Circadian adaptation to night shift work is associated with higher REM sleep duration

Iona Z. Zimberg, PhD, Suzanne Ftouni, PhD, Michelle Magee, PhD, Sally A. Ferguson, PhD, Steven W. Lockley, PhD, Shantha M.W. Rajaratnam, PhD, Tracey L. Sletten, PhD

Objective: To investigate the influence of the degree of circadian adaptation to night work on sleep architecture following night shift.

Methods: Thirty-four night workers (11 females; 33.8 ± 10.1 years) completed a simulated night shift following 2-7 typical night shifts. Participants completed a laboratory-based simulated night shift (21:00-07:00 hours), followed by a recovery sleep opportunity (~09:00-17:00 hours), recorded using polysomnography. Urinary 6-sulphatoxymelatonin (aMT6s) rhythm acrophase was used as a marker of circadian phase. Sleep duration and architecture were compared between individuals with aMT6s acrophase before (unadapted group, n = 22) or after (partially adapted group, n = 12) bedtime.

Results: Bedtime occurred on average 2.16 hours before aMT6s acrophase in the partially adapted group and 3.91 hours after acrophase in the unadapted group. The partially adapted group had more sleep during the week before the simulated night than the unadapted group (6.47 ± 1.02 vs. 5.26 ± 1.48 hours, p < .02). After the simulated night shift, both groups had similar total sleep time (partially adapted: 6.63 ± 0.88 hours, unadapted: 6.63 ± 0.88 hours, p > .05). The partially adapted group had longer total rapid eye movement sleep duration than the unadapted group (106.79 ± 32.05 minutes vs. 77.90 ± 28.86 minutes, p < .01). After 5-hours, rapid eye movement sleep accumulation was higher in the partially adapted compared to the unadapted group (p < .02). Sleep latency and other stages were not affected by circadian adaptation.

Discussion: Partial circadian adaptation to night shift was associated with longer rapid eye movement sleep duration during daytime sleep, highlighting the influence of entrainment between the sleep-wake cycle and the circadian pacemaker in night workers. The findings have important implications for sleep and subsequent alertness associated with shift work.

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Introduction

In recent decades, industrialized societies have become increasingly dependent upon shift work. It is estimated that 15%-29% of the working population in Australia,1 United States,2 and Europe3 are involved in shift work. The most commonly reported consequences of shift work are sleep-wake disturbances, especially not getting enough sleep, difficulties falling asleep and daytime sleepiness,4,5 with at least 75% of shift workers reporting that their sleep is affected.6 Shift workers are more likely to suffer from insomnia as well as excessive daytime sleepiness when compared to their day-shift counterparts.7,8
The major cause of sleep disturbances in shift workers is misalignment of the timing of sleep and wake with respect to the endogenous circadian pacemaker. Shift workers’ circadian rhythms rarely fully adapt to their work and sleep schedule, resulting in wake time and sleep time occurring at adverse circadian phases. Such circadian misalignment has been shown to increase sleepiness, impairment alertness and performance and increase accident risk during night work or while driving home after a night shift. Individual ability to adapt to shift work varies considerably. Some shift workers may intuitively adopt countermeasures that promote some degree of circadian adaptation, while others do not adapt, possibly due to domestic factors, social obligations, inappropriate sleep hygiene or daylight exposure promoting wakefulness. As a result, few night workers completely adapt to the new schedule because the circadian pacemaker is slow to re-synchronize and usually requires many days of consecutive night shifts to re-entrain. Additionally, many shift workers often choose to return to night sleep and daytime activities on their days off from work.

There is a strong relationship between circadian phase and sleep duration and quality. If partial adaptation occurs, typically defined as sleep occurring at a time coinciding with the temperature minimum or 6-sulphatoxymelatonin (aMT6s) peak, then some benefits to sleep accrue. Sleep often remains misaligned and suboptimal in shift workers, however, as the relatively generous definition of “partial” adaptation does not represent a normal phase angle between sleep and circadian phase (where temperature minimum or aMT6s peak would occur 2-3 hours before the end of the sleep episode). In shift workers, delayed melatonin secretion has been associated with better subjective daytime sleep quality and longer objective sleep duration. Both partial and complete circadian entrainment to the night-shift day-sleep schedule during simulated night shift have been shown to be beneficial to neurobehavioural measures, but with only mild associations reported for sleep duration.

