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Cognitive components of simulated driving performance: Sleep loss effects and predictors

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ABSTRACT

Driving is a complex task, which can be broken down into specific cognitive processes. In order to determine which components contribute to drowsy driving impairments, the current study examined simulated driving and neurocognitive performance after one night of sleep deprivation. Nineteen professional drivers (age 45.3 ± 9.1) underwent two experimental sessions in randomised order: one after normal sleep and one after 27 h total sleep deprivation. A simulated driving task (AusEd), the psychomotor vigilance test (PVT), and neurocognitive tasks selected from the Cognitive Drug Research computerised neurocognitive assessment battery (simple and choice RT, Stroop Task, Digit Symbol Substitution Task, and Digit Vigilance Task) were administered at 10:00 h in both sessions. Mixed-effects ANOVAs were performed to examine the effect of sleep deprivation versus normal sleep on performance measures. To determine if any neurocognitive tests predicted driving performance (lane position variability, speed variability, braking RT), neurocognitive measures that were significantly affected by sleep deprivation were then added as a covariate to the ANOVAs for driving performance. Simulated driving performance and neurocognitive measures of vigilance and reaction time were impaired after sleep deprivation ($p < 0.05$), whereas tasks examining processing speed and executive functioning were not significantly affected by sleep loss. PVT performance significantly predicted specific aspects of simulated driving performance. Thus, psychomotor vigilance impairment may be a key cognitive component of driving impairment when sleep deprived. The generalisability of this finding to real-world driving remains to be investigated.

1. Introduction

Drowsy driving is a contributing factor in a large proportion of motor vehicle accidents and related deaths around the world (Horne and Reyner, 1999; Connor et al., 2001). Sleep-related accidents are particularly prevalent in commercial motor vehicle drivers (Lyznicki et al., 1998; Sabbagh-Ehrlich et al., 2005). These types of accidents do not appear to be solely due to the driver falling asleep at the wheel, as laboratory studies have demonstrated that brief sleep episodes do not fully account for all of the performance decrements evident in sleep-deprived individuals (Welsh et al., 1998; Russo et al., 2000). For example, microsleeps, or bursts of delta or theta activity in the EEG, only preceded 18% of crashes in one driving simulator study; which is too infrequent to explain the incidence of crashes (Welsh et al., 1998). Supporting this view, other studies have reported that drivers are often awake and have their eyes open when they crash (Åkerstedt and Gillberg, 1990). This finding suggests that other aspects of motor, perceptual, and/or cognitive processing may be impaired in sleepy drivers, accounting for the increased sleep-related accident risk.

Driving is a complex task that requires a number of skills. The driver continuously receives information from the road scene, analyses it, and reacts according to knowledge of traffic systems, driving regulations, conditions of the vehicle, applications of the road rules and their previous driving experiences. Driving also involves the processing of complex visual, tactile, and auditory information in order to produce a well-coordinated motor output (Anstey et al., 2005). Simulated driving tasks have been designed to tap into the key processes that are involved in the task of driving. In addition, driving simulations have the ability to examine driving-related performance in a controlled, measurable, and safe environment (Gillberg et al., 1996). Sleep deprivation, sleep restriction, circadian variations and extended periods of time-on-task have been shown to cause a qualitative decrement in driving performance in

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both on-road and simulated driving tasks (Welsh et al., 1998; Pizza et al., 2004; Åkerstedt et al., 2005; Howard et al., 2007).

As driving involves a number of cognitive processes working in concert, it is difficult to determine from a simulated driving task alone which components are causing the impairment in overall driving performance. A number of cognitive domains have been associated with crash risk in on-road driving studies, including attention and vigilance, visual processes, processing speed and reaction time, working memory and executive function (Anstey et al., 2005). Many of these functions also overlap with neurocognitive impairments observed in sleep deprived individuals (Koslowsky and Babkoff, 1992; Jackson and Van Dongen, 2011).

Driver inattention has been identified as one of the leading causes of motor vehicle accidents (Treat et al., 1977). Low scores on attention and vigilance tasks are associated with higher crash-risk rates and on-road driving performance (Findley et al., 1995; Arnedt et al., 2005). Visual attention performance significantly predicts real-world accident frequency (Owsley et al., 1991). Aspects of motor speed, such as simple visual reaction time, are also important skills in adverse situations (e.g. being able to brake quickly if a pedestrian steps out on the road). Moderate correlations have been observed between simple reaction time tasks and on-road driving performance, with stronger correlations observed for complex reaction time (McKnight and McKnight, 1999). Slowing of reaction times and lapses in attention are also commonly observed after periods of extended wakefulness (Dinges et al., 1997; Van Dongen et al., 2003), and are associated with lane drifting on a simulated driving task (Baulk et al., 2008).

Driving is primarily automatised, although it does involve some shifts to controlled processing when routine reactions are insufficient to deal with novel or complex traffic situations (Lundqvist, 2001). Therefore, information processing speed is an important component of driving. The driver needs to process multiple stimuli simultaneously, select and filter stimuli according to the road situation, and process the information in a short time frame in order to judge the traffic scene and act appropriately (Lundqvist, 2001). The Digit Symbol Substitution Test (DSST) is one measure that assesses information processing and motor speed, and has been shown to be related to simulated driving performance in rested subjects (Szlyk et al., 2002). Impairments in DSST performance have also been observed in some (Williamson and Feyer, 2000; Van Dongen et al., 2003) but not all (Van Steveninck et al., 1999) studies of sleep restricted subjects.

