Driving Performance Associated with the Morning Commute Improves Over a Week of Simulated Night Shifts

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Abstract

Commuters driving home from a night shift are at greater risk of having a motor vehicle accident due to extended wake episodes, sleep loss and circadian misalignment. Over consecutive night shifts, driving performance may improve as the circadian system adapts to the sleep-wake schedule, or decline with the accumulation of sleep loss. The aim of this study was to investigate driving performance associated with the post night shift commute over seven consecutive night shifts. Sixty-seven subjects undertook seven simulated night shifts under laboratory conditions. Following each shift, participants performed a 20-minute simulated driving task. Driving performance was assessed using lane variability (i.e. standard deviation of lateral position), speed variability (i.e. standard deviation of speed), and the likelihood of crashing and speeding relative to a daytime drive. Lane variability, speed variability and the likelihood of crashing declined over seven consecutive night shifts. The likelihood of speeding exhibited no change. These findings indicate that driving performance improved over the seven consecutive night shifts. The trend in performance likely reflected the adaptation of the circadian system. These results indicate that relatively short sequences of night shifts that dominate most Occupational Health and Safety guidelines may not always be optimal in minimizing fatigue-related risk.

Declaration

"This thesis contains no material which has been accepted for the award of any other degree of diploma in any University, and, to the best of my knowledge, this thesis contains no material previously published except where due reference is made. I give permission for the digital version of this thesis to be made available on the web, via the University of Adelaide's digital thesis repository, the Library Search and through web search engines, unless permission has been granted by the School to restrict access for a period of time."

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Chapter 1

Introduction

1.1 Preamble

Shift work is a fundamental part of the 24-hour society that we live in today. Approximately 1.1 million Australians, or 9.8% of the workforce, undertake night shifts as a part of their normal work schedule (Australian Bureau of Statistics, 2012; 2015). Relative to day workers, those who work at night are more likely to make errors, be injured at work and to have a crash while driving home from a shift (Gold et al., 1992; Horwitz & McCall, 2004; Stutts et al., 2003). These challenges arise due to the misalignment between the sleep-wake schedule imposed by night shifts and the sleep-wake promoting signals of the human circadian system. Specifically, night shift workers are required to work when the circadian system is promoting sleep; and to sleep during the day when the circadian system is promoting wake.

For several decades, experts have debated the best way to arrange shift sequences to minimise problems associated with sleep loss and circadian misalignment (e.g. Folkard, 1992; Wilkinson, 1992). Central to this debate is the question as to whether night shift sequences should be relatively short (i.e. 2-4 days) or relatively long (i.e. 4-14 days). Both approaches have potential advantages; short sequences may reduce the accumulation of sleep loss, while long sequences may provide an opportunity for the circadian system to adapt to the nocturnal schedule (Folkard, 1992; Wilkinson, 1992).

Every time night shift workers commute home from work they are exposed to a significant amount of accident risk (Lee et al., 2016). The sleep promoting effects of the circadian system, in combination with an extended wake episode and prior sleep loss, creates a critical period of alertness and performance vulnerability in the early hours of the morning (Matthews et al., 2012). The number of consecutive night shifts to minimise the risk associated with the post night commute is thus an important practical issue worthy of investigation. The following chapter reviews the literature on the regulation of sleep and wake, the problems associated with shift work, the adverse post night shift effect on driving performance, and the accumulation of sleep loss and adaptation of the circadian system over successive night shifts. The chapter concludes with the rationale, aims and hypotheses of the study.

1.2 The Regulation of Sleep and Wake

The three main variables to consider when examining the sleep and wake function of night shift workers is (i) the amount of sleep obtained between shifts, (ii) the amount of time elapsed since waking, and (iii) the time of day or ‘circadian phase’. The two-process model of sleep/wake regulation provides a theoretical framework for understanding the physiological processes underlying each variable (Borbely, 1982). The two-process model of sleep/wake regulation posits that sleep and wake is regulated by the interaction between a homeostatic process and a circadian process (Borbely, 1982). The circadian process, controlled by the endogenous circadian pacemaker, generates a 24-hour rhythm in sleep propensity and alertness, which promotes wakefulness during the biological day (i.e. one’s habitual wake time) and promotes sleepiness during the biological night (i.e. one’s habitual sleep time; Dijk & Lockley, 2002). The homeostatic process represents a drive for sleep that increases progressively during wakefulness, and decreases progressively during sleep. The homeostatic component is affected by both acute sleep loss (i.e. a continuous wake episode) and chronic sleep loss (i.e. the accumulation of sleep loss over days). Higher homeostatic sleep drive results in impaired cognition, increased sleepiness and increased propensity for sleep (Doran et al., 2001; Van Dongen et al., 2003). It is the interaction between these two processes that influences the quality of waking function and of sleep, and forms the basis for understanding the problems associated with shift work including circadian misalignment, extended wake periods and sleep loss.

1.3 The Problems Associated With Night Shifts

1.3.1 Circadian Misalignment. One of the challenges associated with working night shifts is operating at a time when the circadian system is promoting sleep and sleeping at a time when the system is promoting wake. The endogenous circadian pacemaker maintains the timing of many psychological and physiological variables in humans with a near 24-hour rhythm (Czeisler et al., 1999; Zhou et al., 2011). The circadian rhythm of core body temperature is a robust physiological marker of the timing of the circadian system, and is closely related to the timing of sleep and wake. The daily minimum in core temperature (CBT_{min}), which coincides with the daily nadir of the circadian cycle, occurs ~5 hours after habitual bedtime (Cagnacci et al., 1996; Brown et al., 1997), and the daily maximum in core body temperature (CBT_{max}), which coincides with the daily peak in the circadian cycle, occurs ~12 hours after CBT_{min} (Dijk et al., 1992). In an individual whose habitual sleep time is 23:00-07:00 hours, CBT_{min} will occur in the early hours of the morning (~04:00hr), while CBT_{max} will occur in late afternoon (~16:00hr). Maximal sleepiness and poorest cognitive/physical performance occur 2-3 hours either side of CBT_{min}; in contrast, maximal alertness and optimal cognitive/physical performance occurs 2-3 hours either side of CBT_{max} (Dijk et al., 1992). Figure 1 illustrates the theoretical relationships between time of day/circadian phase and the circadian rhythms of alertness, performance and core body temperature.

Human circadian rhythms are synchronised to the 24-hour day by environmental stimuli referred to as ‘zeitgebers’ (Aschoff et al., 1971). Sunlight is the most powerful zeitgeber for humans (Wever et al., 1983; Czeisler et al., 1986); however, other factors such as physical activity and eating are also likely contributors (Mistlberger & Skene, 2004). The human circadian system cannot immediately entrain to the timing of zeitgebers in a new sleep-wake schedule (Wever, 1980). Therefore, at the beginning of a series of night shifts, when workers are transitioning from a diurnal schedule to a nocturnal schedule, there is a period of desynchrony as the circadian system adapts to the timing of zeitgebers in the sleep-wake schedule imposed by night shifts (Boivin et al., 2007). During this period of desynchrony, night shift workers are required to work at the time of the circadian nadir, when sleepiness is greatest and performance is worst (Dijk et al., 1992), and to sleep in the daytime during the raising phase of the circadian alertness rhythm, when the circadian drive for sleep is low (Czeisler et al., 1980).

1.3.2 Extended Periods of Wakefulness. The amount of time elapsed since waking is an important factor for night shift workers as the cost of prior wakefulness on alertness and performance is greater for individuals operating at night, compared with those who operate during the day. As wakefulness accumulates and the homeostatic drive for sleep increases, performance becomes progressively impaired (Doran et al., 2001). However, during habitual periods of wakefulness (i.e. wake periods that coincide with the normal waking day), alertness and performance remain

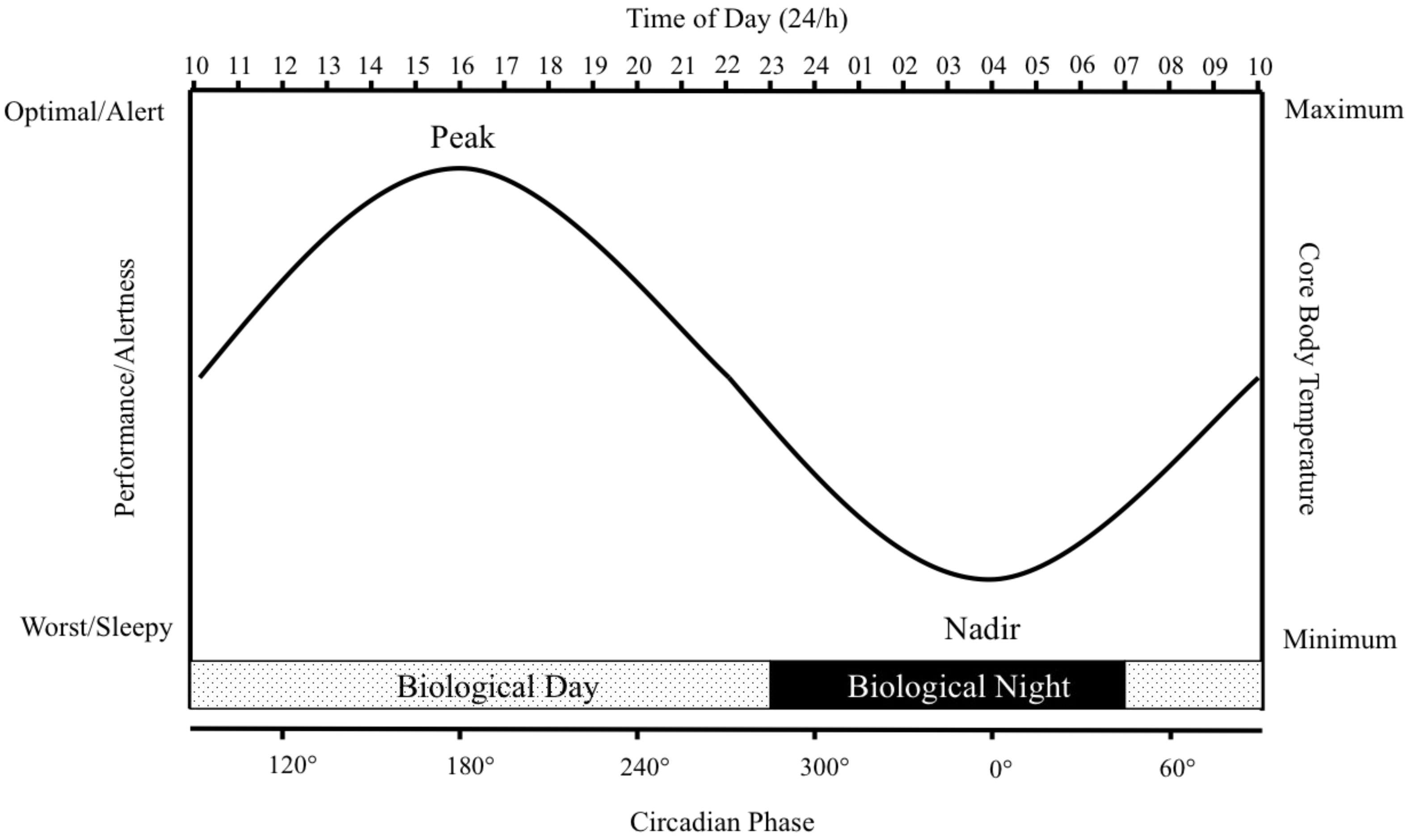

Figure 1. The theoretical relationships between time of day/circadian phase and the circadian rhythms of alertness, performance and core body temperature. The time of day mirrors the circadian phase of an individual whose habitual sleep time (or biological night) is 23:00-07:00 hours.

relatively stable over a period of 16 hours (Dijk et al., 1992; Doran et al., 2001). This instance, experienced by most individuals who operate during the biological day, is due to the effects of the circadian system. The decline in performance associated with prior wake is counteracted by the wake-promoting signals of circadian system during this time (Dijk et al., 1992; Wyatt et al, 1999). During the biological night however, the adverse circadian effect on performance worsens as the hours of wakefulness accumulates (Dijk et al., 1992). Contrary to day operators, prior wake within a range of 0-18 hours during the night impairs performance considerably (Dijk et al., 1992). This interaction implies that those who work during the biological night, such as night shift workers, are most vulnerable to the consequences of circadian misalignment after extended periods of wakefulness.

Wake periods are particularly extended during the first night in a series of shifts (Folkard, 1992). A significant proportion of night shift workers (~50%) do not nap prior to starting the first night shift (Knauth et al. 1981). In such circumstances, workers could be awake for up to 24 consecutive hours by the end of the first night shift, a duration of wakefulness associated with increased accidents, injuries and errors (Folkard, 1992; Barger et al., 2005). Notably, 19 and 24 hours of sustained wakefulness (beginning at 08:00 hours) have been shown to coincide with performance impairments equivalent to blood alcohol concentrations (BAC) of 0.05% and 0.10%, respectively (Dawson & Reid, 1997). Hence, many individuals working the first night in a series of shifts often experience levels of acute sleep deprivation equivalent to proscribed levels of alcohol intoxication towards the end of the shift.

