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RESEARCH PAPER

Multi-Wearable Approach for Monitoring Diurnal Light Exposure and Body Rhythms in Nightshift Workers

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Keywords: circadian | light | shiftwork | sleep

ABSTRACT

Aim: As our understanding of light's impact on human health grows, studies examining light exposure and related health outcomes in everyday settings are increasingly important, particularly in high-risk groups like nightshift workers.

Methods: In this observational study, we monitored personal light exposure and physiological functions in a large cohort of healthcare nightshift workers using a spectrally resolved light dosimeter and wearable body temperature, actigraphy, and electrocardiography sensors.

Results: Our findings revealed a common occurrence of unfavorable light conditions during both shift types. During nightshift work, participants frequently experienced exposure to biologically potent cool-white LED lighting. On dayshifts, melanopic light levels often failed to meet recommended guidelines, with daylight as the primary source of bright light levels. Sleep duration, but not quality, significantly varied between shifts, with longer sleep before the first nightshift but shorter sleep on subsequent nights. Daytime and nighttime napping helped compensate for reduced sleep on nightshifts. Limited associations between light exposure and sleep were found, partially contradicting existing knowledge. Diurnal physiological and activity rhythms followed the change from day-active to night-active schedules; however, the change in physiological rhythms appeared partly dissociated from that of activity, suggesting a circadian modulation. Moreover, physiological functions exhibited bi-directional phase-shifts across consecutive nightshifts, which may have been mediated by differences in daytime light exposure before the first nightshift.

Conclusion: By employing a multi-wearable approach including recent sensors, we provide new insights into the lighting environments experienced by nightshift workers and the potential impact of nightshift work and light exposure on endogenous circadian rhythms.

1 | Introduction

Nightshifts constitute a common working condition, with 19% of EU workers reporting night work at least once a month [1]. Frequent exposure to nightshift work has been associated with several negative consequences for health and wellbeing, including increased risk for cardiovascular and metabolic disorders [2–4], cancer [5–7], and mental disorders [8–10], as well as decreased cognitive performance and more attentional errors during night work [11]. A major cause of these negative health impacts is the misalignment between the internal circadian timing of biological processes and the imposed behavioral rhythm during nightshifts, resulting in mistimed eating patterns along with disturbed and shortened sleep [4, 12], which in itself constitutes a risk factor for poor health and wellbeing [2, 13–15]. Hence, evidence-based strategies for mitigating these negative health consequences are urgently needed.

An important consideration for nightshift work is light [16], given its important role in human physiology and behavior, synchronizing biological processes across the human body to the 24 h day [17, 18], as well as directly affecting sleep propensity and alertness [19, 20] modulated by the spectrum and dose of light through a non-visual retina-brain pathway involving the photopigment melanopsin sensitive to the blue part of the visible light spectrum. As such, light has been recognized to be implicated in general human health and wellbeing [21–23] and can help to mitigate some of the negative effects of nightshift work (e.g., [24–29]). However, little is known about the association between individual light exposure patterns and health outcomes in real-life settings [30]. While a number of studies have started to address this knowledge gap by monitoring personalized light exposure and health-related outcomes with wearable sensors in different populations [31], including nightshift workers (e.g., [32–36]), more research is needed to understand the intricate role of light during everyday life and especially for nightshift work. Specifically, the effects of light exposure on sleep and the timing of the circadian rhythm have not been sufficiently investigated, partly due to a lack of non-invasive methods for monitoring physiological functions and biologically relevant light quantities such as melanopic equivalent daylight illuminance (EDI), which is now recognized as the primary quantity to describe light exposure in chronobiological and sleep research [21, 37]. Moreover, little use has been made yet of recent advances in light sensor technology enabling the characterization of *spectral diets* [38] and with it the lighting environments encountered during daily life and their role in health-related outcomes.

In the present observational study, we used a recently developed spectrally resolved light sensor [39] to measure melanopic EDI profiles and characterize the lighting environment of nightshift workers in a healthcare setting with the aim of assessing the health potential of light exposure patterns experienced during day- and nightshift work. In addition, we aimed to compare self-reported sleep and the phase of diurnal rhythms of activity, heart rate, and core body temperature derived from a non-invasive wearable sensor between both shift types and explore associations with personal light exposure.

2 | Results

In total, 72 adults (82% female; mean age = 32.5 years, SD = 5.8 years) participated in the study during both dayshift and nightshift work, of whom 2 participants were lost to follow-up for dayshift measurements. Most participants were healthcare professionals (36 nurses, 20 physicians, 13 paramedics, 3 others). Average self-reported work schedules were from 07:13 h (SD = 0.6 h) to 16:30 h (SD = 1.7 h) during dayshifts and from 21:40 h (SD = 1.2 h) to 07:30 h (SD = 0.7 h) during nightshifts (See SI Appendix, Table S1 for all cohort characteristics). The exact start and end times of work on each day during the study were not available. Most participants worked three consecutive dayshifts and nightshifts; 12 worked four dayshifts and one participant worked four nightshifts. Among dayshifts, 47 occurred in summer (daylength ≥ 12 h, March–September) and 23 in winter (daylength < 12 h, September–March), and among nightshifts, 32 occurred in summer and 40 in winter.

2.1 | Personal Light Exposure

Spectrally resolved light exposure data were continuously measured with the *Spectrace* [39] dosimeter prototype while awake. Of the 72 participants in the study, no light exposure data were available for 12 participants due to unavailability ($N = 10$), loss ($N = 1$), and malfunctioning ($N = 1$) of the dosimeter, and data from two more participants were excluded *post hoc* due to shifts coinciding with seasonal change in clock time. Consequently, data were available from 58 participants in total, with 43 in both periods, 4 only in dayshifts, and 11 only in nightshifts. Availability of data for only one period was partly due to device loss ($N = 4$) and device unavailability ($N = 10$).

2.1.1 | Light Levels

Melanopic equivalent daylight illuminance (EDI) during the work period (start of first shift until the end of last shift) was compared to recent recommendations [21] for minimum corneal melanopic EDI levels during daytime (> 250 lx), evening (< 10 lx), and night (< 1 lx). Bright levels above 250 lx occurred almost exclusively during the day (Figure 1a) and more frequently during summer compared to winter and on dayshifts compared to nightshifts (SI Appendix, Figure S1a). On dayshifts, the mean bright light duration per day was 1.8 h in summer and 0.6 h in winter ($p < 0.001$). It was also lower on nightshifts than on dayshifts, with 1 h in summer ($p = 0.061$) and 0.2 h in winter ($p < 0.001$), due to sleep during daytime

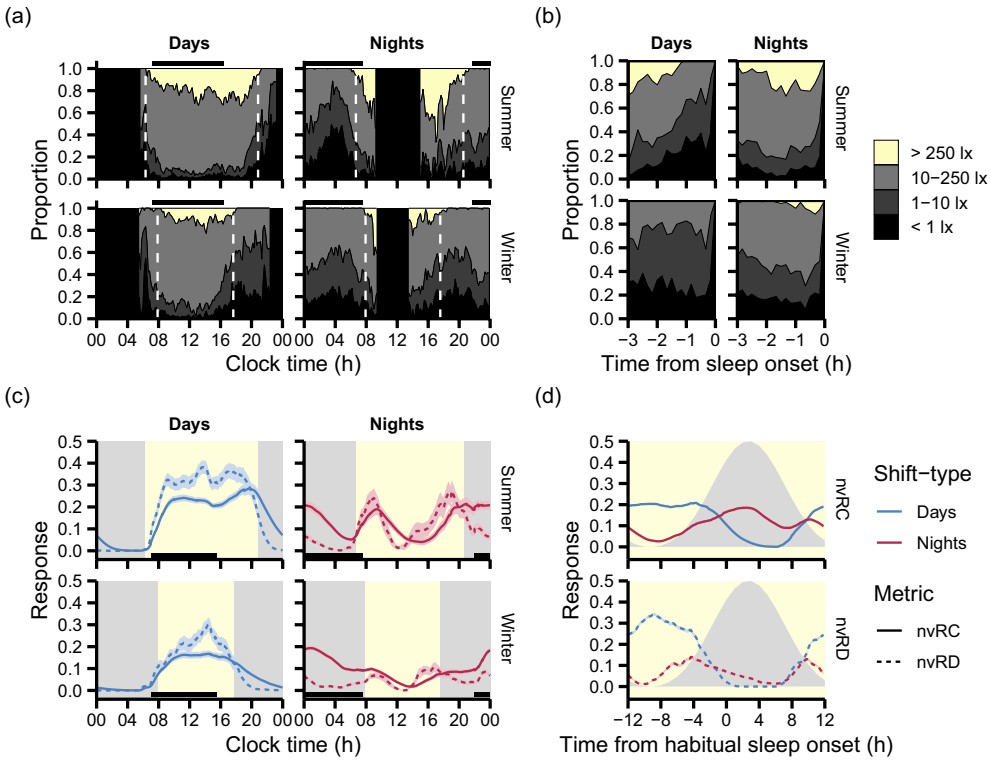

FIGURE 1 | Light levels experienced by participants during the dayshift (Days) and nightshift (Nights) periods (start of first shift to end of last shift) in summer (daylength ≥ 12 h) and winter (daylength < 12 h). (a) Proportion of relevant melanopic equivalent daylight illuminance (EDI) levels [21] while awake across participants and days respective to clock time, and (b) respective to self-reported sleep onset. Dashed vertical lines indicate the mean sunrise and sunset, and the horizontal bars represent the mean work hours. (c) Mean and SEM of non-visual direct (nvRD) and circadian (nvRC) response based on the model proposed by [40], respective to clock time. In contrast to the nvRD model, the nvRC model considers the circadian modulation of the sensitivity to light relative to habitual sleep onset, here calculated as the mean reported sleep onset during dayshifts. The gray shaded areas indicate mean nighttime, and the horizontal bars represent the mean work hours. (d) Mean and SEM of nvRD and nvRC respective to habitual sleep onset. The gray shaded area indicates the modeled circadian sensitivity to light. Note that for all analyses shown in panels (a)–(d), light levels during self-reported sleep were set to 0.1 lx. Cohort sizes per panel: Days, Summer = 28; Days, Winter = 19; Nights, Summer = 16; Nights, Winter = 35.

(Figure 1a). Moreover, light levels in the evening 3 h before self-reported bedtime on dayshifts frequently surpassed the recommended maximum of 10 lx (Figure 1b). This was particularly the case in summer due to the late sunset, with a mean daily duration of 1.3 h above this level. Although the current recommendations for healthy light exposure [21] only apply to day-active individuals (see below), for comparison, on nightshifts, most light levels before bed and to some extent during night work were above 10 lx (Figure 1a).

Given the limitation of the current recommendations to day-active individuals, to interpret the potential impact of light exposure during nightshifts, we used a dynamic model [40] that simulates the effective light input modulating non-visual responses, with and without considering circadian modulation of light sensitivity (circadian response nvRC and direct response nvRD, respectively). Since the nvRD represents a smoothed transformation of raw light exposure, the mean nvRD (Figure 1c) followed the distribution of melanopic EDI levels in Figure 1a. In contrast, the mean nvRC compared to the nvRD was lower during daytime and higher during nightshifts (Figure 1c), due to the high circadian sensitivity after habitual sleep onset (Figure 1d). Notably, the mean nvRC reached similar levels after habitual sleep onset during nightshift work in both seasons as during work on dayshifts in summer (Figure 1c,d). Hence, despite lower light levels during work on nightshifts compared to dayshifts, the theoretical effective input for non-visual responses was almost the same.

