Accident Analysis and Prevention 45S (2012) 55–61

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Simulated driving under the influence of extended wake, time of day and sleep restriction

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ARTICLE INFO

Article history:
Received 2 May 2011
Received in revised form 2 August 2011
Accepted 11 August 2011

Keywords:
Driving
Time of day
Prior wake
Sleep
Forced desynchrony

ABSTRACT

Around a fifth of all road accidents can be attributed to fatigued drivers. Previous studies indicate that driving performance is influenced by time of day and decreases with sustained wakefulness. However, these influences occur naturally in unison, confounding their effects. Typically, when people drive at a poor time of day and with extended wake, their sleep is also restricted. Hence, the aim of the current study was to determine the independent effects of prior wake and time of day on driving performance under conditions of sleep restriction. The driving performance of fourteen male participants (21.8 ± 3.8 years, mean $\pm$SD) was assessed during a 10 min simulated driving task with speed/lane mean, variability and violations (speeding and crashes) measured. Participants were tested at 2.5 h intervals after waking, across 7×28 h days with a sleep:wake ratio of 1:5. By forced desynchrony each driving session occurred at 9 doses of prior wake and within 6 divisions of the circadian cycle based on core body temperature. A mixed models ANOVA revealed significant main effects of circadian phase, prior wake and sleep debt on lane violations. In addition, three significant two-way interactions (circadian phase $\times$ prior wake, prior wake $\times$ sleep debt, sleep debt $\times$ circadian phase) and one three-way interaction (circadian $\times$ prior wake $\times$ sleep debt) were identified. The presence of the large interaction effects shows that the influence of each factor is largely dependent on the magnitude of the other factors. For example, the presence of the time of day influence on driving performance is dependent on the length of prior wake or the presence of sleep debt. The findings suggest that people are able to undertake a low-difficulty simulated drive safely, at least for a short period, during their circadian nadir provided that they have had sufficient sleep and have not been awake too long.

1. Introduction

Globally, it has been acknowledged that fatigue is a significant contributor to road accidents. While fatigue may be a causal factor in around a fifth of all road accidents (Campagne et al., 2004; Lyznicki et al., 1998; Maycock, 1997), surveys conducted in the U.K., U.S., Australia and Finland suggest that crash statistics may portray conservative estimates of the prevalence of fatigue. For example, when 1000 licensed drivers were randomly sampled in New York, more than half reported having 'driven while being drowsy' and more than a quarter reported 'falling asleep at the wheel' (McCartt et al., 1996). A study of naturalistic driving gathered video data from 100 vehicles over one year totalling 43,000 h of driving data (Klauer et al., 2006). Drowsy drivers were close to three times more likely to be involved in a road accident or near accident than non-drowsy drivers. Clearly, driving while fatigued is both prevalent and dangerous.

Understanding and managing the determinants of fatigue is an essential part of minimising the safety hazard that it presents to our society (Gander et al., 2011; Williamson et al., 2011). Fatigue however, is a broad, multi-dimensional and usually ill-defined concept (Noy et al., 2011). Recently, it has been agreed that when using the term 'fatigue', the wisest solution is to adopt a definition that best suites the context (rather than a universal definition) (e.g., Dawson et al., 2011; Horrey et al., 2011; Noy et al., 2011; Williamson et al., 2011). Therefore, for the purposes of this paper, the term fatigue is used as analogous to sleepiness leading to decreased performance. In this context, the factors that contribute to fatigue include: time of day (or circadian phase; Colquhoun, 1971), prior wake (Dinges and Kribbs, 1991), sleep dose (Belenky et al., 2003), and task-related factors (Richter et al., 2005).

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0001-4575/$ – see front matter
doi:10.1016/j.aap.2011.09.027

Many studies have indicated there is a circadian rhythm in simulated driving performance but none have controlled for prior wake effects (Contardi et al., 2004; Lenné et al., 1997; Williamson and Friswell, 2008; Wong et al., 2008). Typically in these studies, participants are kept awake until the early morning when their simulated performance is found to be worst. However, by this time, participants have also accrued between 18 h (Lenné et al., 1997) and 24 h (Contardi et al., 2004) of prior wake. Thus, the prior wake contribution to the performance deficit is attributed to the 'time of day' influence. While prior wake has confounded the reported time of day rhythm of driving performance, the reverse has been true in studies depicting prior wake effects (Arnedt et al., 2001; Powell et al., 2001; Wong et al., 2008).

