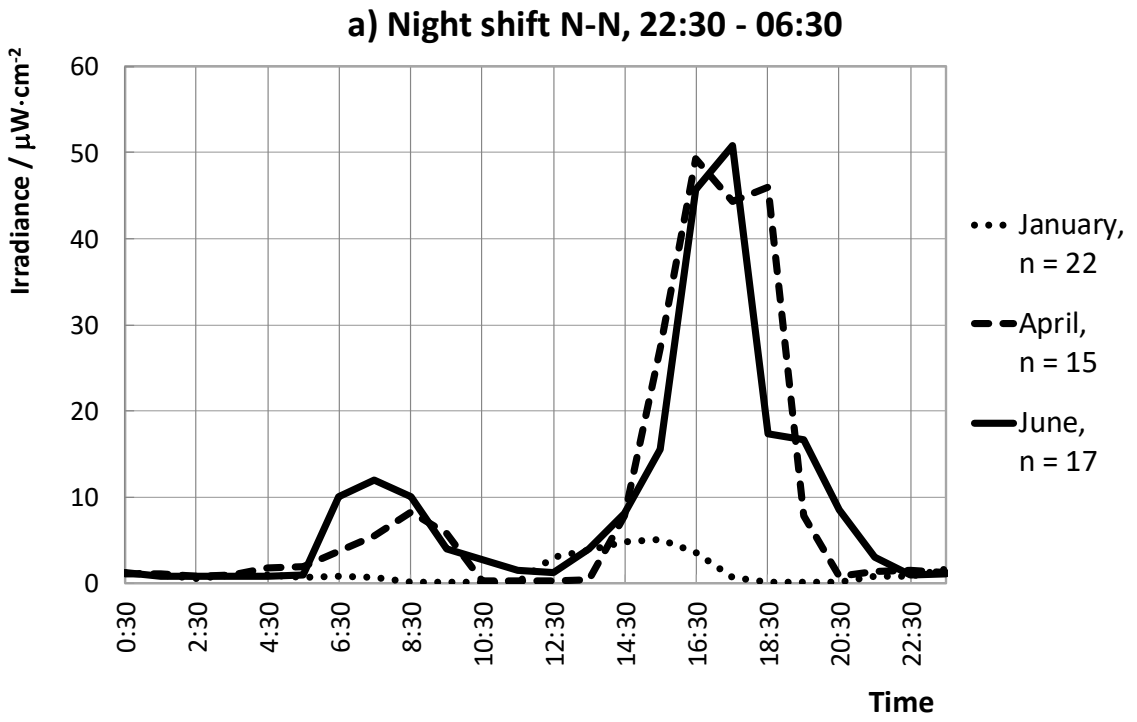


Figure 2 – a) Hourly average melanopic EDI exposures for a 12.5-hour night shift between 19:30 and 08:00, in Kings College Hospital, London, UK.

b) The time-weighted melanopic EDI dose is estimated from the data in a), with the dose at 09:00 before the shift matched to the final dose (using iterative feedback).

For x-N, time away from work between 09:00 and 19:30 is the time prior to the shift, and time away from work between 08:00 and 09:00 is time following the shift.