2.1.2 | Spectral Diet

The use of a spectrally resolved dosimeter allowed to also examine the spectral distributions of recorded light exposures (i.e., the *spectral diet* [38]). The collected data were classified according to seven different light source types (Figure 2a). The most prevalent types were cool white LEDs (44%), daylight (24%) and fluorescent (22%). The separation of LEDs by their correlated color temperature (CCT) into cool white (CCT > 3000 K) and warm white (CCT < 3000 K) aimed to identify periods at home, given the typical use of warm white LEDs in residential lighting. Indeed, higher proportions of warm white LEDs coincided with expected periods at home (Figure 2b). Moreover, warm white LEDs were predominantly (77%) below 10 lx melanopic EDI, in line with recommendations (SI Appendix, Figure S1b).

Daylight constituted a substantial portion of light exposures, being the predominant light source in the afternoon after work

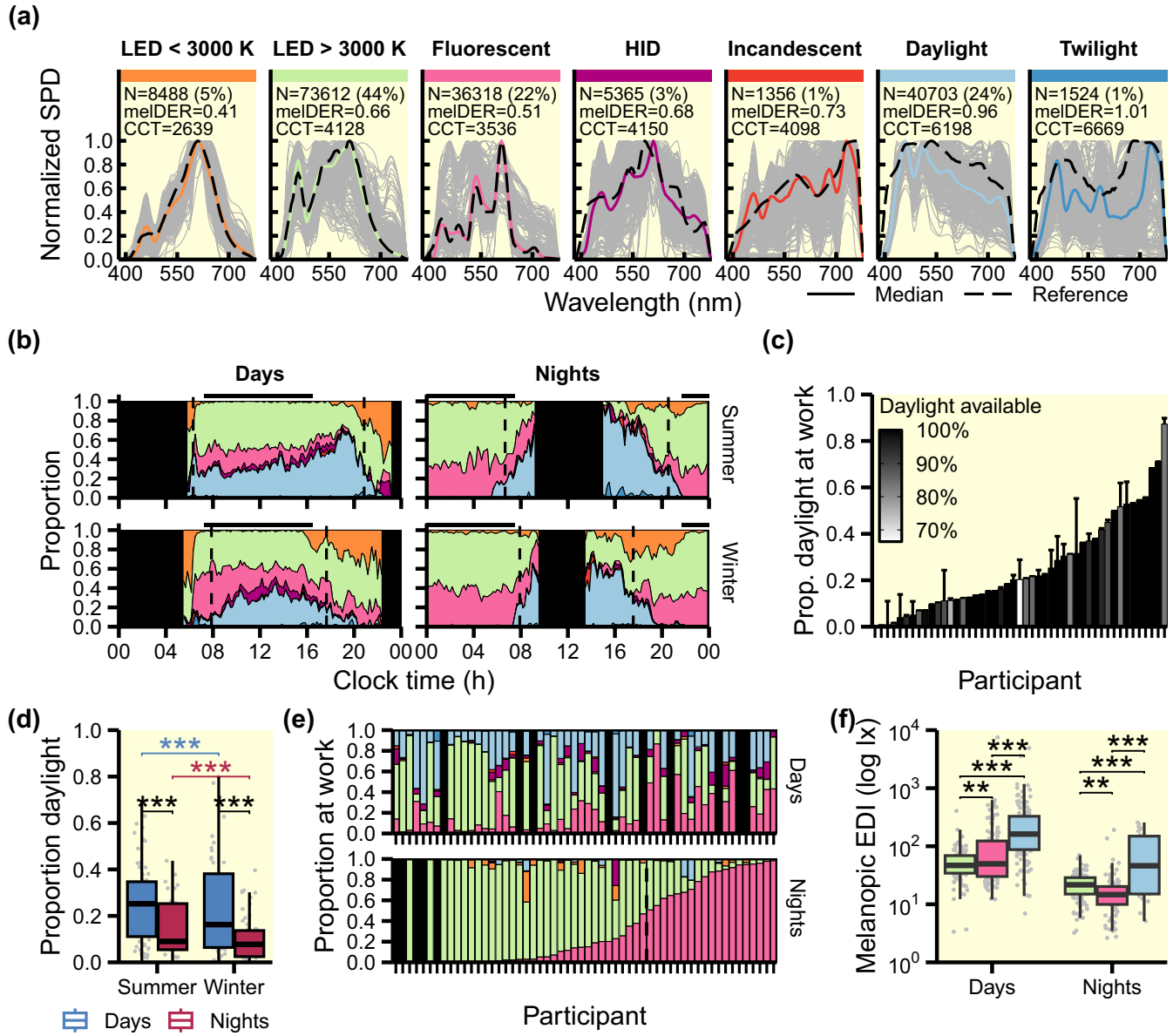

FIGURE 2 | Spectral diet during the dayshift (Days) and nightshift (Nights) periods in summer (daylength ≥ 12 h) and winter (daylength < 12 h). (a) Normalized spectral power distribution (SPD) from light-dosimetry per classified light source type, the median SPD, and the median melanopic daylight efficacy ratio (DER) and correlated color temperature (CCT). The dashed reference SPD indicates the median across the individual classified light source SPDs within each light-source type. HID = high intensity discharge. For legibility only a random subset of 500 SPDs per light source type is plotted. (b) Proportion of light source types (legend in panel a) across participants over of time. The dashed vertical lines indicate mean sunrise and sunset and the black horizontal bars indicate mean typical work hours. (c) Mean proportion of exposure to available daylight at work on dayshifts (dependent on photoperiod length and work schedule, indicated by color gradient) per participant. Error bars indicate the mean daily proportion of invalid data during work. (d) Daily exposure to daylight relative to photoperiod length. (e) Proportion of light source types (legend in panel a) during work hours per participant, sorted by proportion of fluorescent light during nightshifts. The dashed vertical indicates the change of ratio across 1:1 between fluorescent and LED > 3000 K. (f) Mean melanopic equivalent daylight illuminance (EDI) levels during work hours for the three prevalent light source types (legend in panel a). $^{**}p < 0.01$, $^{***}p < 0.001$.

or daytime sleep (Figure 2b), and provided 75% of the recorded melanopic EDI levels above 250 lx (SI Appendix, Figure S1c). However, 60% of daylight light levels were still below 250 lx (SI Appendix, Figure S1b), possibly due to exposure indoors. At work during dayshifts, the mean proportion of daylight exposure varied substantially across participants (0%–88%, Figure 2c) and work environments, with lower exposure for departments such as surgery and emergency and higher exposure for departments such as rehabilitation (SI Appendix, Figure 1d). As expected, from a seasonal perspective, the total daily duration of daylight exposure was higher in summer (2.9 h) compared to winter (1.6 h, $p < 0.001$), even relative to photoperiod length (Figure 2d).

The distribution of light sources during working hours (Figure 2b) suggests that most work environments were lit by cool white LEDs followed by fluorescent sources, which was confirmed by examining the proportion of light source types during nightshifts, indicating that around 65% of participants

experienced predominantly cool white LED and 35% fluorescent lighting at work (Figure 2e; SI Appendix, Figure 1e). This distinction was less clear during dayshifts due to daylight exposure and possibly more frequent change of environments. The melanopic EDI levels associated with the prevalent light sources during work (i.e., LED, fluorescent, and daylight) at ambient light levels where spectra could be reliably identified (>10 lx) were significantly different (Figure 2f): mean levels were highest for daylight during nightshifts (42 lx) and dayshifts (168 lx, all $p<0.001$), while levels during nightshifts were higher for LED (20.3 lx) compared to fluorescent (13.7 lx, $p=0.003$) and vice versa during dayshifts (46.7 lx vs. 66.4 lx, $p=0.005$). Mean photopic illuminance during nightshifts was similar between LED (31.5 lx) and fluorescent (27.7 lx, $p=0.69$), indicating that differences in melanopic EDI were mostly due to differences in spectrum. Correspondingly, the mean melanopic efficacy (daylight efficacy ratio, DER) was higher for LED (0.66) compared to fluorescent (0.51, $p<0.001$). Despite these differences in levels per light source, mean melanopic EDI exposure during nightshift work was rather similar between participants grouped into those with predominantly LED (8.26 lx) and fluorescent lighting (7.03 lx, $p=0.49$), possibly due to mixed exposure to both light sources and dim light levels for which the source could not be identified. Indeed, when considering a temporally smoothed estimate, the difference in light source levels is apparent, demonstrated by a higher cumulative nvRD for the LED (0.72) compared to the fluorescent group (0.40, $p=0.029$).

2.2 | Self-Reported Sleep

Participants indicated daily sleep periods in a sleep diary by marking consecutive sleep states, where consecutive states of sleep or half-sleep constituted individual sleep episodes. The longest sleep period per 24 h interval was considered the main sleep period (SI Appendix, Figure S2). During dayshifts, the main sleep duration remained stable across all three days (7.10 to 7.26 h), while during nightshifts, the main sleep duration was longer during the 24 h sleep interval starting before the first workday (Day 0; 9.03 h) compared to the two following days (5.93 and 5.79 h, both $p<0.001$, Figure 3a). Furthermore, main sleep was longer on Day 0 and shorter on Day 1 and Day 2 compared to dayshifts (all $p<0.001$, Figure 3a). Interestingly, when accounting for all sleep episodes during each 24 h interval (i.e., including naps and shorter sleep bouts), the total sleep duration during nightshifts compared to dayshifts was only slightly lower on Day 1 (6.79 h vs. 7.29 h, $p=0.062$) and Day 2 (6.79 h vs. 7.22 h, $p=0.098$; Figure 3b), which is explained by the increased number of sleep episodes beyond the main sleep period during nightshifts (Figure 3c), compensating for the curtailed main sleep duration. For nightshifts compared to dayshifts, sleep quality showed a similar trend to main sleep duration (Figure 3d), with slightly higher sleep quality on Day 0 (3.86 vs. 3.50, $p=0.054$) and lower sleep quality towards Day 2 (3.54 vs. 3.84, $p=0.065$). Note that the addition of the covariates sex, age, chronotype, or photoperiod length did not result in a better model performance in any of the analyses, indicating little influence on the sleep parameters. While earlier chronotypes had slightly earlier bedtimes than later types on dayshifts (22:18 h vs. 22:54 h) and later bedtimes on nightshifts (08:36 h vs. 08:06 h), none of these differences were significant (all $p>0.72$). Furthermore, we performed regression analyses to examine inter-relationships between sleep parameters, indicating that sleep quality was positively correlated with sleep duration ($R^2=0.06$, $p<0.001$, Figure 3e), in line with the similar trends in Figure 3a,d. Main sleep duration but not quality during nightshifts was also