Executive, higher order function is required for integrating new introspective, sensory and situational information, whilst suppressing distracting information by focusing attention on relevant stimuli and planning a response. A number of tasks that tap into executive functions have been found to correlate with driving skills (Lundqvist, 2001; Daigneault et al., 2002; Szlyk et al., 2002; Ramaekers et al., 2006a,b). The frontal cortex is largely thought to control attention and executive function and is vulnerable to even a single night of sleep deprivation, as demonstrated in neuroimaging studies (Drummond et al., 1999; Thomas et al., 2000; Jackson et al., 2011). Conditions that impair frontal lobe functioning, such as sleep deprivation and aging, may negatively impact on driving performance. This can potentially lead to a driver taking inappropriate risks, having poor insight into performance deficits, perseverating on maladaptive thoughts and actions, and having problems making behavioural modifications based on new information from the road scene.

Precisely what aspects of driving performance are affected in sleep deprived individuals remains unclear. Neurocognitive tasks may detect more subtle underlying impairments in an individuals' driving performance not detected by real-world driving or driving simulators (Szlyk et al., 2002). In particular, the relationship and predictive value of neurocognitive tasks for simulated driving under conditions of sleep deprivation has not been examined. To determine which cognitive functions are associated with sleep-related driving impairment, this study employed a range of neurocognitive tasks that assess different cognitive components of driving and that have previously been shown to relate to crash risk. The aim of this study was to examine simulated driving and neurocognitive performance after a single night of sleep deprivation, and also examined the association between neurocognitive outcomes and driving performance measures.

2. Methods

2.1. Subjects

Nineteen professional drivers (1 female), aged between 23 and 62 years (mean age (sd) = 45.3 (9.1) years) participated. A medical practitioner interviewed subjects obtained other physiological measures (e.g. weight, height, blood pressure). Subjects were excluded if they had a medical condition which could be exacerbated by sleep deprivation such as cardiovascular disease, hypertension, epilepsy, diabetes, or psychiatric illness; a sleep disorder (Multivariate Apnea Prediction score > 0.5 (Maislin et al., 1995) or Epworth Sleepiness Scale (ESS) > 10 (Johns, 1991)); were pregnant; could not abstain from smoking cigarettes for 12-h; were high-level caffeine users, defined as five or more caffeinated beverages per day (Lenne et al., 1998); or if they had a visual impairment that did not correct with glasses. Ethics approval was obtained from the Swinburne University Human Research Ethics Committee and the Austin Health Human Research Ethics Committee, and written informed consent was obtained from all subjects.

2.2. Measures

2.2.1. Simulated driving performance

The AusEd driving simulation task was used to assess driving performance (Desai et al., 2007).

Subjects viewed a full screen projection of the view of night time rural road. Subjects drove for 30 min on a continuous 2-lane highway, with a series of straight and curved roads, and were required to use a steering wheel, and brake and accelerator pedals. A small speedometer was displayed in the top left-hand corner of the screen, out of the line of sight of the road. Subjects were instructed to maintain their position in the middle of the left-hand lane on the road, and to keep their speed between 60 and 80 kph. During the drive, ten slowly moving trucks appeared intermittently, travelling in the same direction as the subject's vehicle. Subjects were instructed to brake as quickly as possible when they saw a truck appear in front of them (the truck appears dangerously close to the driver's car). Subjects undertook a 5-min practice drive prior to the experimental day, to become familiar with the road layout and driving instrumentation (steering wheel and pedals) and reduce possible practice effects. In addition the first 6 min of the driving data were removed from data analyses to reduce any initial learning on the task (Desai et al., 2007).

Lane deviation, defined as movement (in centimetres) of the car from the median position of the left hand side of the road, variation in speed (outside the prescribed speed zone 60–80 kph), braking reaction time (ms) and mean number of crashes (off road events, collisions with slow moving trucks, or stopping events >10 s) were used as outcome measures. This simulated driving task is sensitive to performance changes due to sleep deprivation (Desai et al., 2006), circadian rhythms (Banks et al., 2005), sleep disorders (Desai et al., 2006) and alcohol (Howard et al., 2007; Vakulin et al., 2007).

2.2.2. Driving-related cognitive measures

A battery of neurocognitive tasks that test domains that have been found to relate to driving performance (Szlyk et al., 2002) were selected from the Cognitive Drug Research (CDR) computerised assessment battery. The CDR cognitive assessment battery has been shown to be sensitive to acute and chronic cognitive improvements and impairments (Wesnes et al., 2000).

The simple reaction time (SRT) task measured reaction time in response to a single stimulus. Fifty stimuli were presented with a varying inter-stimulus-interval of between 1 and 4 s. The choice reaction time (CRT) task measured the processing time required to identify the correct stimulus ("yes" or "no") and to respond accordingly. During the task, either the word "yes" or the word "no" appeared on the screen, and subjects were required to respond by pressing the corresponding button on the response box as quickly as possible. There were 50 trials with a varying inter-stimulus-interval of between 1 and 4 s. The primary outcome measures for SRT and CRT were the average reaction time (ms).

The Digit Vigilance task assessed focused and sustained attention, and simple reaction time. This computer task required subjects to respond as quickly as possible to a randomly selected target digit (displayed throughout the task on the right side of the screen) every time it appeared in the centre of the screen. Numbers were presented at the rate of 2.5 digits/s for 5 min. Three measures of vigilance were computed: accuracy, reaction time and number of false alarms.

