SLEEPJ, 2019, 1–13

doi: 10.1093/sleep/zsz074
Advance Access Publication Date: 18 March 2019
Original Article

ORIGINAL ARTICLE

Sleepiness and driving events in shift workers: the impact of circadian and homeostatic factors

Megan D. Mulhall[1,2], Tracey L. Sletten[1,2,*], Michelle Magee[1,2], Julia E. Stone[1,2], Saranea Ganesan[1,2], Allison Collins[1,3], Clare Anderson[1,2], Steven W. Lockley[1,2,4,5], Mark E. Howard[1,2,3] and Shantha M. W. Rajaratnam[1,2,4,5,**]

[1]Cooperative Research Centre for Alertness, Safety and Productivity, Melbourne, Victoria Australia, [2]School of Psychological Sciences and Monash Institute of Cognitive and Clinical Neurosciences, Monash University, Melbourne, Victoria, Australia, [3]Institute for Breathing and Sleep, Austin Health, Melbourne, Victoria, Australia, [4]Division of Sleep and Circadian Disorders, Departments of Medicine and Neurology, Brigham and Women's Hospital, Boston, MA and [5]Division of Sleep Medicine, Harvard Medical School, Boston, MA

Work performed: Intensive Care Unit, Austin Health, Melbourne, Victoria, Australia.

*Corresponding authors. Tracey L. Sletten, School of Psychological Sciences and Monash Institute of Cognitive and Clinical Neurosciences, Sleep and Circadian Medicine Laboratory, 264 Ferntree Gully Road, Notting Hill, Victoria 3168, Australia. Email: tracey.sletten@monash.edu.

**Shantha M. W. Rajaratnam, School of Psychological Sciences and Monash Institute of Cognitive and Clinical Neurosciences, Monash University, Building 17, Wellington Road, Clayton, VIC 3800, Australia. Email: shantha.rajaratnam@monash.edu.

Abstract

We aimed to characterize objective and subjective sleepiness and driving events during short work commutes and examine the impact of circadian and homeostatic factors across different shift types in a shift worker population. Thirty-three nurses were monitored for 2 weeks over day (07:00–15:30), evening (13:00–21:30), and night shifts (21:00–07:30). Sleep was measured via daily sleep logs and wrist actigraphy. Driving logs were completed for each work commute, reporting driving events and a predrive Karolinska Sleepiness Scale (KSS). Ocular data from a subset of participants (n = 11) assessed objective sleepiness using infrared oculography during commutes. Circadian phase was assessed at three time points via urinary 6-sulphatoxymelatonin (aMT6s) collected over 24–48 hours. Subjective and objective sleepiness and sleep-related and hazardous driving events significantly increased following night shift compared with preshift. There were significant shift differences with KSS, sleep-related and inattention-related events highest during the postnight shift commute, compared with day and evening shifts. Sleep-related events were highest following the first night shift, while inattention-related events were most frequent after consecutive night shifts. KSS, sleep-related and hazardous events were increased during drives following ≥16 hours of wakefulness. KSS and sleep-related events increased during drives within ±3 hours of aMT6s acrophase. An interaction between homeostatic and circadian processes was observed, with KSS and sleep-related events highest within ±3 hours of acrophase, when wakefulness was ≥16 hours. In naturalistic conditions, subjective and objective sleepiness and driving events are increased following night shifts, even during short (~30 minutes) commutes and exacerbated by an interaction between circadian phase and duration of wakefulness.

Statement of Significance

This study investigated the impact of measured circadian phase on driving in shift workers in a field setting, rather than using time of day as a proxy. The study examined the impact of various shifts on driving performance, and subjective and objective alertness during short commutes more representative of those seen in the general population compared to longer duration drives assessed in previous research. This work provides insight into changes in driving performance on the first night shift, as well as consecutive night shifts, which may help educate shift workers and employers about the risks associated with night shift work, to keep employees safe not only at work but during the commute home.

Key words: shift work; driving; sleep; wakefulness; homeostatic; circadian; alertness

Submitted: 23 October, 2018; **Revised:** 3 February, 2019

Introduction

Approximately 20%–30% of all motor vehicle crashes (MVCs) are sleep-related, making sleepiness one of the leading causes of preventable deaths on the road [1, 2]. The risks of MVCs are particularly prominent on commuter drives (the drives to and from work). The vast majority of research into drowsy driving has focused on drives of a longer duration (e.g. 2 or more hours) [3–5], however typical commute times are often shorter; in most Australian cities, commute times average around 30 minutes [6]. Public safety campaigns for raising awareness of drowsy driving in Australia have largely been targeted towards longer duration drives, encouraging drivers to take rest breaks after extended periods of driving (e.g. the Driver Reviver campaign) [7]. Less has been done to raise public awareness of the risk of sleepiness during shorter duration drives, including their daily work commute.

Shift workers make up approximately 16% of the work force and engage in a variety of shift types including day, evening, and night shifts [8]. Shift work is associated with increased risks of workplace accident and injury, including during the work commute [3, 9, 10]. Driving performance fluctuates with time of day, with performance becoming increasingly impaired during the early hours of the morning, around the time night shift workers are commuting home [11, 12]. Most studies to date only infer the role of the circadian system on driver performance from the time of day and have not objectively measured circadian phase directly [3, 13, 14]. There are large interindividual differences in circadian phase, of often 5 hours or more, even when measured under identical controlled conditions [15, 16], rendering measures taken at the same clock time potentially many hours different in circadian time between individuals. These interindividual differences are even larger in a shift work population [17], making time of day insufficient to examine the impact of circadian phase on driving performance. Furthermore, shifts other than night shift may also be impacted by sleepiness due to driving at inopportune circadian times, such as an early morning commute to day shifts [18].

In addition to circadian phase, waking function and therefore driving performance is influenced by homeostatic processes, including the duration of time spent awake [19]. Driving after extended periods of wakefulness increases the occurrence of driving performance impairment, with driving impairment revealed from as early as 13 hours of wakefulness [3, 5, 20, 21]. In addition to the impact of acute sleep loss due to continuous time awake, shift worker's sleep is often shorter and more fragmented than regular workers, resulting in additional chronic sleep deficiency and increased homeostatic sleep pressure [22, 23]. Most studies to date that examined both sleepiness and driving performance in shift workers during the work commute have focused on single postnight shift commutes [3, 24, 25]. Few studies have examined the impact of sequential night shifts on sleepiness and driving performance, which has the potential to be exacerbated by chronic sleep deficiency [26, 27]. The contribution of both time of day variation and extended wakefulness to sleep-related driving impairment has been studied extensively in driving simulator and track studies [11, 13, 28]. Few studies have however, systematically examined the circadian and homeostatic influences on driving in shift workers in naturalistic environments [3, 5, 13, 24]. The commute home after a night shift often combines these factors with a long wake episode coinciding with an adverse circadian phase, on a background of chronic sleep loss, making it a particularly vulnerable time for accidents [5, 25, 29].

The present study aimed to characterize subjective and objective sleepiness and self-reported driving events on nurses working day, evening, and night shifts, in a naturalistic setting. Furthermore, we aimed to examine the impact of circadian timing, measured as the peak in urinary concentration of the melatonin metabolite 6-sulphatoxymelatonin (aMT6s), and the homeostatic process, quantified as duration of continuous wakefulness, on self-reported driving events and subjective sleepiness, in nurses working shift work.

Methods

Participants

Thirty-three Intensive Care Unit (ICU) nurses from Austin Health, a metropolitan hospital in Melbourne, Australia, were studied. Most participants were female ($n = 26$), with a mean age of 34.06 ± 11.47 years and were on average moderate evening types, with no morning types in the sample, as measured by the Morningness-Eveningness Composite Questionnaire (MEQ 38.97 ± 6.47, Table 1). They were all experienced drivers, with a minimum of 4 years of driving experience (range 4–40 years).

Participants were recruited through scheduled in-service presentations, poster and e-mail advertisements and targeted recruitment during work shifts. Nurses were deemed eligible to participate if they worked regular rotating shifts in the ICU and drove a minimum of 5 minutes in a motor vehicle commuting to work. Participation dates were determined from participant rosters and were approximately 2 weeks in duration, with participants prioritized for data collection if they were working day/evening shifts followed by at least two consecutive night shifts. This shift schedule of rotation between day or evening shifts to night shifts was common for ICU nurses at this hospital, with 74% of nurses rotating between day, evening and night shifts. Participants worked various combinations of day (07:00–15:30 hours), evening (13:00–21:30 hours), and night shifts (21:00–07:30 hours, see Figure 1). All participants provided written informed consent and were paid AU$100 upon completion of the study. The protocol was approved by the Austin Health and Monash University Human Research Ethics Committees (HREC).