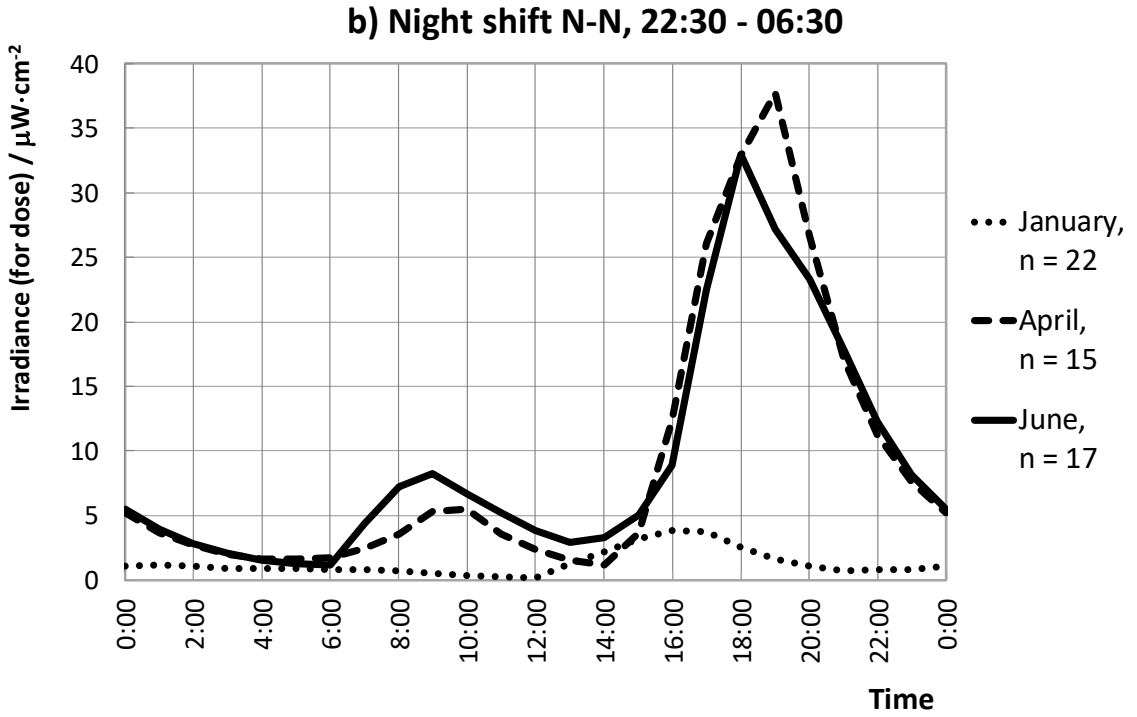


Figure 3 – a) Hourly average B-sensor irradiance exposures for consecutive night shifts between 22:30 and 06:30, in Klinikum, Dortmund, Germany.

b) The time-weighted dose is estimated from the data in a), with the dose at 00:00 matched to the final dose (using iterative feedback).

For N-N, time at work between 00:00 and 06:30 is taken from the first of two consecutive shifts, and time at work between 22:30 and 00:00 is taken from the second shift.

The UK night shifts introduce fence-post exposure profiles, creating approximately 12-hour dose cycles in summer and spring, even after averaging across multiple participants with different sleep habits. These effects are considerably reduced in Germany and even in mid-summer the pre-work exposure period is clearly dominant.

4 Discussion and conclusions

This investigation demonstrates that 24-hour personal light exposure data can be collected for analysis of circadian exposures to light. This is important, as the study of shift work presents additional challenges for data collection and analysis. Daily paper-based questionnaires appeared to overload busy employees and may have reduced actimetry compliance, and alongside dosimetry, app-based diaries and tracking of subjective aspects may be more convenient in future studies. It was necessary to use two actimeters to collect both light and sleep data, with the AWS device being placed on the beside during time in bed. However, asking participants to wear the sleep actimeter before and after sleep would help automate sleep analysis.

The UK exposure profiles, long shift times, exposure to Light at Night (LAN) and sleep opportunities restricted to daytime periods with prior bright light exposure may combine to produce substantial circadian and sleep disruption, when compared to the German shift structure. Even for the long shift lengths in the UK, further investigation might be worthwhile into the potential benefits of introducing morning shift start and end times that are more closely based on sunrise times, and avoiding unwanted post-shift exposures. Further analysis is intended into the data from each of the shifts, and the impact on sleep and wellbeing.

Another group measuring 24-hour personal light exposures in daytime and shift working nurses in Bochum, just 10 km from Dortmund, recently published similar data (Rabstein *et al.*, 2019). Detailed spectral sensitivity data are available which enable the melanopic mismatch to be estimated for the device used in the Bochum study to be 31%, c.f. 12% to 18% for the AWS (Price *et al.*, 2017). The improved spectral match of the combined G- and B- sensor channels of the AWS significantly reduces absolute errors and variations in sensitivity between sources with different spectra when estimating melanopic exposure.

Since the selection of the AWS for this study, the AWS model has been discontinued and the remaining Philips Respironics devices do not share the spectral sensitivity of the AWS. Recently, a modified version of another commercial actimeter has been developed (Condor, ActTrust model code AT0503LF, or ACT_{mod}) with a 17,6% spectral mismatch to the melanopic action spectrum, using a single sensor, and with a 13,5% spectral mismatch to V(λ), using a second sensor (Price and Lyachev, 2017b). With these two sensors, it should be possible to collect exposure data that are reusable for a greater range of the non-visual spectral response models than using melanopic data alone, including recently proposed melanopic/photopic models (Berman and Clear, 2019).

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