The digit symbol substitution test (DSST) (Wechsler, 1997) is a pen-and-paper task involving attention, response speed and visuomotor coordination. This test consists of nine predetermined symbols that are individually matched with numbers one to nine. Subjects are required to substitute these numbers for the appropriately paired symbols on a test sheet as quickly as possible in 90 s. The total number of symbols correctly drawn out of 100 was recorded.

The colour word Stroop (Stroop, 1935) assesses mental flexibility and the ability to inhibit a response. During the task, subjects are given a page of colour words (blue, yellow and red). In the congruent trial, the words are printed in the congruent colour (i.e. the word "BLUE" written in blue ink), and in the incongruent trial, the words are printed in an incongruent colour (i.e. the word "BLUE" in yellow ink). Subjects were instructed to read out aloud, as quickly as possible, the colour of the ink that the word was written in, ignoring the actual word, and the time taken to read the whole page of words for each trial was recorded. Alternative forms of each task were used in each session where appropriate, to minimise order, practice and learning effects.

In addition to the CDR tasks, the Psychomotor Vigilance Task (PVT; (Dinges and Powell, 1985)) was administered. The PVT is a 10 min, computerised task that assesses sustained attention and reaction time, and requires continuous attention to detect randomly occurring stimuli (Dinges and Powell, 1985; Jewett et al., 1999). The PVT is free of aptitude and learning effects and is reliable and sensitive to performance variations due to sleepiness (Doran et al., 2001). Median reaction time (RT), number of lapses (reaction time >500 ms), reciprocal of reaction times (1/RT) and fastest 10% of RTs were measured.

Subjective sleepiness ratings were measured using the Karolinska Sleepiness Scale (KSS; (Åkerstedt and Gillberg, 1990)). The KSS is a single item scale which asks subjects to rate their current state of sleepiness on a 9-point scale (1 = extremely alert, 9 = extremely sleepy, fighting sleep).

2.3. Procedure

Subjects attended the sleep laboratory for an initial screening session to assess their fitness for inclusion in the study. To reduce the impact of learning on task performance, all subjects underwent standardised practice sessions on the neurocognitive and simulated driving tasks.

Subjects completed two experimental conditions; one following a normal night of sleep (normal sleep) and one following 27 h of sleep deprivation. Sessions were counterbalanced across subjects and were separated by a one week wash-out period to allow for the regulation of the subjects sleep patterns for those who completed the sleep deprivation session first. Time-of-day effects were controlled for by testing all subjects at the same time of day to assess the independent impact of sleep deprivation alone on driving-related performance. Additionally, subjects were tested in the mid-morning to avoid testing in the circadian nadir (i.e. 14:00–16:00 h) where there may have been circadian influences on performance. The period of 27 h of sleep deprivation was chosen as it is a common, realistic level of deprivation which has ecological validity, and also allowed for a protocol to be carried out outside of the circadian nadir.

Subjects were asked to have their normal amount of sleep (between 7 and 9 h) on the night prior to each session, and were instructed to complete a sleep diary in a retrospective fashion each morning for the week preceding each study day. The diary measured total sleep per night and sleep latency each night. No caffeine (e.g. coffee, tea, cola, chocolate) or other stimulants were allowed from midday on the day prior to the session until the conclusion of the session. Subjects were also asked to refrain from smoking throughout experimental sessions.

For the sleep deprivation session, subjects were asked to wake at 07:00 h and attend the sleep laboratory at 22:00 h following a normal 8-h day driving shift. Subjects stayed awake all that night until the following morning, monitored by the laboratory staff. During the night subjects performed passive activities, such as watching videos, reading, or playing board games. The following morning at 07:00 h, subjects were taken to the testing laboratory where neurocognitive testing and simulated driving performance were carried out. A light breakfast was provided at 08:00 h. Subjects then completed the simulated driving task and the neurocognitive tasks. The order of the driving task and neurocognitive test battery was counterbalanced between subjects to avoid order effects. Testing took approximately 3 h. At the end of the testing session, subjects were provided with a taxi voucher for transport home.

The normal sleep session was identical to the sleep deprivation session, differing only in that subjects attended the testing laboratory by taxi at 09:00 h after a normal day shift followed by a normal night of sleep, instead of 27 h sleep deprivation.

2.4. Statistical analysis

Outliers of more than three standard deviations from the mean of any single variable were excluded from the analyses. Missing data (equipment issues, incomplete test) reduced the sample size available for analysis to $n = 18$ for the driving task and PVT, $n = 17$ for subjective sleepiness (KSS) and $n = 16$ for the Stroop task.

Non-parametric tests (Wilcoxin) were used to compare subjective sleepiness responses between the sessions. Mixed-effects ANOVAs were performed to examine the effect of sleep deprivation versus non-sleep deprived on subjective sleepiness (KSS), neurocognitive tests (PVT, DSST, DV, CRT SRT and Stroop task) and driving performance measures (lateral lane position, speed variability, braking RT and crashes). Chi squared statistics was used to examine the differences in proportion of crash events in each session. To determine if any neurocognitive tests predicted driving performance, neurocognitive measures that were significantly affected by sleep deprivation were then added as a covariate to the mixed effects ANOVAs for driving performance (lateral lane position, speed variation, braking RT). Linear regression analysis

Table 1
Means and standard deviations (sd) of the AusEd simulated driving task in the normal sleep and sleep deprivation sessions.