Procedures

Participants completed a series of online questionnaires, assessing demographic information, medication use,

Table 1. Partictipant demographic characteristics ($N = 33$)

	n	Mean (*SD*)	Range
Sex (male, female)	7, 26		
Age (years)		34.06 (11.37)	22–64
Body mass index (kg/m^2)		24.56 (4.40)	15.9–36.8
Morning-Eveningness Questionnaire		38.97 (6.47)	23–49
Shift work experience (years)			
Day shift		9.76 (6.78)	0–27
Evening shift		8.85 (6.54)	0–27
Night shift		9.79 (7.47)	1–27
Driving experience (years)		14.36 (9.11)	4–40

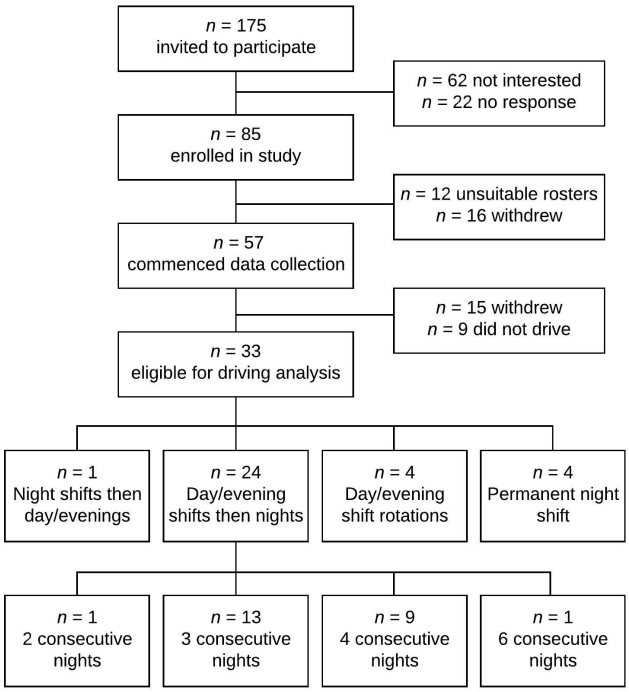

Figure 1. Flowchart of participant recruitment and participation.

employment history, and driving experience. Diurnal preference was assessed using the 13-item MEQ [30].

Participants were instructed to maintain usual sleep, work, and driving behavior during their participation. Sleep–wake behavior was monitored throughout using wrist actigraphs (Actiwatch Spectrum or Actiwatch Spectrum Plus, Respironics Inc, Bend, OR). Actigraphs were worn on the nondominant wrist to continuously record activity in 1-minute epochs (medium sensitivity; 40 activity counts per epoch). Sleep logs were completed daily to report bed and wake times, sleep quality and night time awakenings. Self-reported bed and wake time were used to determine the actigraphic analysis interval for each sleep episode (Actiware 6 software, Respironics Inc). If there was a substantial reduction in activity and light ≥ 30 minutes before or after self-reported bedtime, or a substantial increase ≥ 30 minutes before or after self-reported wake time, sleep and wake times were adjusted to the start of the period of decreased or increased activity, respectively [31]. Participants completed daily work logs in which they reported scheduled and actual work times. The accuracy of self-report work logs was checked against unit rosters and payroll records.

In a self-report driving log participants recorded start and end times of each drive, drive destination (work, home, other), a pre- and postdrive Karolinska Sleepiness Scale (KSS), traffic conditions, drive complexity, and road and weather conditions [24, 25, 32]. Traffic conditions were rated on a scale of 1 (very quiet, no traffic) to 4 (very busy, peak traffic). Events that occurred during each drive were identified from the following list: fighting to stay awake, resting eyes, braked sharply, fixation on interior/exterior object, drove through a stop light, fell asleep at a stop light, being distracted, lack of awareness, hit roadside rumble strips, drifting in lane, pulled over for a nap, and swerved violently [24, 25].

Ocular measures were obtained via infrared reflectance oculography using the Optalert system (Optalert 6.0.4 and Eagle portable device, Richmond, VIC, Australia) [24, 33]. Only participants who had commutes longer than 10 minutes and did not wear prescription glasses for driving were provided with the oculography system (n = 21). Participants were asked to wear the oculography glasses for all commutes to and from work, allowing 4 minutes for the device to calibrate prior to commencing each drive. Commercial drowsiness warnings were disabled for the duration of the study. The oculography system provides various measures of eyelid movements during blinks, averaged over 1-minute intervals. The following variables were analyzed: negative inter-event duration (IED), the time (seconds) between the maximum closing velocity of the eyelid and its maximum reopening velocity [34]; percentage of long eye closures, the percentage of long eyelid closures per minute [34]; Percentage of Time with Eyes Closed (PERCLOS), the percentage of time in a minute that the eyes are closed [34]; mean blink total duration, the mean duration (seconds) of the closing, closed and reopening phases of a blink [35]; negative amplitude-velocity ratio, the ratio of the maximum amplitude to maximum velocity of eyelid movement in the reopening phase of the blink [34]; and Johns Drowsiness Scale (JDS), a measure of drowsiness calculated by combining ocular variables using a proprietary algorithm. JDS is calculated on a scale of 0 to 10, where scores of 4.5–4.9 indicate a cautionary level of drowsiness, and scores of greater than 5 indicate critical levels of drowsiness [36].

Circadian phase was assessed at multiple time points throughout the study: during the last rostered day shift in a series of day and/or evening shifts or days off, and on the first and last night shift in a series of consecutive night shifts. Circadian phase was measured from urinary 6-sulphatoxymelatonin (aMT6s) rhythms [14]. For each assessment multiple urine samples were collected over 24–48 hours, approximately every 4 hours during wake and 8 hours during sleep [17]. Participants recorded the sample collection time and total void volume for each sample, before taking a 5 mL aliquot. Samples were stored at –20°C and were later analyzed for aMT6s concentration at the Adelaide Research Assay Facility (University of Adelaide, Australia) using radioimmunoassay, with reagents purchased from Stockgrand Ltd (University of Surrey, Guildford, UK) [37]. Details of the assay limits and intra-assay coefficients of variation have been reported previously [17]. Cosinor analysis was then performed to determine aMT6s acrophase for each assessment [38].

Data Analysis

Sleep variables (time in bed, total sleep time, sleep onset latency, wake after sleep onset, and sleep efficiency) were calculated for both actigraphic determined sleep and self-reported sleep for every main sleep episode (≥2 hours) prior to each shift (day, evening, first night, consecutive nights [night shifts 2–6] and days off). Where there was more than one main sleep episode before a shift (n = 2, split sleeps of ≥2 hours each), the sum was taken for analysis.

Self-reported driving events were categorized into four event types (sleep-related, inattention, hazardous, and violation) as described previously [24, 39]. Due to few occurrences, the violation events (n = 4, 0.9% of drives) category was excluded from further analysis. Driving events were converted into a rate of events/hour to control for drive duration.

To examine shift differences in sleep and self-reported driving events, data were categorized by shift type (day shift, evening

shift, first night shift, and consecutive nights [nights 2–6]). Preliminary analyses found no significant differences between sleep and self-reported driving events between a second, third or fourth consecutive night shift; therefore, all consecutive night shifts were grouped for analysis. As participants worked varying shift schedules, they contributed a different amount of data to each shift type. Linear mixed models were conducted with participant included as a random factor. Shift type was used as a fixed effect to examine differences in sleep variables between shift types (day, evening, first night shift, consecutive night shifts, and days off). All linear mixed models presented were analyzed using IBM SPSS Statistics 24.0 (IBM Corp., Armonk, NY); using an auto-regressive covariance structure (AR1) for repeated measures [40], and are corrected for multiple comparisons using the Benjamini-Hochberg procedure [41]. All linear mixed model data are presented as estimated marginal means ± standard error [40].

Predrive KSS, sleep-related, inattention, and hazardous driving event rates were all analyzed using linear mixed models for differences between shift types (day, evening, first night, and consecutive night shifts) and differences between pre- and postshift drives. Traffic rating was entered into all driving event models as a random covariate and included in the final model if it significantly improved the model, measured by a significant change in the Corrected Akaike Information Criterion (AICC, $p < .05$, Supplementary Table S1) [40]. Pearson correlations were conducted between predrive KSS and sleep-related, hazardous and inattention event rates to determine if predrive subjective sleepiness was associated with driving event rates.

Ocular data were visually inspected for signal quality, with minute epochs excluded if >50% of the signal was poor quality (see Supplementary Material). Ocular data were analyzed for differences between shift types (day, evening, and night shifts) and pre- and postshift drives. Shift differences on pre- and postshift drives were examined using Kruskal–Wallis nonparametric tests, with significant differences followed up using Mann–Whitney nonparametric tests.

The contribution of prior wakefulness and circadian timing on subjective sleepiness (KSS) and self-reported driving events (sleep-related events, hazardous driving events, and inattention events) were examined. Cumulative wakefulness prior to each drive was calculated by determining the duration of wakefulness between the last main sleep period (total sleep time ≥ 2 hours) and the start of a drive, minus time spent napping. Linear mixed model analysis was conducted to determine shift and drive direction differences. Drives were then dichotomized into those with <16 hours of cumulative wakefulness and those with ≥16 hours of cumulative wakefulness, and linear mixed model analysis was conducted to analyze differences in self-reported driving events, with cumulative wakefulness as a fixed effect. A cut-off of 16 hours of prior wakefulness was chosen, as it is the typical length of the waking day in healthy adults and has a near-linear relationship with performance impairment [27, 35].

Circadian phase was calculated from aMT6s acrophase (peak) time, as previously reported [17]. Drive start time relative to aMT6s acrophase was calculated for drives within ±24 hours of a urine collection (n = 262 drives) by subtracting acrophase time from drive start time. Positive values indicate the drive start time occurred after aMT6s acrophase and negative values indicate that drive time occurred prior to aMT6s acrophase. Drives were dichotomized into two categories, based on whether they occurred within or outside of ±3 hours of aMT6s acrophase, to isolate the interval that corresponds with the peak in the circadian rhythm of sleep propensity [31]. The ±3 hour range was adapted from Ftouni et al. [31], and defined from Lockley et al. [42], who reported mean ± 2-SD range of aMT6s acrophase in normally entrained sighted individuals as 4.2 ± 2.9 hours [42]. Linear mixed model analysis was used to determine differences in self-reported driving events within ±3 hours of aMT6s acrophase range (adverse circadian phase) and outside ±3 hours of aMT6s acrophase range (outside adverse circadian phase), which was modeled as a fixed effect. Optalert data were not examined relative to acrophase due to the limited sample size of simultaneous Optalert and aMT6s data.