A better understanding of how the magnitude of circadian adjustment impacts on diurnal sleep duration and quality in night shift workers is needed. Thus, the aim of this study is to investigate the effect of circadian timing on the duration and architecture of daytime sleep in night shift workers following a series of night shifts worked in the field and a final simulated night shift in the laboratory.

### Participants and methods

#### Participants

Thirty-four night shift workers (23 male, 11 female), aged 33.8 ± 10.1 years (mean ± SD), completed the study at the Monash University Sleep and Circadian Medicine Laboratory (Table 1). Participants were regular night shift workers, with 4 or more night shifts per month, ≥6 hours worked between 22:00 and 08:00 hours and maximum shift length of 12 hours. Participants were required to complete 2-7 consecutive night shifts at their own workplace prior to a laboratory visit, confirmed with work diaries. Recruitment occurred via advertising in the local community including newspapers, posters and online media to reach participants across a range of occupational settings for increased ecological validity. Occupational sectors represented in our sample were Community and Personal Service Workers (n = 7), Machinery Operators and Drivers (n = 7), Healthcare Workers (n = 4), Business Professionals (n = 3), Managers (n = 3), Technicians and Trade Workers (n = 2), Laboratory Workers (n = 2), Communications Professionals (n = 2), Sales Workers (n = 1), Laborers (n = 1) and unknown occupation (n = 2).

Participants were excluded if they had a history or possession of major medical, neurological, visual, auditory, psychiatric disorder; high risk of obstructive sleep apnea according to the Berlin Questionnaire; traveled >2 time zones in the 3 months prior to the study; consumed extreme amounts of caffeine (>500 mg/d), nicotine (>5 cigarettes/d), or alcohol (>14 units/wk) or reported illicit drug use.

All participants provided written informed consent. The study was approved by the Monash University Human Research Ethics Committee. The data presented are part of a larger, multicenter study examining the effects of a novel light intervention on alertness and neurobehavioral performance in night shift workers. The study was registered with the Australian New Zealand Clinical Trials Registry (#ACTRN1261000097044) and data collected between 2010 and 2012.

#### Prelaboratory monitoring

During an initial screening visit participants completed the Epworth Sleepiness Scale (ESS), Pittsburgh Sleep Quality Index (PSQI) and the Morningness/Eveningness Questionnaire (MEQ). For 7 days before the laboratory visit, participants completed a sleep

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>All (n = 34)</th>
<th>Unadapted (n = 22)</th>
<th>Partially adapted (n = 12)</th>
<th>p*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Demographics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sex (N)</td>
<td>23 M, 11 F</td>
<td>12 M, 10 F</td>
<td>11 M, 1 F</td>
<td>.03</td>
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<td>Age (y)</td>
<td>18-51</td>
<td>18-51</td>
<td>18-51</td>
<td></td>
</tr>
<tr>
<td>Body Mass Index (kg/m²)</td>
<td>19-38, 25.82 ± 4.40</td>
<td>19-37, 24.68 ± 3.92</td>
<td>20-36-68, 51.27 ± 8.36</td>
<td>.03</td>
</tr>
<tr>
<td>Morningness-Eveningness Questionnaire</td>
<td>25-68, 50.21 ± 9.35</td>
<td>36-68, 51.27 ± 8.36</td>
<td>25-63, 48.25 ± 11.06</td>
<td>.38</td>
</tr>
<tr>
<td>Morning</td>
<td>7</td>
<td>4</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Intermediate</td>
<td>1</td>
<td>14</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Evening</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Epworth Sleepiness Scale</td>
<td>&lt;10, 2-16, 9.09 ± 3.32</td>
<td>&lt;10, 9.77 ± 3.41</td>
<td>3-13, 7.83 ± 2.86</td>
<td>.10</td>
</tr>
<tr>
<td>Pittsburgh Sleep Quality Index</td>
<td>&lt;5, 1-12, 6.47 ± 2.96</td>
<td>&lt;5, 6.23 ± 2.76</td>
<td>3-12, 6.92 ± 3.37</td>
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<td>Work history</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>No. night shifts/week</td>
<td>2-7, 3.97 ± 1.59</td>
<td>2-7, 3.64 ± 1.62</td>
<td>3-7, 4.58 ± 1.38</td>
<td>.07</td>
</tr>
<tr>
<td>No. consecutive night shifts</td>
<td>2-7, 3.62 ± 1.67</td>
<td>2-7, 3.32 ± 1.64</td>
<td>2-7, 4.17 ± 1.64</td>
<td>.11</td>
</tr>
<tr>
<td>Hours worked 7-d prior (h)</td>
<td>14-77, 30.20 ± 15.44</td>
<td>14-63, 28.37 ± 13.97</td>
<td>14-77, 33.57 ± 17.99</td>
<td>.52</td>
</tr>
<tr>
<td>Mean duration of shift 7-d prior (h)</td>
<td>4.5-14.5, 8.90 ± 2.07</td>
<td>6.7-14.5, 9.07 ± 2.04</td>
<td>4.5-12, 8.60 ± 2.16</td>
<td>.92</td>
</tr>
<tr>
<td>Mean night shift times (clock time, h)</td>
<td>20:50-06:05</td>
<td>20:47-06:03</td>
<td>20:56-6:10</td>
<td></td>
</tr>
</tbody>
</table>