1.3.3 Sleep Loss. Obtaining an adequate amount of sleep between shifts is a significant challenge for night shift workers (Akerstedt, 2003). This is because sleep duration is dependent on the circadian phase at which it occurs (Czeisler et al., 1980). Sleep initiated at the nadir of the core body temperature rhythm (i.e. in the early morning) tends to be shorter and of decreased quality than sleep initiated at or after the peak of the core body temperature rhythm (i.e. in the late evening), even when homeostatic factors such as the duration of prior wake are controlled for (Czeisler et al., 1980). Considering night shift workers typically initiate sleep in close proximity to the termination of their shift (Knauth et al., 1981), sleep occurs in the morning, following the nadir of the core body temperature rhythm and during the rising phase of the circadian alertness rhythm. As a consequence, frequent sleep disruption and inadequate amounts of sleep between shifts are common in the shift worker population (Akerstedt, 2003). Workers will typically sleep between 2-4 hours less during the day following a night shift (i.e. ~4-6 hours total), than at night following a day shift (i.e. ~6-8 hours total; Torsval et al., 1989; Akerstedt et al., 1991).

The accumulation of sleep loss has significant consequences for night shift workers undertaking a series of night shifts. Research shows that an average of 7-8 hours of sleep per night is required for daily optimal neurobehavioral function (Van Dongen et al., 2003). Chronic sleep restriction of nocturnal sleep episodes to less than 6 hours per night results in cumulative and dose-dependent performance deficits (Van Dongen et al., 2003). Specifically, sleep restricted to 4 and 6 hours per night for 14 consecutive nights produces neurobehavioral performance deficits equivalent to two and one night(s) of total sleep deprivation, respectively (Van Dongen et al., 2003). Evidently, the adverse impact of sleep restriction is most pronounced at the core body temperature nadir (i.e. in the early hours of the morning) than at the peak (i.e. in the late evening; Zhou et al., 2011). In this sense, the elevated homeostatic sleep pressure attributable to chronic sleep restriction is amplified by the circadian sleep-promoting stimuli during the biological night. This interaction implies that the sleep restriction studies described earlier (Van Dongen et al., 2003), which assessed individuals performance during the biological day, likely underestimate the extent of neurobehavioral impairment experienced by chronically sleep deprived individuals who operate during the biological night, such as night shift workers (Zhou et al., 2011).

1.4 Minimising the Problems Associated with Working at Night via the Arrangement of Shift Sequences

The minimisation of risk is an important factor when considering the arrangement of night shift schedules. Relative to day workers, those who work at night are more likely to make errors, be injured at work and to have a crash while driving home from a shift (Gold et al., 1992; Horwitz & McCall, 2004; Stutts et al., 2003). The optimal length of night shift sequences to reduce these risks depends on the adaptation of the circadian system and the accumulation of sleep loss over successive nights. Short sequences (i.e. 1-4 nights) may reduce the accumulation of sleep loss, while long sequences (i.e. 4-14 nights) provide an opportunity for the circadian system to adapt to the nocturnal schedule. The following section discusses the literature on the adaptation of the circadian system and accumulation of sleep loss over successive nights.

1.4.1 The Accumulation of Sleep Loss Over Consecutive Night Shifts. The accumulation of sleep loss over successive night shifts is typically cited as the mechanism responsible for the observed increase in accident and injury risk over successive night shifts. Folkard & Akerstedt (2004) reviewed a number of studies and calculated the risk of accidents and injuries on successive night shifts relative to the first night shift. The risk for accident and injury was 6% higher on the second night shift, 17% higher on the third night shift, and 36% higher on the fourth night shift. It was hypothesized that the progressive increase in risk associated with successive night shifts is best explained by the accumulation of sleep loss over successive nights (Folkard & Akerstedt, 2004). However, the review did not calculate risk beyond four night shifts, as only two out of the seven studies reported incident rates beyond this period (Vinogradova et al., 1975; Wagner, 1988). Notably, in these studies, risk began to decline following the fourth night shift (Vinogradova et al., 1975; Wagner, 1988). This could be taken as evidence for the adaptation of the circadian system. However, the authors of the review discounted these findings, as they were based on a relatively small number of incidents (Folkard & Akerstedt, 2004).

The trend in neurobehavioral performance is also cited as evidence for the accumulation of sleep loss over successive nights. In a number of field studies, when sleep was found to be less than ~6 hours per day, the effect of sleep loss on performance over successive night shifts varied (Magee et al., 2016; Ganesan et al., 2019; Ferguson et al., 2011; Hansen et al., 2010). Neurobehavioral performance either declined as a function of consecutive night shifts (Magee et al., 2016; Ferguson et al., 2011), remained stable over the course of successive nights (Ganesan et al., 2019), or improved with each consecutive shift (Hansen et al., 2010). In the few studies that assessed circadian phase, it was evident that very little or no circadian adaptation occurred when performance declined over successive nights (Magee et al., 2016; Ferguson et al., 2011). However, when circadian adaptation did occur (i.e. when the circadian phase of maximal sleepiness shifted later in the day) performance improved, even when the average sleep duration between shifts was ~6 hours (Hansen et al., 2010). The adverse impact of chronic sleep restriction on performance is well established (Van Dongen et al., 2003), however the extent to which it contributes to performance deficits in the night shift population remains unclear, and likely depends on the adaptation of the circadian system.

1.4.2 The Adaptation of the Circadian System Over Consecutive Night Shifts. The problematic symptoms of night work can be reduced by the adaptation of the circadian system over successive nights. When the circadian system delays, and the period of maximal sleepiness shifts later in the day, the benefit is two-fold: performance and alertness improve while at work, and daytime sleep improves in the break between shifts (Boudreau et al., 2013). The light-dark cycle, in which all diurnal individuals experience naturally when they sleep at night and are awake during the day, is the most powerful zeitgeber in humans (Wever et al., 1983; Czeisler et al., 1986). When altered, it has the ability to reset, or phase shift, the circadian system until the proper phase relationship between the light-dark cycle and the circadian system is restored, a process called re-entrainment. The direction and size of the phase shift in response to light exposure depends on the circadian phase at which it occurs. Light exposure in the ~12 hours prior to CBT_{min} results in a phase delay (i.e. shifts the circadian system later), and light exposure in the ~12 hours after CBT_{min} results in a phase advance (i.e. shifts the circadian system earlier; Czeisler et al., 1989; Khalsa et al., 2003). The largest phase shifts transpire when light exposure occurs in the 3-6 hours either side of CBT_{min}, when the duration of exposure is relatively long, and when the intensity of light is relatively high (Czeisler et al., 1989; Khalsa et al., 2003)

The phase shifting ability of the sleep-wake schedule imposed by night shifts and it’s effect on performance and sleep quality have been demonstrated in a number of night shift simulation studies. In theory, the sleep-wake schedule of a night shift worker should facilitate a phase delay, as night shift workers are typically exposed to a greater proportion of light prior to CBT_{min} than after CBT_{min} (Czeisler et al., 1989). Under laboratory conditions, the rate of circadian delay over a number of simulated night shifts ranges from 0.2 and 1.4 hours per day (Dawson & Campbell, 1991; Dawson et al., 1995; Harma et al., 1994). Provided adaptation is sufficient over a number of days, the circadian period of maximal sleepiness may no longer occur during the night shift but rather during the day when workers are required to sleep. Lamond et al. (2003) showed that when the circadian system delays over a number of consecutive night shifts, both neurobehavioral performance and the quality of day sleep improves with each successive night shift.

The extent of adaptation among night shift workers in the field, however, varies considerably. A review of six studies examining the adaptation of permanent night shift workers reported that only a relatively small proportion of workers showed complete (<3%) or partial (21%) adaptation to night work following 3-9 consecutive night shifts (Folkard, 2008). Notably, these studies were reviewed on the basis of typicality, in the sense that night work was conducted in typical urban environments. The conflict between night work and social life, coupled with the inevitability of conflicting light-dark exposure, serves as a likely explanation for the lack of adaptation shown in these environments (Folkard, 2008).

The adaptation of night shift workers in atypical environments such as remote mine sites, offshore oilrigs and arctic bases, provide an important insight to this phenomenon due to limited family and social contact, and varying degrees of light exposure (Ferguson et al., 2012; Hansen et al., 2010; Midwinter & Arendt, 1991).

When night shift workers are exposed to dim lighting at night (i.e. >10 lux), such as tipper truck drivers, their circadian system does not delay, day sleep does not improve, and performance declines over consecutive shifts (Ferguson et al., 2012). However, when shift workers are exposed to normal indoor light at night (i.e. ~350-500 lux), such as control room operators, their circadian system delays, day sleep gets better, and performance improves over successive night shifts (Hansen et al., 2010). This implies that adaptation to night shifts may be dependent on a number of variables such as lighting conditions and the social environment.

In summary, circadian adaptation to night shifts may reduce the risks associated with working at night due to the improvement in alertness, performance and day sleep over consecutive nights (Hansen et al., 2010; Lamond et al., 2003). However, the absence of circadian adaptation is problematic due to the accumulation of sleep loss and it's ensuing impairment of alertness and performance over successive night shifts (Magee et al., 2016; Ferguson et al., 2012). Circadian adaptation to night shifts is most likely dependent on environmental and job specific factors (e.g. Ferguson et al., 2012; Hansen et al., 2010). Therefore, relatively long sequences of night shifts may only be optimal in reducing risk in work places/environments that favor circadian adaptation, while short sequences may only be optimal in work places where circadian adaptation is unlikely to occur.

1.5 The Night Shift Driving Commute

In Australia, approximately 20-30% of all motor vehicle crashes are sleep-related, making it one of the most preventable causes of deaths on the road (Austroads, 2016; Australian Transport Safety Bureau, 2002). Shift workers are over represented in sleepiness-related motor vehicle crashes (Crummy et al., 2008), with the commute home following a night shift associated with the greatest risk (Barger et al., 2005).

As previously discussed, the alertness and performance of night shift workers are compromised by three main factors: an adverse circadian phase, an extended wake episode, and the accumulation of sleep loss. A number of studies have explored both the independent effects of, and interactions between each variable on driving performance (Mathews et al., 2012; Kosmadopoulos et al., 2017). Driving performance is worst at the nadir of the core body temperature rhythm, and declines with increasing hours of prior wake and with the accumulation of sleep loss over a number days (Matthews et al., 2012; Kosmadopoulos et al., 2017). The performance cost of prior wake and sleep loss also depends on circadian phase (Matthews et al., 2012; Kosmadopoulos et al., 2017). Specifically, the performance impairment due to the sleep promoting effects of the circadian system at the circadian nadir amplifies as the hours of prior wake and sleep loss accumulates (Matthews et al., 2012; Kosmadopoulos et al., 2017).

Following a night shift, elevated levels of homeostatic sleep pressure attributable to an extended period of wakefulness and the accumulation of sleep loss, interacts with the sleep promoting signals of the circadian system. This interaction creates a critical period of alertness and performance vulnerability in the early hours of the morning when commuters are required to drive home (Matthews et al., 2012; Kosmadopoulos et al., 2017). This critical period of performance vulnerability is reflected in numerous studies reporting a severe post night shift effect on driving performance. The following changes in driving performance have been observed following a night shift: (i) an increase in lane variability and major incidents in a driving simulator (Akerstedt et al., 2005; Reyner & Horne, 1998); (ii) an increase in the objective assessment of dangerous driving and near-crash events while operating a real motor vehicle (Lee et al., 2016); and (iii) an increase in self-reported instances of adverse driving events in naturalistic settings (Ftouni et al., 2013; Mulhall et al., 2019).

Yet, studies investigating driving performance over consecutive night shifts are sparse. Currently, the only published study to investigate driving performance over successive night shifts examined self-reported driving incidents among a sample of shift workers in their natural environment (Mulhall et al., 2019). Over four consecutive night shifts, sleep-related events (e.g. falling asleep at a stop light) were highest following the first night, inattention-events (e.g. being distracted) were highest on subsequent nights, and hazardous driving events (e.g. braking sharply) exhibited no change over consecutive night shifts. Notably, inferences associated with these findings are limited by the unreliability of self-report measures, and the relatively short number of consecutive night shifts that were examined.

1.6 The Current Study

The number of consecutive night shifts to minimise the risks associated with circadian misalignment and sleep loss is of great practical interest to stakeholders in the shift work industry. Every time night shift workers drive home from work they are exposed to a significant amount of accident risk (Lee et al., 2016). Most studies to date have only examined driving performance associated with single post night shift commutes (e.g. Akerstedt et al., 2005; Lee et al., 2016). Few studies have investigated driving performance over consecutive night shifts (Mulhall et al., 2019), which has the potential to improve as the circadian system adapts to the sleep-wake schedule

(Boudreau et al., 2013; Lamond, 2003), or decline with the accumulation of sleep loss (Van Dongen et al., 2003). The current study aimed to address this research gap by investigating simulated driving performance associated with the post night shift commute over seven consecutive simulated night shifts. Driving performance was assessed in a driving simulator following each consecutive night shift. Lane variability (i.e. the standard deviation of lateral position), speed variability (i.e. the standard deviation of speed), and the likelihood of crashing and speeding relative to a daytime drive (using a relative risk ratio) were used as the performance outcomes. Subjective pre-drive sleepiness was also assessed using the Karolinska Sleepiness Scale (KSS). It was hypothesised that the performance on each variable would improve over the seven consecutive night shifts. The specific research aims and hypotheses are presented in Table 1. The underlying rationale for the hypotheses of the study were based on the expectation that individuals would adapt to the sleep-wake schedule imposed by the night shift simulation.