The interaction of circadian phase and wakefulness on self-reported driving events was examined by linear mixed model analysis with phase (adverse and outside adverse circadian phase) and prior wakefulness (< and ≥ 16 hours of wakefulness) as fixed effects.

Results

Data Retention

A total of 504 driving logs were completed during the study; 8.5% (n = 43) were excluded from analysis (n = 33 were not pre- or postshift drives, n = 4 missing drive start/end times, n = 3 duplicate driving entries, n = 2 riding motorbike, n = 1 stopped at gym). A total of 461 drives were included for analysis, with participants each contributing an average of 13.84 ± 3.11 drives (range = 7–19). The number of pre- and postshift drives for each shift type is reported in Table 2. On day shifts, 90.9% (n = 30) of the participants reported at least one drive, 87.9% (n = 29) on evening shifts, 84.4% (n = 28) on first night shifts, and 87.9% (n = 29) on consecutive night shifts.

Work logs (458 entries), unit rosters, and payroll were compared for shift start and end times and demonstrated 90.4% agreement on shift type (414 entries). Work logs were used for 93.67% (429 entries) of shifts, payroll records for 5.68% (26 entries), scheduled rosters for 0.44% (2 entries), and 0.22% (1 entry) of shifts could not be determined.

Of the 33 participants who completed data collection, 15.2% (n = 5) had inadequate aMT6s data for all three time points (insufficient number of urine samples for analysis, or poor quality aMT6s rhythm as determined by cosinor analysis). Half (n = 14) of the remaining participants had aMT6s data for all three time points, 25% (n = 7) were missing assessments from day shifts, 17% (n = 5) first night shift, and 32% (n = 9) from final night shifts.

Participants who wore prescription glasses for driving or had a drive time of less than 10 minutes were not fitted with Optalert glasses (n = 12). Of the 21 participants fitted with Optalert, 47.6% (n = 10) were excluded due to poor fitment, resulting in poor signal quality for >50% of all drive sessions. The remaining 11 participants had n = 136 drives, 47% (n = 64) of which were excluded due to poor signal quality throughout the drive. The percentage of ocular data excluded is comparable to that found in previous field studies [24, 35].

Shift Differences in Sleep

Total sleep time between consecutive night shifts (night shifts 2–6, 5.60 ± 0.18 hours) and before day shifts (5.57 ± 0.18 hours)

was significantly shorter than sleep before days off (7.42 ± 0.14 hours), evening shifts (8.09 ± 0.19 hours), and first night shifts (7.38 ± 0.23 hours; $p < .001$ for all comparisons, Table 3). This was consistent with observed differences in total time in bed between consecutive night shifts (6.63 ± 0.20 hours) and day shifts (6.48 ± 0.20 hours); and evening shifts (9.46 ± 0.22 hours), first night shifts (8.87 ± 0.26 hours), and days off (8.82 ± 0.16 hours, $p < .001$ for all comparisons). No differences were found in total sleep time or time in bed between evening shifts, first night shifts, or days off.

Drive Sleepiness and Performance

Compared with preshift drives, postshift drives on night shifts were associated with significantly higher mean negative IED ($p = .02$), max PERCLOS ($p = .02$), mean and maximum % of long closures ($p = .04$ and $p = .01$, respectively), and mean and maximum JDS ($p = .04$ and $p = .006$, respectively, Table 4). Postshift drives on day shifts were associated with significantly higher mean and max PERCLOS ($p = .04$ and $p = .03$, respectively) and mean and maximum % of long eye closures ($p = .02$ and $p = .01$, respectively) compared with preshift drives. KSS was significantly different between drives pre- and postshift. KSS was highest on postshift drives on evening, first night, and consecutive night shifts compared with the preshift drive. In contrast, preshift KSS was significantly higher prior to day shift compared with postshift drives ($p < .001$ for all comparisons, Figure 2).

There was a significant main effect of drive direction for driving events, with sleep-related events significantly higher postshift on first ($p < .001$) and consecutive night shifts ($p < .001$), and hazardous event rates higher postconsecutive night shifts ($p = .04$, Figure 2). No change between pre- and postshift drives was observed in sleep-related or hazardous driving events on day or evening shifts.

When comparing between shifts, percentage of long eye closures (mean and maximum) on postevening shift drives were significantly lower than following day or night shifts ($p = .04$, $p = .008$ for day shifts, respectively and $p = .02$, $p = .01$ for night shifts, respectively). There were no significant differences in any ocular measures between day and night shifts. KSS was higher prior to day shifts (5.13 ± 0.22) than evening (2.83 ± 0.25), first night (4.03 ± 0.25), and consecutive night shifts (4.12 ± 0.20, $p < .001$ for all comparisons). Higher KSS was reported postshift on first night (6.90 ± 0.28) and consecutive night shifts (6.46 ± 0.25) compared with day (3.85 ± 0.25) and evening shifts (4.10 ± 0.23, $p < .001$ for all comparisons).

Preshift drives were not significantly different between shifts for sleep-related or hazardous driving events, however consecutive night shifts demonstrated a significantly higher rate of inattention events on the preshift commute compared with day shifts (2.12 ± 0.45 vs 0.53 ± 0.44, $p = .008$). Sleep-related event rate postshift was highest on first night shifts (1.59 ± 0.26) compared with consecutive night shifts (1.01 ± 0.22, $p = .04$), evening shifts (–0.09 ± .20, $p < .001$) and day shifts (0.12 ± 0.22, $p < .001$). Consecutive night shifts (2.85 ± 0.52) had significantly higher postshift inattention event rates compared with day (0.69 ± 0.49, $p = .01$), evening (1.10 ± 0.51, $p = .02$) and first night shifts (1.26 ± 0.57, $p = .02$). Predrive KSS was positively associated with sleep-related ($r = .35$, $p < .001$), hazardous ($r = .15$, $p = .002$), and inattention event rates ($r = .16$, $p = .001$).

Prior wakefulness was significantly different between pre- and postshift drives for all shift types (Figure 3). Prior wakefulness on preshift drives was significantly longer on first night shifts (8.33 hours ± 0.38) compared with day (0.68 hours ± 0.28), evening (3.80 hours ± 0.31), and consecutive night shifts (4.19 hours ± 0.26, $p < .001$ for all comparisons, Figure 3). This pattern was the same for postshift drives, with postshift wakefulness longest on first night shift (18.31 hours ± 0.84) compared with all other shift types. Drives with ≥16 hours cumulative wakefulness had significantly higher subjective sleepiness (6.60 ± 0.26, $p < .001$) and a significantly higher rate of sleep-related (1.18 ± 0.17, $p < .001$) and hazardous events (0.67 ± 0.18, $p = .04$) compared with drives with <16 hours cumulative wakefulness, regardless of shift type.

Table 2. Characteristics of drives both pre- and postshift, for each shift type

		Day shift		Evening shift		First night shift		Consecutive night shifts	
		Preshift	Postshift	Preshift	Postshift	Preshift	Postshift	Preshift	Postshift
	N (*n*)	30 (65)	27 (63)	27 (52)	29 (55)	28 (35)	28 (34)	29 (81)	28 (71)
Drive start time	Mean (SEM)	06:16 (00:03)	15:39 (00:03)	12:15 (00:03)	21:36 (00:03)	20:05 (00:04)	07:39 (00:04)	20:22 (00:03)	07:36 (00:03)
Drive end time	Mean (SEM)	06:43 (00:02)	16:17 (00:06)	12:41 (00:03)	22:02 (00:06)	20:33 (00:03)	07:47 (00:08)	20:43 (00:02)	08:04 (00:05)
Drive duration (minutes)	Mean (SEM)	25.14 (2.34)	33.36 (2.64)†	26.82 (2.40)	25.98 (2.64)*	28.32 (2.34)°	28.50 (2.76)	23.34 (2.40)^	27.48 (2.76)
Traffic rating	Mean (SEM)	2.35 (0.11)	3.12 (0.12)†	2.58 (0.12)*°	1.74 (0.12)*°°	2.06 (0.13)†	3.12 (0.14)†	2.11 (0.11)†	3.17 (0.12)†
Drives ≥1 sleep-related events	*n* (%)	5 (7.7)	6 (9.5)	0 (0)	1 (1.8)	3 (8.6)	17 (50)	5 (6.2)	25 (35.2)
Drives ≥1 hazardous events	*n* (%)	6 (9.2)	14 (22.2)	4 (7.7)	7 (12.7)	2 (5.7)	7 (20.6)	6 (7.4)	18 (25.4)
Drives ≥1 inattention events	*n* (%)	12 (18.5)	17 (27.0)	7 (13.5)	15 (27.3)	9 (25.7)	11 (32.4)	20 (24.7)	28 (39.4)
Cumulative wakefulness < 16 hours	*n* (%)	65 (100)	63 (100)	52 (100)	52 (94.5)	35 (100)	10 (29.4)	81 (100)	46 (64.8)
Cumulative wakefulness ≥ 16 hours	*n* (%)	0 (0)	0 (0)	0 (0)	3 (5.5)	0 (0)	24 (70.6)	0 (0)	25 (35.2)
Drives within ± 3 hours of acrophase (adverse circadian phase)	*n* (%)	19 (29.2)	0 (0)	0 (0)	0 (0)	3 (8.6)	8 (23.5)	6 (7.4)	23 (32.4)
Drives outside ± 3 hours of acrophase (outside adverse circadian phase)	*n* (%)	11 (16.9)	30 (47.6)	22 (42.3)	26 (47.2)	22 (62.9)	15 (44.1)	50 (61.7)	27 (38.0)

All *p* values have been corrected for multiple comparisons using the Benjamini-Hochberg method.
Traffic rating is significantly different between pre- and postshift drives for all shift types ($p < .05$).
Drive duration is significantly different between pre- and postshift drive on day shift and consecutive night shifts ($p < .05$).
*Significantly different to day shifts ($p < .05$).
†Significantly different to evening shift ($p < .05$).
^Significantly different to first night shift ($p < .05$).
°Significantly different to consecutive night shifts ($p < .05$).
N = number of participants in group.
n = number of driving logs in each group.