The prior wake and time of day effects have been confounded in previous studies and in an applied setting, both influences do occur in unison. Therefore, the benefit of quantifying the influences individually may not be clear. Two recent reviews (Horrey et al., 2011; Williamson et al., 2011) have called for a systematic examination of both the time of day effects and sleep homeostatic influence in isolation. These reviews argue that our ability to manage the adverse effects of fatigue depends on our understanding of each determinant and how they combine. The identification of what constitutes high-risk conditions will allow better management by targeting controls, such as shift duration and countermeasures, to minimise the fatigue risk.

The sleep homeostatic influence is driven by both the amount of prior wake and sleep. This is important to consider because operating in the early morning (at the performance nadir) is associated with extended wake and reduced sleep. Hence the aim of the current study was to determine how the factors of prior wake and time of day interact to influence driving performance under conditions of sleep restriction.

2. Methods

2.1. Participants

The study sample consisted of fourteen healthy male participants with an average (±SD) age of 21.8 (±3.8) years and an average (±SD) body mass index of 22.4 (±2.5) kg/m^2. These participants were non-smoking, non-shift working, low coffee drinkers (<2 cups per week), having no sleep disorders or transmeridian travel in the last three months. Following an expression of interest, participants underwent a three-stage screening process consisting of a general health questionnaire, an interview and one week of activity monitoring. Ethics approval for the study was granted by the University of South Australia Human Research Ethics Committee using guidelines established by the National Health and Medical Research Council of Australia.

2.2. Apparatus and measures

Driving performance was measured using the York Driving Simulator (York Computer Technologies, Kingston, Ontario). Drives were set to 10 min to minimise time-on-task effects. The drive was aimed to simulate a night-time/twilight rural drive with 100 km/h straight sections of road and 80 km/h winding sections. A single carriageway, two-lane road (traffic in both directions) was used throughout the test. There were no intersections but there was a single car to overtake (7 min into the test) traveling 20 km/h slower than the participant's vehicle. Participants were instructed to stay in left lane (standard for Australia) – apart from when overtaking another car – and keep as close as possible to the speed limit. Driving performance was assessed using six dependent variables: three speed and three lane position measures.

The speed measurements were calculated as the speed subtracted from the speed limit sampled 25 times per second. From this, mean deviation from the speed limit and speed variability (the standard deviation around these means) were calculated. The third variable was speed violations: the cumulative time (in minutes) that participants spent more than 5 km/h over the speed limit during the 10 min task.

Lane position was taken as the distance in meters from the centre point of the car to the road verge. With participants driving in the left lane this was the left edge of the road. Again, sampled 25 times per second, mean lane position and lane position variability (standard deviation) were calculated, as well as a measure of lane violations. This was a count of the number of occasions that the centre line of the car left the road or the car made contact with the car being overtaken (also known as crash frequency) (Arnedt et al., 2001).

Measurements of core body temperature (CBT) were recorded using a self-administered indwelling rectal thermistor (Steri-probe 491B, Cincinatti Sub-Zero Products, Cincinnati, Ohio) worn by the participants continuously during the study, connected to a Mini Mitter data logger (Bend, Oregon) worn as a waist pack.

2.3. Protocol

In order to assess the effect of prior wake and circadian phase independently, a 28 h forced desynchrony protocol was used, adapted from the protocol explained by Darwent et al. (2010) and reported elsewhere (Sargent et al., 2010; Zhou et al., 2010, 2011a,b). The current protocol differed by the addition of a sleep restriction component to the 28 h forced desynchrony frame work. The protocol ran for 12 days consisting of two training days and a baseline day, followed by seven 28 h days comprising of 23.33 h of wake followed by 4.67 h of time in bed. During the two training days, participants completed seven training drives to extinguish learning effects. Following this, participants completed performance test batteries 2 h after waking and at 2.5 h intervals after that, totalling nine tests per day. Each 28 h day lasted 4 h longer than the circadian day, so that each day of testing commenced at six different times of the day – or circadian phases. As a result, performance was measured for each prior wake dose of 2 h, 4.5 h, 7 h, 9.5 h, 14.5 h 17 h, 19.5 h and 22 h in each of the six circadian phases 0°, 60°, 120° 180° 240° and 300°. This allowed for comparisons of performance at the same time of day but with different doses of prior wake, or for comparisons of performance at the same dose of prior wake but at different times of the day, thereupon uncovering the desynchronised effects of time of day and prior wake. Profile of Mood States, subjective sleepiness and Psychomotor Vigilance Test data are presented elsewhere (Hampton et al., 2010; Heath et al., 2010; Zhou et al., 2010, 2011a,b). Sound, temperature (22 ± 1 °C), light (10–15 lux) and meals were controlled and participants were temporally and socially isolated throughout the experimental protocol.

