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

M.L. Jackson[a,b,*], R.J. Croft[c], G.A. Kennedy[a,b], K. Owens[d], M.E. Howard[b]

[a] School of Social Sciences and Psychology, Victoria University, Victoria, Australia
[b] Institute for Breathing and Sleep, Department of Respiratory and Sleep Medicine, Austin Health, Australia
[c] School of Psychology, University of Wollongong, Wollongong, Australia
[d] Brain Sciences Institute, Swinburne University of Technology, Melbourne, Australia

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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

* Corresponding author at: School of Social Sciences and Psychology, Victoria University, St. Albans 3021, Victoria, Australia. Tel.: +61 3 99199582; fax: +61 3 99192218.
E-mail address: melinda.jackson@vu.edu.au (M.L. Jackson).

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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).