Table 3. Characteristics of last main sleep period (≥2 hours) prior to each shift type

	Day shift		Evening shift		First night shift		Consecutive night shifts		Days off	
	Mean (SEM)	Range	Mean (SEM)	Range	Mean (SEM)	Range	Mean (SEM)	Range	Mean (SEM)	Range
Sleep log	*N* = 27 (*n* = 59)		*N* = 27 (*n* = 49)		*N* = 26 (*n* = 30)		*N* = 28 (*n* = 83)		*N* = 29 (*n* = 95)	
Sleep onset time	23:11 (00:18)	21:45–01:00	23:09 (00:20)	20:30–01:30	23:33 (00:24)	21:30–03:35	09:08 (00:16)	7:50 –15:35	23:20 (00:15)	21:20–02:15
Sleep offset time	05:36 (00:12)	4:50–06:45	07:53 (00:13)	4:00–10:45	08:14 (00:16)	4:30–12:00	15:23 (00:11)	11:30–18:15	07:59 (00:10)	5:06–11:30
Time in bed (h)	6.78 (0.21)†‖	5.00–8.75	9.23 (0.23)*◦	5.25–14.17	9.00 (0.28)*◦	5.92–12.25	6.42 (0.19)†‖	2.33–9.93	9.05 (0.17)*◦	4.75–12.50
Total sleep time (h)	5.99 (0.21)†‖	4.00–8.08	8.23 (0.23)*◦	2.50–11.98	8.20 (0.28)*◦	4.83–11.08	5.87 (0.20)†‖	1.75–9.22	8.27 (0.18)*◦	4.33–12.42
Sleep onset latency (min)	18.91 (2.77)◦	0.00–120.00	22.33 (2.99)◦	0.00–180.00	13.95 (3.69)	0.00–45.00	8.74 (2.51)*†	0.00–60.00	16.72 (2.28)	0.00–180.00
Wake after sleep onset (min)	6.94 (3.34)	0.00–60.00	11.51 (3.64)	0.00–270.00	10.42 (4.50)	0.00–50.00	12.85 (2.98)	0.00–150.00	8.34 (2.72)	0.00–90.00
Self-rated sleep quality	4.98 (0.21)†‖	2.00–8.00	4.02 (0.23)*◦	1.00–7.00	4.27 (0.29)	2.00–7.00	4.91 (0.19)†‖	2.00–9.00	4.00 (0.17)*◦	2.00–8.00
Actigraphy	*N* = 23 (*n* = 51)		*N* = 22 (*n* = 43)		*N* = 23 (*n* = 28)		*N* = 22 (*n* = 61)		*N* = 28 (*n* = 90)	
Sleep onset	23:19 (00:09)	21:52–00:32	23:17 (00:10)	21:15–01:50	23:47 (00:11)	21:30–02:32	09:12 (00:09)	07:30–16:11	23:37 (00:07)	20:04–2:15
Sleep offset	05:28 (00:12)	4:43–06:29	08:18 (00:13)	4:44–10:57	08:08 (00:15)	4:47–11:55	15:29 (00:12)	12.31–18:59	07:57 (00:10)	4:42–11:02
Time in bed (h)	6.48 (0.20)†‖	4.35–8.00	9.46 (0.22)*◦‖	5.02–12.25	8.87 (0.26)*◦	5.70–12.77	6.63 (0.20)†‖	3.00–9.93	8.82 (0.16)*†◦	4.75–11.80
Total sleep time (h)	5.57 (0.18)†‖	3.77–7.48	8.09 (0.19)†^◦‖	4.47–11.08	7.38 (0.23)*†◦	4.05–10.77	5.60 (0.18)†‖	2.62–7.80	7.42 (0.14)*†◦	4.45–10.17
Sleep onset latency (min)	10.52 (2.27)	0.00–63.00	11.98 (2.43)	0.00–69.00	11.94 (2.93)	0.00–64.00	6.46 (2.20)‖	0.00–31.00	15.63 (1.77)◦	0.00–81.00
Wake after sleep onset (min)	36.30 (3.65)†‖	11.00–100	57.95 (3.80)*◦	16.00–115.00	54.30 (4.23)*◦	20.00–113.00	41.33 (3.90)†‖	9.00–175.00	53.43 (3.06)*◦	12.00–125.00
Sleep efficiency (%)	86.07 (0.94)	62.97–96.49	85.07 (0.99)	75.44–93.55	83.64 (1.12)	56.27–93.53	84.79 (0.98)	55.24–96.43	84.68 (0.77)	63.5–94.75

All *p* values have been corrected for multiple comparisons using the Benjamini-Hochberg method.
*Significantly different to day shift ($p < .05$).
†Significantly different to evening shift ($p < .05$).
^Significantly different to first night shift ($p < .05$).
◦Significantly different to consecutive night shifts ($p < .05$).
‖Significantly different to days off ($p < .05$).
N = number of participants in group.
n = number of sleeps in each group.

Table 4. Ocular measures of drowsiness (mean [*SD*]) on drives both pre- and postshift, for each shift type

	Day shift		Evening shift		Night shifts	
	Preshift	Postshift	Preshift	Postshift	Preshift	Postshift
	N = 6 (*n* = 9)	*N* = 6 (*n* = 10)	*N* = 5 (*n* = 10)	*N* = 6 (*n* = 12)	*N* = 5 (*n* = 12)	*N* = 9 (*n* = 19)
Mean negative inter-event duration (ms)	91.92 (13.56)	97.11 (18.80)	93.82 (14.88)	97.27 (16.01)	85.70 (11.74)	110.67 (33.07)*
Max inter-event duration (ms)	148.67 (56.04)	177.30 (56.60)	166.80 (49.33)	162.92 (67.16)	160.00 (72.53)	197.11 (91.23)
Mean percentage of time eyes closed	0.52 (0.26)	1.05 (0.70)*	0.85 (0.20)	0.79 (0.46)	0.67 (0.39)	1.50 (1.13)
Max percentage of time eyes closed	2.23 (1.54)	4.19 (2.38)*	3.03 (1.76)	2.70 (1.94)◦	2.26 (1.09)	4.43 (2.78)*^
Mean blink total duration (ms)	279.53 (42.87)	298.71 (84.62)	281.88 (60.29)	284.20 (60.75)	294.78 (45.50)	333.13 (105.58)
Max blink total duration (ms)	396.22 (82.58)	532.10 (208.97)	440.00 (140.43)	385.50 (123.75)◦	454.92 (158.86)	519.58 (202.08)^
Mean negative amplitude-velocity ratio	1.51 (0.18)	1.58 (0.26)	1.52 (0.19)	1.68 (0.33)	1.58 (0.14)	1.68 (0.21)
Mean percentage of long eye closures	0.16 (0.25)	0.53 (0.54)*^	0.32 (0.43)	0.22 (0.39)†◦	0.21 (0.19)	0.61 (0.54)*^
Max percentage of long eye closures	1.26 (1.40)	3.36 (2.36)*^	1.91 (1.58)	1.53 (2.00)†◦	1.47 (0.83)	3.06 (2.37)*^
Mean JDS	1.02 (0.63)	1.45 (0.84)	0.92 (0.63)	1.56 (1.19)	0.96 (0.38)	1.73 (.93)*
Max JDS	2.09 (1.35)	2.94 (1.40)	1.89 (1.04)	2.49 (1.55)	1.78 (0.68)	2.88 (1.12)*

JDS, John's Drowsiness Scale.
*Significant difference between pre- and postshift drives on respective shift type ($p < .05$).
†Significantly different to postday shift drive ($p < .05$).
^Significantly different from postevening shift drive ($p < .05$).
◦Significantly different to postnight shift drives ($p < .05$).
N = number of participants in group.
n = number of drives in each group.

Subjective sleepiness pre- and postshift, relative to aMT6s acrophase for each shift type is shown in Figure 4. There was a significant main effect of circadian phase, with drives that occurred during an adverse circadian phase (<±3 hours of aMT6s acrophase) reporting higher subjective sleepiness and higher rates of sleep-related events compared with drives that occurred outside of this window ($p < .001$ and $p = .04$, respectively). There were no differences in inattention events and hazardous driving events between acrophase groups.