2.4. Statistical analysis

The CBT measurements recorded throughout the study were used to derive estimates for the intrinsic circadian period for each participant, and were divided into six × 60° bins of circadian phase using a method described in Darwent et al. (2010). Speed and lane data were extracted from the simulator in .04 s epochs and mean, variability and violation dependent variables were calculated from this. Performance data were expressed relative to each participant's average on the baseline day and were folded into the six circadian phase bins and the nine doses of prior wake. A mixed models analysis of variance was run for each dependent variable, with fixed factors of prior wake, circadian phase, a 'Day' variable – to capture growing sleep debt – as well as two-way and three-way interaction terms (circadian phase × prior wake, prior wake × sleep debt, sleep debt × circadian phase, circadian phase × prior wake × sleep debt). The variable of 'Subject ID' was also entered as a random effect into the analyses to account for between-subject variability.

3. Results

The results are reported by circadian, prior wake, day and interaction effects. Fig. 1 presents the performance change measured by all six driving variables as a function of prior wake and time of day relative to participants' mean baseline scores. Results of the mixed models ANOVA are summarised in Tables 1A and 1B.

3.1. Time of day effect

The results from the mixed models ANOVAs depicted a main effect of time of day on all dependent variables of speed variability, lane position variability and lane violations, shown in Tables 1A and 1B. From Fig. 1 it can be seen that performance was worst after the circadian nadir (60°) which coincides with the early morning hours under normal entrainment, while performance was best at the circadian peak (180°) which corresponds with early evening hours.

3.2. Prior wake effect

There was a main effect of prior wake on the lane-keeping variables of lane position variability and lane violations (Table 1B). Performance declined with increasing hours of prior wake, and this was particularly evident as prior wake extended past the habitual 16 h of wakefulness (Fig. 1).

3.3. Day/sleep debt effect

The 'Day' variable, capturing the growing sleep debt through the protocol, was also significant for all driving measures with the exception of mean lane position (Tables 1A and 1B). The performance on Day 1 (low sleep debt) was better than on Day 7 under conditions of high sleep debt. While this day effect is thought to be due to the growing sleep debt, it cannot be isolated from any possible time in laboratory effect.

3.4. Interactions

In the speed deviation and lane violations measures there were two-way interaction effects (circadian phase × prior wake, prior wake × sleep debt, sleep debt × circadian phase) between all of the independent variables (Fig. 2). Additionally, for all of the driving measures there was a three-way (circadian × prior wake × sleep debt) interaction effect (Tables 1A and 1B). By plotting the extreme points (both high and low) for each variable (in Fig. 2) the directions of the two-way interactions become clear. Each interaction has been plotted twice to observe the effect in both directions. Fig. 2A shows that when prior wake is short there is little to no circadian effect on simulated driving performance. However, there was a large circadian effect when prior wake is long. At the circadian peak (Fig. 2B), there was no effect of prior wake (even with 22 h of wakefulness). However, the effect of prior wake was more prominent at the circadian nadir. The influences of prior wake and circadian position were both present on Day 1 and Day 7 (Fig. 2D and F), but on Day 7 (with high sleep debt) the effects of prior wake and circadian position were more pronounced.

4. Discussion

Previous literature has listed circadian position (time of day), sleep homeostasis and task related factors as determinants of fatigue (Williamson et al., 2011). While task differences were not explored in the current study, time of day and sleep homeostasis - in terms of prior wake and sleep debt - were shown to have a significant influence on simulated driving performance, individually. In addition to these main effects, significant two-way and three-way interactions were also observed.