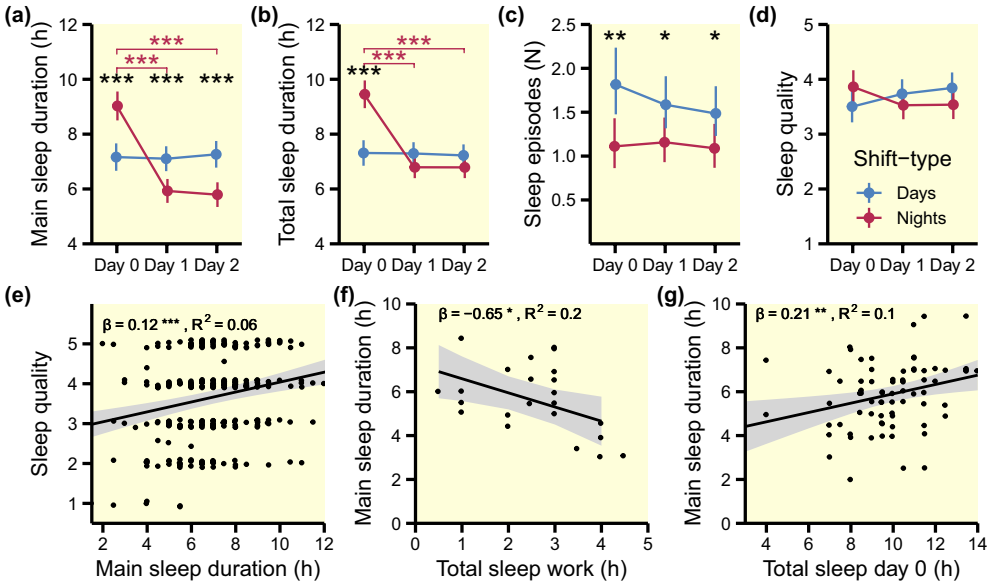

FIGURE 3 | Estimated marginal means (EMMs with 95% confidence interval) of subjective sleep parameters within 24 h intervals starting on 20:00 h the day before work (day 0) and the two workdays (day 1 and 2) between dayshifts (Days) and nightshifts (Nights). (a) Main sleep duration (sum of sleep episodes during longest sleep period). Legend in panel (d). (b) Total sleep duration (sum of all sleep episodes). Legend in panel (d). (c) Number of sleep episodes. Legend in panel (d). (d) Sleep quality of main sleep period (1 = "very bad", 5 = "very good"). (e) Sleep quality was associated with main sleep duration across shift-types. (f) Association of main sleep duration with total sleep during work hours on nightshifts and (g) with total sleep duration on the day before nightshift work. Panels (e)–(g) show linear regression lines with 95% confidence intervals. *$p<0.05$, **$p<0.01$, and ***$p<0.001$.

correlated to total sleep duration during work and the day before work, with shorter duration after more sleep at work ($R^2 = 0.2$, $p = 0.018$, Figure 3f), but longer duration with more sleep on Day 0 ($R^2 = 0.10$, $p = 0.009$, Figure 3g). Since total sleep on Day 0 also showed a positive tendency with sleep during work ($R^2 = 0.23$, $p = 0.098$), the latter result might rather indicate a tendency for good sleepers.

2.3 | Associations Between Daily Light Exposure and Sleep

To evaluate the possible influence of light exposure on sleep patterns, we examined associations between personal light exposure and self-reported main sleep onset, duration, and quality using aggregate light exposure metrics calculated for different daily intervals on workdays (SI Appendix, Figure S1f): during work, the 16 h and 3 h before main sleep onset, and the 3 h before and after habitual sleep onset. Contrary to our expectations, only a few statistically significant associations were found between light metrics and sleep parameters. Earlier bedtime (Figure 4a) on nightshifts was associated with higher mean melanopic DER during work ($R^2 = 0.07$, $p = 0.042$) and the 3 h before bed ($R^2 = 0.16$, $p = 0.008$), which may have been due to increased morning daylight exposure stemming from later bedtime. Similarly, longer sleep duration (Figure 4b) on dayshifts was associated with higher mean melanopic DER ($R^2 = 0.31$, $p = 0.027$) and greater temporal variability in light levels ($R^2 = 0.20$, $p = 0.045$) during the 3 h before sleep and correspondingly the 3 h before and after habitual sleep onset. The association with melanopic DER may have been due to increased daylight exposure stemming from earlier bedtime allowing for a longer sleep opportunity. Better sleep quality (Figure 4c) on dayshifts was associated with more time spent at bright light levels (melanopic EDI > 250 lx) in the 3 h before bed ($R^2 = 0.19$, $p = 0.026$) and on nightshifts with less time spent at low light levels (melanopic EDI < 10 lx) around habitual sleep onset ($R^2 = 0.07$, $p = 0.043$). Note that the effect of bright light levels during the pre-bed period on dayshifts was not significantly moderated by exposure to bright light levels in the 13 h prior to the pre-bed period ($p = 0.87$).

2.4 | Diurnal Rhythms of Activity, Heart Rate, and Core Body Temperature

In addition to light exposure, we assessed the effects of shift work on diurnal rhythms of physiological parameters by monitoring continuous physical activity, heart rate (HR) and core body temperature (CBT) with wearable sensors. Valid data for HR and activity were available from 62 participants during dayshifts and 56 during nightshifts, while CBT data were available from 31 participants during dayshifts and 27 during nightshifts, due to the introduction of the CBT sensor halfway through the study. Overall, the mean rhythms of the three response variables were substantially phase-shifted between dayshifts and nightshifts as well as in relation to each other (Figure 5a, SI Appendix Figure S3a). Specifically, comparing acrophase (i.e., the timing of the rhythm peak) between variables per day revealed a later phase for CBT compared to activity and HR on day-active days (i.e., dayshifts and Day 0 on nightshifts, Figure 5b), while on nightshifts, the acrophase of both CBT and HR was earlier than for activity. During dayshifts, CBT acrophase was on average 2.2 h later than activity and 1.7 h later than heart rate (both $p < 0.001$), while during nightshifts, the CBT acrophase was 1.4 h earlier than activity on Day 1 ($p = 0.026$) and 1.1 h earlier (not significantly) on Day 2 ($p = 0.15$). While the acrophase of HR

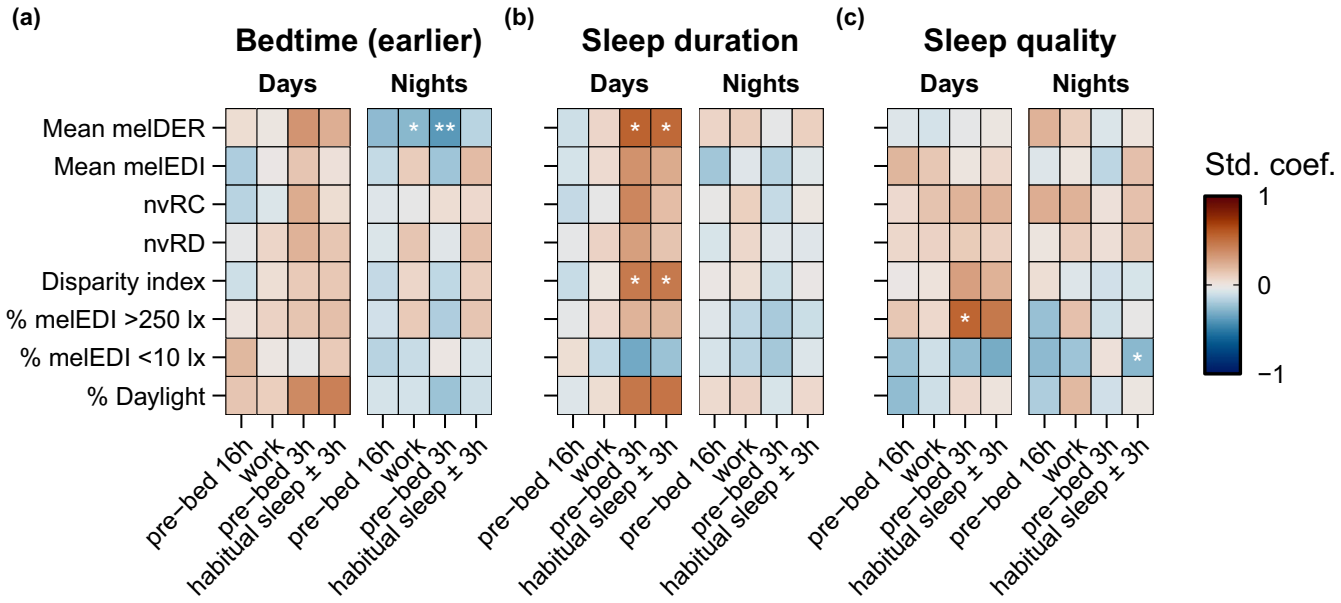

FIGURE 4 | Linear mixed model analyses of associations between sleep parameters and aggregate metrics of melanopic EDI during work, 16 h and 3 h before main sleep onset, and 3 h before and after habitual sleep onset (mean onset of main sleep period during dayshifts) on workdays for dayshifts (Days) and nightshifts (Nights). melDER: Melanopic daylight efficacy ratio. melEDI: Melanopic equivalent daylight illuminance. nvRD: Sum of non-visual direct response [40]. nvRC: Sum of non-visual circadian response [40]. Disparity index: Temporal variability of light levels. (a) Association with earlier main sleep onset, (b) main sleep duration, and (c) main sleep quality. The color scale represents standardized regression coefficients, with red indicating a positive effect direction and blue a negative. *$p < 0.05$, **$p < 0.01$.