To examine the relationship of the circadian and homeostatic processes, subjective sleepiness and driving events were categorized based on whether they were at an adverse circadian phase (<±3 hours and ≥±3 hours of acrophase) and prolonged prior wakefulness (≥16 hours and <16 hours prior wakefulness, Figure 5). KSS was significantly different between all four categories: KSS was highest when driving at an adverse circadian phase and following ≥16 hours of wakefulness (7.40 ± 0.46, $p < .05$ for all comparisons, Figure 6). Sleep-related event rates were also higher on drives

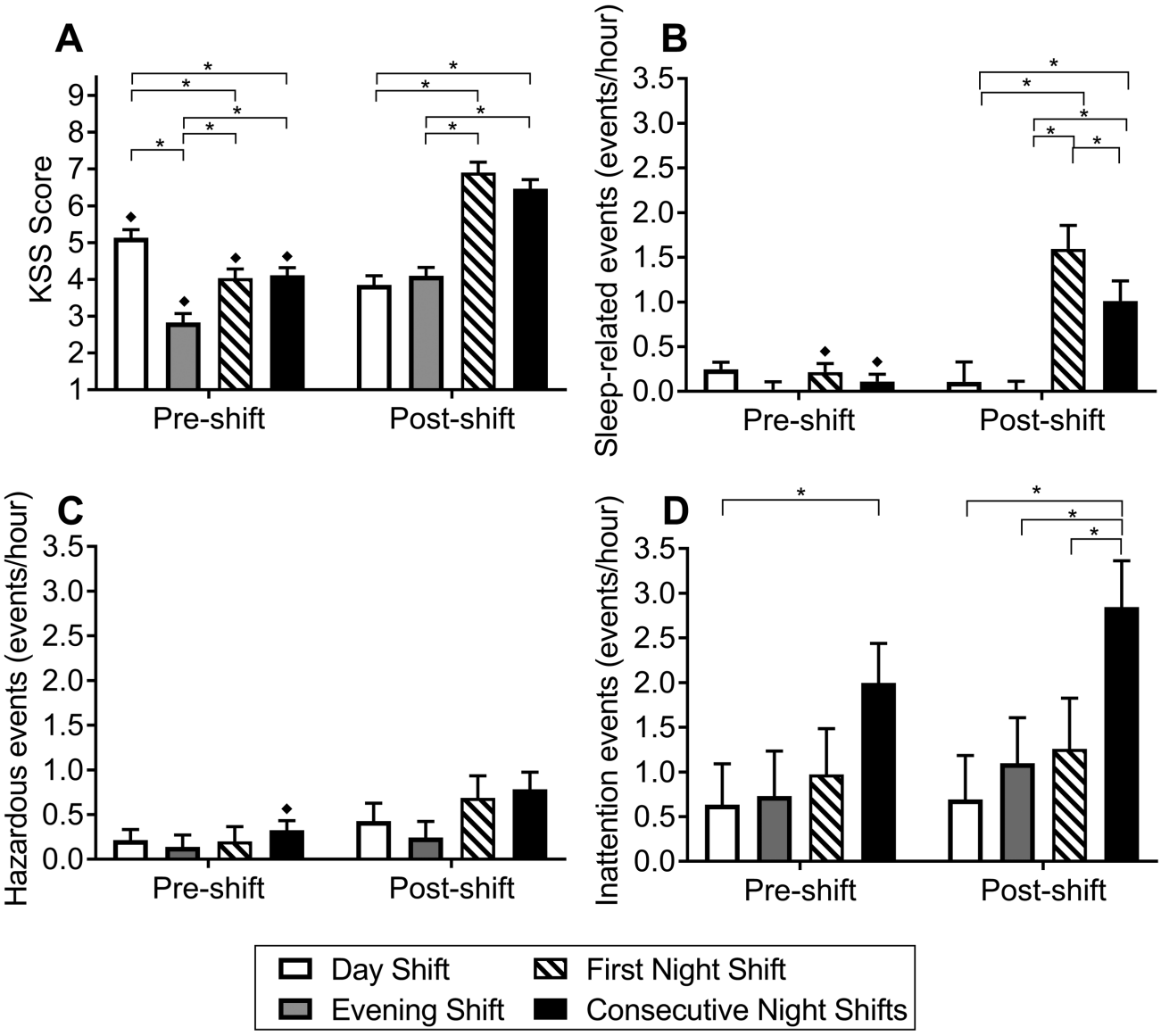

Figure 2. Differences between shift types in predrive Karolinska Sleepiness Scale (KSS) scores (A) and the rate of self-reported sleep-related (B), hazardous (C), and inattention (D) driving events per hour. Pre- and postshift drive differences represented as a diamond above error bar. Data are presented as mean + SEM. *$p < .05$.

which occurred after 16 hours wakefulness when compared with less than 16 hours wakefulness, both when at an adverse circadian phase and outside this range ($p < .001$). Sleep-related event rates were highest when prior wakefulness was ≥16 hours and the drive also occurred at an adverse circadian phase (2.25 ± 0.28). There were no significant differences in inattention or hazardous driving event rates based on circadian timing and duration of wakefulness.

Discussion

This study uniquely evaluated the impact of shift schedules, duration of wakefulness, and circadian timing on sleepiness and driving performance during relatively short work commutes, using both subjective and objective measures in a naturalistic setting. The study demonstrated significant increases in self-reported sleepiness and driving events on the postnight shift commute, when compared with both the preshift commute and to other shift types, in shift working nurses. Sleep-related driving events were highest after the first night shift, compared with consecutive night shifts. The opposite, however, was true for inattention-related driving events, which occurred most frequently after consecutive night shifts compared with the first night shift. Objective measures further demonstrated this increase in postshift sleepiness on night shifts. We demonstrated that differences in subjective sleepiness and self-reported driving events can be explained by a combination of prior wakefulness and circadian timing.

Differences in pre- and postshift sleepiness were demonstrated across day, evening, first night, and consecutive night shifts on subjective sleepiness measures, with evening, first night, and consecutive nights all demonstrating an increase in sleepiness postshift. Significantly more long eye closures, higher PERCLOS, and JDS on ocular measures of sleepiness after night shifts compared with preshift further supported this finding. On postnight shift drives, at their most sleepy, driver's eyes were closed for an average of 4.4% of a minute, equating to travelling 74 m with their eyes closed each minute when driving at 100 km/hour, the speed limit on metropolitan freeways in

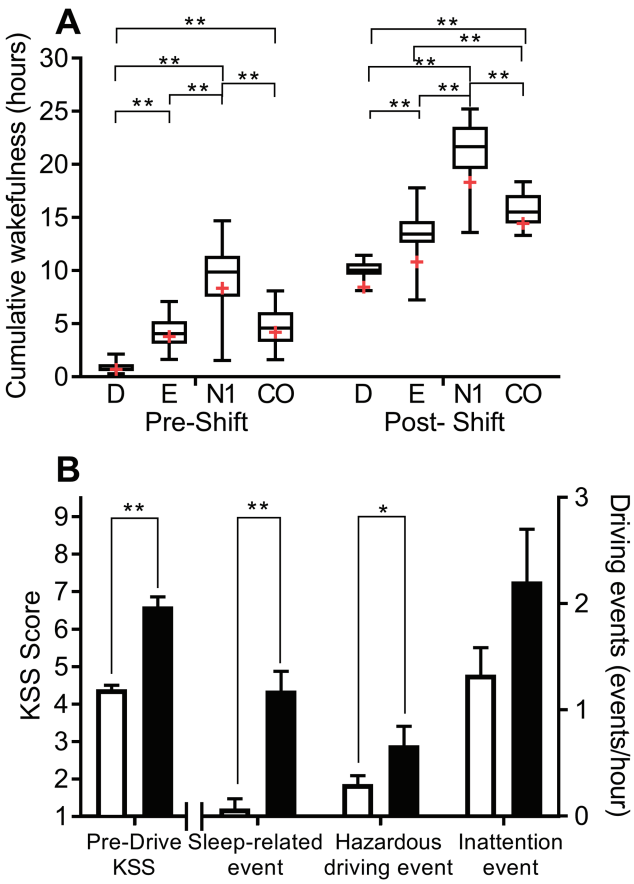

Figure 3. Cumulative wakefulness since last main sleep episode (≥2 hours) at the start of drive for (A) each shift type (D = day shift, E = evening shift, N1 = first night shift, CN = consecutive night shifts). The whiskers represent the minimum and maximum values of wakefulness, the box extending to the 25th and 75th percentile, the middle line representing the median and the red + representing the mean. (B) Predrive KSS, sleep-related events, hazardous driving events and inattention events for drives associated with <16 hours of cumulative wakefulness (white) and ≥16 hours cumulative wakefulness (black). Error bars indicate SEM. $^{*}p < .05$.

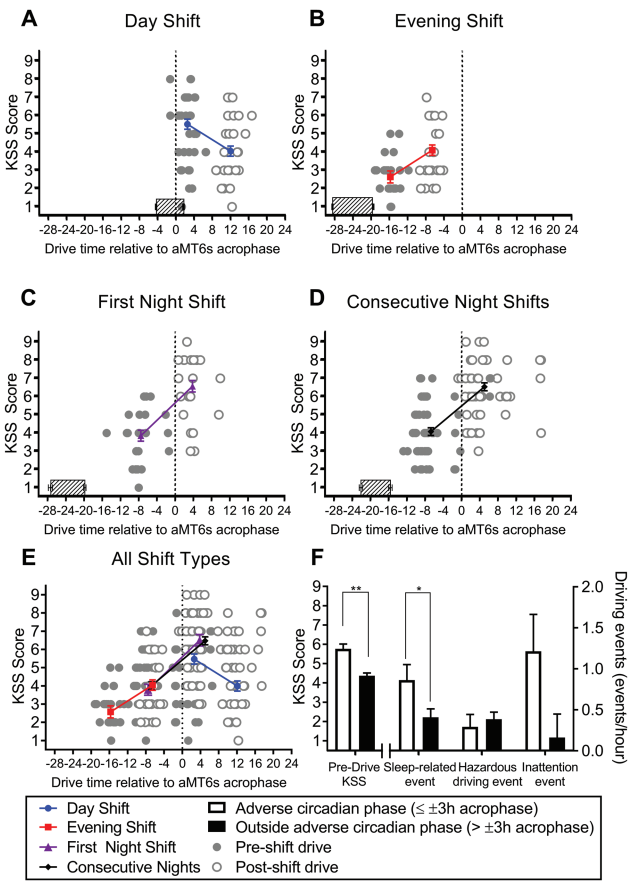

Figure 4. Predrive Karolinska Sleepiness Scale (KSS) scores and drive time relative to 6-sulphatoxymelatonin (aMT6s) acrophase time on day (A), evening (B), first night (C), consecutive night shifts (D) and all shift types (E). Negative values indicate the drive occurred prior to acrophase while positive numbers indicate the drive occurred after acrophase. Mean sleep time relative to aMT6s acrophase is shown in shaded bars, and mean KSS is show for day (blue), evening (red), first night (purple) and consecutive night shifts (black). Drives were categorized as within ±3 hours of acrophase (adverse circadian phase) or outside of aMT6s acrophase range (outside adverse circadian phase). Differences in KSS and the rate of sleep-related, hazardous and inattention events were examined (F). Asterisks indicate significant differences ($^{**}p < .001$, $^{*}p < .05$), and error bars represent SEM.