4.1. The prior wake and time of day interaction

Driving performance under sleep restriction was influenced by both hours of prior wake and time of day; however, the influences were largely dependent upon each other. The performance-cost of every hour of prior wake changed greatly depending on what time of day it was. To consider the interaction in the opposite direction, the time of day (circadian position) became a bigger factor when prior wake was extended. These findings are consistent with those of previous studies that attempted to measure time of day and prior wake influences. When Williamson and Friswell (2008) compared two 28 h sleep deprivation groups – one started at midnight while the other started at 06:00 h – they also found a significant interaction. Although time of day and extended wake (sleep deprivation) main effects were not found, when large prior wake coincided with the early morning the performance deficits were greatest. The lack of main effects reported by Williamson and Friswell (2008) may have been due to several reasons. In the current study, each of the nine prior wake doses occurred in every 60° circadian phase bin allowing for multiple comparisons. Williamson and Friswell (2008) could only make a single comparison. Circadian position in the current study was measured from core body temperature, and all the circadian positions were aligned. Williamson and Friswell (2008) kept participants on their natural cycle so the position of each participant's circadian nadir would have differed according to individual differences.

4.2. The lack of time of day effects in the absence of other influences

The findings suggest that the presence of the time of day influence on driving performance (under this short task duration) is dependent on the length of prior wake or the presence of sleep debt (expressed in Fig. 2A and E). This finding is also consistent with previous studies. Macchi et al. (2002) showed that the presence of a 3 h afternoon nap (reducing prior wake) was sufficient in greatly decreasing the circadian influence on performance. The finding that the time of day effect depends on prior wake and sleep shows promise. It suggests (from simulated driving) that people are able to drive safely, at least for a short period, during their circadian nadir provided that the conditions are very well controlled – they have had sufficient sleep, have not been awake too long and the drive is of minimal difficulty. In the present study, the drive was of low stimulus frequency; without traffic lights, intersections, oncoming traffic and little leading traffic. This was to keep a level of monotony within the task, without which the brief drive may have lacked sensitivity. These impractical provisos limit the applicability of the findings to the real world. Still, the finding does provide a positive base from which longer and more complex driving tasks can be examined.

4.3. Sleep restriction drives the other influences

The most significant conclusion that can be drawn from the results is that all of the factors (prior wake, time of day and the