*Characteristics between unadapted and partially adapted groups were compared using Student’s t-test. Sex was compared using chi-square test. Bold type, p ≤ .05.
Simulated night shift protocol

Participants attended the sleep laboratory at 17:30 hours. Between 17:30 and 21:00 hours participants were screened for illicit drug use via urine toxicology, provided the last urine sample for assessment of circadian phase (detailed description of circadian phase assessment in section Urinary aMT6s), and performed alertness and neurobehavioral performance tests every hour as part of a larger protocol reported elsewhere.\(^\text{16,28,29}\)

The simulated night shift was scheduled from 21:00 to 08:00 hours. The sleep laboratory was free of time cues including no access to windows, clocks, television, radio, internet, or telephone. During the simulated night shift participants were required to remain awake and seated in randomized controlled lighting conditions (standard white light 4000 K or blue-enriched polychromatic light 17,000 K, 84-89 lux at eye level, 137 cm from the floor, in the vertical plane) and were monitored continuously by trained staff.\(^\text{29}\) Since no significant differences were observed between the lighting condition groups (4000 K vs. 17,000 K) in the amount of sleep obtained prior to the study, or during the laboratory visit, or in circadian timing (aMT6s acrophase) of participants,\(^\text{29}\) data from the lighting condition groups were combined for the current analyses examining the impact of circadian timing on daytime sleep.

Recovery sleep protocol

At 08:15 hours, following the simulated night shift, participants were provided with a calorie-controlled meal (male: ∼500 calories; female: ∼300 calories), polysomnographic electrode placement was checked and participants were provided with an 8-hour sleep opportunity beginning at approximately 09:00 hours. Participants remained in bed for the entire 8-hour opportunity.

Sleep was polysomnographically recorded using a wireless polysomnography system (Siesta, Compumedics Ltd, Victoria, Australia). Electroencephalographic (EEG), electrooculographic (EOG), and electromyogram (EMG) recordings were monitored simultaneously and continuously during the sleep. EEG electrodes were positioned according to the International 10/20 System and recorded at 8 sites (C3-A2, C4-A1, O1-A2, O2-A1) with a Cz reference and subsequently digitally rereferenced to linked mastoids references (M1 and M2). EOG was recorded with electrodes (LOC-A2, ROC-A1) placed 2 cm above and below lateral canthi of the left and right eye, respectively. EEG and EOG data were sampled at 512 Hz and electrode impedances were <10 kΩ. Data were visually scored using the Profusion software (Compumedics, Victoria, Australia) and were digitally band-pass filtered (0.3-30 Hz; 24 dB/ octave). Recordings were visually scored according to American Academy of Sleep Medicine (AASM) recommendations.\(^\text{33}\) Measures derived included TIB, TST, SOL, SE, wake after sleep onset, and the duration of nonrapid eye movement (NREM) stage 1, stage 2, stage 3, and rapid eye movement (REM). Cumulative sum (in minutes) of each sleep stage (NREM and REM) over the 480-minute sleep was computed, per subject followed by mean calculation per group. The average length of each REM cycle (in minutes) was manually calculated for each participant. REM cycles were considered if of at least 2 minutes duration. If a cycle was interrupted by 5 minutes or less of wakefulness or NREM sleep, it was considered to be part of the same REM cycle.