Variable	N	Normal sleep mean (sd)	Sleep deprivation mean (sd)	df	F	p-Value
Lateral lane position (cm)	17	48.4 (18.1)	60.4 (22.6)	1, 16	21.4	0.001
Speed deviation (kph)	17	2.3 (1.0)	3.3 (2.0)	1, 16	9.9	0.006
Mean braking RT (ms)	18	1251.2 (451.3)	1446.5 (500.0)	1, 17	10.9	0.004

RT, reaction time; ms, milliseconds; cm, centimetres; kph, kilometres per hour.

Table 2
Means and standard deviations (sd) of the neurocognitive tasks and the sleepiness scale in the normal sleep and sleep deprivation sessions.

Variable	N	Normal sleep mean (sd)	Sleep deprivation mean (sd)	df	F	p-Value
PVT lapses	18	1.9 (2.6)	5.06 (6.4)	1, 17	6.1	0.02
PVT median RT	18	231.2 (21.6)	256.2 (42.4)	1, 17	11.5	<0.005
Fastest 10% RT	18	189.9 (15.4)	200.3 (24.3)	1, 17	8.8	0.01
1/RT	18	2.7 (0.5)	2.3 (0.8)	1, 17	7.9	0.01
Mean simple RT	18	242.1 (22.9)	258.2 (30.1)	1, 17	11.7	0.003
Mean choice RT	18	424.9 (37.6)	459.9 (55.1)	1, 17	9.7	0.006
Digit Vigilance RT	18	410.6 (30.7)	428.7 (43.4)	1, 17	3.4	0.08
Digit Vigilance FA	18	2.0 (1.8)	1.8 (1.5)	1, 17	0.2	NS
Congruent Stroop (s)	16	32.0 (5.8)	33.4 (5.0)	1, 16	0.01	NS
Incongruent Stroop (s)	17	71.7 (15.8)	72.7 (13.9)	1, 16	0.01	NS
DSST	19	73.9 (16.7)	70.2 (15.8)	1, 17	1.9	0.19
KSS	16	3.0 (2.0)	7.5 (1.7)	1, 15	70.4	<0.001

PVT, psychomotor vigilance test; RT, reaction time; FA, false alarms; DSST, digit symbol substitution test.

was used to determine the proportion of variance in driving performance was explained by the neurocognitive measures. SAS 9.2 (SAS Institute, Cary, NC) was used to perform the Mixed-effects ANOVAs, and SPSS 14 (SPSS Inc., Chicago, IL, USA) was used for all other statistical analyses.

3. Results

3.1. Prior sleep of the subjects

The sleep diary results for the averaged hours of sleep each night for one week prior to each session did not differ between the normal sleep session (mean (sd) = 6.76 (0.99) h) and the sleep deprivation session (6.79 (1.14) h; $p = 0.55$). Similarly, there was no difference in the number of hours of sleep recorded on the night prior to the normal sleep session (6.68 (0.88) h) and the sleep deprivation session (6.90 (0.92) h; $p = 0.98$).

3.2. Effect of total sleep deprivation on performance and subjective sleepiness

Means and standard deviations of the simulated driving task variables are displayed in Table 1.

The simulated driving performance measures lateral lane deviation and speed variability were significantly impaired after sleep deprivation compared to after normal sleep. Subjects were also significantly slower to brake in response to up-coming trucks when sleep deprived. Two subjects had a crash event during the drive in the sleep deprivation session, and three in the normal sleep condition; this was not significantly different ($\chi_2 = 0.45$, $p = 0.50$).

Results from the neurocognitive measures in each condition are displayed in Table 2. Scores on the Karolinska Sleepiness Scale (KSS) were significantly higher in the sleep deprivation session than the normal sleep session, indicating that the sleep deprivation protocol was sufficient to induce higher levels of subjective sleepiness. Simple RT and choice RT were impaired after sleep deprivation. Similarly, PVT lapses and the reciprocal of reaction times were significantly higher in the sleep deprivation session. Median RT and fastest 10% of RTs were significantly slower in the sleep deprivation session.

For the Digit Vigilance task, there was a trend for slower reaction times to targets in the sleep deprivation session. However, there was no significant difference in false alarms between sessions. Information processing speed, measured with the DSST was not significantly affected by sleep deprivation. Executive functioning measured by the Stroop interference score was not significantly different in the sleep deprivation session compared to the normal sleep session.

3.3. Relationship between neurocognitive tasks and driving performance

The PVT was the only task responding significantly to sleep deprivation that was related to driving performance. PVT lapses (RTs > 500 ms) significantly predicted variability in lane position ($F(1, 14) = 5.10$; $p < 0.05$; Fig. 1). PVT median RT ($F(1, 14) = 11.53$; $p < 0.005$), and PVT fastest 10% of RT ($F(1, 14) = 6.37$; $p < 0.05$) predicted a significant proportion of the variance in speed variations (Fig. 2). PVT lapses (RTs > 500 ms) explained 9.9% of the variability in lane position. PVT median RT predicted 40% of the variance in speed variations, and PVT fastest 10% of RT predicted 28% of the variance in speed variations.

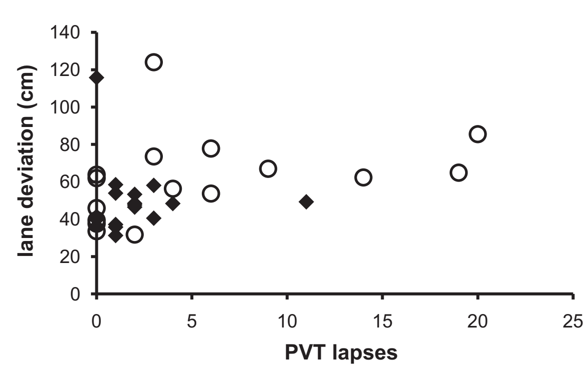

Fig. 1. Relationship between lateral lane deviation on a driving simulator and PVT lapses in the sleep deprivation (open circles) and normal sleep (closed diamonds) sessions.