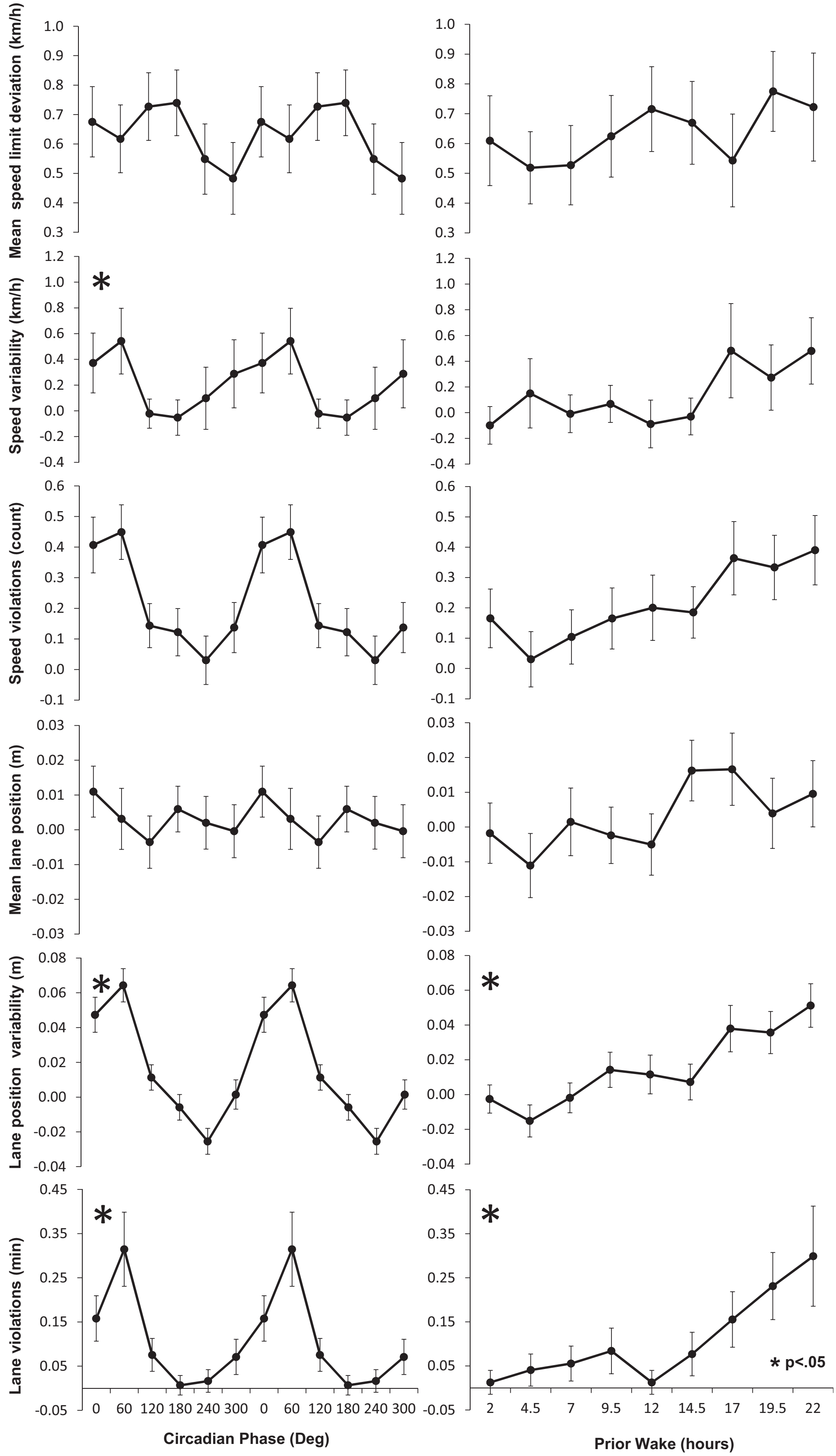

Fig. 1. Speed and lane measures of driving performance, relative to baseline, split by circadian position and hours of prior wake, shown with standard errors.

Table 1A
Empirical results from mixed models ANOVAs for speed variables ($n = 14$).

	df	Speed variables (*P* values)		
		Mean	Standard Deviation	Violations
Time of day	1566	ns	.006	ns
Prior wake	8566	ns	ns	ns
Day	6566	.016	.010	.007
Circadian × Prior wake	40,566	ns	.014	ns
Circadian × Day	30,566	ns	.007	ns
Prior Wake × Day	48,566	ns	.031	ns
Circadian × Prior wake × Day	40,566	<.001	<.001	.017

Table 1B
Empirical results from mixed models ANOVAs for lane variables ($n = 14$).

	df	Lane variables (*P* Values)		
		Mean	Standard Deviation	Violations
Time of day	1566	ns	<.001	<.001
Prior wake	8566	ns	.005	<.001
Day	6566	ns	.008	<.001
Circadian × Prior wake	40,566	ns	ns	<.001
Circadian × Day	30,566	ns	ns	<.001
Prior Wake × Day	48,566	ns	ns	<.001
Circadian × Prior wake × Day	40,566	.002	.001	<.001