Table 1

Aims and Hypotheses for the Current Study

Aim 1:	Investigate lane and speed variability over seven consecutive night shifts
Hypothesis 1:	The standard deviation of lateral position (SDLP) will decline over the seven consecutive night shifts
Hypothesis 2:	The standard deviation of speed (SDSP) will decline over the seven consecutive night shifts
Aim 2:	Investigate pre-drive sleepiness over seven consecutive night shifts
Hypothesis 3:	Pre-drive Karolinska Sleepiness Scale (KSS) scores will decline over the seven consecutive night shifts
Aim 3:	Investigate the likelihood of crashing and speeding over seven consecutive night shifts
Hypothesis 4:	The relative risk of a crash occurring (relative to a daytime drive) will decline over the seven consecutive night shifts
Hypothesis 5:	The relative risk of a speed violation occurring (relative to a daytime drive) will decline over the seven consecutive night shifts

Chapter 2

Method

2.1 Participants

Participants were 34 healthy males and 33 healthy females with a mean (±SD) age of 22.94 (3.56) years and body mass index of 21.55 (1.92) kg/m^2. Participants were recruited via advertisements on the public sales website ‘Gumtree’ and flyers placed on noticeboards at local universities and backpacker hostels (Appendix A). Participants were required to pass a screening process that involved an interview with a senior member of the research staff and the completion of a general health questionnaire (Appendix B). Wrist actigraphy and sleep dairy data were used to ensure participants maintained consistent sleep durations (between 7-9 hours per night) and bedtimes (between 22:00 and 00:00 hours) in the week prior to study admission (Appendix C & D). Participants were excluded from the study if they smoked, used caffeine or alcohol excessively, had any medical or physical disorders, had irregular sleep patterns, or had undertaken shift work or trans meridian travel in the previous two months. Participants received an honorarium for their involvement that amounted to $1080 AUD. Five participants voluntarily withdrew from the study for personal reasons.

2.2 Ethics

The human research ethics committee of Central Queensland University granted ethics approval for the study (approval number: [redacted]).

2.3 Measures

2.3.1 Simulated Driving Task. Driving was assessed using the York Driving Simulator (York Computer Technologies, Kingston, Canada). The simulated driving task was conducted on a desktop computer using a steering wheel fixed to the desk and acceleration and brake pedals attached to the floor. The simulator monitor presents a forward view from the driver's seat, with standard lane markings and signs suitable for a road environment. A digital speedometer is located on the dashboard. The driving task was 20-minutes in duration and simulated a nighttime rural drive on a two-way single lane road, with target speeds of 110km/h on straight sections and 80km/h on winding sections. Participants were instructed to keep as close to the target speeds as possible and maintain a position within the middle of the left lane.

Driving performance was assessed using a number of lane and speed variables. Speed was sampled at 25 times per second. Speed variability was operationalised as the standard deviation of speed (SDSP) for the total drive. Lateral position was also sampled 25 times per second and reflected the distance in meters from the center point of the car to the center point of the left lane. Lane variability was operationalised as the standard deviation of lateral position (SDLP) for the total drive. SDLP and SDSP are standard measures of driving performance and measure the extent to which the driver has control over the lateral position and speed of the vehicle (Verster & Roth, 2011). An increase in either SDSP or SDLP is indicative of greater speed and lane variability, respectively, and thus poorer driving performance (Verster & Roth, 2011).

Crash and speed violations were used as the binary factor for the calculation of crash and speed risk. A crash occurred when all four wheels of the simulated motor vehicle exited the road environment. Given Australian drivers typically adhere to a speeding tolerance of 10% above the speed limit (Fleiter & Watson, 2006), a speed violation was computed when the speed limit was exceeded by 10% in 110km/h zone (i.e. speeds greater than 121km/h). Speed violations in the 80km/h zone were not included in the analyses as the majority of participants exceeded 80km/h by 10% when transitioning from the 110km/h to the 80km/h zone.

The York Driving Simulator has been used as an assessment of driving performance in a number of fatigue-related studies, and is sensitive to the effects of extended wakefulness (Arnedt et al., 2005); sleep loss (Kosmadopoulous et al., 2017), and circadian misalignment (Mathews et al., 2012).

2.3.2 Pre-drive Sleepiness. Subjective Sleepiness was assessed using the 9-point Karolinska Sleepiness Scale (KSS). The scale requires participants to rate their current alertness/sleepiness level, from 1 = “Extremely alert”, to 9 = “Very sleepy, great effort to keep awake, fighting to sleep” **(**Appendix E). Subjective ratings of sleepiness using the KSS are considered a sensitive and valid indicator of insufficient sleep and impaired waking function, comparable to objective measures (Akerstedt et al., 2014).

2.4 Procedure

2.4.1 Setting. The study was performed in a windowless and sound attenuated laboratory. The laboratory was configured to accommodate six participants at a time. Participants were assigned their own private bedroom, living room, workstation and bathroom facility. A communal dining area was utilised for meal consumption. The behavior of the participants was monitored in person and via surveillance cameras (except in the bathrooms) to ensure compliance with the study protocols.

The temperature in the laboratory was controlled to maintain a constant ambient temperature between 21-23°C. During the night shift simulation, the lighting changed in accordance with the time of day and sleep/wake schedule. During wake periods, the lighting was set to a bright setting (350 lux) between the hours of the 07:00–22:30, and a dim setting (75 lux) between the hours of 22:30–07:00. During all designated sleep periods, the lights were extinguished (<0.03 lux).

2.4.2 Protocol. The protocol ran for nine days and consisted of two training days, followed by seven consecutive night shifts (Figure 2 - Panel A). Training days were utilised for training participants on the driving simulator task, which included three practice sessions. Participants were given feedback to ensure they were adhering to the speed limit and keeping the car in the middle of left lane. Baseline measures for the driving simulator task were taken after the practice sessions and on the second training day. Sleep periods during this time functioned to eliminate any prior sleep debt, and were delayed to help transition participants onto the first night shift the following night, a strategy utilised by many shift workers (Akerstedt, 2003).

Over the course of the night shifts, participants performed five test batteries. Each test battery consisted of five cognitive and neurobehavioral tasks. Four tasks were performed one after the other on a desktop computer and the final task was performed on a portable handheld unit. Each test battery was identical and took approximately 40 minutes to complete. In between test batteries, participants had free time and were permitted to watch movies, read, draw or listen to music.

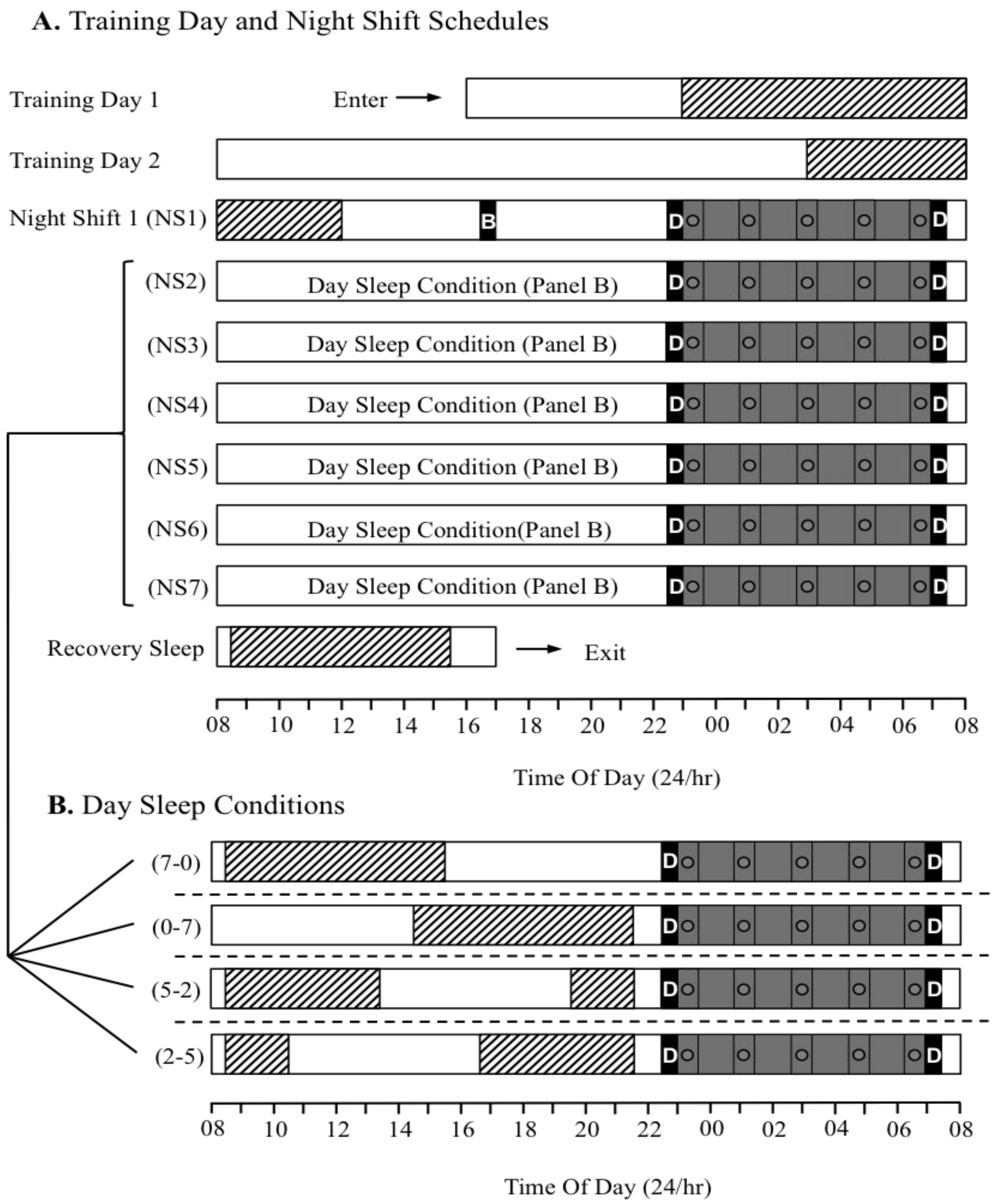

Figure 2. Study Protocol. In panel **(A)**, the Y-axis represents days in the protocol. In panel **(B)** the Y-axis represents the day sleep conditions. In both panels, the striped rectangles represent time in bed (TIB), the black rectangles with the letter 'D' represent the driving simulator task while the letter 'B' corresponds to the baseline measure. Grey rectangles represent the night shift simulation and the circles within the night simulation corresponds to the five test batteries. In panel **(B)**, the temporal placement of TIB between night shifts depended on whether participants were randomly assigned the morning strategy (7-0), the evening strategy (0-7), the polymorphic strategy #1 (5-2) or the polymorphic strategy #2 (2-5).

To simulate a commute to and from work, participants performed the driving simulator task immediately before and after each night shift. For the simulation following the night shift, a light box was placed behind the computer display screen to simulate the expected light exposure from the sun when driving home in the morning with sunglasses on (~750-800 lux). Participant's subjective sleepiness (via KSS) was recorded immediately before each drive.

Given the current study was a part of a broader study investigating the efficacy of common daytime sleep strategies adopted by shift workers, participants were randomly assigned to one of four daytime sleep conditions between night shifts (Roach et al. 2016). Figure 2 - Panel B represents the four day-sleep conditions. The morning condition (7-0 condition) constituted a single 7-hour sleep episode in the morning (n = 18); the evening condition (0-7 condition) constituted a single 7-hour sleep episode in the evening (n = 16); and the polyphasic conditions constituted two sleep episodes, a 5-hour sleep episode in the morning and a 2-hour sleep episode in the evening (5-2 condition; n = 15), or vise versa (2-5 condition; n = 16). Sleep was monitored during all episodes using standard polysomnography (Kushida et al., 2005).

Participants were provided with three calorie-controlled meals per day. The calorie intake was based on a typical western diet (Whitney & Rolfes, 2008). Participants also had four optional snack opportunities over the course of the day and night, which included a choice of muesli bar, yogurt or packaged fruit.

2.5 Data Analysis

The study employed a repeated measures design with one within-subject factor (Night Shift; 7 levels; Night Shift 1 – Night Shift 7). The trend in driving performance over the seven consecutive night shifts was only assessed using the data associated with the post night shift drive, as this was the focus of the study. The efficacies of the daytime sleep conditions on the performance outcomes were not included in the data analyses, as this was beyond the scope of the investigation. Data were analysed using SPSS Statistics Version 25 (IBM corp., Armonk, NY).

2.5.1 Lane and Speed Variability. Changes in SDLP (i.e. lane variability) and SDSP (i.e. speed variability) over the seven consecutive night shifts were assessed using a repeated measures ANOVA. For tests that reached the acceptable level of significance, post hoc pairwise comparisons with a Bonferroni correction were conducted to determine which night shift(s) significantly varied from the first night shift. Adjusted *p*-values are reported. Values are reported as mean (Standard Error). Effect sizes are reported using partial eta squared (η_p^2), where values of 0.01, 0.06 and 0.14 were considered small, medium and large, respectively (Cohen, 1988).