Melbourne. This poses a significant risk to driving, as evidenced by the increased rate of driving events also observed postnight shift. Sleep-related, hazardous, and inattention events all occurred more frequently on postnight shift drives compared with prenight shift drives, consistent with the previous reports of increased adverse driving events after night shift [24]. Given that objective and subjective sleepiness and self-reported driving events are all sensitive to homeostatic changes in sleepiness [24, 35, 43, 44], increasing wakefulness postshift can likely explain part of this postnight shift increase in sleepiness and impairment. Circadian effects also contributed to the postshift sleepiness and driving events, as postnight shift commutes occurred at 07:36 am. This resulted in 24% of first night and 32% consecutive night postshift commutes occurring at an adverse circadian phase (within 3 hours of aMT6s acrophase), contributing to an increase in driving impairment [11, 12].

Pre- and postshift differences for day shifts demonstrated a different but expected pattern to night shifts, with higher rating of subjective sleepiness on the commute to work (rather than after work), which often occurred during an adverse circadian phase or at a time when sleep inertia may have not yet dissipated [45]; on day shifts, the preshift drive occurred during the early morning (mean wake time 06:16 am) and shortly after waking (mean prior wakefulness of 0.7 hours). This means that preday shift drives are likely to be influenced by circadian effects due to drives occurring close to the circadian nadir in alertness, and possible sleep inertia effects. Objective measures of sleepiness, however, showed the opposite trend with ocular measures significantly higher postshift and no differences in self-reported driving events after the day shift. Given that subjective sleepiness was measured predrive, it may show greater influence of sleep inertia effects than objective sleepiness and self-reported driving events which are measured over the duration of the drive, providing more time for sleep inertia effects to dissipate. Alternatively, sleep inertia effects are known to vary dramatically depending on the measure [46] and no sleep inertia effect may be seen in the ocular and self-reported driving measures due to a decreased sensitivity to sleep inertia, particularly as these are both measured during driving, a more cognitively stimulating task than the KSS [46].

Differences in sleepiness were also found between shift types, with subjective sleepiness highest on postnight shift

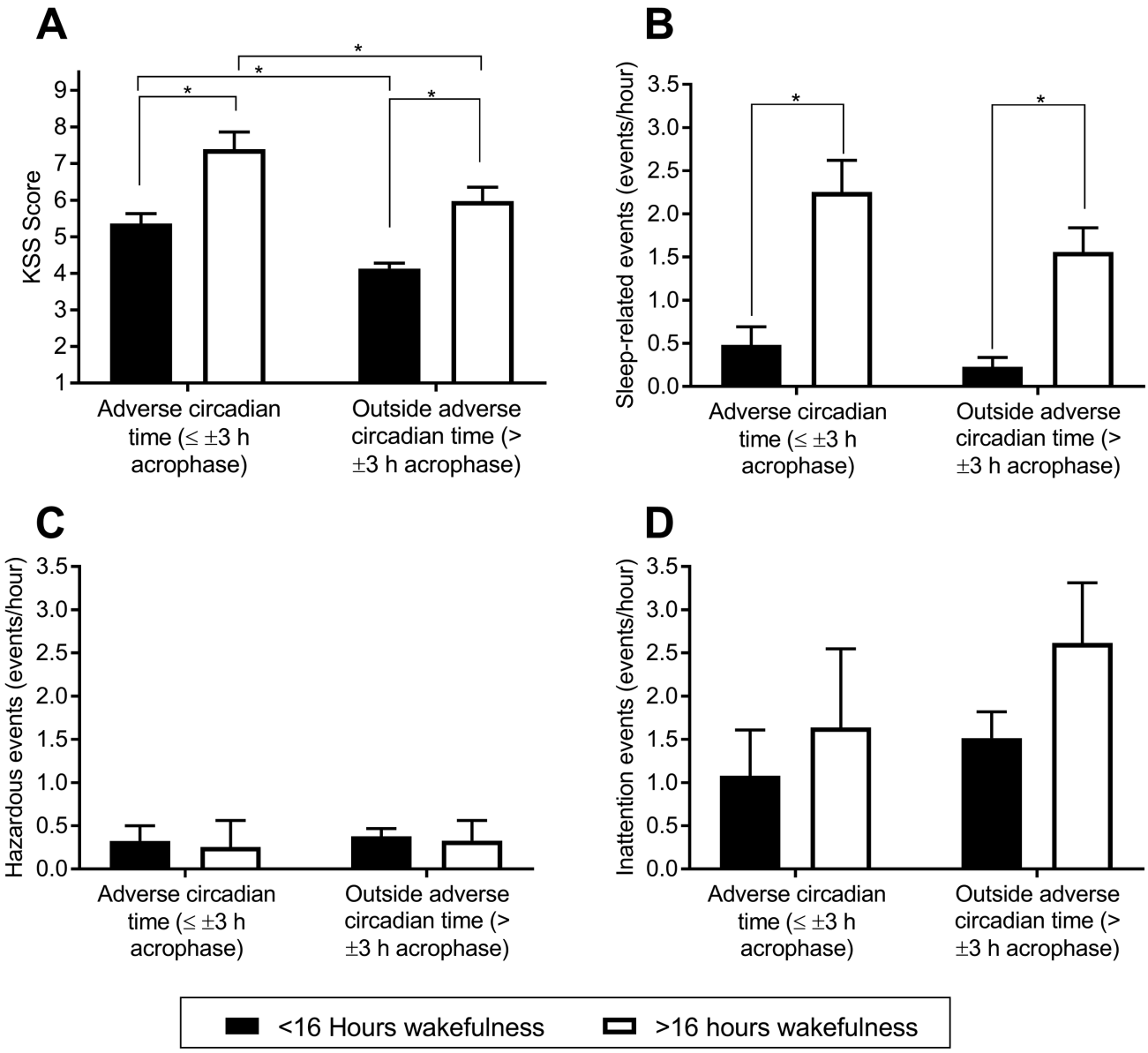

Figure 5. To investigate the interaction of circadian phase and prior wakefulness drives were categorized as occurring within an adverse circadian phase (≤ ±3 hours aMT6s acrophase range) and outside adverse circadian phase (> ±3 hours aMT6s acrophase range) and categorized as ≥16 hours and <16 hours of wakefulness. Differences in KSS score (A) and the rate of sleep-related (B), hazardous (C), and inattention (D) driving events are shown, with error bars representing SEM. *$p < .05$ after Benjamini-Hochberg correction for multiple comparisons.

commutes (both first and consecutive nights) compared with day or evening shifts. Objective sleepiness followed a similar pattern, with significantly longer long eye closures postnight shift compared with evening shifts. Both first and consecutive night shifts also reported a significantly higher rate of sleep-related driving events than day and evening shifts, however sleep-related events were highest on first night shift compared with consecutive nights. The differences between shifts may be explained in part by differences in prior wakefulness. Prior wakefulness on first (18.3 hours) and consecutive night shifts (14.4 hours) was longer than on day (8.4 hours) or evening shifts (10.8 hours). This extended prior wakefulness after night shifts may explain the increase in sleep-related driving events, compared with other shift types. Given that after 18.5 hours awake, driving performance becomes impaired to an equivalent level as people with a blood alcohol level of 0.05% (the legal limit in Victoria, Australia), this extended wake episode represents a significant risk to driving performance [28].

Interestingly, sleep-related events occurred most frequently on the first night shift, whilst inattention events occurred most frequently on subsequent night shifts. Longer prior wakefulness on first night shifts relative to consecutive night shifts (Figure 3) may explain the higher rates of extreme driving events such as falling asleep while driving and struggling to keep eyes open. Extended prior wakefulness following consecutive night shifts, may have resulted in a higher occurrence of distraction, a known consequence of sleepiness [47, 48]. This increased distractibility due to sleep loss also represents a significant risk to driving, with distraction involved in an estimated 21% of motor vehicle accidents on Australian roads [49].

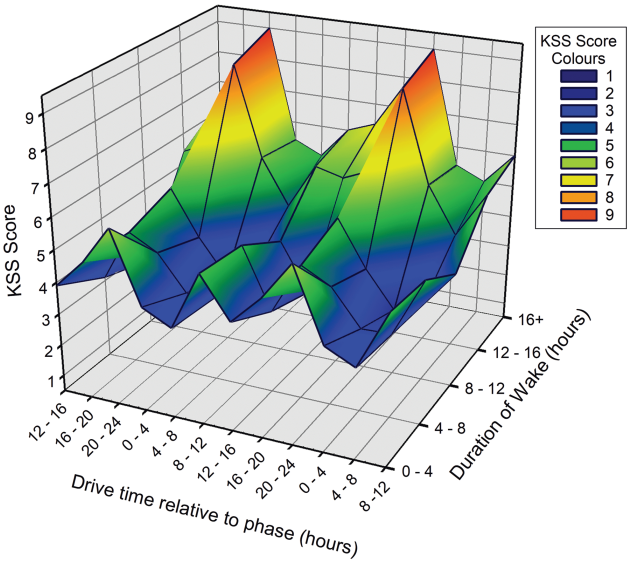

Figure 6. Interaction of circadian phase and wakefulness on predrive subjective sleepiness (KSS). Duration of wake is categorized into 4-hour bins, and drive time relative to circadian phase is categorized into 4-hour bins (double plotted), with 0 representing acrophase. There is a clear circadian rhythm in subjective sleepiness that becomes more evident after extended wakefulness, and a clear effect of wakefulness, with subjective sleepiness increasing with duration of wake.