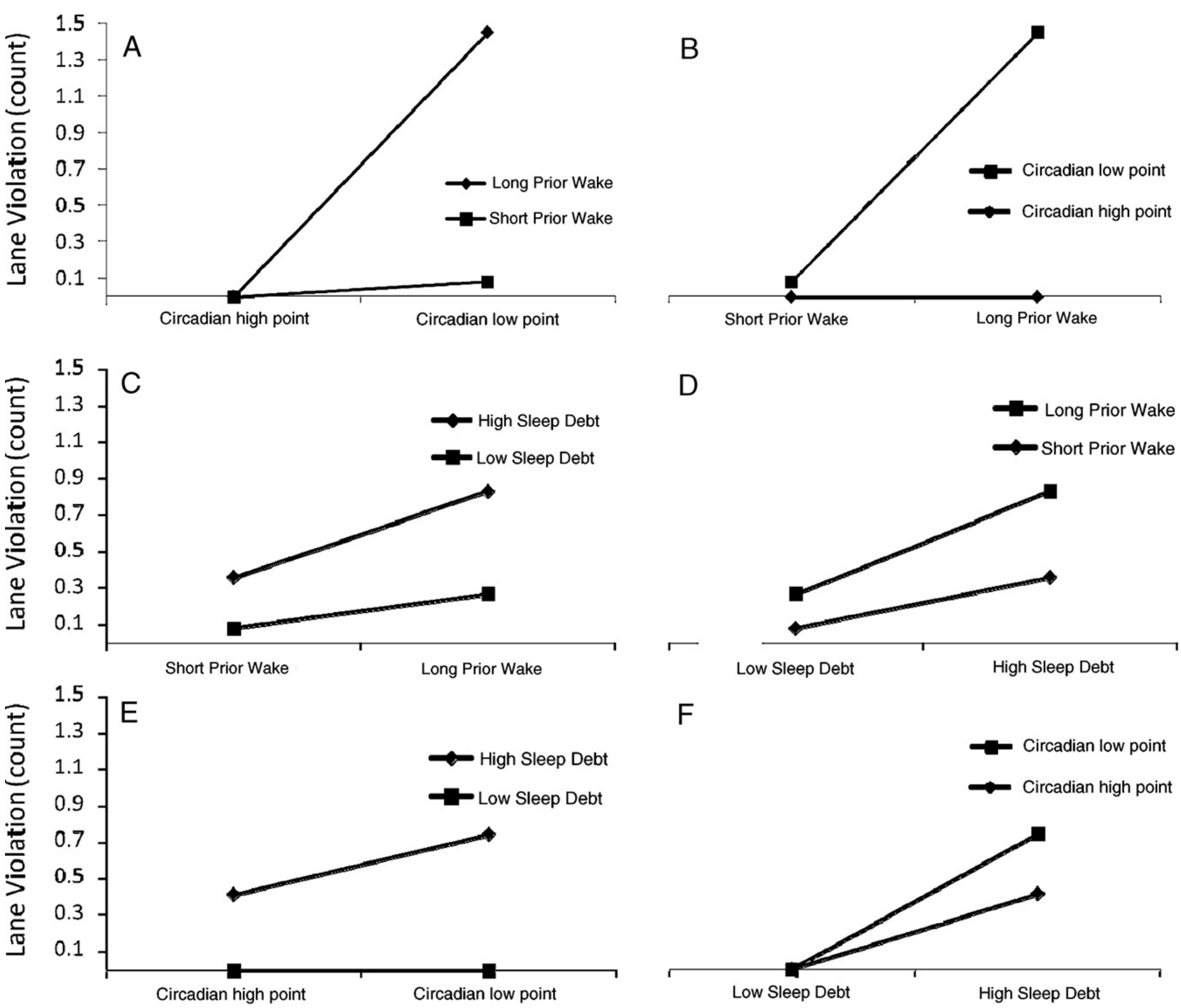

Fig. 2. Mean count of lane violations during the 10 min simulated drive, relative to participants' baseline performance, graphed by minimum and maximum for circadian, prior wake and sleep debt scores, indicating the direction each two-way interaction effects.

interactions) become more influential when sleep is restricted. Driving performance is worse due to the effect of sleep restriction, but in addition, the effect of increasing prior wake on driving performance becomes larger, the time of day effect becomes larger, and finally the three-way interaction term adds a compounding effect in addition to these others. These results mean that performance gets a lot worse and it gets worse more quickly when sleep is restricted. This conclusion is mirrored by accident studies. Connor et al. (2002) investigated the association between sleepiness and the risk of an injury-causing crash. They concluded that sleepiness while driving increased the risk of a road accident considerably – especially between 02:00 h and 05:00 h.

4.4. The magnitude of the driving performance deficit

It has been clearly shown that performance in simulator studies overestimates the deficits in naturalistic 'real world' driving (Philip et al., 2005). The York driving simulator has also been used to investigate driving performance under the influence of alcohol (Arnedt et al., 2001; Powell et al., 2001). Extrapolating from Arnedt et al. (2001) 5 minute task block, the frequency of lane violations (crashes) escalated from .2 with a zero Blood Alcohol Concentration (BAC) to one at .05% BAC and two violations per 10 min at .08% BAC. It follows then that the change in performance associated with this interaction (22 h of prior wake at the circadian nadir) equates to driving performance seen in individuals that have BACs of between .05% and .08%, which is dangerous in the real world.