Extreme outliers were assessed via inspection of histograms and boxplots. Outliers that were more than three standard deviations above the mean were adjusted to a value that was one unit greater than the next highest in the distribution. The adjusted value therefore remained on the tail end of the distribution and retained its rank within the set, as per the recommendations by Tabachnick & Fidell (2007). This procedure was preferred to excluding the outliers, as by doing so the entire data set for that participant would be removed from the analyses given the nature of ANOVA testing. A Shaprio-Wilk test indicated that the distributions of SDLP and SDSP were non-normal. However, after the inspection of histograms it was determined that the deviation from normal was relatively minor in the context of ANVOA testing, and therefore appropriate to use the repeated measures ANOVA (Appendix F). Mauchly's test of sphericity indicated that the assumption of sphericity had been violated for both variables. As such, the Greenhouse and Geisser (1959) procedure was applied to produce more conservative degrees of freedom for all ANOVA analyses. Adjusted *p*-values are reported.

Finally, in order to examine the robustness of the main effect for time obtained using the conventional general liner model above, the main effect of time (i.e. consecutive night shifts) was assessed using a mixed model approach with an auto-regressive covariance assumption (AR1). This model allows for error terms associated with observations that are closer together in time to be more highly correlated. The findings confirmed that the same effect was obtained in both model types (Appendix G). The conventional model is reported because it provides a clearer and more intuitive description of the effects and the effect size.

2.5.2 Pre-drive Sleepiness. Changes in KSS scores over the seven consecutive night shifts were assessed using a Friedman Test, as this is the standard analysis for repeated measures of ordinal data. Pairwise comparisons using multiple Wilcoxon-signed ranks tests were used to determine which night shift(s) significantly differed from the first night shift. A Bonferroni correction was applied for multiple comparisons. Significance was accepted at $p < .007$. Reporting medians as the central tendency is standard for Friedman testing. However, the median KSS value for each within subjects factor was the same (median = 8). As such, mean (Standard Error) values were reported as this provided a more intuitive description of the data, and allowed for comparisons to be made between other studies reporting mean values for KSS scores (e.g. Akerstedt et al., 2014).

2.5.3 Crash and Speed Likelihood. The crash and speeding violation data were dichotomised for each drive. As such, each drive was categorized as either a 0 (i.e. no crash or speeding violation occurred), or a 1 (i.e. one or more crashes or speeding violations occurred). Using a relative risk ratio (Tenny & Hoffman, 2019), the relative risk of crashing and speeding following each consecutive night shift were calculated relative to the baseline drive. Notably, in the context of the current study, the term 'risk' is used when referring to the specific variable of relative risk, and the term 'likelihood' is used when referring to the concept, as this is technically correct (Tenny & Hoffman, 2019).

To test for reliable changes in relative risk, significant differences in the proportion of crashing and speeding for each consecutive night shift were assessed using a Cochran's Q analysis (Cochran, 1950). It was determined that the sample size was sufficient to use the χ^2-distribution approximation (Tate & Brown, 1970). Pairwise comparisons were performed using Dunn's (1964) procedure with a Bonferroni correction for multiple comparisons. Adjusted *p*-values are reported.

2.5.4 Analysis of Practice Effects. The presence of practice effects were investigated by examining the trend in performance associated with the drives conducted immediately before each night shift. It was expected that performance during this time would remain relatively constant over seven consecutive night shifts as each drive was performed under near optimal conditions (i.e. a relatively short wake period prior to the drive and a favorable circadian phase). Night Shift 1 did not differ significantly from Night Shift 7 for all driving variables outlined above (Appendix H). These results imply that the three practice driving sessions likely extinguished practice effects prior to starting the first night shift.

2.5.5 Power Analysis. A post hoc sensitivity analysis was used to determine the reliability of detecting a given effect size for the main repeated measures ANOVA analyses. Given the sample size of 65 and 80% power, a small effect size ($\eta_p^2 > .035$) would be detected at alpha $\leq .05$ (Appendix I). This suggests that the study was able to detect small, statistically significant effects for the ANOVA analyses.

Chapter 3

Results

3.1 Data Cleaning

One participant was excluded from the driving performance analyses' and one participant was excluded from the pre-drive sleepiness analysis due to missing data. Data were missing due to random technical errors. One participant had extreme outliers (values three standard deviations above the mean) for SDLP and/or SDSP in all seven drives and was excluded from all analyses as it was deemed to represent an extreme case. The final data set consisted of 65 participants. Fourteen extreme outliers out of the total sample of 910 data points for the SDLP and SDSP data sets were adjusted according to the procedure outlined in Section 2.5.1.

3.2 Aim 1: Investigate Lane and Speed Variability Over Seven Consecutive Night Shifts

3.2.1 Lane Variability. Consistent with Hypothesis 1, SDLP (i.e. lane variability) declined over the seven consecutive night shifts (F [4.53, 290.03] = 7.192, $p < .001$). The size of the effect was medium-large ($\eta_p^2 = 0.101$). The SDLP for Night Shift 1 ($\mu = 0.44[0.02]$) was significantly greater than Night Shift 6 ($\mu = 0.35[0.02]$, $p = .004$) and Night Shift 7 ($\mu = 0.34[0.02]$, $p < .001$). The results are presented in Figure 3 - Panel A.

3.2.2 Speed Variability. Consistent with Hypothesis 2, SDSP (i.e. speed variability) declined over the seven consecutive night shifts (F[4.06, 260.01] = 5.76, $p < .001$). The size of the effect was medium-large ($\eta_p^2 = 0.083$). The SDSP for Night Shift 1 ($\mu = 14.82[0.54]$) was significantly greater than Night Shift 5 ($\mu = 13.34[0.29]$, $p = .018$), Night Shift 6 ($\mu = 13.07[0.24]$, $p = .010$) and Night Shift 7 ($\mu = 13.24[0.27]$, $p = .048$). The results are presented in Figure 3 - Panel B.

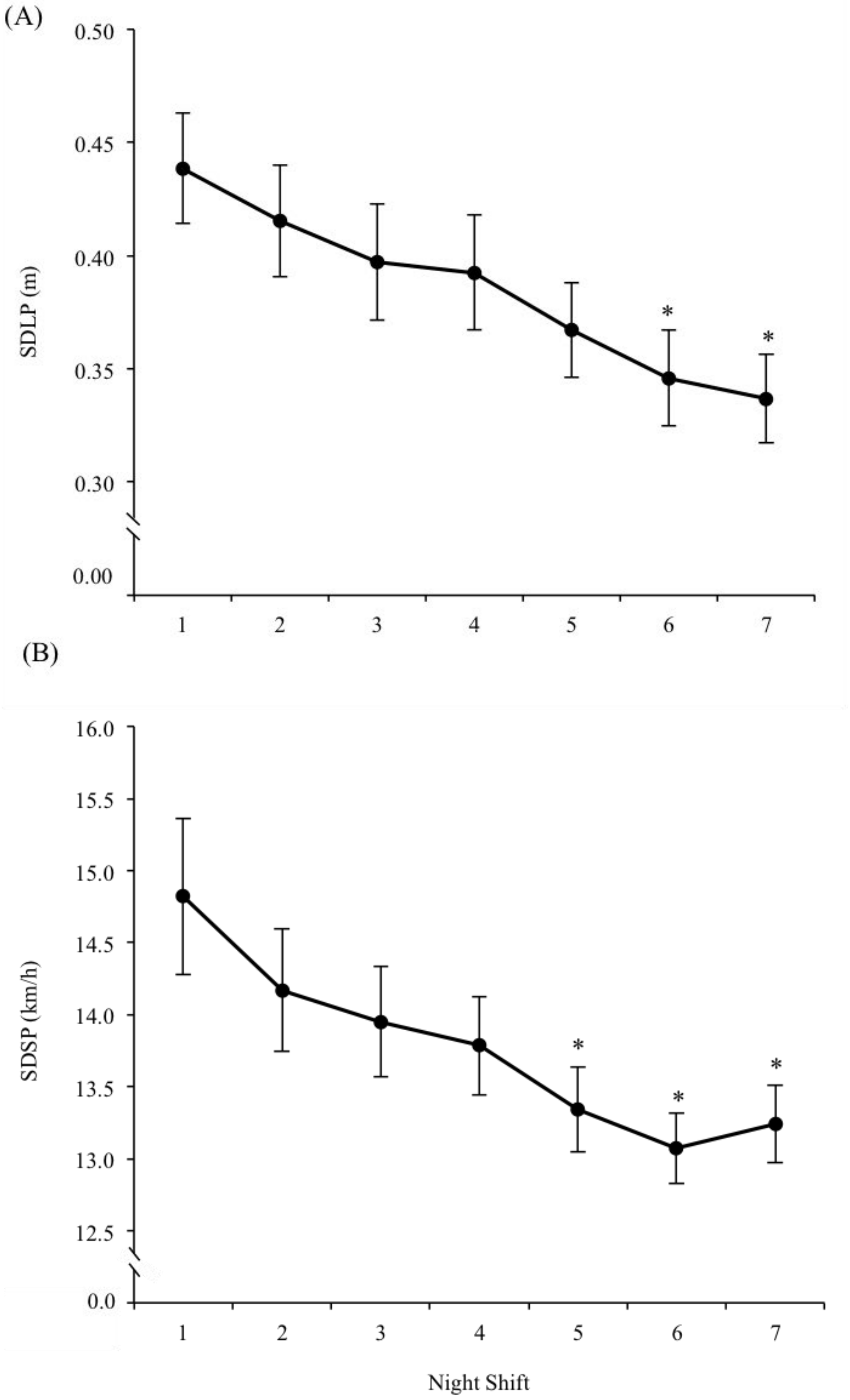

Figure 3. Mean SDLP (Panel A) and SDSP (Panel B) over seven consecutive night shifts. Error bars represent standard errors. * indicates shifts that were significantly different from the first night shift. Statistical significance was accepted at $p < .05$. Type I error probability adjusted for multiple comparisons (Bonferroni).

3.3 Aim 2: Investigate Pre-drive Sleepiness Over Seven Consecutive Night Shifts

3.3.1 Pre-drive Sleepiness. Consistent with Hypothesis 3, pre-drive KSS scores (i.e. subjective sleepiness) declined over the seven consecutive night shifts ($\chi^2(6) = 33.75$, $p < .001$). The results are presented in Figure 4. Pre-drive KSS scores for Night Shift 1 (μ = 8.03[0.15]) were significantly greater than all subsequent night shifts including Night Shift 2 (μ = 7.26[0.20], $p < .001$), Night Shift 3 (μ = 7.38[0.19], $p < .001$), Night Shift 4 (μ = 7.54[0.18], $p < .001$), Night Shift 5 (μ = 7.38[0.19], $p < .001$), Night Shift 6 (μ = 6.98[0.24], $p < .001$) and Night Shift 7 (μ = 7.06[0.23], $p < .001$).

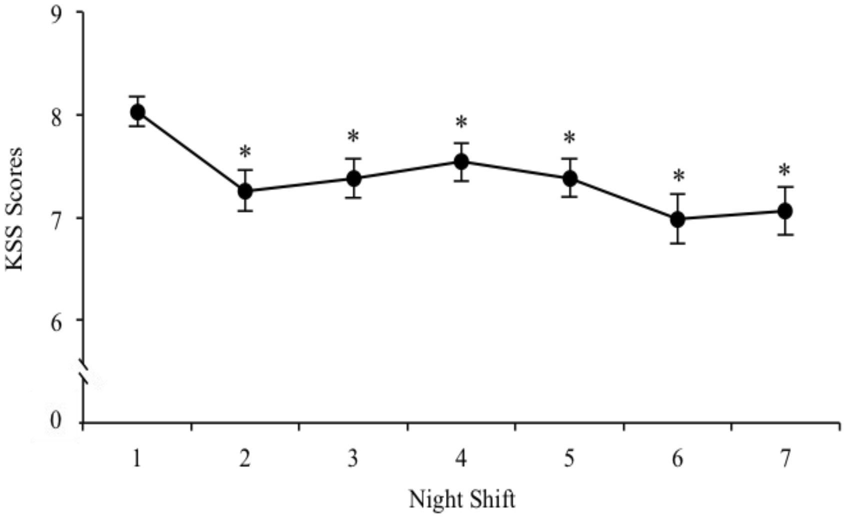

Figure 4. Mean KSS scores over seven consecutive night shifts. Error bars represent standard errors. * indicates shifts that were significantly different from the first night shift. Statistical significance was accepted at $p < .007$. Type I error probability adjusted for multiple comparisons (Bonferroni).

3.4 Aim 3: Investigate the Likelihood of Crashing and Speeding Over Seven Consecutive Night Shifts

3.4.1 Crash Likelihood. Consistent with Hypothesis 4, the risk of a crash occurring relative to a daytime drive declined over the seven consecutive night shifts. Relative to the baseline drive, participants were 4.67 times more likely to crash following Night Shift 1, and 2.33 times more likely to crash following Night Shift 7. The results are presented in Figure 5 - Panel A. Indicative of a reliable decline in relative risk, the proportion of participants crashing differed significantly over the seven consecutive night shifts ($\chi^2(6) = 24.21$, $p < .001$). There was a significant decrease in the proportion of participants crashing following Night Shift 6 (16%, $p = .002$) and Night Shift 7 (21%, $p = .027$), relative to Night Shift 1 (43%). The results are presented in Table 2.

3.4.2 Speed Likelihood. While a decline in relative speeding risk was observed over the seven consecutive night shifts, Hypothesis 5 was not supported, as the effect did not reach the acceptable level of significance. Relative to baseline, participants were 1.47 times more likely to speed following Night Shift 1, and 0.82 times more likely to speed following Night Shift 7. The results are presented in Figure 5 - Panel B. The Cochran's Q analysis revealed a significant difference in the proportion of speeding violations over the seven consecutive night shifts ($\chi^2(6) = 13.88$, $p = .031$). However, after correcting for multiple comparisons, the acceptable level of significance was not satisfied for any differences between night shifts. The results are presented in Table 2.