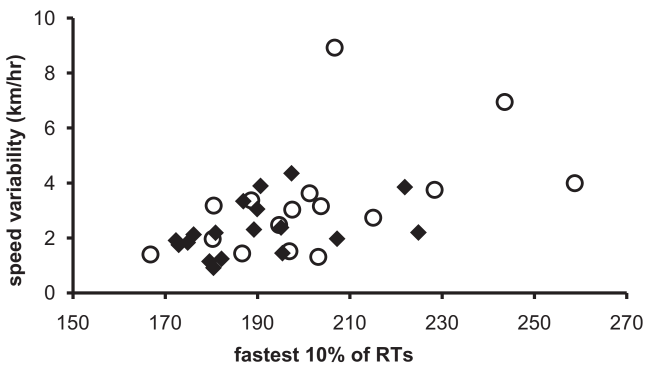

Fig. 2. Relationship between PVT fastest 10% of reaction times (RTs) and speed variability in the sleep deprivation (open circles) and normal sleep (closed diamonds) sessions.

4. Discussion

Sleep deprivation is associated with increased accident risk and driving impairment, although the cognitive dysfunction underlying this impairment is not well understood. The current study sought to examine separate cognitive processes that are used in the task of driving, to determine which of these were most affected by sleep loss, and further, to examine which cognitive functions were *associated* with driving impairment. The main finding of this study was that measures of psychomotor vigilance explained a significant proportion of the variance in simulated driving performance changes observed following sleep deprivation, suggesting that vigilance is a key component of drowsy driving impairments.

Subjects reported higher levels of sleepiness in the sleep deprivation session, indicating that our protocol of one night without sleep was sufficient to produce a significant subjective increase in sleepiness. This was also reflected in the behavioural performance. Performance on the simulated driving task was significantly impaired following one night of sleep deprivation compared to after normal sleep. Lateral lane deviations, variations in speed, and braking reaction times all deteriorated with sleep loss, consistent with previous studies using the AusEd driving simulator (Howard et al., 2007; Vakulin et al., 2007). Variability in lateral lane position is consistently observed in sleepy subjects (Arnedt et al., 2001, 2005; Lenne et al., 1998; Baulk et al., 2008), both on road (Philip et al., 2005a), and in simulator settings (George, 2000; Lenne et al., 1998). This measure is a sensitive indicator of sleepiness-related performance impairment.

Increased variation in speed has been identified during simulated driving following up to 36 h of sleep deprivation (Lenne et al., 1998; Arnedt et al., 2001, 2005; Baulk et al., 2008), consistent with the current findings. Larger variations in speed in the AusEd driving task after sleep deprivation are consistent with a reduced ability to divide attention between the road scene and the speedometer (which is in the top left hand corner of the screen). Previous studies have also noted significant speed decreases and variations outside the prescribed speed range with sleep loss, both of which are indicative of unsafe driving (Brookhuis et al., 2003).

No difference in crash events was observed after sleep deprivation, consistent with previous studies (Philip et al., 2003; Baulk et al., 2008). Crash events on simulators are not as reliable or sensitive to sleep loss as other continuous measures (i.e. lane and speed deviations). Although the current study design resulted in deterioration in other aspects of driving performance, the degree of sleepiness experienced by the subjects in this study may not have been sleepy enough to cause crash events.

The task of driving has been broken down into its constituent parts previously (Lundqvist, 2001; Szlyk et al., 2002). Motor responses, executive functions, working memory and visual reaction time are all important components. Performance on sustained attention tasks (Psychomotor Vigilance Test), and simple reaction time tasks (simple and choice RT) all significantly deteriorated after 27 h of sleep deprivation. These are motor tasks involving vigilance and attention, and performance on such tasks has been shown to decline significantly with sleep loss (Koslowsky and Babkoff, 1992; Lim and Dinges, 2008; Jackson and Van Dongen, 2011). Sleep loss-related performance decrements may be explained by the "lapse hypothesis" (Williams et al., 1959), which suggests that sleep deprived subjects can perform at a relatively high and stable level until a period of inattention occurs and there is a delay in the subjects response. This was reflected by an increase in the number of PVT lapses in sleep-deprived subjects in the current study. Lapse event may have serious consequences for real-world driving performance.

Of the measures that were significantly altered by sleep loss, only PVT performance significantly predicted specific aspects of simulated driving performance. In simulation studies using non-sleep deprived subjects, measures of focused and divided attention, and processing speed, have been found to correlate most highly with lane position, driving speed and brake pedal pressure (Anstey et al., 2005). Similarly, in the current study, PVT lapses significantly predicted variations in lateral lane position. This finding is consistent with Baulk et al. (2008) who reported a significant correlation between PVT lapses and lane drift on the York simulator. Changes in lateral lane position following sleep deprivation indicate a decreased level of vigilance on this performance measure, as has been previously hypothesised (Riemersma et al., 1977; Pizza et al., 2004). Variations in speed were also significantly predicted by speed of motor responses on the PVT. Thus, psychomotor vigilance impairment may be a key cognitive component of driving impairment when sleep deprived.