Urinary aMT6s

For 48 hours prior to the beginning of the simulated night shift, approximately 4 hourly sequential urine samples (~8-hour during sleep episodes) were collected for determination of circadian phase via measurement of the urinary metabolite of melatonin, aMT6s, as previously described.\(^\text{30}\) Participants collected 9-12 urine samples across the 48-hour sampling period (10.3 ± 0.8 samples on average), as expected. Urinary aMT6s concentrations were determined by radioimmunoassay conducted at the Adelaide Research Assay Facility (University of Adelaide), with an intra-assay coefficient of variation (CV) of 7.2%, inter-assay CVs of 23% at 3.6 ng/mL, 7% at 15.6 ng/mL, and 11% at 29.6 ng/mL, and minimum detectable concentration of 0.5 ng/mL. Cosinor analysis was conducted to determine the timing of the acrophase (peak) of the aMT6s rhythm, as previously described.\(^\text{34}\) The phase angle between aMT6s acrophase and the timing of the recovery sleep episode was calculated by subtracting aMT6s acrophase time from the participants’ bedtime in the laboratory visit.

Data analysis

Participants were classified into groups based on the timing of their aMT6s acrophase relative to the daytime sleep episode. Participants for whom aMT6s acrophase occurred at any time during the daytime sleep episode were considered to be partially adapted. Participants with an aMT6s acrophase occurring prior to bedtime and not within the sleep episode were considered unadapted.\(^\text{17}\)

Independent samples t-tests (two-tailed), and chi-square tests were used to compare demographic, sleep survey, work history, and pre-laboratory parameters between the groups. Group differences in the timing, duration, and architecture of the recovery sleep were assessed using analysis of covariance (ANCOVA) controlling for sex, age, body mass index (BMI), TIB in the 24 hours prior to the laboratory, night shifts 7 days prior and hours worked 7 days prior. Sex, BMI, and TIB were included as covariates because they significantly differed between groups, age was included because it is related to changes in the timing of circadian regulation\(^\text{35}\) and the number of night shifts and work hours in the previous week were included as they can influence the night shift adaptation process.\(^\text{36}\) TIB in the 24 hours prior to the laboratory was extracted from diaries. Cumulative REM sleep and REM cycles during recovery sleep were analyzed using a mixed-model analysis of variance with aMT6s acrophase group as the independent factor. Greenhouse-Geisser epsilon corrections were used to correct for violations of Mauchly’s test of sphericity for the within-subjects effects. Where a significant interaction was found, simple main-effects analyses were conducted to determine the source of the interaction. When normality was violated, data were transformed. Statistical analyses were conducted using SPSS version 22.0 (SPSS Inc, Chicago, IL). Data are presented as Mean ± SD unless otherwise stated. Significance level was set to p ≤ 0.05.

Results

A total of 40 night shift workers were enrolled. After cosinor analysis of the aMT6s rhythm, 6 of 40 participants were classified as having poor quality aMT6s rhythm (α set at 0.10) and were excluded from analyses. The remaining 34 participants exhibited a significant cosinor fit \(p < .01\); 85% had a model fit of \(p < .05\). Fig. 1 illustrates the degree of variability in aMT6s acrophase between participants.
relative to recovery sleep bedtime (also summarized in Table 2). The aMT6s acrophase occurred 3.91 ± 2.70 hours before recovery sleep bedtime for the unadapted group (range = −8.74 to −0.06 hours), while aMT6s acrophase occurred 2.16 ± 1.55 hours after bedtime in the partially adapted group (range = 0.56-4.39 hours). Only one participant had aMT6s acrophase in the second half of the daytime sleep and no participant had aMT6s acrophase after the sleep.