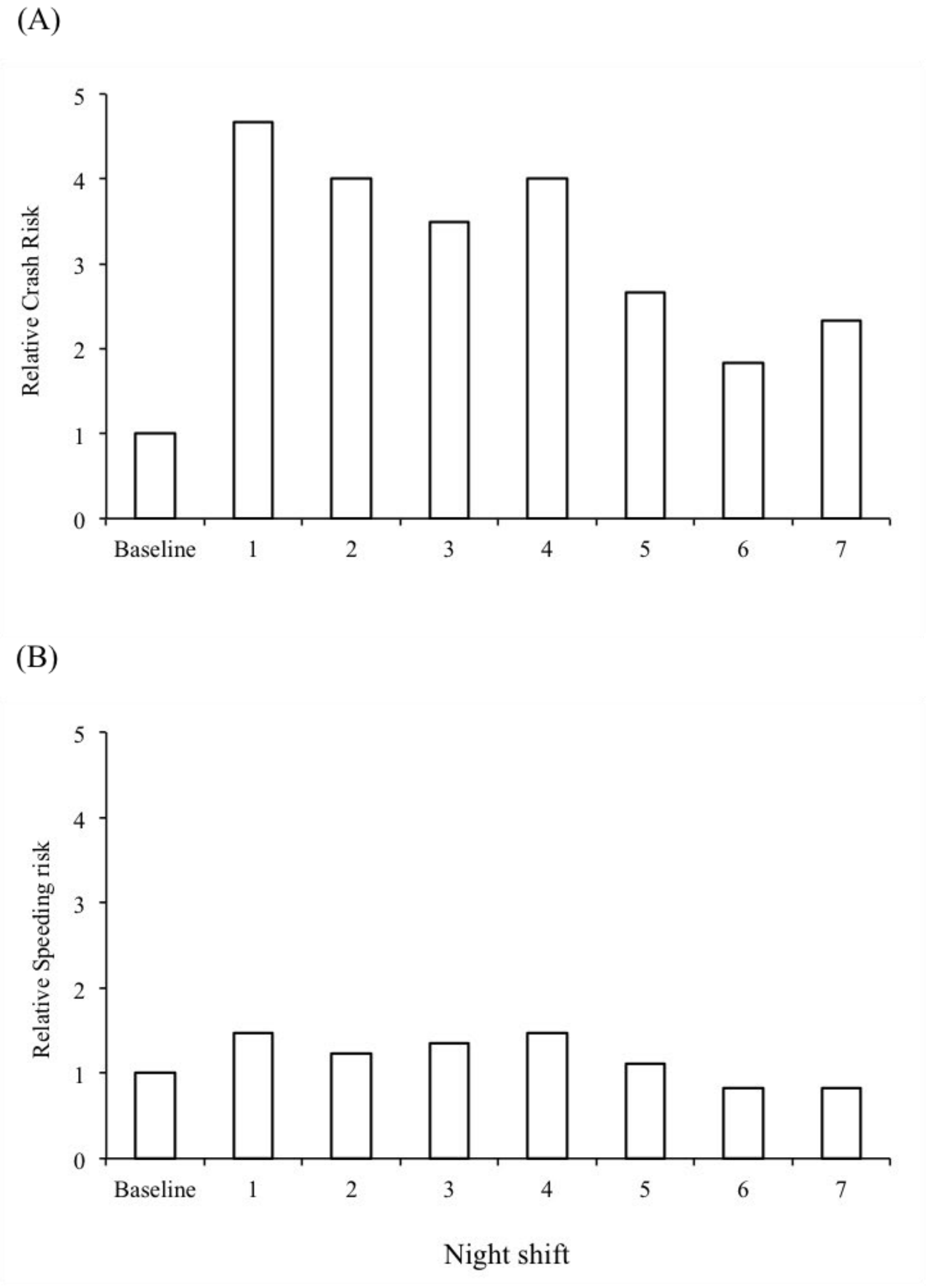

Figure 5. The risk of crashing (Panel A) and speeding (Panel B) following each consecutive night shift relative to the baseline drive.

Table 2

The Proportion of Participants Crashing and Speeding Over Seven Consecutive Night Shifts

	Crashing		Speeding	
Time	Frequency	Proportion	Frequency	Proportion
Baseline	6	9%	17	26%
Night Shift 1	28	43%	25	38%
Night Shift 2	24	36%	21	32%
Night Shift 3	21	32%	23	35%
Night Shift 4	24	36%	25	38%
Night Shift 5	16	24%	19	29%
Night Shift 6	11	16% *	14	21%
Night Shift 7	14	21% *	14	21%

Note. *n* = 65. A crash occurred when all four wheels of the simulated motor vehicle exited the road environment. A speed violation occurred when the limit was exceeded by 10% in the 110km/h zone. * indicates night shifts that were significantly different from the first night shift (excludes baseline). Statistical significance was accepted at $p < .05$. Type I error probability adjusted for multiple comparisons (Bonferroni).

Chapter 4

Discussion

4.1 Overview

The primary purpose of this study was to investigate driving performance associated with the post night shift commute over seven consecutive night shifts. Due to the expectation that the circadian system would adapt to the sleep-wake schedule imposed by the night shift simulation, it was hypothesised driving performance would improve over the seven consecutive night shifts. Lane variability, speed variability and the likelihood of crashing improved over the seven simulated night shifts. Pre-drive sleepiness declined over the same time period, while the likelihood of speeding exhibited no significant change. The trend in driving performance and sleepiness likely reflected the adaptation of the circadian system over successive night shifts. The following chapter evaluates these findings, and discusses the limitations and implications of the study.

4.2 Summary of Findings

4.2.1 Lane and Speed Variability. The first aim of the study was to investigate lane and speed variability over seven consecutive night shifts. Hypothesis 1 and Hypothesis 2 was supported: SDLP and SDSP declined over the seven consecutive night shifts. These findings suggest that lane and speed variability declined, and therefore improved, across the week of simulated night work. A medium-large effect of consecutive night shifts on lane and speed variability was found. The decrease in lane and speed variability over the seven consecutive night shifts was of similar magnitude to the decrease in lane and speed variability observed among individuals driving in a simulator under the influence of significant alcohol intoxication (BAC = 0.11%) and when driving sober (BAC = 0.00%; Mets et al., 2011). The well-established driving impairment associated with elevated levels of alcohol intoxication (Martin et al., 2013), and the medium-large effect found for both variables, highlights the practical significance of the improvement in driving performance observed over the seven consecutive night shifts.

Considering the lack of studies investigating lane and speed variability over successive night shifts, studies that have assessed self-reported driving events and trends in neurobehavioral performance provide meaningful comparisons seeing the constructs are related (Kosmadopolous et al., 2017). The maximal performance impairment following the first night shift found in the current study was consistent with the increase in sleepiness-related driving events following the first night in a series of shifts observed among shift workers in the field (Mulhall et al., 2019). The relatively long wake episode associated with the first night shift is the likely mechanism for such instances (Folkard, 1992; Knauth et al. 1981; Akerstedt, 2003). The improvement in lane and speed variability over the seven consecutive night shifts was consistent with the trend in neurobehavioral performance reported in a number of field and laboratory studies (Lamond et al., 2003; Hansen et al., 2010). In these studies, the adaptation of the circadian system, supported by a mean 4.1-5.5 hour phase delay of the melatonin rhythm, was cited as the mechanism responsible for the observed improvement in neurobehavioral performance (Lamond et al., 2003; Hansen et al., 2010). While circadian adaptation was not assessed in the current study, it also serves as the likely explanation for the observed improvement in driving performance over successive night shifts.

4.2.2 Pre-drive Sleepiness. The second aim of the study was to investigate pre-drive sleepiness over seven consecutive night shifts. Consistent with Hypothesis 3, KSS scores declined over the seven consecutive shifts. Pre-drive sleepiness was highest following the first night shift and lowest following the final night shift. The decrease in sleepiness over the seven consecutive night shifts was in the expected direction considering the improvements in lane variability and speed variability outlined above. As such, it is possible that the improvement in driving performance over the week of simulated night work was mediated by the decrease in sleepiness (or increase in alertness) over the same time period.

The practical significance of the one unit decrease in KSS from Night Shift 1 (KSS = 8, Sleepy but some effort to keep awake) to Night Shift 7 (KSS = 7, Sleepy but no effort to keep awake) is highlighted by the relationship between KSS scores and driving performance. Anund et al. (2008) investigated simulated driving performance following prolonged wakefulness and found that the first time of being in contact with a lane marking was at KSS = 8.1. In a separate study, a mean KSS score of 8.5 was associated with the premature termination of a real drive on an operating highway due to dangerous driving (Akerstedt et al., 2013). Those who competed the drive had a mean KSS of 6.9. These studies demonstrate that a KSS score greater than 8 may be a critical indicator of dangerous driving. As such, the decline in KSS from 8 to 7 over the seven consecutive night shifts likely reflects a practically significant change in subjective sleepiness, particularly in the context of driver safety.

4.2.3 Crash and Speed Likelihood. The third aim of the study was to investigate the likelihood of crashing and speeding over seven consecutive night shifts. The likelihood of crashing relative to the baseline drive reduced by approximately half over the seven consecutive night shifts. As such, Hypothesis 4 was supported. While these findings, together with the trend in driving performance and sleepiness outlined above, suggest that the risk for errors, accidents and injuries may improve over consecutive night shifts, there is some evidence to the contrary. A meta-analysis of data from several studies has shown that the risk for accidents and injuries can in fact increase over four consecutive night shifts (Folkard & Akerstedt, 2004). One explanation for the inconsistent findings is the possibility that four consecutive night shifts do not allow enough time for the circadian system to adapt and for risk to improve. Most notably, the authors of the review reported that in two out of the seven studies reviewed (Vinogradova et al., 1923; Wagner, 1988), risk began to decline following the fourth night shift, but were discredited as they were based on a relatively small number of incidents (Folkard & Akerstedt, 2004). Considering statistically significant improvements in the proportion of participants crashing were detected following night shifts six and seven in the current study, it is possible that a decline in accident and injury risk may be imminent beyond four night shifts as the circadian system adapts over successive nights.

The likelihood of speeding did not decline over the seven consecutive night shifts. As such, Hypothesis 5 was not supported. Notably, the proportion of participants speeding was similar in the baseline condition than following all consecutive night shifts. These findings (along with the decline in the likelihood of crashing outlined above) suggest that when people are sleepy it may be within their control to remain below the speed limit, but not within their control to keep the vehicle in an appropriate position within the lane. Assuming sleepiness was driving the affect, the capacity to keep the car in an appropriate position within the lane may be mediated by higher order or executive functions, while remaining below the speed limit may not require the same level of cognitive ability and is therefore easier to control when fatigued (Burke et al., 2015).

4.3 Strengths and Limitations

A number of limitations and boundary conditions should be taken into account when interpreting the results of the study. The participants in the current study were considerably younger than the shift worker population (Australian Bureau of Statistics, 2010). Several studies have demonstrated that age is negatively correlated with sleep quality and length (Foret et al., 1981; Akerstedt & Torsvall, 1981). In general, sleep becomes more fragmented, shorter and lighter in shift workers increasing with age (Costa et al., 1989; Tepas et al., 1993). As such, the quantity and quality of sleep obtained between shifts for the participants in the study may have been greater than that of the shift worker population. As a result, they may have been more alert and able to perform better over the seven consecutive night shifts than shift workers in the field.

The environmental conditions of the laboratory most likely enhanced the quality of day sleep and the adaptation of the circadian system to night shifts. The participants in the study were provided with very dark and quiet sleep areas, had essentially no social or domestic commitments and were not exposed to morning outdoor light. These factors together likely enhance the quality of day sleep and reduce the exposure to phase advancing light that would otherwise be a significant factor inhibiting the phase delay of the circadian system for shift workers in their natural environment (Parks, 1994; Monk & Wagner, 1989). In an attempt to mitigate against the latter, a light box was placed behind the driving simulator screen to simulate the expected light exposure from the sun when driving home in the morning with sunglasses on (~750-800 lux). While this may improve the ecological validity of the study to some extent by exposing participants to phase advancing light during the simulated commute home, shift workers in their natural environment are still probably less likely to adapt to night work than the participants in the study.

It should be emphasised that the present data were obtained in a driving simulator, which comes with certain limitations concerning the generalisability of results. While strong associations have been reported between simulated and on-road driving, sleepiness and driving impairment are typically inflated under simulated conditions (Lee et al., 2003; Philip et al., 2005). In the current study, the proportion of participants crashing in the baseline condition (9%) and following each consecutive night shift (21-43%) was much higher than the crash rate in the shift worker population (Crummy et al., 2008). The consequences of crashing in the driving simulator are not as severe as crashing in a real motor vehicle. As such, the motivation to perform well on the simulated task may have been comparatively less than when driving under real conditions. Furthermore, sleepiness and driving impairment may more pronounced during simulated driving due to the lower level of stimulation associated with the task (Phillip et al., 2005). As such, both instances may be responsible for the greater than expected crash rate in the current study. While absolute values of performance impairment may have been inflated, it is reasonable to infer that relative comparisons between time points on a driving simulator still reflect valid differences (Hallvig et al., 2013). As such, the relative comparison of driving performance used in the current study, such as the calculation of crash risk relative to a baseline drive, provided some protection against this limitation. Further, computer based simulated driving tasks such as the one used in the current study capture more skills required for driving than simple neurobehavioral measures, and as such are more ecologically valid than other instruments attempting to predict driving performance (Jackson et al., 2013; Lee et al., 2003).