Some tasks were unaffected by sleep loss in the current experiment, including more complex tasks of executive functioning. This may have been due to the timing of test battery. Sleepiness and performance are believed to be influenced by two biological factors; homeostatic drive (time since waking) and input from the circadian rhythm (time of day) (Borbély, 1982). The interaction between these two systems causes fluctuations in daily performance. Further, these systems have been shown to influence different cognitive tasks in distinct ways (Folkard, 1983). Since the current study focused on the effects of sleep loss and tested subjects during a favourable circadian phase, minimal impact of circadian processes on performance were expected. If we had tested subjects during an adverse circadian time we may have found a greater impairment in driving and vigilance performance, and possibly the emergence of other impairments (e.g. of executive functions).

Nonetheless, there have been conflicting findings regarding the impact of sleep deprivation on the performance of executive tasks (Harrison and Horne, 1998; Sagaspe et al., 2006). Such tasks are the summation of a number of processes, from the initial encoding of information, to motor execution of the response and later cognitive processes, such as attention and memory. Studies that have dissociated the different cognitive components of executive and working memory tasks have found that sleep deprivation affects performance on some, but not all, components of the task (Tucker et al., 2010). Thus, although it may appear that global task performance is unaffected by sleep deprivation, components of the task may still be impaired to some degree. The development and implementation of performance tasks that allow the dissociation and examination of constituent cognitive processes opens up new avenues for understanding the effects of sleepiness on cognitive components of driving.

4.1. Limitations

This study is limited in its generalisability to real world driving due to the use of a simulated driving task. The use of a laboratory based driving task may affect the drivers' decision-making and levels of sleepiness. This may also be limited due to the absence of personal exposure to risk, therefore subjects may not as motivated to perform well on simulated tasks as they are for real-world tasks (i.e. the consequences of crashing on the simulator are not as severe as crashing during actual on-road driving). However, mitigating against this limitation, strong associations have been reported between on-road driving and simulated driving performance in non-sleepy subjects indicating a high transferability of observations between simulated driving and actual driving situations (Lee et al., 2003). Specifically in relation to sleepy individuals, driving simulators can produce performance and sleepiness impairment earlier on in the time course of the drive when compared to real driving (Philip et al., 2005b). However, to date there has been little validation of driving simulators in relation to sleepiness and on-road driving, and so the effect of sleepiness on real-life driving performance needs further evaluation. Although there are clear differences between simulated driving performance and real world driving, this study provides insight into the effects of sleepiness on different skills essential to driving. Real world driving is likely to include additional cognitive elements, such as planning, a different level of motivation, and decision making processes (e.g. hazard perception). Further research in required to evaluate the validity of simulated driving in relation to in situ driving, and to examine the associations between real-world driving and cognition.

5. Conclusion

The findings from the present experiment suggest that a period of acute sleep deprivation can lead to deterioration in a number of driving-related processes, which in turn may affect individuals' ability to drive safely. We identified decrements in driving and psychomotor function and subjective sleepiness following 27 h of acute sleep deprivation during a circadian peak period. While executive function was not significantly affected in this study, combined sleep deprivation and circadian effects (as commonly occurs during night time driving) might have more significant effects on executive function.

Deterioration in vigilance and psychomotor performance explained a large proportion of the variance in lateral lane position and speed variability respectively. This suggests that these measures of vigilance may be large determinants of driving impairment in drowsy drivers.

Laboratory driving tasks do not replicate all the decision making processes of real world driving and it is possible that other cognitive functions would be important in this setting. Psychomotor function and vigilance appears to be a major determinant of laboratory based assessment of driving function. This might be different during real world driving when additional decision making processes are required and other cognitive processes may be important.