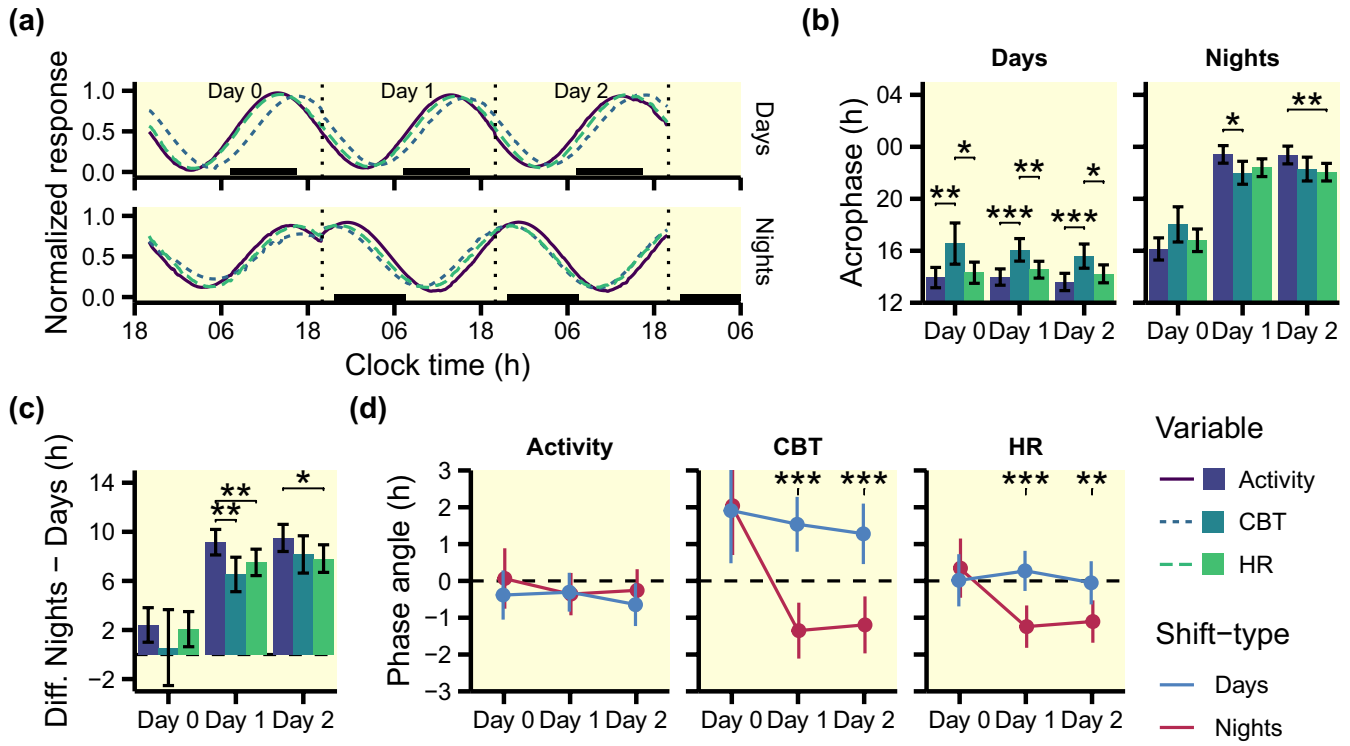

FIGURE 5 | Analyses of diurnal rhythms of activity, heart rate (HR) and core body temperature (CBT) derived from cosinor analysis for dayshifts (Days) and nightshifts (Nights). (a) Mean fitted 24 h rhythms for the three response variables per shift-type. The vertical dotted lines indicate the 24 h intervals for which cosinor fits were obtained. The horizontal black bars indicate the typical work period. (b) Estimated marginal means (EMM) of acrophase (relative to clock time) between variables per day. (c) EMMs of phase difference (in hours) across shift-types (nightshifts—dayshifts) between variables per day. (d) EMMs of phase angle (in hours) of bathyphase with the midpoint of the main sleep period between shift-type per day. Acrophase: Timing of rhythm peak. Bathyphase: Timing of rhythm trough. Error bars in panels (b)–(d) indicate 95% confidence intervals. *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$.

was similar to activity during dayshifts, HR acrophase shifted to being 1 h earlier (not significant) on Day 1 ($p = 0.068$) and 1.4 h earlier on Day 2 ($p = 0.01$). Between shift types, on workdays (Day 1 and 2), the acrophase of all three variables was significantly later on nightshifts ($p < 0.001$, SI Appendix Figure S3b). Interestingly, except for CBT, the acrophase of activity and HR was also slightly but significantly later for Day 0 on nightshifts compared to dayshifts (both $p < 0.001$, SI Appendix Figure S3b). Furthermore, the change in phase between shift type (difference nightshifts—dayshifts) was not consistent across variables on Day 1 and 2 (Figure 5c), with a significantly larger phase difference for activity compared to CBT and HR, suggesting that CBT and HR are not exclusively a reflection of activity patterns, but may partly reflect the underlying endogenous circadian modulation.

Since activity patterns are typically strongly related to sleep–wake behavior, the activity bathyphase (i.e., the timing of the rhythm trough, 12 h difference from acrophase) should be close to the midpoint of sleep. To examine this relationship, we compared the phase angle between bathyphase and the midpoint of the main sleep period on the corresponding day per variable between shift-type (Figure 5d). As expected, the phase angle for activity was close to zero and not significantly different between shift-type on all days. In contrast, the phase angle was earlier on nightshifts compared to dayshifts for CBT on Day 1 (−1.4 h vs. +1.5 h, $p < 0.001$) and Day 2 (−1.2 h vs. +1.3 h, $p < 0.001$), as well as for HR on Day 1 (−1.2 h vs. +0.2 h, $p < 0.001$) and Day 2 (−1.1 h vs. −0.05 h, $p = 0.007$). The differences in phase angle for CBT and HR on nightshift workdays were unlikely to be associated with sleep during work (all $p > 0.41$). Overall, these results highlight that the phase relationship between sleep, core body temperature, and HR was systematically perturbed during nightshifts compared to dayshifts.

2.5 | Changes in Phase Angle During Nightshifts and Association With Light and Sleep

Following these findings, we investigated how the phase of HR and CBT changed between consecutive nightshifts and whether phase changes were associated with light and sleep outcomes. To do so, we calculated the difference in phase angle from sleep midpoint between the first and second nightshift and divided participants into two groups based on positive shifts in phase angle (*Delay*) and negative shifts in phase angle (*Advance*) per response variable (Figure 6a). Phase angle was significantly different between groups on Day 2 for activity and on Day 1 and 2 for CBT and HR (all $p < 0.05$), as well as between Day 1 and Day 2 per group for all variables (all $p < 0.01$). Since there was good correspondence between the phase-shift groups derived from HR and CBT data (SI Appendix Figure S3c), we combined the groups from both variables to examine whether light exposure and sleep were different between the advanced and delayed

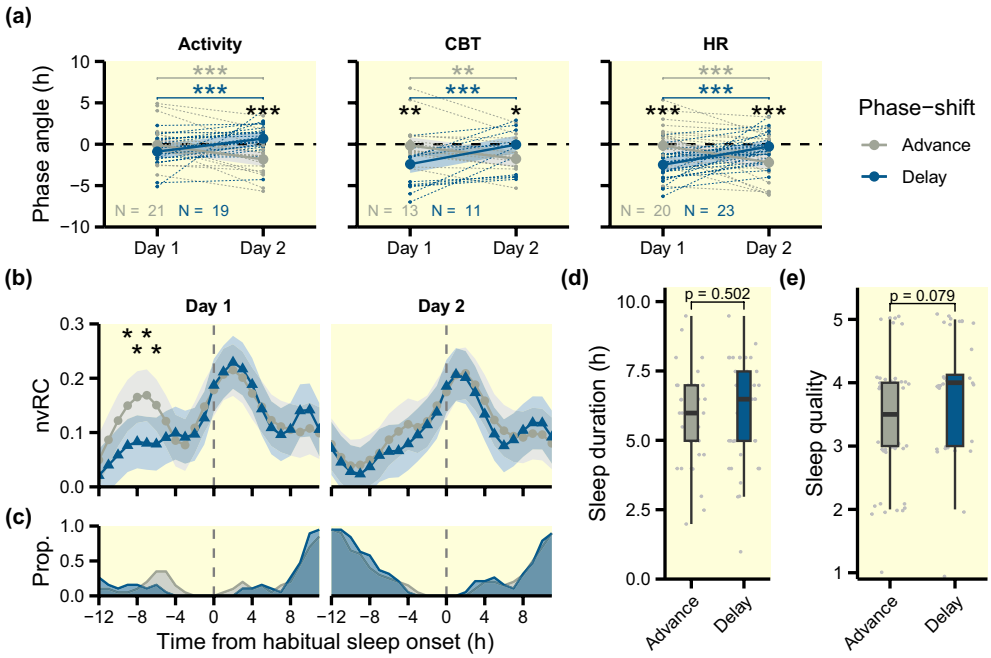

FIGURE 6 | Comparison of participants where the phase angle of bathyphase with sleep midpoint shifted later (phase delay) versus earlier (phase advance) during consecutive nightshift workdays. (a) Phase angle per response variable between phase-shift groups across participants. The solid line indicates the estimated marginal means (EMM) of phase angle per day. CBT: Core body temperature. HR: Heart rate. The following panels compare data from participants in the phase-shift groups based on a combination of HR and CBT (see SI Appendix Figure 2b). (b) EMMs of the mean hourly non-visual circadian response (nvRC) and (c) proportion of participants asleep, as a function of time from habitual sleep onset between phase-shift groups. (d) Duration and (e) quality of the main sleep period on nightshift workdays between phase-shift groups. The shaded areas in panels (a) and (b) indicate 95% confidence intervals. $*p < 0.05$, $**p < 0.01$, and $***p < 0.001$.

phase-shift groups. To consider individual differences in circadian sensitivity to light, we compared nvRC during nightshift workdays as a function of habitual sleep onset between phase-shift groups (Figure 6b), indicating significantly higher light exposure in the *Advance* compared to the *Delay* group 6–9 h before habitual sleep onset on the first day ($p < 0.039$). No differences in nvRC during work were observed (SI Appendix Figure S3d). Note that light exposure was influenced by sleep, visible in a (delayed) reduction of mean nvRC during times when more participants were asleep (Figure 6c). The duration and quality of the main sleep episodes were not significantly different between phase-shift groups (Figure 6d,e), although a trend for better sleep quality in the *Delay* compared to the *Advance* group could be observed (3.84 vs. 3.41, $p = 0.079$, Figure 6e), in line with the effects expected from an adaptation to nightshift work. Note that chronotype did not influence sleep outcomes, nor was it significantly different between groups despite a tendency for more moderately early types in the *Advance* compared to the *Delay* group (9 vs. 4, $p = 0.18$).

3 | Discussion

Nightshift work is common and has been identified as a risk factor for poor health and wellbeing due to the misalignment of internal circadian rhythms and the imposed sleep–wake pattern [13]. While evidence from experimental studies has shown that light plays an important role in circadian adaptation and modulating health-related outcomes [16, 30], current understanding of these relationships in everyday life is far from complete, necessitating the assessment of personal light exposure and lighting environments in combination with relevant outcome measures in real-life settings. With this observational study, we were able to describe daily light levels and lighting conditions experienced by individuals working nightshifts and dayshifts by using a spectrally resolved wearable light sensor enabling the measurement of biologically relevant light quantities and the identification of spectral distributions. These ambulatory light measurements were combined with sleep diaries and non-invasive, wearable sensors for electrocardiographic and body temperature measurements, revealing the detrimental effects of nightshift work on sleep duration, the disruption of physiological processes, and indications for the role of light in sleep and circadian adaptation.

A major consequence of nightshift work lies in altered light exposure patterns compared to regular daytime work. The observations of this study are in line with previous studies in night shift workers, showing reduced daytime light levels and low but persistent light exposure during the night compared to dayshift work [32, 35, 41, 42]. Interestingly, even on dayshifts, light levels often failed to meet recent recommendations for optimal daytime and evening light exposure [21]. These findings are not unique to healthcare settings but have recently been reported by a similar study in a large general sample of the UK population [43], indicating that daytime indoor (work) environments are often too dim and evenings too bright. Importantly, our results show that daylight played a central role in meeting recommended daytime light levels, yet daylight exposure at work varied substantially across participants despite correcting for

seasonal differences in photoperiod. Reduced daylight exposure at work was thus likely the result of different lighting conditions at the workplace, highlighting work environments that may benefit from targeted interventions, such as in surgery or emergency wards. However, we note that the sample population was too heterogeneous to directly compare personal light exposure between specific departments and professions.