A significant factor of the study was the random assignment of participants to day sleep conditions. One may argue that this was a limitation of the study, as participants were not able to exhibit their natural sleeping behavior. However, the day sleep strategies used in the current study were based on observations of shift workers in their natural settings (Roach et al., 2016). Night shift workers either have a single sleep in the morning straight after work (45%), a single sleep in the evening prior to work (15%), or one sleep in the morning and another in the evening (40%). These strategies are typically employed to either maximise the quantity/quality of sleep obtained between shifts and/or limit the duration of wakefulness prior to starting a shift. Therefore, by assigning novice shift workers to common day sleep strategies, it captures the sleeping behavior of shift workers in their natural environment and may improve the ecological validity of the study.

4.4 Implications and Future Research

The length of night shift sequences plays a pivotal role in the management of fatigue-related risk. Currently, relatively short sequences of night shifts (i.e. 2-4 nights in a row) are predominant in the Occupational Health and Safety (OHS) guidelines in most industrialised countries, including Australia (e.g. Australian Council of Trade Unions, 2000; Safe Work Australia, 2013). Relatively long sequences of night shifts (i.e. 4-14 nights in a row) are perceived as less advantageous as there is some evidence to suggest that the circadian rhythms of night shift workers rarely adjust to night work, particularly in urban environments (Folkard, 1992; Folkard, 2008). As such, sleep loss may accumulate and the risk for accidents and injuries may increase over successive night shifts (Folkard & Akerstedt, 2004). However, the data of the current study suggests that in the context of driver safety, short sequences of night shifts may not always be the optimal solution. In the current study, the likelihood of crashing was comparatively less in the latter half of the night shift sequence. By working longer sequences of night shifts less often, the average exposure to fatigue-related crash risk over time would be less than that produced by working relatively shorter sequences of night shifts more often. As such, the OHS guidelines that recommend a blanket limit on night shifts to a maximum of 2-4 in a row may inadvertently expose shift workers to greater fatigue-related crash risk than is necessary in some workplaces. It should be emphasised however, that the conditions of current study, such as the optimal sleeping environment and absence of social and domestic commitments, were predicted to facilitate circadian adaptation. As such, this implication may best apply to workplaces that more closely mimic these conditions such as remote mine sites, offshore oilrigs, or artic bases (Hansen et al., 2010; Midwinter & Arendt, 1991).

The findings of the current study suggest that strategies and countermeasures aimed at reducing crash risk may be most effective when targeted towards the first night in a series of shifts. In the current study, the likelihood of crashing was greatest following the first night shift. This was most likely a function of the extended wake episode following the first simulated night shift relative to subsequent night shifts. This is particularly relevant, as the amount of time elapsed since waking tends to be extended in shift workers following the first night shift, as individuals typically wake at a normal time in the morning and remain awake until the end of their shift (Knauth et al. 1981). As such, shift workers may be awake for up to 24 hours prior to driving home from the first night shift (Folkard, 1992), a duration of wakefulness 4 hours greater than what occurred in the current study. In this sense, an increase in the likelihood of crashing following the first night shift may apply to most shift workers irrespective of their environment and adaptation of their circadian system. Having a nap prior or during the night shift has been shown to improve alertness and neurobehavioral performance towards the end of the shift (Purnell et al., 2002; Harma et al., 1989), and may be an effective solution in reducing the motor vehicle accident risk associated with the first night shift. However, it is duly noted that this strategy does not always succeed in improving subsequent performance (Centofanti et al., 2017; Hilditch et al., 2017) and may be ineffective if individuals are unable to sleep at this time. As such, more costly measures such as catching public transport or providing employees with taxi vouchers following the first night shift may be a better alternative.

The management of risk associated with the post night shift commute would benefit from future research replicating and expanding on the findings of the current study. Replicating the current study examining shift workers in their natural environment and/or employing a high fidelity driving simulator would address the main limitations of the current study. Further, the optimal length of night shift sequences to minimise fatigue-related crash risk likely depends on the adaptation of the circadian system. Future research investigating the environmental conditions or work places under which circadian adaptation is likely or unlikely to occur will allow for a more targeted approach for the management of fatigue-related risk. Finally, future research could investigate the efficacy of sleepiness countermeasures, such as napping and alertness monitoring devices, as the validity of such measures are not well understood.

4.5 Conclusion

The findings of the current study suggest that relatively short sequences of night shifts that dominate most OHS guidelines may not always be optimal in minimizing fatigue-related risk. The optimal length of night shift sequences to reduce fatigue-related crash risk may depend on the adaptation of the circadian system. Future research focused on the conditions under which individuals are likely to adapt to night work will allow for more targeted and effective risk management strategies to be applied.

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Appendix A: Study Flyer

Participants Wanted for UNIVERSITY SLEEP STUDY

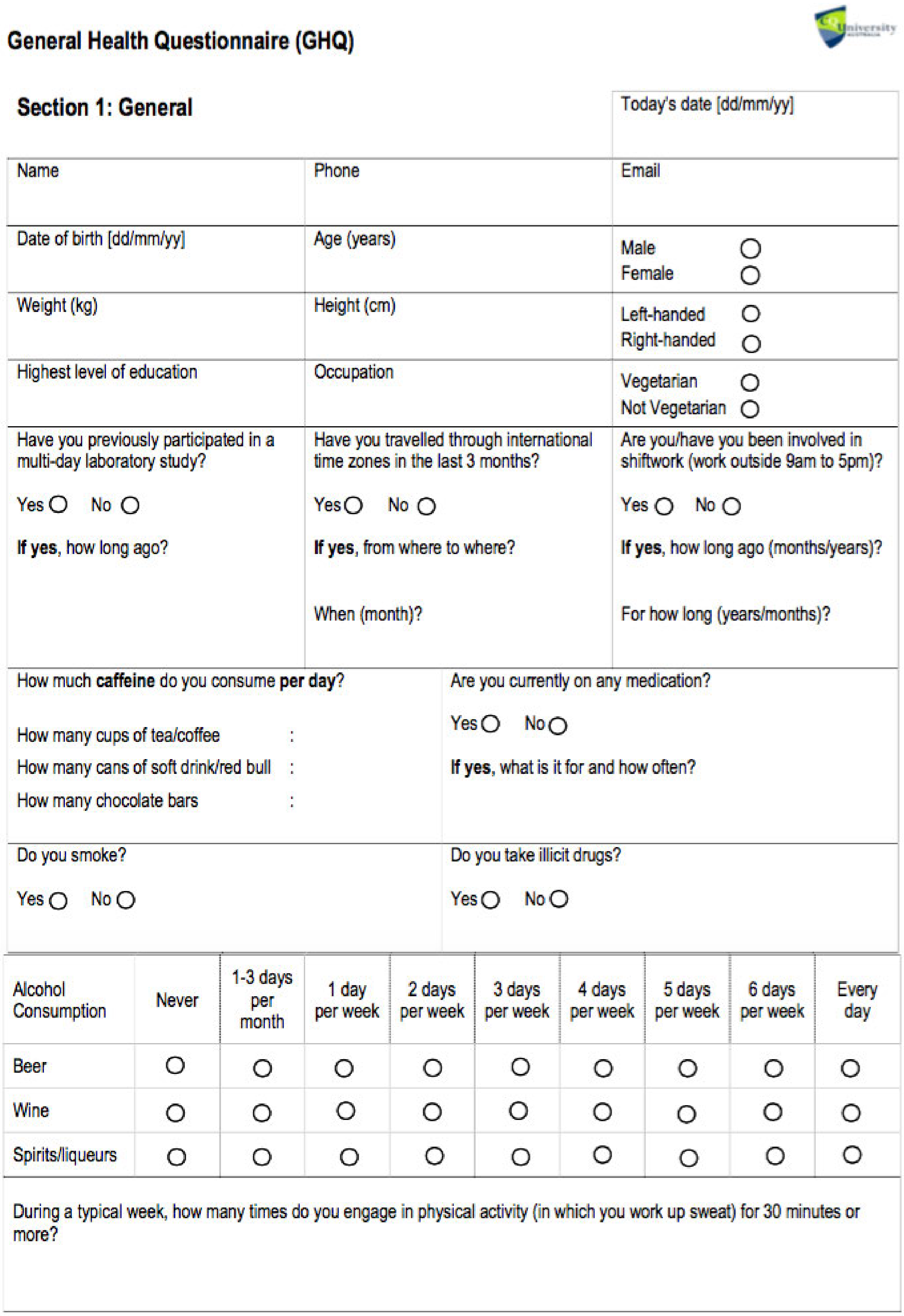
CQUniversity's Appleton Institute in Adelaide is seeking volunteers to participate in a study of the effect of different sleep strategies on performance and health during a week of simulated night shifts.

We are looking for healthy men and women aged between 18 and 30.

The study will require you to live full-time in our sleep laboratory for 10 days and nights. We will monitor your sleep and performance at different times during the study. You will be financially compensated for your participation **($1080).**

NEXT STUDY: Tue 21 May to Fri 31 May 2019

Appendix B: General Health Questionnaire



General Health Questionnaire (GHQ)

Section 1: General		Today's date [dd/mm/yy]
Name	Phone	Email
Date of birth [dd/mm/yy]	Age (years)	Male ○ Female ○
Weight (kg)	Height (cm)	Left-handed ○ Right-handed ○
Highest level of education	Occupation	Vegetarian ○ Not Vegetarian ○
Have you previously participated in a multi-day laboratory study? Yes ○ No ○ **If yes**, how long ago?	Have you travelled through international time zones in the last 3 months? Yes ○ No ○ **If yes**, from where to where? When (month)?	Are you/have you been involved in shiftwork (work outside 9am to 5pm)? Yes ○ No ○ **If yes**, how long ago (months/years)? For how long (years/months)?

How much **caffeine** do you consume **per day**? How many cups of tea/coffee : How many cans of soft drink/red bull : How many chocolate bars :	Are you currently on any medication? Yes ○ No ○ **If yes**, what is it for and how often?
Do you smoke? Yes ○ No ○	Do you take illicit drugs? Yes ○ No ○

Alcohol Consumption	Never	1-3 days per month	1 day per week	2 days per week	3 days per week	4 days per week	5 days per week	6 days per week	Every day
Beer	○	○	○	○	○	○	○	○	○
Wine	○	○	○	○	○	○	○	○	○
Spirits/liqueurs	○	○	○	○	○	○	○	○	○

During a typical week, how many times do you engage in physical activity (in which you work up sweat) for 30 minutes or more?

MEDICAL CONDITIONS: Have you experienced/are you experiencing any of the following medical conditions?

	Don't know	No	Yes, in the past	Yes, sometimes	Yes, at present
Metabolic disorders	○	○	○	○	○
Diabetes	○	○	○	○	○
Thyroid problems	○	○	○	○	○
Cardiovascular disease	○	○	○	○	○
Heart problems	○	○	○	○	○
Epilepsy	○	○	○	○	○
Clinical depression	○	○	○	○	○
Stress/anxiety	○	○	○	○	○
Vision impairment	○	○	○	○	○
Difficulty reading/writing	○	○	○	○	○
Migraine	○	○	○	○	○
Asthma	○	○	○	○	○
Eczema	○	○	○	○	○
Allergies (i.e. hay fever)	○	○	○	○	○
Arthritis/rheumatism	○	○	○	○	○
Stomach problems	○	○	○	○	○
Colour blindness	○	○	○	○	○
STD/STI (e.g. HIV/Aids, hepatitis B/C)	○	○	○	○	○
Bed bugs	○	○	○	○	○
Tinea	○	○	○	○	○
Scabies	○	○	○	○	○
Impetigo	○	○	○	○	○
Other contagious condition	○	○	○	○	○
Head injuries (i.e. concussion)	○	○	○	○	○