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References

Åkerstedt, T., Gillberg, M., 1990. Subjective and objective sleepiness in the active individual. International Journal of Neuroscience 52 (1), 29–37.
Åkerstedt, T., Peters, B., Anund, A., Keckland, G., 2005. Impaired alertness and performance driving home from the night shift: a driving simulator study. Journal of Sleep Research 14, 17–20.
Anstey, K., Wood, J., Lord, S., Walker, J., 2005. Cognitive, sensory and physical factors enabling driving safety in older adults. Clinical Psychology Review 25 (1), 45–65.
Arnedt, J.T., Geddes, M.a.C., Maclean, A.W., 2005. Comparative sensitivity of a simulated driving task to self-report, physiological, and other performance measures during prolonged wakefulness. Journal of Psychosomatic Research 58 (1), 61–71.
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 (3), 337–344.
Banks, S., Catcheside, P., Lack, L., Grunstein, R.R., McEvoy, D., 2005. The maintenance of wakefulness test and driving simulator performance. Sleep 28 (11), 1381–1385.
Baulk, S.D., Biggs, S.N., Reid, K.J., Van Den Heuvel, C.J., Dawson, D., 2008. Chasing the silver bullet: measuring driver fatigue using simple and complex tasks. Accident Analysis and Prevention 40 (1), 396–402.
Borbély, A.A., 1982. A two-process model of sleep regulation. Human Neurobiology 1, 195–204.
Brookhuis, K.A., De Waard, D., Fairclough, S.H., 2003. Criteria for driver impairment. Ergonomics 46 (5), 433–445.
Connor, J., Whitlock, G., Norton, R., Jackson, R., 2001. The role of driver sleepiness in car crashes: a systematic review of epidemiological studies. Accident Analysis and Prevention 33 (1), 31–41.
Daigneault, G., Joly, P., Frigon, J.-Y., 2002. Executive functions in the evaluation of accident risk of older drivers. Journal of Clinical and Experimental Neuropsychology 24 (2), 221–238.
Desai, A., Marks, G., Jankelson, D., Grunstein, R., 2006. Do sleep deprivation and time of day interact with mild obstructive sleep apnea to worsen performance and neurobehavioral function? Journal of Clinical Sleep Medicine 2 (1), 63–70.
Desai, A.V., Wilsmore, B., Bartlett, D., Unger, G., Constable, B., Joffe, D., Grunstein, R.R., 2007. The utility of the AudEd driving simulator in the clinical assessment of driver fatigue. Behaviour Research Methods 39, 673–681.
Dinges, D.F., Pack, F., Williams, K., Gillen, K.A., Powell, J.W., Ott, G.E., Aptowicz, C., Pack, A.I., 1997. Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. Sleep 20 (4), 267–277.
Dinges, D.F., Powell, J.W., 1985. Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. Behavioral and Research Methods Instruments and Computers 17, 652–655.
Doran, S.M., Van Dongen, H.P.A., Dinges, D.F., 2001. Sustained attention performance during sleep deprivation: evidence of state instability. Archives Italiennes de Biologie 139 (3), 253–267.
Drummond, S.P., Brown, G.G., Stricker, J.L., Buxton, R.B., Wong, E.C., Gillin, J.C., 1999. Sleep deprivation-induced reduction in cortical functional response to serial subtraction. Neuroreport 10 (18), 3745–3748.
Findley, L., Unverzagt, M., Guchu, R., Fabrizio, M., Buckner, J., Suratt, P., 1995. Vigilance and automobile accidents in patients with sleep apnea or narcolepsy. Chest 108 (3), 619–624.
Folkard, S., 1983. Diurnal Variation in Human Performance. Wiley, Chichester, England.
George, C.F., 2000. Vigilance impairment: assessment by driving simulators. Sleep 23, S115–118.
Gillberg, M., Kecklund, G., Akerstedt, T., 1996. Sleepiness and performance of professional drivers in a truck simulator—comparisons between day and night driving. Journal of Sleep Research 5 (1), 12–15.
Harrison, Y., Horne, J.A., 1998. Sleep loss impairs short and novel language tasks having a prefrontal focus. Journal of Sleep Research 7 (2), 95–100.
Horne, J.A., Reyner, L., 1999. Vehicle accidents related to sleep: a review. Occupational and Environmental Medicine 56 (5), 289–294.
Howard, M.E., Jackson, M.L., Kennedy, G.A., Swann, P., Barnes, M., Pierce, R.J., 2007. The interactive effects of extended wakefulness and low-dose alcohol on simulated driving and vigilance. Sleep 30 (10), 1334–1340.
Jackson, M.L., Hughes, M., Croft, R., Howard, M.E., Crewther, D., Kennedy, G., Owens, K., Pierce, R., O'Donoghue, F., Johnston, P., 2011. The effect of sleep deprivation on bold activity elicited by a divided attention task. Brain Imaging and Behavior 5 (2), 97–108.
Jackson, M.L., Van Dongen, H.P.A., 2011. Cognitive effects of sleepiness. In: Thorpy, M., Billiard, M. (Eds.), Sleepiness. Cambridge University Press, Cambridge, UK, pp. 72–81.
Jewett, M.E., Dijk, D.J., Kronauer, R.E., Dinges, D.F., 1999. Dose–response relationship between sleep duration and human psychomotor vigilance and subjective alertness. Sleep 22 (2), 171–179.
Johns, M.W., 1991. A new method for measuring daytime sleepiness: the Epworth Sleepiness Scale. Sleep 14 (6), 540–545.
Koslowsky, M., Babkoff, H., 1992. Meta-analysis of the relationship between total sleep deprivation and performance. Chronobiology International 9 (2), 132–136.
Lee, H.C., Lee, A.H., Cameron, D., Li-Tsang, C., 2003. Using a driving simulator to identify older drivers at inflated risk of motor vehicle crashes. Journal of Safety Research 34 (4), 453–459.
Lenne, M.G., Triggs, T.J., Redman, J.R., 1998. Interactive effects of sleep deprivation, time of day, and driving experience on a driving task. Sleep 21 (1), 38–44.
Lim, J., Dinges, D.F., 2008. Sleep deprivation and vigilant attention. Annals of the New York Academy of Sciences 1129, 305–322.
Lundqvist, A., 2001. Neuropsychological aspects of driving characteristics. Brain Injury 15 (11), 981–994.
Lyznicki, J.M., Doege, T.C., Davis, R.M., Williams, M.A., 1998. Sleepiness, driving and motor vehicle crashes. Journal of the American Medical Association 279 (23), 1908–1913.

Maislin, G., Pack, A.I., Kribbs, N.B., Smith, P.L., Schwartz, A.R., Kline, L.R., Schwab, R.J., Dinges, D.F., 1995. A survey screen for prediction of apnea. Sleep 18 (3), 158–166.

McKnight, A.J., McKnight, A.S., 1999. Multivariate analysis of age-related driver ability and performance deficits. Accident Analysis and Prevention 31 (5), 445–454.

Owsley, C., Ball, K., Sloane, M.E., Roenker, D.L., Bruni, J.R., 1991. Visual/cognitive correlates of vehicle accidents in older drivers. Psychology and Aging 6 (3), 403–415.

Philip, P., Sagaspe, P., Moore, N., Taillard, J., Charles, A., Guilleminault, C., Bioulac, B., 2005a. Fatigue, sleep restriction and driving performance. Accident Analysis and Prevention 37, 473–478.