Note that the recent guidelines by Brown et al. [21] are provisional, and target light levels may need to be refined with evolving research. Moreover, they only allow interpretation of personal light exposures in their potential to support health and wellbeing of daytime-active individuals, while consensus recommendations for nightshift workers do not yet exist. One of the main problems with lighting advice for nightshifts is the targeted outcome, given that light at night has the potential to shift circadian rhythms and increase alertness, but also to suppress melatonin [13]. Light exposure targeting circadian adaptation may only be advantageous for longer shift periods [44], although partial adaptation has been proposed as a potential means to improve sleep for rapidly rotating shift schedules [27]. However, the bright melanopic light levels required to induce circadian adaptation may lead to the suppression of melatonin [42], a potential factor in the carcinogenicity of nightshift work [45]. Since dim light levels may also be disadvantageous due to increased sleepiness [46], short-wavelength attenuated light with a lower melanopic efficacy has been proposed as a possible solution to maintain alertness while limiting melatonin suppression and circadian adaptation [47]. Here we found that workplaces were lit by either fluorescent lighting or modern cool white LEDs, the latter having a higher melanopic efficacy than fluorescent sources and much higher efficacy than typical residential lighting, resulting in higher melanopic light levels at night. Hence, an argument could be made to employ LEDs with a lower melanopic efficacy during nightshifts. Please note that data corresponding to LEDs could also have originated from computer screens rather than ambient lighting, given that health care professionals spend a substantial amount of time in front of computer screens [48]. Therefore, the true proportion of fluorescent lighting may be higher for participants where the LED light from screens dominated over ambient fluorescent lighting. Of note is also the large proportion of bright daylight exposures after sleep on nightshifts, highlighting a potential behavioral strategy that may benefit from further investigation given the potentially desensitizing effects of prior bright light exposure on melatonin suppression and circadian phase resetting [49–51], and may relate to the observed phase-shifts discussed below.

Another problem is that quantitative targets for light exposure during nightshifts to promote desired outcomes do not yet exist. To address this issue, we used a model of non-visual response dynamics, simulating the effective light input to the non-visual system [40]. With this model, we showed that the effective light input during night work could be similar to that during daytime work if we consider a circadian modulation in light sensitivity [52, 53], despite much lower light levels during night work. Although the model does not predict effects on physiological functions, it allows better comparison of light exposure between dayshifts and nightshifts and may help to assess and design lighting interventions. For example, in a simulated nightshift study, similar modeling has been employed successfully to design a targeted light intervention for accelerated circadian adaptation to nightshift work [25].

3.1 | Influence of Shift Work on Sleep and Association With Light Exposure

A crucial aspect in nightshift work is the misalignment of endogenous circadian rhythms with sleep–wake behavior, which is associated with shortened and disrupted daytime sleep [12, 13, 54–56]. Indeed, we found that the duration of self-reported sleep in between nightshifts (i.e., the main sleep period) was on average ~1.5 h shorter than main sleep during dayshifts, in line with typical findings for shift workers [12, 57–59]. However, shorter sleep episodes and naps seemed to make up for curtailed main sleep, with total sleep duration of approximately 7 h, as recommended in recent consensus guidelines for healthy sleep in shift workers [60]. In addition, a clear strategy for pre-sleeping on the day before the first nightshift was apparent, with longer main sleep and naps, adding up to a total sleep duration of almost ~10 h. Overall, these results confirm findings of a large study in Dutch healthcare workers [58], whose shift schedules are comparable to Switzerland. Moreover, these results are in line with occupational health recommendations by the Swiss government, advising napping and pre-sleeping as behavioral strategies during nightshifts. These findings may also explain the lack of differences in self-reported sleep quality and the generally high ratings, which contrast with previous findings [12, 59, 61]. Sleep quality also correlated to some extent with main sleep duration, emphasizing the importance of sufficient sleep. While chronotype [62, 63] and age [58] have been reported to influence sleep in shift workers, neither emerged as relevant factors in any of our analyses, possibly due to the rather low variability in chronotypes and the young age of the studied population.

Contrary to our expectations, we did not find strong associations between light exposure and sleep. Based on previous research, we anticipated a positive effect of bright daytime light exposure [43, 64, 65] and a detrimental impact of high melanopic light levels shortly before bed [43, 66, 67] on subsequent sleep parameters during dayshifts, and possibly a positive association of light during night work with sleep, due to circadian adaptation effects [13, 25, 27]. While we found that a higher average melanopic DER close to bedtime was related to longer sleep duration on dayshifts and later bedtime on nightshifts, these results are more indicative of a modulation of light exposure by sleep rather than the opposite. That is, a later bedtime after nightshifts allows for more time during the photoperiod before bed and hence an influence of daylight, resulting in higher melanopic DER. The association with longer sleep duration during dayshifts may have followed a similar principle, as longer sleep duration was associated with earlier bedtime on workdays. However, the relationship between more time spent at high melanopic EDI levels in the 3 h before bed and better sleep quality is surprising as it is not consistent with previous findings but may be related to elevated light levels due to an earlier bedtime and longer sleep duration, although these associations were not statistically significant. On the other hand, the finding of lower sleep quality with more time spent at lower light levels around habitual sleep onset may be due to less circadian adaptation due to lower light

exposure during the delay region of the human phase response curve [52]. Note that the analyses of the associations between light exposure and sleep were limited by a large number of invalid light data in the 3 h before bed on dayshifts and after waking up on nightshifts and possibly due to social activities during which participants neglected to wear the light sensor. Moreover, the low variability in sleep quality across participants and/or the use of a crude 5-point scale to assess sleep quality may have prevented finding stronger associations.

3.2 | Differential Effects of Nightshift Work on Rhythms of Activity and Physiology

As expected from a change from a day-active to a night-active schedule, our findings show a substantial delay of 24 h rhythms of activity, heart rate, and core body temperature from day shifts to night shifts, in line with previous findings for wrist and body temperature [68–70]. Note, however, that this change in overt rhythms does not necessarily reflect a change in endogenous circadian rhythms [15]. While CBT and HR are closely correlated biomarkers that are modulated by the endogenous circadian rhythm [71], they are strongly affected by other factors such as sleep, activity, meal intake, and external temperature, masking the endogenous circadian modulation [72]. Interestingly, despite these masking effects, we observed a dissociation in the effect of night shifts on rhythm phase and phase angle with sleep between activity and the two physiological variables, suggesting that the CBT and HR data reveal a modulation by processes other than activity. Under conventional sleep conditions, the CBT minimum (CBT_{min}) typically occurs in the latter part of the habitual sleep period, with HR_{min} being slightly phase-advanced relative to CBT_{min} [71], which is clearly demonstrated here during day shifts. The substantial shift of the overt CBT_{min} and HR_{min} towards the beginning of the sleep period observed during night shifts may be caused by the endogenous circadian modulation due to sleep onset closer to the circadian nadir of these processes. Although masking effects of sleep initiation [73] cannot be excluded, such effects should be consistent between day and night shifts, which was not the case here.

Light exposure during the night is known to shift the phase of endogenous circadian rhythms and thereby allows for adaptation to nightshift work, which is typically assessed using melatonin or blood samples [13]. For example, a previous study in healthcare professionals in Australia found an average delay of 1.1 h in urinary 6-sulfatoxymelatonin acrophase after 3–4 nightshifts, with a strong association between phase shifts and personal light exposure around the baseline acrophase [36]. Since melatonin assays were not available in this study, we divided participants into groups of an advance or delay in CBT_{min} and HR_{min} sleep phase angle, with an average phase advance of 1.6–2.0 h or delay of 2.2–2.4 h after one nightshift, which is much larger than what has been reported in the previous study. Interestingly, contrary to expectations, we did not find evidence for phase delaying effects of light after habitual sleep onset (i.e., the delay region of the phase response curve [52]), but rather for potential phase advancing effects of light exposure during daytime before the first nightshift. Assuming a causal role of light exposure, possible mechanisms may be either by means of acutely advancing circadian phase, or by reducing the sensitivity for phase delaying effects of light during the subsequent night [49–51]. In line with beneficial effects of circadian adaptation to nightshifts, sleep quality tended to be slightly better for participants whose phase angle with sleep delayed during nightshifts. Together, these findings suggest a potential role of daytime light exposure before nightshifts on the degree and direction of circadian adaptation. Moreover, we show that continuous monitoring of CBT or HR may be a useful non-invasive and cost-effective method to assess circadian phase in shift workers, further highlighting the potential of physiological functions with wearable sensors as demonstrated by previous studies [69, 70]. However, validation of such biomarkers derived from wearable devices with robust circadian phase markers such as melatonin concentration or clock gene expression in blood samples or hair follicles [13, 15] is required. Finally, beyond rhythm phase, shift work and light exposure also influence the amplitude and temporal stability of circadian rhythms [13]. To maintain the focus of this article on light, sleep, and circadian phase, further detailed analyses of cardiometabolic rhythms will be presented in future studies.

3.3 | Limitations

We would like to acknowledge limitations to this study, some of which were already discussed above. These limitations were imposed largely by the challenges (i.e., logistics and minimizing participant burden) of performing field research under operational conditions in a sensitive domain such as healthcare. Due to the complexity of work schedules, the time gap between the two shift periods ranged from weeks to several months across participants. As a result, some participants worked both shift periods in different seasons and/or under different social-, work-, health-, or lifestyle-related circumstances, which may have biased the comparisons between shifts. The inclusion of a baseline day before each period could have helped to partly overcome this limitation. Moreover, day shifts occurred more frequently in summer compared to winter and vice versa for night shifts. Although seasonal day length was not a significant predictor in the analyses of sleep parameters, non-visual sensitivity to light can vary with season [74], hence we cannot exclude a bias due to the unbalanced distribution across seasons. Furthermore, light data were only available from 83% of participants, mainly due to the lack of sufficient light sensors while multiple subjects participated in parallel. In addition, data were missing due to the loss of four sensors. Given their wearing location on the outer clothing, light sensors are at a higher risk of being lost (e.g., falling off when changing clothes, in emergency situations etc.), which should be considered when planning similar studies. The analyses of self-reported sleep timing were limited by the 30 min resolution of the sleep diary. Moreover, not all participants completed the diary for each day. Due to the core study period ending directly after the last shift, it was not possible to examine how different light exposure and sleep strategies affected recovery from night shifts (cf. [75]). Additionally, due to lack of full 24 h data on the last night shift workday, changes in phase angle across consecutive night shifts could only be calculated between the first two days. More days may have given a more robust indication of phase shifting behavior and its effects on sleep. Furthermore, CBT data were only available for a subset of participants due to a late inclusion of the wearable thermal

sensor in the study, complicating the comparison of phase estimates for HR and CBT data.

4 | Materials and Methods

4.1 | Participants and Study Design

The study was conducted among healthcare workers in the Geneva area, Switzerland. We aimed to study individuals during a short period of nightshift work (as common for rotating shift conditions) and an equivalent period of dayshifts for comparison. Participants were recruited via postings, announcements, and the hospital website. Seventy-two individuals agreed to participate in the study (see SI Appendix, Table S1 for cohort characteristics). Inclusion criteria were: adults aged between 20–50 years, working ≥ 80% full-time equivalent and scheduled to work three to five consecutive nightshifts and three to five consecutive dayshifts during the study period. Key exclusion criteria were: planned or current pregnancy during the study, menopausal women, major illness and hospitalization in the past month, travel across multiple time zones in the past month or during the study. We aimed to include a large sample of individuals to maintain statistical power with a sufficient margin for invalid data due to compliance and technological issues common in observational studies with wearable sensors. To achieve this aim given the recruitment criteria, data were collected between January 2021 to August 2024. The study was conducted in accordance with Good Clinical Practices and the Swiss Human Research Act and was approved by the cantonal research ethics committee of Geneva (BASEC no. 2021-01008) and registered on ClinicalTrials.gov (NCT05177965). Written informed consent was obtained from each individual prior to participation and participants received a monetary compensation upon completion.