5. Conclusions

This research helps to fill a gap in the knowledge indicated in the recent fatigue and safety review by Williamson et al. (2011). The circadian influence was revealed and its combined effects with other determinants of fatigue have been shown. A systematic investigation of the prior wake influence was also achieved. These two factors combined with reduced sleep are identified with conditions of high fatigue risk. In simulated driving, this is when long prior wake occurs at the circadian nadir (early morning), or a large sleep debt coincides either with the circadian nadir or with long prior wake. These conditions should be managed and minimised through education, counter-measures and altered shift duration implemented by fatigue risk management systems or regulatory frameworks. Restricting driving to times when prior wake is low and biological alertness is high is impractical. However, we can encourage good sleeping habits through education campaigns and continue to develop fatigue risk management systems that help ensure that sufficient sleep is obtainable, in order to minimise the influences of prior wake, time of day and their associated interaction effects, on driving performance.

Acknowledgments

The authors would like to acknowledge the Australian Research Council for its financial support; Kathryn Reid, Stuart Baulk, and Cameron van den Heuvel for providing access to, and support of, the York Driving Simulator; Gemma Paech, Louise Williams and Georgina Heath for their substantial contribution to data collection.

References

Arnedt, J.T., Wilde, G.J.S., Munt, P.W., MacLean, A.W., 2001. How do prolonged wakefulness and alcohol compare in the decrements they produce on a simulated driving task? Accident Analysis and Prevention 33, 47–54.

Belenky, G., Wesensten, N.J., Thorne, D.R., Thomas, M.L., Sing, H.C., Redmond, D.P., Russo, M.B., Balkin, T.J., 2003. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose–response study. Journal of Sleep Research 12, 1–12.

Campagne, A., Pebayle, T., Muzet, A., 2004. Correlation between driving errors and vigilance level: influence of the driver's age. Physiology and Behavior 80, 515–524.

Colquhoun, W.P, 1971. Circadian variation in mental efficiency. In: Colquhoun, W.P. (Ed.), Biological Rhythms in Human Performance. Academic Press, New York, pp. 39–107.

Connor, J., Norton, R., Ameratunga, S., Robinson, E., Civil, I., Dunn, R., Bailey, J., Jackson, R., 2002. Driver sleepiness and risk of serious injury to car occupants: population based case control study. British Medical Journal 324, 1–5.

Contardi, S., Pizza, F., Sancisi, E., Mondini, S., Cirignotta, F., 2004. Reliability of a driving simulation task for evaluation of sleepiness. Brain Research Bulletin 63, 427–431.

Darwent, D., Ferguson, S.A., Sargent, C., Paech, G., Williams, L., Zhou, X., Matthews, R.W., Dawson, D., Kennaway, D.J., Roach, G.D., 2010. Contribution of core body temperature, prior wake time, and sleep stages to cognitive throughput performance during forced desynchrony. Chronobiology International 27, 898–910.

Dawson, D., Noy, Y.I., Härmä, M., Åkerstedt, T., Belenky, G., 2011. Modelling fatigue and the use of fatigue models in work settings. Accident Analysis and Prevention 43, 549–564.

Dinges, D.F., Kribbs, N., 1991. Performing while experimentally sleepy: effects of experimentally-induced sleepiness. In: Monk, T.H. (Ed.), Sleep, Sleepiness and Performance. John Wiley & Sons Ltd., Chichester, pp. 97–128.

Gander, P., Hartley, L., Powell, D., Cabon, P., Hitchcock, E., Mills, A., Popkin, S.M., 2011. Fatigue risk management: organizational factors at the regulatory and industry/company level. Accident Analysis and Prevention 43, 573–590.

Hampton, L.K., Darwent, D., Matthews, R.W., Heath, G., Ferguson, S.A., Sargent, C., Kennaway, D.J., Roach, G.D., 2010. The influence of circadian phase and prior wake on positive and negative mood during a sleep-restricted forced desynchrony protocol. In: Sargent, C., Darwent, D., Roach, G.D. (Eds.), Living in a 24/7 World: The Impact of Circadian Disruption on Sleep, Work and Health. Australasian Chronobiology Society, Adelaide, pp. 13–17.

Heath, G., Sargent, C., Darwent, D., Ferguson, S.A., Kennaway, D.J., Hampton, L.K., Matthews, R.W., Roach, G.D., 2010. Subjective mood is influenced by sleep-related and circadian processes in a forced desynchrony protocol with severe sleep restriction. In: Sargent, C., Darwent, D., Roach, G.D. (Eds.), Living in a 24/7 World: The Impact of Circadian Disruption on Sleep, Work and Health. Australasian Chronobiology Society, Adelaide, pp. 7–11.