Participant characteristics and sleep-wake behavior

Participant characteristics are reported in Table 1. Sex was significantly different between groups, with more men in the partially adapted group compared to the unadapted group. Only one woman had aMT6s acrophase after bedtime (1/11 females and 11/23 males, Pearson chi-square, p = 0.03). The partially adapted group had significantly higher BMI than the unadapted group (27.9 vs. 24.7 kg/m²; p = 0.04). There was no significant difference between groups in age, type of work and work schedule prior to the laboratory visit (ie, number of shifts prior to laboratory visit, mean hours worked and duration of shift) (data not shown), MEQ, ESS, or PSQI. There was, however, a trend for a higher number of night shifts per week in the partially adapted group compared to the unadapted group, though this did not reach significance (12 night shifts more per week prior to the laboratory visit, p = .07).

Habitual sleep characteristics during the week prior to the laboratory visit are shown in Table 2. The partially adapted group had significantly longer average actigraphic TIB and TST over the 7 days before the laboratory visit than the unadapted group (TIB: 1.54 hours difference, \(F_{1,30} = 5.53, p < .01\); TST: 1.21 hours difference, \(F_{1,30} = 4.08, p = .02\); respectively). The partially adapted group had significantly less variation in their diurnal sleep onset time during the week prior to the laboratory visit than the unadapted group (1.80-hour deviation was observed in 83% of the subjects of the partially adapted group while 5.86-hour deviation was observed in 77% of the unadapted group, Pearson chi-square, p < .01). Individuals in the unadapted group were more likely to nap or split their sleep; 77% of individuals in the unadapted group had at least one occasion of multiple sleep episodes in a 24-hour period during the week prior to the laboratory visit, compared to 25% in the partially adapted group.

Recovery sleep

During the recovery sleep opportunity, TST was not different between the groups (partially adapted: 6.68 ± 0.80 hours, unadapted: 6.63 ± 0.88 hours, p = .65, Table 3). All measures except REM sleep were similar between groups. A significant interaction between sleep and the circadian group was detected only for REM sleep duration. The partially adapted group had a significantly longer total REM duration (minutes and percentage of TST; by approximately 29 minutes or 7% more), than the unadapted group even after controlling for age, sex, BMI, mean TIB in the 24 hours prior, and night shifts and hours worked 7 days prior to the laboratory visit (REMS: \(F_{1,32} = 9.34, p < .001, \eta^2_p = 0.39\)). The partially adapted group also had a significantly higher accumulation of REM after 300 minutes of sleep opportunity than the unadapted group (\(F_{1,32} = 4.45, p = 0.02, \eta^2_p = 0.17,\) Fig. 2). The results persisted even when age, sex, BMI and TIB in the 24 hours prior to the laboratory visit were included as covariates.

Onset time of the first REM sleep episode (minutes from stage 1 to the first REM episode) was not significantly different between

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**Table 2**

Participant sleep-wake and circadian characteristics prior to the simulated night shift in the laboratory according to circadian group

<table>
<thead>
<tr>
<th></th>
<th>All (n = 34)</th>
<th>Unadapted (n = 22)</th>
<th>Partially adapted (n = 12)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Range</td>
<td>M ± SD</td>
<td>M ± SD</td>
<td>M ± SD</td>
</tr>
<tr>
<td><strong>Circadian phase assessment</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>aMT6s acrophase (clock time, h)</td>
<td>0.05-23.95</td>
<td>7.73 ± 4.58</td>
<td>4.86 ± 2.70</td>
<td>11.01 ± 1.55</td>
</tr>
<tr>
<td>Phase angle difference (clock time, h)</td>
<td>− 8.74 to 4.39</td>
<td>− 1.77 ± 3.76</td>
<td>− 3.91 ± 2.70</td>
<td>2.16 ± 1.55</td>
</tr>
<tr>
<td><strong>24 h prior to simulated night shift</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleep onset time (clock time, h)</td>
<td>3:59-17:45</td>
<td>9:34 ± 3:33</td>
<td>10:19 ± 3:44</td>
<td>8:20 ± 2:57</td>
</tr>
<tr>
<td>Sleep onset latency (min)</td>
<td>3:00-54:67</td>
<td>15:64 ± 11:72</td>
<td>13:21 ± 9:31</td>
<td>19:69 ± 14:44</td>
</tr>
<tr>
<td>Sleep offset time (clock time, h)</td>
<td>7:29-14:59</td>
<td>12:23 ± 1:43</td>
<td>12:06 ± 1:51</td>
<td>12:50 ± 1:27</td>
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<tr>
<td>Sleep offset latency (min)</td>
<td>6:50-16:16</td>
<td>13:27 ± 2:02</td>
<td>13:09 ± 2:15</td>
<td>13:57 ± 3:33</td>
</tr>
<tr>
<td>TIB (h)</td>
<td>3.67-9.56</td>
<td>6.38 ± 1.56</td>
<td>5.81 ± 1.58</td>
<td>7.35 ± 0.98</td>
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<tr>
<td>TST (h)</td>
<td>3.39-8.97</td>
<td>5.71 ± 1.44</td>
<td>5.26 ± 1.48</td>
<td>6.47 ± 1.02</td>
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<td>Sleep efficiency (%)</td>
<td>55.99-90.66</td>
<td>76.97 ± 7.58</td>
<td>76.63 ± 7.04</td>
<td>77.53 ± 7.04</td>
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<tr>
<td>Wakefulness prior to recovery sleep (h)</td>
<td>6.83-23.15</td>
<td>18.47 ± 2.66</td>
<td>18.42 ± 3.12</td>
<td>18.55 ± 1.69</td>
</tr>
</tbody>
</table>