The study comprised two measurement periods of three to five days during which participants were asked to: (1) continuously wear an ambient light sensor, a combined electrocardiography and actigraphy monitor, and a body temperature sensor; (2) fill in a daily sleep diary; and (3) complete a baseline questionnaire at the initial meeting. Participants met the research team for a total of 4 study visits, two per shift period, one at the start (study visit 1 and 3) and one at the end (study visit 2 and 4). The dayshift period was scheduled so that it was not preceded by nightshifts for at least 10 days. Except for one individual, participants started with a nightshift period. The first and third visits occurred ~24 h before the first work shift, when the different wearable sensors were set up. The devices were returned at the second and fourth visits, scheduled immediately after the last work shift.

4.2 | Outcome Measures

Spectrally resolved personal light exposure data were collected using the *Spectrace* [39] dosimeter prototype (SI Appendix, Figure S4a) attached to the outer layer of clothing at chest-height. Physical activity and heart rate were measured with a wearable integrated three-axis accelerometer and single-lead electrocardiography monitor (Actiheart version 5, CamNtech Ltd., Fenstanton, UK; SI Appendix, Figure S4b) and core body temperature data were estimated from a combination of continuous skin temperature and heat flux measurements collected with a wearable thermal sensor (CALERA Research, greenTEG, Zurich, Switzerland; SI Appendix, Figure S4c). Both devices were directly attached to the skin on the chest. Participants were asked to wear the three devices continuously throughout the measurement period, except for the light sensor, which was not worn during sleep in bed. All continuous data were aggregated to 1 min intervals for further analyses. A detailed description of the sensors is provided in the SI Appendix.

In conjunction with these continuous physical measurements, we assessed daily sleep patterns using a paper sleep diary (SI Appendix, Figure S5), in which participants were asked to indicate when they slept by marking sleep states (sleep, half-sleep, wake, long wake, drowsy) in 30 min bins, as well as the sleep quality of the main sleep period per day on a scale from 1 (very bad) to 5 (very good). Moreover, a baseline questionnaire was administered at the first study visit, including demographic and work-related information, such as age, sex, profession and department, and typical shift schedules. Moreover, we assessed chronotype with the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ [76]) and general sleep quality with the Pittsburgh Sleep Quality Index (PSQI [77]).

4.3 | Statistical Analysis

All data processing, analyses, and figures were performed using R version 4.2.2 [78]. Associations between daily outcome variables and factors of interest were investigated with linear mixed models (LMM) using the *lme4* (v1.1–31) and *lmerTest* (v3.1–3) R packages. Generalized LMMs were used with a Poisson distribution for count data and with a binomial distribution for proportion data. All LMMs reported here were composed of participants as a random effect. The addition of age, sex, chronotype, and photoperiod length as covariates to each analysis was assessed by comparing model performance (i.e., higher corrected AIC weights) and are only mentioned in the results in case they were included. Estimated marginal means were compared using the *emmeans* (v1.8.3) R package, with Bonferroni adjustment of p-values for multiple comparisons. All statistical tests assumed a two-sided significance limit of 0.05.

4.3.1 | Light Exposure

Melanopic equivalent daylight illuminance (EDI), melanopic daylight efficacy ratio (DER), and correlated color temperature (CCT) were calculated from the interpolated spectral irradiance data. Effective light input to the non-visual system was estimated using the direct response (nvRD) and circadian response (nvRC) model [40] with habitual sleep onset as indicated in the PSQI questionnaire. Types of spectral power distributions (SPDs) in the data were identified by means of a distance-based classification method with a large set of reference spectra (see SI Appendix for details). Invalid data (i.e., periods of non-wear and sensor obstruction, see SI Appendix for details) were set to missing. Data where participants reported being asleep were set to 0.1 lx for melanopic EDI and photopic illuminance, and missing for CCT and melanopic DER.

4.3.2 | Diurnal Rhythms of Activity, Heart Rate, and Body Temperature

The activity, heart rate (HR), and core body temperature (CBT) data were subjected to cosinor analysis, a common straightforward method to model circadian rhythms in timeseries data [79]. Each dataset was split into 24 h intervals starting at 20:00 h (to avoid splitting during sleep periods, see SI Appendix Figure S2), resulting in three intervals per shift type, outcome measure, and participant. For each interval, a 24 h single-component cosine was fitted to the normalized data using least-squares optimization (*circacompare* R package, v0.2.0) from which the rhythm peak (acrophase) and 12 h later minimum (bathyphase) were calculated. The validity of the selected intervals was confirmed by moving 24 h window cosinor analysis in 1 h increments, showing that acrophase stabilized after 24 h starting from 20:00 h the day before the first nightshift and stable phase on dayshifts (SI Appendix Figure S3a). Before analysis, any invalid data (see SI Appendix for details) were set to missing, and intervals with more than 50% missing data were excluded. Activity data were log-transformed before analysis, with zero values set to 0.1. After subsequent analysis, cosine fits with an R^2 value of less than 0.05 were excluded. LMMs were used to compare rhythm parameters between outcome measures, shift type, and daily intervals.

4.3.3 | Self-Reported Sleep

Self-reported sleep parameters derived from daily sleep diaries were compared using LMMs with shift-type and day as fixed factors. Moreover, sleep onset of the main sleep period was compared with chronotype as an additional fixed factor. Associations among continuous sleep parameters were examined using covariate-only LMMs without additional fixed factors. Associations between light exposure (melanopic EDI) on workdays and sleep quality, duration, and onset of the subsequent main sleep period were assessed using aggregate metrics calculated for four pre-bed periods: work, the 16 h before sleep onset (the typical wake period), 3 h before sleep onset (period with potential direct effects on sleep [21]), and the 3 h before and after habitual sleep onset (measure of internal time related to onset of melatonin release [80, 81]). These metrics included: mean melanopic DER, mean melanopic EDI (log-transformed), cumulative nvRD, and nvRC [40], disparity index (a measure of temporal variability [82]), the percentage of time spent above 250 lx melanopic EDI and below 10 lx, and the percentage of exposure to daylight. Note that exposure to specific light sources other than daylight was not included due to a lack of evidence for effects beyond differences in melanopic activation. Metrics were selected based on a recent review [83] and calculated using the *LightLogR* (v0.4.2) package [84]. Periods with more than 25% invalid light data were excluded from the calculation of metrics. All analyses were performed using LMMs with the light exposure metric as an independent variable, separately per shift-type and pre-bed period.

5 | Conclusion

This observational study in a representative cohort of healthcare nightshift workers in Switzerland using novel spectrally resolved wearable light sensing technology showed that light exposure patterns and lighting environments differed markedly between day- and nightshifts as well as among individuals and job roles. Potentially unfavorable lighting conditions including little daylight exposure and low daytime light levels were frequently experienced during day- and nightshift work. Additionally, differential effects of nightshift work on phase shifting between heart rate, core body temperature, and physical activity suggest that physiological functions monitored with wearable sensors could be used as non-invasive biomarkers of endogenous circadian rhythms. Nevertheless, associations of light exposure with sleep and circadian parameters were limited, possibly due to existent behavioral strategies. While the observational nature of the study does not allow for generating direct advice for best (lighting) practices, our findings highlight the potential of wearable sensor technology and open promising avenues for further research, including the investigation of lighting solutions with low melanopic efficacy, as well as the impact of daytime light exposure and daylight on sleep and circadian adaptation in nightshift workers.

Author Contributions

Steffen L. Hartmeyer: conceptualization, software, methodology, formal analysis, writing – original draft, writing – review and editing, visualization. **Nicholas E. Phillips:** conceptualization, methodology, investigation, data curation, writing – review and editing. **Friedrich C. Jassil:** writing – review and editing. **Céline Joris:** writing – review and editing, investigation, data curation. **Charna Dibner:** writing – review and editing. **Tinh-Hai Collet:** conceptualization, methodology, investigation, project administration, supervision, writing – review and editing, funding acquisition, resources. **Marilyne Andersen:** project administration, supervision, writing – review and editing, funding acquisition, resources.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Eurofound, A. Wilczynska, J. Cabrita, et al., *6th European Working Conditions Survey—2017 Update* (Publications Office, 2017), https://doi.org/10.2806/422172.

2. L. Kervezee, A. Kosmadopoulos, and D. B. Boivin, "Metabolic and Cardiovascular Consequences of Shift Work: The Role of Circadian Disruption and Sleep Disturbances," *European Journal of Neuroscience* 51, no. 1 (2020): 396–412, https://doi.org/10.1111/ejn.14216.

3. C. Vetter, E. E. Devore, L. R. Wegrzyn, et al., "Association Between Rotating Night Shift Work and Risk of Coronary Heart Disease Among Women," *Journal of the American Medical Association* 315, no. 16 (2016): 1726–1734, https://doi.org/10.1001/jama.2016.4454.

4. A. Hemmer, J. Mareschal, C. Dibner, et al., "The Effects of Shift Work on Cardio-Metabolic Diseases and Eating Patterns," *Nutrients* 13, no. 11 (2021): 4178, https://doi.org/10.3390/nu13114178.

5. P. F. Innominato, V. P. Roche, O. G. Palesh, A. Ulusakarya, D. Spiegel, and F. A. Lévi, "The Circadian Timing System in Clinical Oncology," *Annals of Medicine* 46, no. 4 (2014): 191–207, https://doi.org/10.3109/07853890.2014.916990.

6. J. Philippe and C. Dibner, "Thyroid Circadian Timing: Roles in Physiology and Thyroid Malignancies," *Journal of Biological Rhythms* 30, no. 2 (2015): 76–83, https://doi.org/10.1177/0748730414557634.

7. E. M. Ward, D. Germolec, M. Kogevinas, et al., "Carcinogenicity of Night Shift Work," *Lancet Oncology* 20, no. 8 (2019): 1058–1059, https://doi.org/10.1016/S1470-2045(19)30455-3.

8. J. P. Brown, D. Martin, Z. Nagaria, A. C. Verceles, S. L. Jobe, and E. M. Wickwire, "Mental Health Consequences of Shift Work: An Updated Review," *Current Psychiatry Reports* 22, no. 2 (2020): 7, https://doi.org/10.1007/s11920-020-1131-z.

9. M. F. Eldevik, E. Flo, B. E. Moen, S. Pallesen, and B. Bjorvatn, "Insomnia, Excessive Sleepiness, Excessive Fatigue, Anxiety, Depression and Shift Work Disorder in Nurses Having Less Than 11 Hours In-Between Shifts," *PLoS One* 8, no. 8 (2013): e70882, https://doi.org/10.1371/journal.pone.0070882.