Philip, P., Sagaspe, P., Taillard, J., Moore, N., Guilleminault, C., Sanchez-Ortuno, M., Akerstedt, T., Bioulac, B., 2003. Fatigue, sleep restriction, and performance in automobile drivers: a controlled study in a natural environment. Sleep 26 (3), 277–280.

Philip, P., Sagaspe, P., Taillard, J., Valtat, C., Moore, N., Akerstedt, T., Charles, A., Bioulac, B., 2005b. Fatigue, sleepiness, and performance in simulated versus real driving conditions. Sleep 28 (12), 1511–1516.

Pizza, F., Contardi, S., Mostacci, B., Mondini, S., Cirignotta, F., 2004. A driving simulation task: correlations with multiple sleep latency test. Brain Research Bulletin 63 (5), 423–426.

Ramaekers, J.G., Kauert, G., Van Ruitenbeek, P., Theunissen, E.L., Schneider, E., Moeller, M.R., 2006a. High-potency marijuana impairs executive function and inhibitory motor control. Neuropsychopharmacology 31 (10), 2296–2303.

Ramaekers, J.G., Moeller, M.R., Van Ruitenbeek, P., Theunissen, E.L., Schneider, E., Kauert, G., 2006b. Cognition and motor control as a function of [delta]9-thc concentration in serum and oral fluid: limits of impairment. Drug and Alcohol Dependence 85 (2), 114–122.

Riemersma, J.B.J., Sanders, A.F., Wildervanck, C., Gaillard, A.W., 1977. Performance Decrement During Prolonged Night Driving. Plenum Press, New York.

Russo, M., Thorne, D., Thomas, M., Sing, H., Redmond, D., Hall, S., Balkin, T.J., Wesensten, N.J., Belenky, G., 2000. Sleep-deprivation-induced transient peripheral visual neglect in a driving simulator study. Neurology 54 (Suppl. 3), A206.

Sabbagh-Ehrlich, S., Friedman, L., Richter, E.D., 2005. Working conditions and fatigue in professional truck drivers at Israeli ports. Injury Prevention 11, 110–114.

Sagaspe, P., Sanchez-Ortuno, M., Charles, A., Taillard, J., Valtat, U., Bioulac, B., Philip, P., 2006. Effects of sleep deprivation on color-word, emotional, and specific Stroop interference and on self-reported anxiety. Brain and Cognition 60 (1), 76–87.

Stroop, J.R., 1935. Studies of interference in serial verbal reactions. Journal of Experimental Psychology 18 (6), 643–662.

Szlyk, J.P., Myers, L., Zhang, Y.X., Wetzel, L., Shapiro, R., 2002. Development and assessment of a neuropsychological battery to aid in predicting driving performance. Journal of Rehabilitation Research and Development 39 (4), 483–496.

Thomas, M., Sing, H., Belenky, G., Holcomb, H., Mayberg, H., Dannals, R., Wagner, H., Thorne, D., Popp, K., Rowland, L., Welsh, A., Balwinski, S., Redmond, D., 2000. Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. Journal of Sleep Research 9 (4), 335–352.

Treat, J.R., Tumbas, N.S., Mcdonald, S.T., Shinar, D., Hume, R.D., Mayer, R.E., Stansifer, R.L., Castellan, N.J., 1977. Tri-level Study of the Causes of Traffic Accidents. Government Printing Office, Washington, DC.

Tucker, A.M., Whitney, P., Belenky, G., Hinson, J.M., Van Dongen, H.P.A., 2010. Effects of sleep deprivation on dissociated components of executive functioning. Sleep 33 (1), 47–57.

Vakulin, A., Baulk, S.D., Catcheside, P.G., Anderson, R., Van Den Heuvel, C.J., Banks, S., Mcevoy, R.D., 2007. Effects of moderate sleep deprivation and low-dose alcohol on driving simulator performance and perception in young men. Sleep 30 (10), 1327–1333.

Van Dongen, H.P.A., Maislin, G., Mullington, J.M., Dinges, D.F., 2003. The cumulative cost of additional wakefuleness: dose–response effects on neurobehavioual functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep 26 (2), 117–126.

Van Steveninck, A.L., Van Berckel, B.N.M., Schoemaker, R.C., Breimer, D.D., Van Gerven, J.M.A., Cohen, A.F., 1999. The sensitivity of pharmacodynamic tests for the central nervous system effects of drugs on the effects of sleep deprivation. Journal of Psychopharmacology 13 (1), 10–17.

Wechsler, D., 1997. WAIS-III Administration and Scoring Manual. The Psychological Corporation, San Antonio, Texas.

Welsh, A., Thomas, M., Thorne, D., 1998. Effects of 64 h of sleep deprivation on accidents and sleep events during a driving simulator test. Sleep 21, S234.

Wesnes, K.A., Ward, T., Mcginty, A., Petrini, O., 2000. The memory enhancing effects of a ginkgobiloba/panax ginseng combination in healthy middle aged volunteers. Psychopharmacology 152, 353–361.

Williams, H., Lubin, A., Goodnow, J., 1959. Impaired performance with acute sleep loss. Psychological Medicine. Monograph Supplement 73, 1–23.

Williamson, A.M., Feyer, A.M., 2000. Moderate sleep deprivation produces impairments in cognitive and motor performance equivalent to legally prescribed levels of alcohol intoxication. Occupational and Environmental Medicine 57 (10), 649–655.