In addition to shift differences in sleepiness and driving events, there were differences in the duration of sleep prior to each shift type. Sleep prior to an evening shift and first night shift was on average the same duration as sleep prior to a day off and was within the daily range recommended for adults by the National Sleep Health Foundation [50]. Sleep prior to day shifts and consecutive night shifts was shortest, with total sleep times of 5.57 and 5.60 hours, respectively. This is shorter than the minimum recommended daily sleep duration for adults (7 hours), and is likely to result in some performance impairment, particularly after multiple days of less than 6 hours of sleep, which can result in chronic sleep deprivation and associated neurobehavioral and attentional deficits [27, 50]. Shorter sleep prior to the day shift is likely explained by the early start time on day shifts, resulting in sleep being truncated due to having to wake early. This problem is further exacerbated when day shifts are preceded by an evening shift, as the late to early transition only allows 9.5 hours between shifts for commute and sleep opportunity [51].

The interaction of driving after prolonged wakefulness (≥16 hours) and during an adverse circadian phase increased subjective sleepiness, sleep-related and hazardous driving events, demonstrating that subjective sleepiness and driving performance are sensitive to homeostatic changes with sleep [12, 29]. As postnight shift drives were predominantly those with ≥16 hours wakefulness and these drives occurred during the morning, a time associated with driving impairment [12], the contribution of the circadian phase must also be considered. This study was the first to examine objectively, the effects of measured circadian phase on driving performance in shift workers in a naturalistic setting, rather than the more inaccurate proxy time of day [3, 5, 17]. Circadian phase affected both subjective sleepiness and sleep-related events. When circadian timing and wakefulness were considered together, driving after prolonged wakefulness and at an adverse circadian phase significantly increased subjective sleepiness and sleep-related events, suggesting that both factors need to be considered when assessing sleepiness and sleep-related driving performance impairments. These findings further highlight why postnight shift commutes, when driving after being awake for a long time and at an adverse biological time represented the highest rates of sleepiness sleep-related driving events.

The present study had high ecological validity, as it is one of few studies in shift workers to examine driving under naturalistic conditions. Limitations in sample size and circadian phase variation restricted the analysis of circadian phase on driving performance to dichotomized variables. Due to the naturalistic nature of the study, it was difficult to examine driving performance via objective measures such as lane departures and steering deviation that are commonly used in simulated and track-based driving studies [3, 5]. The objective measures of sleepiness (mean blink duration, JDS) used in the current study have been linked with objective measures of driving performance in simulator studies, providing evidence that these objective measures are appropriate for studying sleep-related driving impairment [52]. Furthermore, all driving event types were positively associated with predrive subjective sleepiness, with sleep-related events showing the strongest relationship, providing further evidence that the self-reported driving events were all sensitive to sleep-related impairment [44]. It is noted that factors such as variability in light conditions between shift types, which are known to affect sleepiness during driving tasks, were not controlled for in this study [53]. We did, however, control for other factors likely to influence sleepiness and driving performance by examining the number of driving events relative to drive duration and controlling for traffic density [3, 24].

This study demonstrated that sleepiness and driving impairment are increased following a night shift, and are modulated by the circadian pacemaker, duration of prior wakefulness, and interaction of both processes. We demonstrated that these impairments can occur, even during relatively short commutes (i.e. 30 minutes). Increases in sleepiness and driving events after night shift have implications for public safety, putting both shift workers and the public at risk. Differences in the types of impairment associated with the first compared with consecutive night shifts should be a consideration when scheduling multiple night shifts, with countermeasures specifically targeting vulnerability to sleepiness on the first night shift. Given that predrive subjective sleepiness was associated with increased driving events, shift workers were aware of their sleepiness and the potential hazard prior to driving. This awareness provides a target for educational campaigns to educate drivers on the risks of drowsy driving, and that unsafe driving can occur even during a short commute [54]. Future research could investigate the efficacy of sleepiness countermeasures, such as caffeine and/or napping, and alertness monitoring devices for reducing risk of sleep-related driving impairment. Napping in particular should be further examined, as it is one of the most widely recommended countermeasures for drowsy driving. Studies have, however, demonstrated mixed results depending on how naps are implemented, with some studies finding that naps produced no improvement in objective driving performance [55–57]. The impact of shift work on staff and patients has not

been successfully addressed in healthcare systems despite ubiquitous use of shift work. Implementation of programs to address shift work related impairment, such as optimization of shift schedules and education regarding sleep before night shift, could reduce risk for healthcare staff and patients.

Supplementary Material

Supplementary material is available at *SLEEP* online.

Acknowledgments

We thank Jessica Papaleo, Matthew McLaren, Aaron Johnson, Kaitlyn Crocker, Niamh McDonald, Emma Giliberto, and Trisha D'Lima from the Sleep and Circadian Medicine Laboratory, School of Psychological Sciences and Monash Institute of Cognitive and Clinical Neurosciences, Monash University, Melbourne, Australia for their assistance with data collection. We thank Dr Glenn Eastwood, Helen Young, Dr Graeme Hart, and the staff of the Intensive Care Unit at Austin Health, Melbourne, Australia for their support. We also thank Mark Salkeld at the Adelaide Research Assay Facility, Adelaide, Australia for conducting the aMT6s radioimmunoassays.

Author Contributions

All authors contributed to the work presented and have given final approval for its publication. M.D.M. contributed to data collection, analysis of data and compiled the manuscript. T.L.S. contributed to the conception of study design, facilitated data collection and study implementation and provided critical insight and comment on the analysis, interpretation and manuscript draft. M.M. contributed to the conception of study design, data collection and study implementation, data cleaning and provided critical insight and comment on the analysis, interpretation and manuscript draft. J.E.S. and S.G. contributed to data collection, data cleaning and analysis and provided comments on interpretation and the manuscript draft. A.C. facilitated data collection and study implementation, provided comment and insight on manuscript draft. C.A., S.W.L., M.H., and S.W.R. contributed to the conception of study design, facilitated data collection and study implementation and provided critical insight and comments on interpretation and the manuscript draft.

Funding

This research is supported by the Cooperative Research Centres, Australian Government Department of industry..

Conflict of interest statement: M.D.M. has no conflicts to declare. T.L.S. and M.M. serve as a Project Leaders in the CRC for Alertness, Safety and Productivity, Melbourne, Australia. J.E.S., S.G., and A.C. have no conflicts to declare. C.A. has received a research award/prize from Sanofi-Aventis; contract research support from VicRoads, Rio Tinto Coal Australia, National Transport Commission, Tontine/Pacific Brands; and lecturing fees from Brown Medical School/Rhode Island Hospital, Ausmed, Healthmed and TEVA Pharmaceuticals; and reimbursements for conference travel expenses from Philips Healthcare. In addition, she has served as a consultant through her institution to the Rail, Bus and Tram Union, the Transport Accident Commission (TAC), and the National Transportation Committee (NTC) and VicRoads. She has also served as an expert witness and/or consultant in relation to fatigue and drowsy driving. C.A. is a Theme Leader in the Cooperative Research Centre for Alertness, Safety and Productivity which funded this work. S.W.L. has had a number of commercial interests in the last 12 months (2017–2018). He is a Program Leader for the CRC for Alertness, Safety and Productivity, Melbourne, Australia, which funded this work. No other interests are directly related to the research or topic reported in this paper but, in the interests of full disclosure, are outlined below. S.W.L. is a Program Leader for the CRC for Alertness, Safety and Productivity, Australia, which funded this work. He has had a number of commercial interests in the last 2 years (2017–2018) which are not directly related to the research or topic reported in this paper but, in the interests of full disclosure, are as follows: consulting fees from BHP Billiton, Consumer Sleep Solutions, Noble Insights, Pegasus Capital Advisors, and Team C Racing, and has ongoing consulting contracts with Akili Interactive, Apex 2100 Ltd., Headwaters Inc., Hintsa Performance AG, Light Cognitive, Lighting Science Group Corporation, Mental Workout, Six Senses, and Wyle Integrated Science and Engineering; has received unrestricted equipment gifts from Bionetics Corporation and F. Lux Software LLC; royalties from Oxford University Press; honoraria plus travel, accommodation or meals for invited seminars, conference presentations or teaching from BHP Billiton, Estee Lauder and Teague; travel, accommodation and/or meals only (no honoraria) for invited seminars, conference presentations or teaching from DIN and the Society for Light Treatment and Biological Rhythms; ongoing investigator-initiated research grants from F. Lux Software LLC; Dr Lockley also holds a process patent for "Systems and methods for determining and/or controlling sleep quality" which is assigned to the Brigham and Women's Hospital per Hospital policy. M.E.H. serves as a Theme Leader in the CRC for Alertness, Safety and Productivity Melbourne, Australia, which funded this work; and has received grants from Prevention Express and TEVA, which are not related to the work reported in this paper. S.M.W.R. reports grants from Vanda Pharmaceuticals, Philips Respironics, Cephalon, Rio Tinto and Shell, and has received equipment support and consultancy fees through his institution from Optalert, Tyco Healthcare, Compumedics, Mental Health Professionals Network, and Teva Pharmaceuticals, which are not related to this paper. S.M.W.R is also a Program Leader for the CRC for Alertness, Safety and Productivity, Melbourne, Australia, which funded this work.