10. T. Woo, R. Ho, A. Tang, and W. Tam, "Global Prevalence of Burnout Symptoms Among Nurses: A Systematic Review and Meta-Analysis," *Journal of Psychiatric Research* 123 (2020): 9–20, https://doi.org/10.1016/j.jpsychires.2019.12.015.

11. P. B. de Cordova, M. A. Bradford, and P. W. Stone, "Increased Errors and Decreased Performance at Night: A Systematic Review of the Evidence Concerning Shift Work and Quality," *Work* 53, no. 4 (2016): 825–834, https://doi.org/10.3233/WOR-162250.

12. G. Kecklund and J. Axelsson, "Health Consequences of Shift Work and Insufficient Sleep," *BMJ (Clinical Research Ed.)* 355 (2016): i5210, https://doi.org/10.1136/bmj.i5210.

13. D. B. Boivin, P. Boudreau, and A. Kosmadopoulos, "Disturbance of the Circadian System in Shift Work and Its Health Impact," *Journal of Biological Rhythms* 37, no. 1 (2022): 3–28, https://doi.org/10.1177/07487304211064218.

14. T. L. Sletten, F. P. Cappuccio, A. J. Davidson, E. Van Cauter, S. M. W. Rajaratnam, and F. A. J. L. Scheer, "Health Consequences of Circadian Disruption," *Sleep* 43, no. 1 (2020): zsz194, https://doi.org/10.1093/sleep/zsz194.

15. C. Vetter, "Circadian Disruption: What Do We Actually Mean?," *European Journal of Neuroscience* 51, no. 1 (2020): 531–550, https://doi.org/10.1111/ejn.14255.

16. A. Lowden and G. Kecklund, "Considerations on How to Light the Night-Shift," *Lighting Research & Technology* 53, no. 5 (2021): 437–452, https://doi.org/10.1177/14771535211012251.

17. J. F. Duffy and K. P. Wright, "Entrainment of the Human Circadian System by Light," *Journal of Biological Rhythms* 20, no. 4 (2005): 326–338, https://doi.org/10.1177/0748730405277983.

18. T. Roenneberg, S. Daan, and M. Merrow, "The Art of Entrainment," *Journal of Biological Rhythms* 18, no. 3 (2003): 183–194, https://doi.org/10.1177/0748730403018003001.

19. S. L. Chellappa, R. Steiner, P. Blattner, P. Oelhafen, T. Götz, and C. Cajochen, "Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep us Alert?," *PLoS One* 6, no. 1 (2011): e16429, https://doi.org/10.1371/journal.pone.0016429.

20. S. L. Chellappa, R. Steiner, P. Oelhafen, et al., "Acute Exposure to Evening Blue-Enriched Light Impacts on Human Sleep," *Journal of Sleep Research* 22, no. 5 (2013): 573–580, https://doi.org/10.1111/jsr.12050.

21. T. M. Brown, G. C. Brainard, C. Cajochen, et al., "Recommendations for Daytime, Evening, and Nighttime Indoor Light Exposure to Best Support Physiology, Sleep, and Wakefulness in Healthy Adults," *PLoS Biology* 20, no. 3 (2022): e3001571, https://doi.org/10.1371/journal.pbio.3001571.

22. R. M. Lunn, D. E. Blask, A. N. Coogan, et al., "Health Consequences of Electric Lighting Practices in the Modern World: A Report on the National Toxicology Program's Workshop on Shift Work at Night, Artificial Light at Night, and Circadian Disruption," *Science of the Total Environment* 607-608 (2017): 1073–1084, https://doi.org/10.1016/j.scitotenv.2017.07.056.

23. I. C. Mason, M. Boubekri, M. G. Figueiro, et al., "Circadian Health and Light: A Report on the National Heart, Lung, and Blood Institute's Workshop," *Journal of Biological Rhythms* 33, no. 5 (2018): 451–457, https://doi.org/10.1177/0748730418789506.

24. M. P. J. Aarts, S. L. Hartmeyer, K. Morsink, H. S. M. Kort, and Y. A. W. de Kort, "Can Special Light Glasses Reduce Sleepiness and Improve Sleep of Nightshift Workers? A Placebo-Controlled Explorative Field Study," *Clocks & Sleep* 2, no. 2 (2020): 225–245, https://doi.org/10.3390/clockssleep2020018.

25. A. Guyett, N. Lovato, J. Manners, et al., "A Circadian-Informed Lighting Intervention Accelerates Circadian Adjustment to a Night Work Schedule in a Submarine Lighting Environment," *Sleep* 47 (2024): zsae146, https://doi.org/10.1093/sleep/zsae146.

26. M. Hébert, A. A. Lavigne, J. Auclair, et al., "A Blue-Enriched Light Intervention Counteracts the Alertness Decrement Among Mine Workers on Extended 12-Hour Night Shift Periods," *Journal of Occupational and Environmental Medicine* 65, no. 7 (2023): 584–589, https://doi.org/10.1097/JOM.0000000000002849.

27. M. R. Smith and C. I. Eastman, "Night Shift Performance Is Improved by a Compromise Circadian Phase Position: Study 3. Circadian Phase After 7 Night Shifts With an Intervening Weekend Off," *Sleep* 31, no. 12 (2008): 1639–1645, https://doi.org/10.1093/sleep/31.12.1639.

28. E. Sunde, A. Harris, O. K. Olsen, and S. Pallesen, "Moral Decision-Making at Night and the Impact of Night Work With Blue-Enriched White Light or Warm White Light: A Counterbalanced Crossover Study," *Annals of Medicine* 56, no. 1 (2024): 2331054, https://doi.org/10.1080/07853890.2024.2331054.

29. D. Vethe, J. Scott, M. Engstrøm, et al., "The Evening Light Environment in Hospitals Can Be Designed to Produce Less Disruptive Effects on the Circadian System and Improve Sleep," *Sleep* 44, no. 3 (2021): zsaa194, https://doi.org/10.1093/sleep/zsaa194.

30. C. Vetter, P. M. Pattison, K. Houser, et al., "A Review of Human Physiological Responses to Light: Implications for the Development of Integrative Lighting Solutions," *LEUKOS* 18, no. 3 (2022): 387–414, https://doi.org/10.1080/15502724.2021.1872383.

31. S. L. Hartmeyer, F. S. Webler, and M. Andersen, "Towards a Framework for Light-Dosimetry Studies: Methodological Considerations," *Lighting Research and Technology* 55, no. 4–5 (2023): 377–399, https://doi.org/10.1177/14771535221103258.

32. S. Daugaard, A. H. Garde, J. P. E. Bonde, et al., "Night Work, Light Exposure and Melatonin on Work Days and Days Off," *Chronobiology International* 34, no. 7 (2017): 942–955, https://doi.org/10.1080/07420528.2017.1327867.

33. A. Grundy, M. Sanchez, H. Richardson, et al., "Light Intensity Exposure, Sleep Duration, Physical Activity, and Biomarkers of Melatonin Among Rotating Shift Nurses," *Chronobiology International* 26, no. 7 (2009): 1443–1461, https://doi.org/10.3109/07420520903399987.

34. K. Papantoniou, O. J. Pozo, A. Espinosa, et al., "Circadian Variation of Melatonin, Light Exposure, and Diurnal Preference in Day and Night Shift Workers of Both Sexes," *Cancer Epidemiology, Biomarkers & Prevention* 23, no. 7 (2014): 1176–1186, https://doi.org/10.1158/1055-9965.EPI-13-1271.

35. S. Rabstein, K. Burek, M. Lehnert, et al., "Differences in Twenty-Four-Hour Profiles of Blue-Light Exposure Between Day and Night Shifts in Female Medical Staff," *Science of the Total Environment* 653 (2019): 1025–1033, https://doi.org/10.1016/j.scitotenv.2018.10.293.

36. J. E. Stone, T. L. Sletten, M. Magee, et al., "Temporal Dynamics of Circadian Phase Shifting Response to Consecutive Night Shifts in Healthcare Workers: Role of Light–Dark Exposure," *Journal of Physiology* 596, no. 12 (2018): 2381–2395, https://doi.org/10.1113/JP275589.

37. CIE, *System for Metrology of Optical Radiation for ipRGC-Influenced Responses to Light* (CIE, 2018).

38. F. S. Webler, M. Spitschan, R. G. Foster, M. Andersen, and S. N. Peirson, "What Is the "Spectral Diet" of Humans?," *Current Opinion in Behavioral Sciences* 30 (2019): 80–86, https://doi.org/10.1016/j.cobeha.2019.06.006.

39. F. S. Webler, G. Chinazzo, and M. Andersen, "Towards a Wearable Sensor for Spectrally-Resolved Personal Light Monitoring," *Journal of Physics: Conference Series* 2042, no. 1 (2021): 012120, https://doi.org/10.1088/1742-6596/2042/1/012120.

40. M. L. Amundadottir, "Light-Driven Model for Identifying Indicators of Non-Visual Health Potential in the Built Environment." (PhD thesis, EPFL, 2016).

41. M. P. J. Aarts, S. L. Hartmeyer, K. Morsink, and H. S. M. Kort, "Exploring Light Exposure of Hospital Nurses Working Rapidly Rotating Shifts in Relation to Sleepiness and Sleep," *Journal of Physics: Conference Series* 2042, no. 1 (2021): 012111, https://doi.org/10.1088/1742-6596/2042/1/012111.

42. A. Grundy, J. Tranmer, H. Richardson, C. H. Graham, and K. J. Aronson, "The Influence of Light at Night Exposure on Melatonin Levels Among Canadian Rotating Shift Nurses," *Cancer Epidemiology, Biomarkers & Prevention* 20, no. 11 (2011): 2404–2412, https://doi.org/10.1158/1055-9965.EPI-11-0427.

43. A. Didikoglu, N. Mohammadian, S. Johnson, et al., "Associations Between Light Exposure and Sleep Timing and Sleepiness While Awake in a Sample of UK Adults in Everyday Life," *National Academy of Sciences of the United States of America* 120, no. 42 (2023): e2301608120, https://doi.org/10.1073/pnas.2301608120.

44. B. Bjorvatn, Å. Kecklund Gör, and T. Åkerstedt, "Bright Light Treatment Used for Adaptation to Night Work and Re-Adaptation Back to Day Life. A Field Study at an Oil Platform in the North Sea," *Journal of Sleep Research* 8, no. 2 (1999): 105–112, https://doi.org/10.1046/j.1365-2869.1999.00146.x.

45. E. S. Schernhammer and K. Schulmeister, "Melatonin and Cancer Risk: Does Light at Night Compromise Physiologic Cancer Protection by Lowering Serum Melatonin Levels?," *British Journal of Cancer* 90, no. 5 (2004): 941–943, https://doi.org/10.1038/sj.bjc.6601626.

46. C. Cajochen, M. Münch, S. Kobialka, et al., "High Sensitivity of Human Melatonin, Alertness, Thermoregulation, and Heart Rate to Short Wavelength Light," *Journal of Clinical Endocrinology and Metabolism* 90, no. 3 (2005): 1311–1316, https://doi.org/10.1210/jc.2004-0957.

47. M. van de Werken, M. C. Giménez, B. de Vries, D. G. M. Beersma, and M. C. M. Gordijn, "Short-Wavelength Attenuated Polychromatic White Light During Work at Night: Limited Melatonin Suppression Without Substantial Decline of Alertness," *Chronobiology International* 30, no. 7 (2013): 843–854, https://doi.org/10.3109/07420528.2013.773440.