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aMT6s, 6-sulphatoxymelatonin; TIB, time in bed; TST, total sleep time; Phase angle difference = aMT6s acrophase time - bedtime.

Bedtimes and rise times reported in sleep diaries were used to determine the duration of time in bed and the timing of sleep and nap episodes for actigraphic analysis. The remaining sleep variables were calculated based on actigraphy. No participants napped (<1 hour) in the 24 hours prior to the simulated night shift. Bold type indicates statistical significance (p ≤ .05).
groups (partially adapted: 71.58 ± 59.92 minutes and unadapted: 71.07 ± 42.14 minutes, p = .57). A between-group effect, however, was observed in the duration of REM sleep in successive cycles (F(1,19) = 9.57, p = .006, n² = 0.34, Fig. 3), as the partially adapted group had significantly higher REM duration in the second and third REM cycles when compared to the unadapted group (cycle 2: 17.00 vs. 22.83 minutes, p = .05; cycle 3: 16.23 vs. 24.75 minutes, p = .03). Both groups had 3-6 REM cycles (median: 5) during the sleep episode. The partially adapted group had a slight increase in the duration of REM cycles through the first 3 cycles with the last cycle being of the longest duration (cycle 1: 40.8 minutes, cycle 2: 45.7 minutes, cycle 3: 49.5 minutes, cycle 4: 42.4 minutes, and cycle 5: 50.9 minutes, no significant difference). The unadapted group had similar REM cycle durations throughout the recovery sleep, except for cycle 4 which was the longest (cycle 1: 30.2 minutes, cycle 2: 34.0 minutes, cycle 3: 32.4 minutes, cycle 4: 44.2 minutes and cycle 5: 29.7 minutes, no significant difference).

**Discussion**

This study has demonstrated that REM sleep duration during a daytime recovery sleep episode was significantly longer in night shift workers whose circadian phase was partially adapted to the night shift, compared to shift workers who were less adapted. The higher duration of REM in the partially adapted group was predominantly observed in the second half of the sleep episode (after 300 minutes of sleep).

Considerable variability in circadian timing observed in this sample, as assessed by the timing of the peak in the aMT6s rhythm, is likely to be due to individual variability in light-dark exposure between the night workers, although not directly examined in this study. Compared to the unadapted group, the partially adapted group tended to work more nights shifts per week, worked more consecutive night shifts prior to the laboratory visit (though not significant), maintained a more regular bedtime with less napping and/or split sleep behavior, and had 1.2 hours longer TST during the week prior the laboratory visit. These differences could have contributed to the observed differences in circadian phase but could also be a consequence of the circadian adaptation, that is, circadian adaptation could have facilitated better sleep. Previous findings have also reported that a longer TST was positively associated with the degree of circadian adaptation in a simulated night work experiment. Sleep indirectly influences entrainment of the circadian system through the influence of light exposure.