Horrey, W.J., Noy, Y.I., Folkard, S., Popkin, S.M., Howarth, H.D., Courtney, T.K., 2011. Research needs and opportunities for reducing the adverse safety consequences of fatigue. Accident Analysis and Prevention 43, 591–594.

Klauer, S., Sudweeks, J., Hickman, J., Neale, V., 2006. How risky is it? An Assessment of the Relative Risk of Engaging in Potentially Unsafe Driving Behaviors. AAA Foundation for Traffic Safety Research Report. Virginia Tech Transportation Institute, Virginia.

Lenné, M.G., Triggs, T.J., Redman, J.R., 1997. Time of day variations in driving performance. Accident Analysis and Prevention 29 (4), 431–437.

Lyznicki, J.M., Doege, T.C., Davis, R.M., Williams, M.A., 1998. Sleepiness, driving, and motor vehicle crashes. American Medical Association 279, 1908–1913.

Macchi, M.M., Boulos, Z., Ranney, T., Simmons, L., Campbell, S.S., 2002. Effects of an afternoon nap on nighttime alertness and performance in long-haul drivers. Accident Analysis and Prevention 34 (6), 825–834.

Maycock, G., 1997. Sleepiness and driving: the experience of U.K. car drivers. Accident Analysis and Prevention 29, 453–462.

McCartt, A.T., Ribner, S.A., Pack, A.I., Hammer, M.C., 1996. The scope and nature of the drowsy driving problem in New York State. Accident Analysis and Prevention 28, 511–517.

Noy, Y.I., Horrey, W.J., Popkin, S.M., Folkard, S., Howarth, H.D., Courntey, T.K., 2011. Future directions in fatigue and safety research. Accident Analysis and Prevention 43, 495–497.

Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Åkerstedt, T., Charles, A., Bioulac, B., 2005. Fatigue, sleepiness, and performance in simulated versus real driving conditions. Sleep 28, 1511–1516.

Powell, N.B., Schechtman, K.B., Riley, R.W., Li, K., Troell, R., Guilleminault, C., 2001. The road to danger: the comparative risks of driving while sleepy. Laryngoscope 111, 887–893.

Richter, S., Marsalek, K., Glatz, C., Gundel, A., 2005. Task-dependent differences in subjective fatigue scores. Journal of Sleep Research 14, 393–400.

Sargent, C., Ferguson, S.A., Darwent, D., Kennaway, D.J., Roach, G.D., 2010. The influence of circadian phase and prior wake on neuromuscular function. Chronobiology International 27, 911–921.

Williamson, A.M., Friswell, R., 2008. Fatigue and driving: disentangling the relative effects of time of day and sleep deprivation. In: Proceedings of the 2008 Australasian Road Safety Research, Policing and Education Conference, Adelaide, p. 7.

Williamson, A., Lombardi, D.A., Folkard, S., Stutts, J., Courtney, T.K., Connor, J.L., 2011. The link between fatigue and safety. Accident Analysis and Prevention 43, 498–515.

Wong, K.K.H., Marshall, N.S., Grunstein, R.R., Dodd, M.J., Rogers, N.L., 2008. Comparing the neurocognitive effects of 40 h sustained wakefulness in patients with untreated OSA and healthy controls. Journal of Sleep Research 17, 322–330.

Zhou, X., Ferguson, S.A., Matthews, R.W., Sargent, C., Darwent, D., Kennaway, D.J., Roach, G.D., 2010. Interindividual differences in neurobehavioral performance in response to increasing homeostatic sleep pressure. Chronobiology International 27, 922–933.
Zhou, X., Ferguson, S.A., Matthews, R.W., Sargent, C., Darwent, D., Kennaway, D.J., Roach, G.D., 2011a. Dynamics of neurobehavioral performance variability under forced desynchrony: evidence of state instability. Sleep 34, 57–63.
Zhou, X., Ferguson, S.A., Matthews, R.W., Sargent, C., Darwent, D., Kennaway, D.J., Roach, G.D., 2011b. Mismatch between subjective alertness and objective performance under sleep restriction is greatest during the biological night. Journal of Sleep Research, doi:10.1111/j.1365-2869.2011.00924.x.