48. N. Wenger, M. Méan, J. Castioni, P. Marques-Vidal, G. Waeber, and A. Garnier, "Allocation of Internal Medicine Resident Time in a Swiss Hospital: A Time and Motion Study of Day and Evening Shifts," *Annals of Internal Medicine* 166, no. 8 (2017): 579–586, https://doi.org/10.7326/M16-2238.

49. A. M. M. Chang, F. A. Scheer, and C. A. Czeisler, "The Human Circadian System Adapts to Prior Photic History," *Journal of Physiology* 589, no. 5 (2011): 1095–1102, https://doi.org/10.1113/jphysiol.2010.201194.

50. M. Rufiange, C. Beaulieu, P. Lachapelle, and M. Dumont, "Circadian Light Sensitivity and Rate of Retinal Dark Adaptation in Indoor and Outdoor Workers," *Journal of Biological Rhythms* 22, no. 5 (2007): 454–457, https://doi.org/10.1177/0748730407305375.

51. M. Hébert, S. K. Martin, C. Lee, and C. I. Eastman, "The Effects of Prior Light History on the Suppression of Melatonin by Light in Humans," *Journal of Pineal Research* 33, no. 4 (2002): 198–203.

52. S. B. S. Khalsa, M. E. Jewett, C. Cajochen, and C. A. Czeisler, "A Phase Response Curve to Single Bright Light Pulses in Human Subjects," *Journal of Physiology* 549 (2003): 945–952, https://doi.org/10.1113/jphysiol.2003.040477.

53. R. E. Kronauer, D. B. Forger, and M. E. Jewett, "Quantifying Human Circadian Pacemaker Response to Brief, Extended, and Repeated Light Stimuli Over the Phototopic Range," *Journal of Biological Rhythms* 14, no. 6 (1999): 501–516, https://doi.org/10.1177/074873049901400609.

54. T. Akerstedt, "Work Hours, Sleepiness and the Underlying Mechanisms," *Journal of Sleep Research* 4, no. S2 (1995): 15–22, https://doi.org/10.1111/j.1365-2869.1995.tb00221.x.

55. D. B. Boivin and P. Boudreau, "Impacts of Shift Work on Sleep and Circadian Rhythms," *Pathologie Biologie* 62, no. 5 (2014): 292–301, https://doi.org/10.1016/j.patbio.2014.08.001.

56. J. J. Pilcher, B. J. Lambert, and A. I. Huffcutt, "Differential Effects of Permanent and Rotating Shifts on Self-Report Sleep Length: A Meta-Analytic Review," *Sleep* 23, no. 2 (2000): 1–9, https://doi.org/10.1093/sleep/23.2.1b.

57. T. Åkerstedt and K. P. Wright, "Sleep Loss and Fatigue in Shift Work and Shift Work Disorder," *Sleep Medicine Clinics* 4, no. 2 (2009): 257–271, https://doi.org/10.1016/j.jsmc.2009.03.001.

58. G. Hulsegge, B. Loef, L. W. van Kerkhof, T. Roenneberg, A. J. van der Beek, and K. I. Proper, "Shift Work, Sleep Disturbances and Social Jetlag in Healthcare Workers," *Journal of Sleep Research* 28, no. 4 (2019): e12802, https://doi.org/10.1111/jsr.12802.

59. C. A. Wyse, C. A. Celis Morales, N. Graham, et al., "Adverse Metabolic and Mental Health Outcomes Associated With Shiftwork in a Population-Based Study of 277,168 Workers in UK Biobank," *Annals of Medicine* 49, no. 5 (2017): 411–420, https://doi.org/10.1080/07853890.2017.1292045.

60. A. E. Shriane, G. Rigney, S. A. Ferguson, Y. S. Bin, and G. E. Vincent, "Healthy Sleep Practices for Shift Workers: Consensus Sleep Hygiene Guidelines Using a Delphi Methodology," *Sleep* 46, no. 12 (2023): zsad182, https://doi.org/10.1093/sleep/zsad182.

61. K. McDowall, E. Murphy, and K. Anderson, "The Impact of Shift Work on Sleep Quality Among Nurses," *Occupational Medicine* 67, no. 8 (2017): 621–625, https://doi.org/10.1093/occmed/kqx152.

62. M. Juda, C. Vetter, and T. Roenneberg, "Chronotype Modulates Sleep Duration, Sleep Quality, and Social Jet Lag in Shift-Workers," *Journal of Biological Rhythms* 28, no. 2 (2013): 141–151, https://doi.org/10.1177/0748730412475042.

63. J. Korsiak, J. Tranmer, M. Leung, M. M. Borghese, and K. J. Aronson, "Actigraph Measures of Sleep Among Female Hospital Employees Working Day or Alternating Day and Night Shifts," *Journal of Sleep Research* 27, no. 4 (2018): e12579, https://doi.org/10.1111/jsr.12579.

64. M. Boubekri, I. N. Cheung, K. J. Reid, C. H. Wang, and P. C. Zee, "Impact of Windows and Daylight Exposure on Overall Health and Sleep Quality of Office Workers: A Case-Control Pilot Study," *Journal of Clinical Sleep Medicine* 10 (2014): 603–611, https://doi.org/10.5664/jcsm.3780.

65. A. U. Viola, L. M. James, L. J. Schlangen, and D. J. Dijk, "Blue-Enriched White Light in the Workplace Improves Self-Reported Alertness, Performance and Sleep Quality," *Scandinavian Journal of Work, Environment & Health* 34, no. 4 (2008): 297–306, https://doi.org/10.5271/sjweh.1268.

66. S. W. Cain, E. M. McGlashan, P. Vidafar, et al., "Evening Home Lighting Adversely Impacts the Circadian System and Sleep," *Scientific Reports* 10, no. 1 (2020): 19110, https://doi.org/10.1038/s41598-020-75622-4.

67. J. R. Cho, E. Y. Joo, D. L. Koo, and S. B. Hong, "Let There Be no Light: The Effect of Bedside Light on Sleep Quality and Background Electroencephalographic Rhythms," *Sleep Medicine* 14, no. 12 (2013): 1422–1425, https://doi.org/10.1016/j.sleep.2013.09.007.

68. T. W. Jang, H. Kim, S. H. Kang, S. H. Choo, I. S. Lee, and K. H. Choi, "Circadian Rhythm of Wrist Temperature Among Shift Workers in South Korea: A Prospective Observational Study," *International Journal of Environmental Research and Public Health* 14, no. 10 (2017): 1109, https://doi.org/10.3390/ijerph14101109.

69. H. E. Molzof, A. Prapanjaroensin, V. H. Patel, M. V. Mokashi, K. L. Gamble, and P. A. Patrician, "Misaligned Core Body Temperature Rhythms Impact Cognitive Performance of Hospital Shift Work Nurses," *Neurobiology of Learning and Memory* 160 (2019): 151–159, https://doi.org/10.1016/j.nlm.2019.01.002.

70. Y. Zhang, E. Cordina-Duverger, S. Komarzynski, et al., "Digital Circadian and Sleep Health in Individual Hospital Shift Workers: A Cross Sectional Telemonitoring Study," *eBioMedicine* 81 (2022): 104121, https://doi.org/10.1016/j.ebiom.2022.104121.

71. K. Kräuchi and A. Wirz-Justice, "Circadian Rhythm of Heat Production, Heart Rate, and Skin and Core Temperature Under Unmasking Conditions in Men," *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* 267, no. 3 (1994): 819–829, https://doi.org/10.1152/ajpregu.1994.267.3.R819.

72. K. J. Reid, "Assessment of Circadian Rhythms," *Neurologic Clinics* 37, no. 3 (2019): 505–526, https://doi.org/10.1016/j.ncl.2019.05.001.

73. K. Kräuchi, C. Cajochen, and A. Wirz-Justice, "A Relationship Between Heat Loss and Sleepiness: Effects of Postural Change and Melatonin Administration," *Journal of Applied Physiology* 83, no. 1 (1997): 134–139, https://doi.org/10.1152/jappl.1997.83.1.134.

74. I. Schöllhorn, O. Stefani, C. Blume, and C. Cajochen, "Seasonal Variation in the Responsiveness of the Melanopsin System to Evening Light: Why we Should Report Season When Collecting Data in Human Sleep and Circadian Studies," *Clocks & Sleep* 5, no. 4 (2023): 651–666, https://doi.org/10.3390/clockssleep5040044.

75. H. C. Thorne, S. M. Hampton, L. M. Morgan, D. J. Skene, and J. Arendt, "Returning From Night Shift to Day Life: Beneficial Effects of Light on Sleep," *Sleep and Biological Rhythms* 8, no. 3 (2010): 212–221, https://doi.org/10.1111/j.1479-8425.2010.00451.x.

76. J. A. Horne and O. Östberg, "A Self-Assessment Questionnaire to Determine Morningness-Eveningness in Human Circadian Rhythms," *International Journal of Chronobiology* 4 (1976): 97–110.

77. D. J. Buysse, C. F. Reynolds, T. H. Monk, S. R. Berman, and D. J. Kupfer, "The Pittsburgh Sleep Quality Index: A New Instrument for Psychiatric Practice and Research," *Psychiatry Research* 28, no. 2 (1989): 193–213, https://doi.org/10.1016/0165-1781(89)90047-4.

78. R Core Team, *R: A Language and Environment for Statistical Computing* (R Foundation for Statistical Computing, 2022), https://www.R-project.org/.

79. G. Cornelissen, "Cosinor-Based Rhythmometry," *Theoretical Biology & Medical Modelling* 11, no. 1 (2014): 16, https://doi.org/10.1186/1742-4682-11-16.

80. T. L. Sletten, S. Vincenzi, J. R. Redman, S. W. Lockley, and S. M. Rajaratnam, "Timing of Sleep and Its Relationship With the Endogenous Melatonin Rhythm," *Frontiers in Neurology* 1 (2010), https://doi.org/10.3389/fneur.2010.00137.

81. H. J. Burgess and C. I. Eastman, "The Dim Light Melatonin Onset Following Fixed and Free Sleep Schedules," *Journal of Sleep Research* 14, no. 3 (2005): 229–237, https://doi.org/10.1111/j.1365-2869.2005.00470.x.

82. M. Fernández-Martínez, S. Vicca, I. A. Janssens, J. Carnicer, J. Martín-Vide, and J. Peñuelas, "The Consecutive Disparity Index, D: A Measure of Temporal Variability in Ecological Studies," *Ecosphere* 9, no. 12 (2018): e02527, https://doi.org/10.1002/ecs2.2527.

83. S. L. Hartmeyer and M. Andersen, "Towards a Framework for Light-Dosimetry Studies: Quantification Metrics," *Lighting Research and Technology* 56, no. 4 (2024): 337–365, https://doi.org/10.1177/14771535231170500.

84. J. Zauner, S. L. Hartmeyer, and M. Spitschan, "LightLogR: Working With Wearable Light Logger Data." Published online 2023, https://doi.org/10.5281/zenodo.11562600.

Supporting Information

Additional supporting information can be found online in the Supporting Information section.