In the current study, 12 out of 34 (35%) of the night workers showed partial circadian adaptation to night shift work, defined as aMT6s acrophase during the sleep opportunity (between bedtime and rise time). A previous study with young nonshift working individuals exposed to five consecutive simulated night shifts defined partial adaptation (re-entrainment) by the temperature minimum occurring in the first half of the sleep episode, and complete when it occurred in the second half of the sleep episode. Applying similar definitions to the current study, one participant might have been considered fully adapted to the daytime sleep as their aMT6s acrophase (a highly correlated marker to the temperature minimum) occurred in the second half of sleep, while the remaining 11 were only partially adapted. The proportion of individuals showing partial or complete adaptation in the present study (35%) is slightly higher than that observed in a group of permanent night shift workers (25%) in a previous study. Our finding is also in line with that of other previous studies where circadian entrainment to night shift work was achieved from exposure to environmental synchronizers, such as favorable light-dark exposure and the maintenance of a fixed daytime sleep-wake schedule for 3-7 consecutive days.

Only one woman (out of a total of 11; 9%) was partially adapted to night work and day sleep, compared to 11 of 23 men (48%). Sex differences in terms of the relative timing of circadian rhythms with respect to usual sleep-wake times have been described in the literature and may explain a large proportion of the variation in circadian timing in response to shift work in this cohort. Women under a constant routine protocol were found to have a phase advanced melatonin timing relative to habitual sleep-wake time when compared to men. Assessment of the circadian response to consecutive night shifts in healthcare workers identified that while all men experienced a circadian delay, 30% of women experienced a phase advance. These differences may be related to the sensitivity to the phase shifting effects of light, either reduced sensitivity to phase delaying light or greater sensitivity to phase-advancing light, or both. Variation in circadian adaptation between sexes may also be related to differences in domestic factors and social obligations influencing sleep-wake behavior. We note that circadian adaptation was not associated with a difference in mornin...
social or domestic disturbances (i.e., in a controlled laboratory environment), the night workers still present a shorter daytime sleep relative to their nighttime sleep duration recorded using actigraphy. This may be because, despite partial adaptation of the circadian pacemaker to the night shift schedule, there is still not optimal alignment of circadian timing and the sleep-wake cycle in all individuals. For example, some individuals are still sleeping at a relatively late circadian phase, and consequently experience decreased circadian drive for sleep later in the sleep episode. As sleep progresses, the pressure for wakefulness exceeds the pressure for sleep, and individuals tend to wake, thus curtailing the sleep episode. This may also explain why the unadapted group experienced longer sleep duration in the laboratory than during the week prior, due to the earlier bedtime and sleep onset time for the recovery sleep (average 1.48 hours earlier than the usual sleep onset time), and consequently sleeping at an earlier circadian phase with increased circadian drive for sleep relative to the week prior. Shorter TIB and TST of the unadapted group at home in the week prior to the simulated night shift may also be related to greater napping and/or split sleep behavior. They may also be related to other real-world influences including environmental disruptions to sleep (i.e., light,
noise), or the demands of social and family commitments. It was noted in a study where participants were required to sleep in the laboratory for consecutive simulated night shifts that in optimal conditions sleep debt is minimized and circadian adaptation maximized. Along with total sleep duration, slow wave sleep (SWS), a primary indicator of homeostatic sleep pressure, was not significantly different between groups although there was much more variability in SWS in the unadapted group compared to the partially adapted group. As the unadapted group had a shorter TST before entering the laboratory, a difference in total duration and SWS may have been expected due to chronic sleep restriction, as SWS is influenced by prior sleep and waking duration. Indeed SOL was relatively short in both groups (4.91 ± 1.64 and 6.70 ± 3.55 minutes for unadapted and adapted groups, respectively), which is close to the threshold used to define excessive sleepiness (SOL of < 5 minutes) using multiple sleep latency test criteria \(^{38}\) and in diagnosing shift work disorder.\(^{26,49}\) Our results indicate confirmation of the influence of circadian phase on REM sleep, while sleep duration and SWS remain under the influence of homeostatic sleep pressure due to sleep restriction. The early evening time of laboratory admission may have reduced the opportunity for individuals to nap on the day of attendance, thereby increasing the duration of wakefulness prior to the recovery sleep and increasing sleep pressure.