References

1. Australian Transport Safety Bureau. Road safety research report OR23. Fatigue related crashes: An analysis of fatigue-related crashes on Australian roads using an operational definition of fatigue. 2002. https://infrastructure.gov.au/roads/safety/publications/2002/Fatigue_related_sum.aspx. Accessed October 3, 2018.
2. Austroads. 15- 16 Annual report. 2016. https://austroads.com.au/about-austroads/annual-reports. Accessed October 8, 2018.
3. Lee ML, *et al*. High risk of near-crash driving events following night-shift work. *Proc Natl Acad Sci USA*. 2016;**113**(1):176–181.
4. Di Milia L, *et al*. Sleepiness, long distance commuting and night work as predictors of driving performance. *PLoS One*. 2012;**7**(9):e45856.

5. Akerstedt T, *et al*. Impaired alertness and performance driving home from the night shift: a driving simulator study. *J Sleep Res*. 2005;**14**(1):17–20.
6. IBM Corporation. *Australian Commuter Pain Survey*. Melbourne, Australia: IBM Corporation; 2011.
7. Towards Zero. Driver Reviver Pit Stops. https://www.towardszero.vic.gov.au/news/articles/driver-reviver-pit-stop. Accessed October 8, 2018.
8. Australian Bureau of Statistics. *Working Time Arrangements. Vol Cat no. 6342.0*. Canberra: Author; 2012. http://www.abs.gov.au/ausstats/abs@.nsf/mf/6342.0. Accessed October 3, 2018.
9. Australian Bureau of Statistics. *Work-Related Injuries, Australia, Jul 2013 to Jun 2014. Vol Cat no. 6324.0*. Canberra: Author; 2014. http://www.abs.gov.au/ausstats/abs@.nsf/mf/6324.0. Accessed October 8, 2018.
10. Folkard S, *et al*. Shiftwork: safety, sleepiness and sleep. *Industrial health*. 2005;**43**(1):20–23.
11. Lenné MG, *et al*. Time of day variations in driving performance. *Accid Anal Prev*. 1997;**29**(4):431–437.
12. Matthews RW, *et al*. Simulated driving under the influence of extended wake, time of day and sleep restriction. *Accid Anal Prev*. 2012;**45**(Suppl):55–61.
13. Lenné MG, *et al*. Interactive effects of sleep deprivation, time of day, and driving experience on a driving task. *Sleep*. 1998;**21**(1):38–44.
14. Bojkowski CJ, *et al*. Melatonin secretion in humans assessed by measuring its metabolite, 6-sulfatoxymelatonin. *Clin Chem*. 1987;**33**(8):1343–1348.
15. Wright KP Jr, *et al*. Intrinsic period and light intensity determine the phase relationship between melatonin and sleep in humans. *J Biol Rhythms*. 2005;**20**(2):168–177.
16. Sletten TL, *et al*. Timing of sleep and its relationship with the endogenous melatonin rhythm. *Front Neurol*. 2010;**1**:137.
17. Stone JE, *et al*. Temporal dynamics of circadian phase shifting response to consecutive night shifts in healthcare workers: role of light-dark exposure. *J Physiol*. 2018;**596**(12):2381–2395.
18. Horne J, *et al*. Sleep related vehicle accidents. *BMJ*. 1995;**310**(6979):565–567.
19. Dijk DJ, *et al*. Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance. *J Sleep Res*. 1992;**1**(2):112–117.
20. Anund A, *et al*. The effects of driving situation on sleepiness indicators after sleep loss: a driving simulator study. *Ind Health*. 2009;**47**(4):393–401.
21. Barger LK, *et al*.; Harvard Work Hours, Health, and Safety Group. Extended work shifts and the risk of motor vehicle crashes among interns. *N Engl J Med*. 2005;**352**(2):125–134.
22. Akerstedt T. Shift work and disturbed sleep/wakefulness. *Occup Med (Lond)*. 2003;**53**(2):89–94.
23. St Hilaire MA, *et al*. Modeling neurocognitive decline and recovery during repeated cycles of extended sleep and chronic sleep deficiency. *Sleep*. 2017;**40**(1):zsw009.
24. Ftouni S, *et al*. Objective and subjective measures of sleepiness, and their associations with on-road driving events in shift workers. *J Sleep Res*. 2013;**22**(1):58–69.
25. Anderson C, *et al*. Self-reported drowsiness and safety outcomes while driving after an extended duration work shift in trainee physicians. *Sleep*. 2018;**41**(2). doi:10.1093/sleep/zsx195.
26. Magee M, *et al*. Associations between number of consecutive night shifts and impairment of neurobehavioral performance during a subsequent simulated night shift. *Scand J Work Environ Health*. 2016;**42**(3):217–227.
27. Van Dongen HP, *et al*. The cumulative cost of additional wakefulness: dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep*. 2003;**26**(2):117–126.
28. Arnedt JT, *et al*. How do prolonged wakefulness and alcohol compare in the decrements they produce on a simulated driving task? *Accid Anal Prev*. 2001;**33**(3):337–344.
29. Akerstedt T, *et al*. Reaction of sleepiness indicators to partial sleep deprivation, time of day and time on task in a driving simulator–the DROWSI project. *J Sleep Res*. 2010;**19**(2):298–309.
30. Smith CS, *et al*. Evaluation of three circadian rhythm questionnaires with suggestions for an improved measure of morningness. *J Appl Psychol*. 1989;**74**(5):728–738.
31. Ftouni S, *et al*. Ocular measures of sleepiness are increased in night shift workers undergoing a simulated night shift near the peak time of the 6-sulfatoxymelatonin rhythm. *J Clin Sleep Med*. 2015;**11**(10):1131–1141.
32. Gillberg M, *et al*. Relations between performance and subjective ratings of sleepiness during a night awake. *Sleep*. 1994;**17**(3):236–241.
33. Johns MW, *et al*. Monitoring eye and eyelid movements by infrared reflectance oculography to measure drowsiness in drivers. *Somnologie*. 2007;**11**(4):234–242.
34. Wilkinson VE, *et al*. The accuracy of eyelid movement parameters for drowsiness detection. *J Clin Sleep Med*. 2013;**9**(12):1315–1324.
35. Anderson C, *et al*. Assessment of drowsiness based on ocular parameters detected by infrared reflectance oculography. *J Clin Sleep Med*. 2013;**9**(9):907–20, 920A.
36. Stephan K, *et al*. *The Relationship Between Driving Performance and the Johns Drowsiness Scale as Measured by the Optalert System*. Melbourne: Monash Accident Research Centre, Monash University; 2006.
37. Aldhous ME, *et al*. Radioimmunoassay for 6-sulphatoxymelatonin in urine using an iodinated tracer. *Ann Clin Biochem*. 1988;**25(Pt 3)**:298–303.
38. Nelson W, *et al*. Methods for cosinor-rhythmometry. *Chronobiologia*. 1979;**6**(4):305–323.
39. Reason J, *et al*. Errors and violations on the roads: a real distinction? *Ergonomics*. 1990;**33**(10–11):1315–1332.
40. Field A. *Discovering statistics using IBM SPSS statistics*. London, UK: Sage Publications Ltd; 2013.
41. Benjamini Y, *et al*. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *J R Stat Soc B Met*. 1995:289–300.
42. Lockley SW, *et al*. Relationship between melatonin rhythms and visual loss in the blind. *J Clin Endocrinol Metab*. 1997;**82**(11):3763–3770.
43. Ftouni S, *et al*. Temporal dynamics of ocular indicators of sleepiness across sleep restriction. *J Biol Rhythms*. 2013;**28**(6):412–424.
44. Anderson C, *et al*. Deterioration of neurobehavioral performance in resident physicians during repeated exposure to extended duration work shifts. *Sleep*. 2012;**35**(8):1137–1146.
45. Jewett ME, *et al*. Time course of sleep inertia dissipation in human performance and alertness. *J Sleep Res*. 1999;**8**(1):1–8.
46. Tassi P, *et al*. Sleep inertia. *Sleep Med Rev*. 2000;**4**(4):341–353.
47. Anderson C, *et al*. Driving drowsy also worsens driver distraction. *Sleep Med*. 2013;**14**(5):466–468.
48. Anderson C, *et al*. Sleepiness enhances distraction during a monotonous task. *Sleep*. 2006;**29**(4):573–576.
49. McEvoy SP, *et al*. The prevalence of, and factors associated with, serious crashes involving a distracting activity. *Accid Anal Prev*. 2007;**39**(3):475–482.

50. Hirshkowitz M, *et al*. National Sleep Foundation's sleep time duration recommendations: methodology and results summary. *Sleep Health*. 2015;**1**:40–3.
51. Ganesan S, *et al*. The Impact of Shift Work on Sleep, Alertness and Performance in Healthcare Workers. *Scientific Reports*. 2019;**9**(1):4635.
52. Jackson ML, *et al*. The utility of automated measures of ocular metrics for detecting driver drowsiness during extended wakefulness. *Accid Anal Prev*. 2016;**87**:127–133.
53. Ahlström C, *et al*. The effect of daylight versus darkness on driver sleepiness: a driving simulator study. *J Sleep Res*. 2018;**27**(3):e12642.
54. Alvaro PK, *et al*. Driver education: enhancing knowledge of sleep, fatigue and risky behaviour to improve decision making in young drivers. *Accid Anal Prev*. 2018;**112**:77–83.
55. Centofanti SA, *et al*. Do night naps impact driving performance and daytime recovery sleep? *Accid Anal Prev*. 2017;**99**(Pt B):416–421.
56. Hilditch CJ, *et al*. Sleep inertia associated with a 10-min nap before the commute home following a night shift: a laboratory simulation study. *Accid Anal Prev*. 2017;**99**(Pt B):411–415.
57. Philip P, *et al*. The effects of coffee and napping on nighttime highway driving: a randomized trial. *Ann Intern Med*. 2006;**144**(11):785–791.