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

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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 ±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 × prior wake, prior wake × sleep debt, sleep debt × circadian phase) and one three-way interaction (circadian × prior wake × 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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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