Night shift workers in the partially adapted group exhibited higher REM in recovery sleep when compared to workers in the unadapted group, especially in the second and third cycles of REM. It is well described in the literature that REM sleep density is under strong circadian control,\(^{10}\) and can be used as a marker of circadian phase shift.\(^{50}\) Studies also demonstrate, however, that REM sleep is homeostatically regulated due to sleep deprivation.\(^4\) As the relationship between REM sleep and circadian phase was maintained even after controlling for the prior sleep duration, we suggest that the reduction of REM sleep in the unadapted night shift workers was mainly influenced by circadian misalignment. The degree of circadian misalignment during night shift work has been associated with the degree of sleepiness, performance impairment and mood disturbance.\(^{4,15}\) The current findings indicate that a reduction in REM sleep associated with circadian misalignment may play a role in the adverse impacts of shift work.

Only a few studies have explored the association between circadian adaptation and sleep architecture in shift workers. One study in 17 police officers on rotating shifts examined their degree of adaptation to night shift (based on aMT6s acrophase relative to sleep) and did not find any significant differences in daytime sleep stages, only a reduction in TST.\(^{17}\) Other polysomnographic studies have showed a reduction in REM duration during the daytime sleep of night workers but without any association to the degree of entrainment.\(^{51-54}\)

While this study used a relatively small sample (n = 34), it was conducted in a sample of real-world night shift workers and therefore extends the body of knowledge examining the relationship between circadian timing (aMT6s acrophase) and sleep patterns. A limitation is that only one measurement of the melatonin rhythm was taken and, thus, the day-to-day variability, as well as phase shift across the week, were not measured. Future assessment will be strengthened by assessing circadian timing directly across the simulated night shift and the recovery sleep opportunity itself to determine the influence of any potential changes in circadian phase. It should also be noted that participants were required to remain in bed for 8 hours during the recovery sleep opportunity, regardless of the amount of sleep achieved, and that participants’ sleep quality and tolerance of this requirement were not tested. Future studies should explore subjective sleep quality and participant satisfaction with a required sleep schedule, as these factors may help with understanding the sleep schedule preferences of shift workers.

In conclusion, shift workers who are partially adapted to night shift work, defined as having the peak of the urinary melatonin rhythm after bedtime, display an increased REM duration in daytime recovery sleep after night shift. Circadian misalignment between the sleep-wake cycle and the endogenous circadian pacemaker, which is highly prevalent in shift workers, is known to be associated with marked adverse impacts on alertness and cognition as well as on metabolic and hormonal disturbances.\(^{11,55}\) From the current study it is apparent that the degree of circadian misalignment in shift workers significantly impacts the architecture (ie, REM sleep) of daytime sleep.

Public health relevance

Given that sleep disturbances are among the most common problems experienced by shift workers, and the evidence of the negative effects of reduced REM sleep, the current findings indicate that interventions aligning the phase relationship between the sleep opportunity and the circadian pacemaker may improve the restorative value of sleep in shift workers. Such interventions would subsequently contribute to reducing the risks of alertness impairment, productivity losses, and errors and accidents in the workplace that are common amongst shift workers. Interventions to improve circadian adaptation to night shift may also improve longer-term health given the inverse relationship between REM sleep and cognitive decline and dementia,\(^{56,57}\) alterations in the cellular and inflammatory mediators,\(^{54}\) and risk of all-cause, cardiovascular and other noncancer-related mortality.\(^{58}\) Caution needs to be taken, however, in the application of circadian adaptation practices to ensure delays in circadian timing do not place the biological night during the commute home from night shifts and compromise safe driving.

Professor Czeisler’s contribution

The two-process model of sleep regulation, developed by Alexander Borbély, characterized the interaction between the homeostatic and circadian processes to generate the timing of sleep and wake.\(^{12,13}\) Professor Charles Czeisler, along with Professor Derk-Jan Dijk, conducted core research providing empirical support for the model and the impact on sleep propensity and the structure of sleep. This model and the evidence established by Professor Czeisler provided the necessary basis for the current study and the examination of the impact of circadian adaptation to night shift on daytime sleep duration and architecture in night shift workers. The study particularly provides further support for Professor Czeisler’s work demonstrating the links between the circadian pacemaker and REM sleep.\(^2\)

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