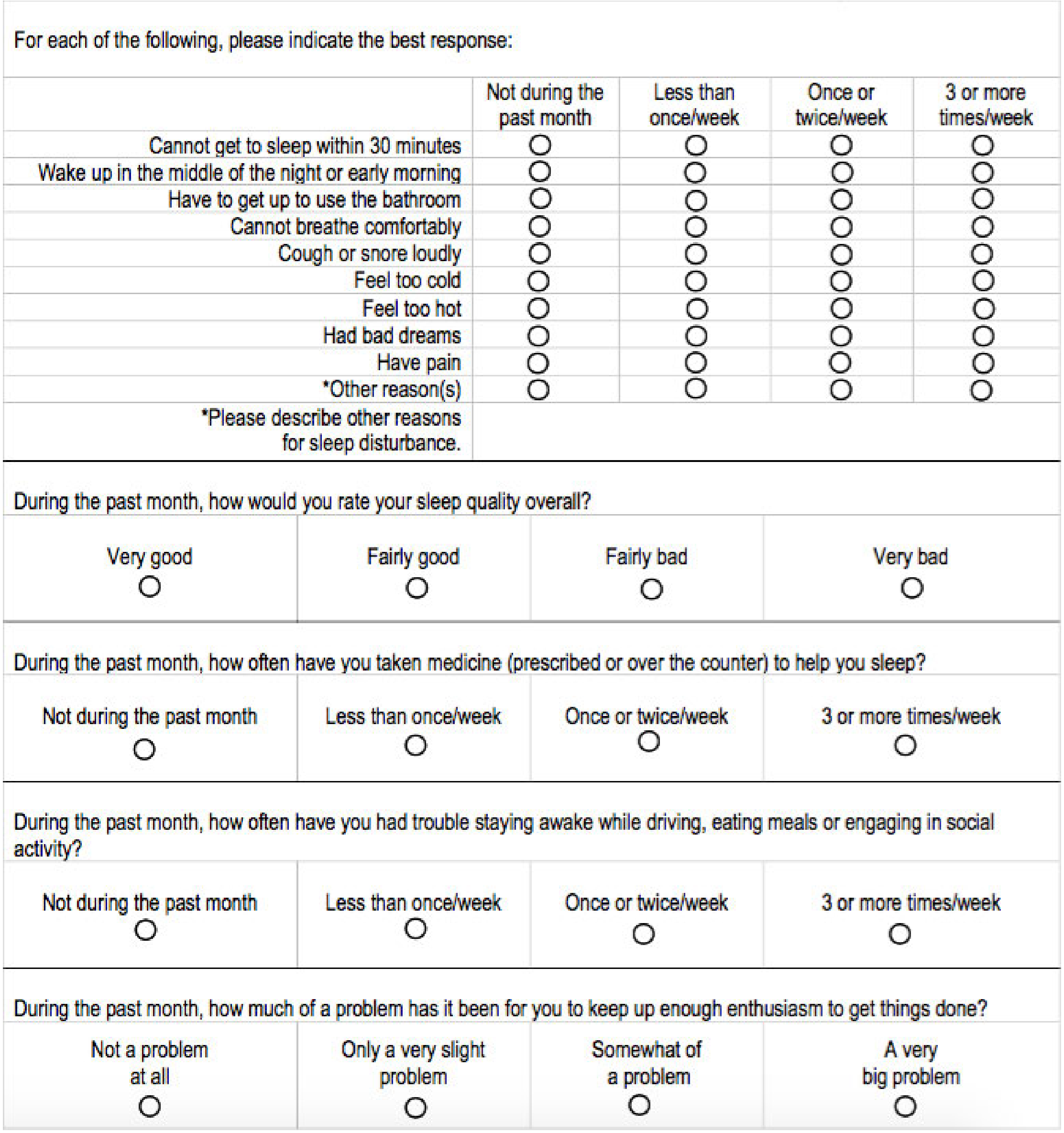
Section 2: Sleep

How likely are you to fall asleep or doze off in the following situations, rather than just feeling tired? This refers to your usual way of life in recent times. Even if you have not done some of these things recently try to work out how they would affect you. Please tick the most appropriate box for each situation.

	Never	Slight chance	Moderate chance	High chance
Sitting and reading	○	○	○	○
Watching TV	○	○	○	○
Sitting inactive in a public place (e.g. theatre/meeting)	○	○	○	○
As a passenger in a car for an hour without a break	○	○	○	○
Lying down in the afternoon when circumstances permit	○	○	○	○
Sitting and talking to someone	○	○	○	○
Sitting quietly after lunch without alcohol	○	○	○	○
In a car, while stopped for a few minutes in traffic	○	○	○	○

The following questions relate to your usual sleep habits during the past month only. Your answers should indicate the most accurate reply for the majority of days and nights in the past month

During the past month, what time have you usually gone to bed at night?	
During the past month, how long (in minutes) has it usually taken you to fall asleep each night?	
During the past month, what time have you usually gotten up in the morning?	
During the past month, how many hours of actual sleep did you get at night (this may be different to the number of hours you spent in bed)?	



For each of the following, please indicate the best response:

	Not during the past month	Less than once/week	Once or twice/week	3 or more times/week
Cannot get to sleep within 30 minutes	○	○	○	○
Wake up in the middle of the night or early morning	○	○	○	○
Have to get up to use the bathroom	○	○	○	○
Cannot breathe comfortably	○	○	○	○
Cough or snore loudly	○	○	○	○
Feel too cold	○	○	○	○
Feel too hot	○	○	○	○
Had bad dreams	○	○	○	○
Have pain	○	○	○	○
*Other reason(s)	○	○	○	○
*Please describe other reasons for sleep disturbance.				

During the past month, how would you rate your sleep quality overall?

Very good ○	Fairly good ○	Fairly bad ○	Very bad ○

During the past month, how often have you taken medicine (prescribed or over the counter) to help you sleep?

Not during the past month ○	Less than once/week ○	Once or twice/week ○	3 or more times/week ○

During the past month, how often have you had trouble staying awake while driving, eating meals or engaging in social activity?

Not during the past month ○	Less than once/week ○	Once or twice/week ○	3 or more times/week ○

During the past month, how much of a problem has it been for you to keep up enough enthusiasm to get things done?

Not a problem at all ○	Only a very slight problem ○	Somewhat of a problem ○	A very big problem ○

Appendix C: Sleep Dairy

Name:				**Study ID:**							
		SLEEP PERIOD[1]						**SLEEPINESS**[2]		**SUBJECTIVE RATINGS**[3-4]	
DATE (dd/mm/yy)	**DAY** (Mon-Sun)	**BED TIME** (hh:mm)	**SLEEP ONSET TIME** (hh:mm)	**WAKE TIME** (hh:mm)	**GET UP TIME** (hh:mm)	**No. OF AWAKENINGS**	**TOTAL TIME AWAKE** (minutes)	**BEFORE** (1-7)	**AFTER** (1-7)	**SLEEP QUALITY** (1-5)	**HOURS OF SLEEP**

SLEEP DIARY INSTRUCTIONS

STEP ONE: Record the time you go to bed and the time that you get out of bed. Also record the time you that you actually went to sleep and at what time you finally wake up. This should be done for ANY and EVERY sleep period, including short naps. Also record how many times you woke up during the sleep period, and the TOTAL amount of time you were awake for after you add each of these awakenings together.

STEP TWO: The second step involves rating how sleepy/awake you feel just before you go to bed and as soon as you wake up. Do this using the SLEEPINESS SCALE below. Choose the statement which best describes your state of sleepiness immediately BEFORE and AFTER the sleep period.

SLEEPINESS SCALE

1 = Feeling active and vital. Alert and wide awake
2 = Functioning at a high level but not at peak. Able to concentrate.
3 = Relaxed, awake, responsive, not at full alertness.
4 = A little foggy. Not at peak. Let down.
5 = Fogginess. Beginning to lose interest in remaining awake. Slowed down.
6 = Sleepy. Prefer to be lying down. Fighting sleep. Woozy.
7 = Almost in reverie. Sleep onset will be soon. Lost struggle to remain awake.

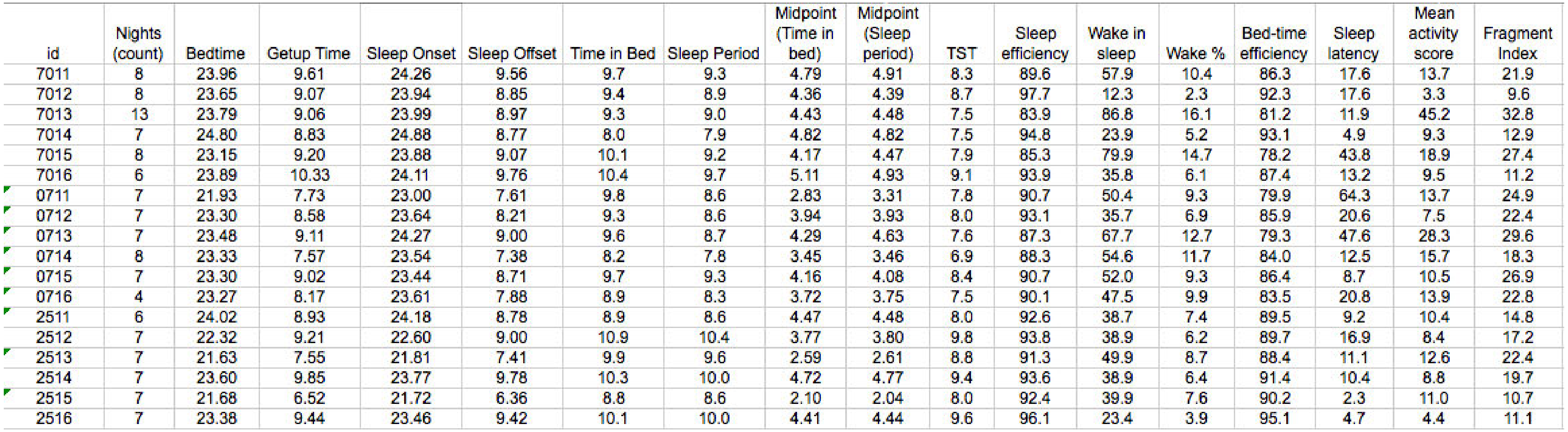
STEP THREE: The third step requires a subjective evaluation to be made about how well you slept. Simply select a number from the following scale, and record it in the column marked “SLEEP QUALITY”:

HOW YOU SLEPT

1 = Very Well
2 = Well
3 = Average
4 = Poorly
5 = Very Poorly

STEP FOUR: Finally, first thing after waking, please record how many hours of sleep it felt like you obtained. Accuracy is not important – we are more interested in your subjective estimate.

Appendix D: Wrist actigraphy example data



id	Nights (count)	Bedtime	Getup Time	Sleep Onset	Sleep Offset	Time in Bed	Sleep Period	Midpoint (Time in bed)	Midpoint (Sleep period)	TST	Sleep efficiency	Wake in sleep	Wake %	Bed-time efficiency	Sleep latency	Mean activity score	Fragment Index
7011	8	23.96	9.61	24.26	9.56	9.7	9.3	4.79	4.91	8.3	89.6	57.9	10.4	86.3	17.6	13.7	21.9
7012	8	23.65	9.07	23.94	8.85	9.4	8.9	4.36	4.39	8.7	97.7	12.3	2.3	92.3	17.6	3.3	9.6
7013	13	23.79	9.06	23.99	8.97	9.3	9.0	4.43	4.48	7.5	83.9	86.8	16.1	81.2	11.9	45.2	32.8
7014	7	24.80	8.83	24.88	8.77	8.0	7.9	4.82	4.82	7.5	94.8	23.9	5.2	93.1	4.9	9.3	12.9
7015	8	23.15	9.20	23.88	9.07	10.1	9.2	4.17	4.47	7.9	85.3	79.9	14.7	78.2	43.8	18.9	27.4
7016	6	23.89	10.33	24.11	9.76	10.4	9.7	5.11	4.93	9.1	93.9	35.8	6.1	87.4	13.2	9.5	11.2
0711	7	21.93	7.73	23.00	7.61	9.8	8.6	2.83	3.31	7.8	90.7	50.4	9.3	79.9	64.3	13.7	24.9
0712	7	23.30	8.58	23.64	8.21	9.3	8.6	3.94	3.93	8.0	93.1	35.7	6.9	85.9	20.6	7.5	22.4
0713	7	23.48	9.11	24.27	9.00	9.6	8.7	4.29	4.63	7.6	87.3	67.7	12.7	79.3	47.6	28.3	29.6
0714	8	23.33	7.57	23.54	7.38	8.2	7.8	3.45	3.46	6.9	88.3	54.6	11.7	84.0	12.5	15.7	18.3
0715	7	23.30	9.02	23.44	8.71	9.7	9.3	4.16	4.08	8.4	90.7	52.0	9.3	86.4	8.7	10.5	26.9
0716	4	23.27	8.17	23.61	7.88	8.9	8.3	3.72	3.75	7.5	90.1	47.5	9.9	83.5	20.8	13.9	22.8
2511	6	24.02	8.93	24.18	8.78	8.9	8.6	4.47	4.48	8.0	92.6	38.7	7.4	89.5	9.2	10.4	14.8
2512	7	22.32	9.21	22.60	9.00	10.9	10.4	3.77	3.80	9.8	93.8	38.9	6.2	89.7	16.9	8.4	17.2
2513	7	21.63	7.55	21.81	7.41	9.9	9.6	2.59	2.61	8.8	91.3	49.9	8.7	88.4	11.1	12.6	22.4
2514	7	23.60	9.85	23.77	9.78	10.3	10.0	4.72	4.77	9.4	93.6	38.9	6.4	91.4	10.4	8.8	19.7
2515	7	21.68	6.52	21.72	6.36	8.8	8.6	2.10	2.04	8.0	92.4	39.9	7.6	90.2	2.3	11.0	10.7
2516	7	23.38	9.44	23.46	9.42	10.1	10.0	4.41	4.44	9.6	96.1	23.4	3.9	95.1	4.7	4.4	11.1

Appendix E: Karolinska Sleepiness Scale

Can you please point to the number that describes how you are feeling right now:

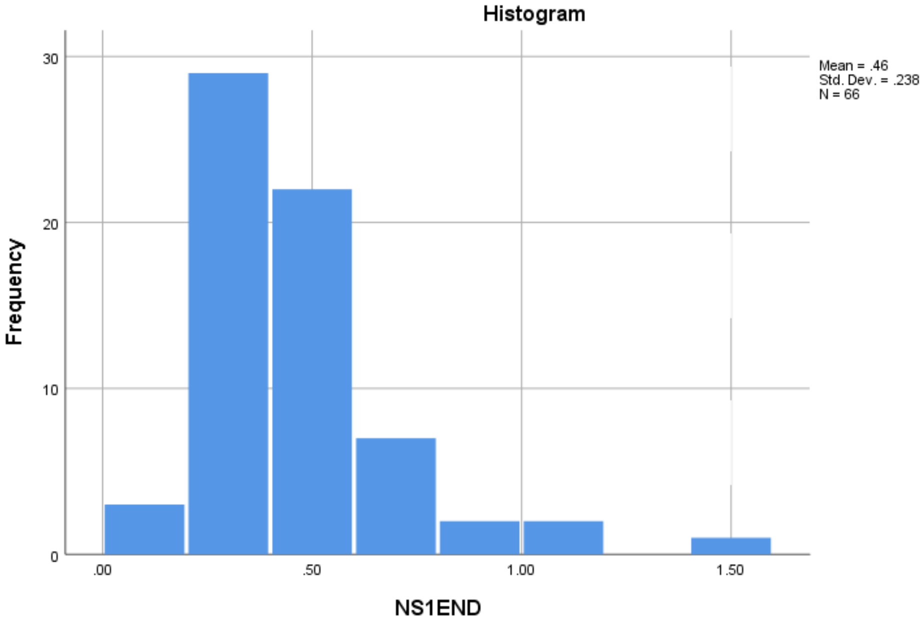
1. Extremely alert
2. Very alert
3. Alert
4. Fairly alert
5. Neither alert nor sleepy
6. Some signs of sleepiness
7. Sleepy, but no effort to keep awake
8. Sleepy, some effort to keep awake
9. Very sleepy, great effort to keep awake, fighting sleep

Appendix F: SDLP and SDSP histograms for each within subjects factor

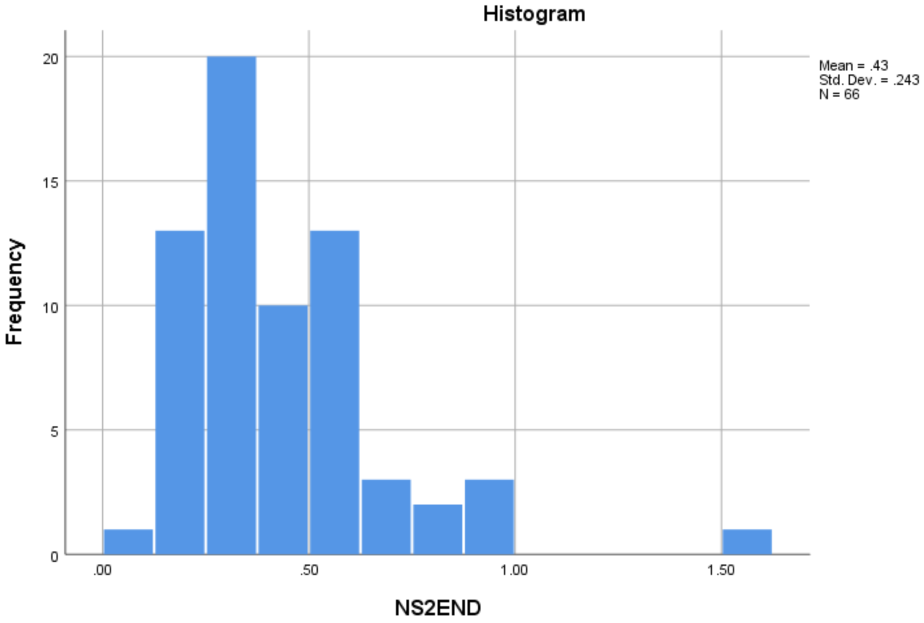
Note: Outliers on the tale end of the distribution were either adjusted or removed according to the procedures outlined in section 2.5.1 and 3.1, respectively.

<u>SDLP (7x night shifts)</u>

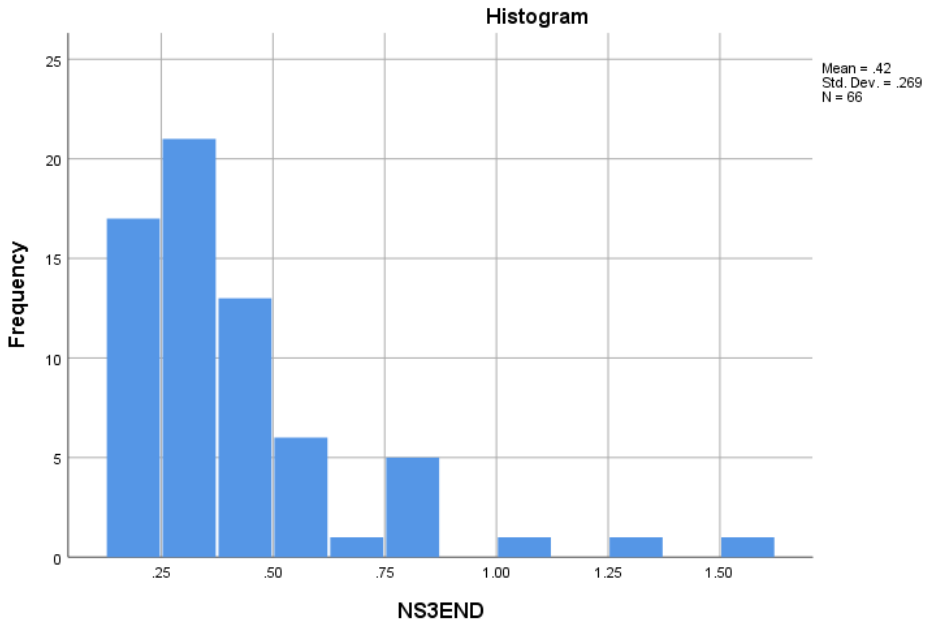
Night Shift 1



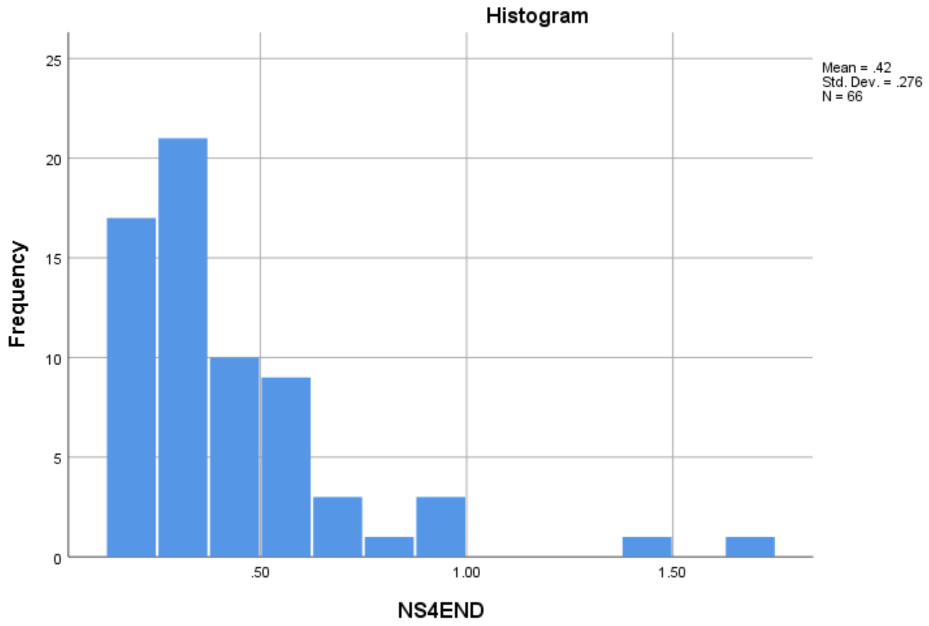
Night Shift 2



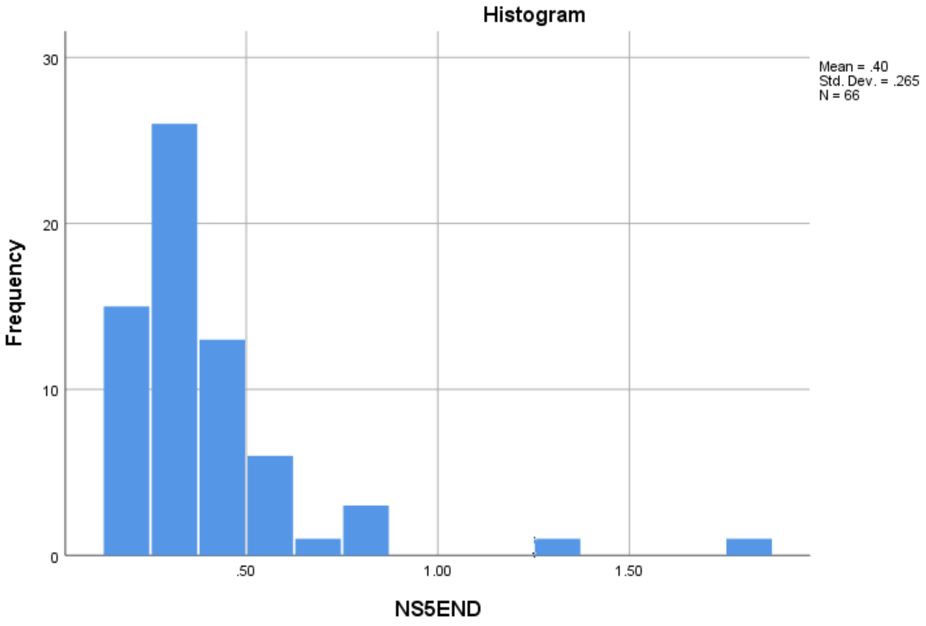
Night Shift 3



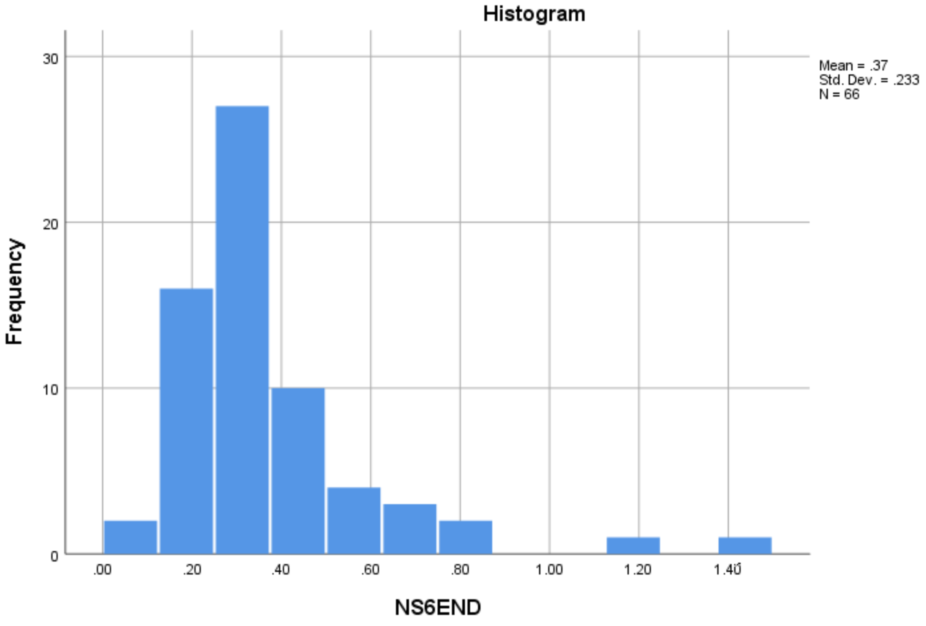
Night Shift 4



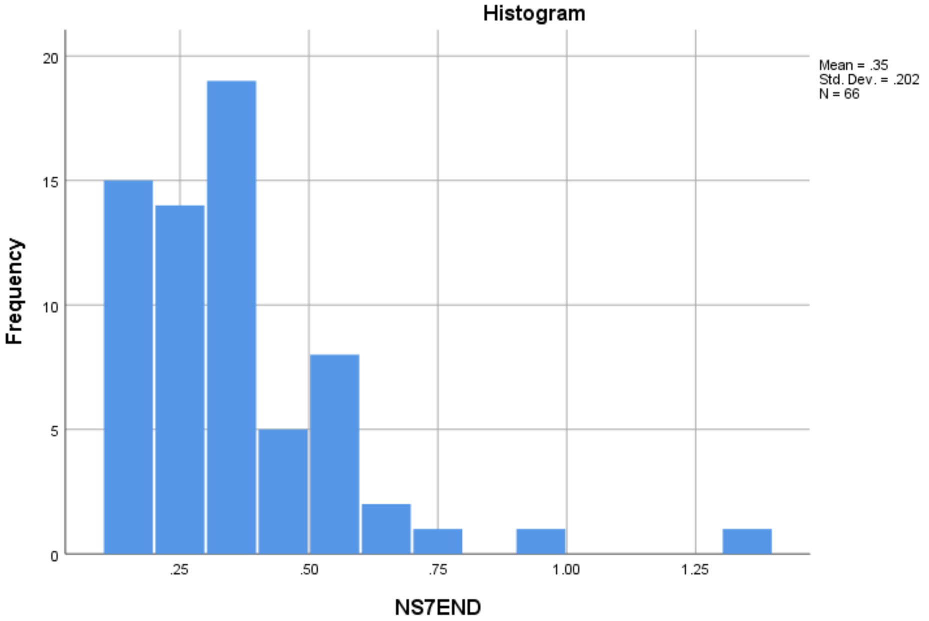
Night Shift 5



Night Shift 6

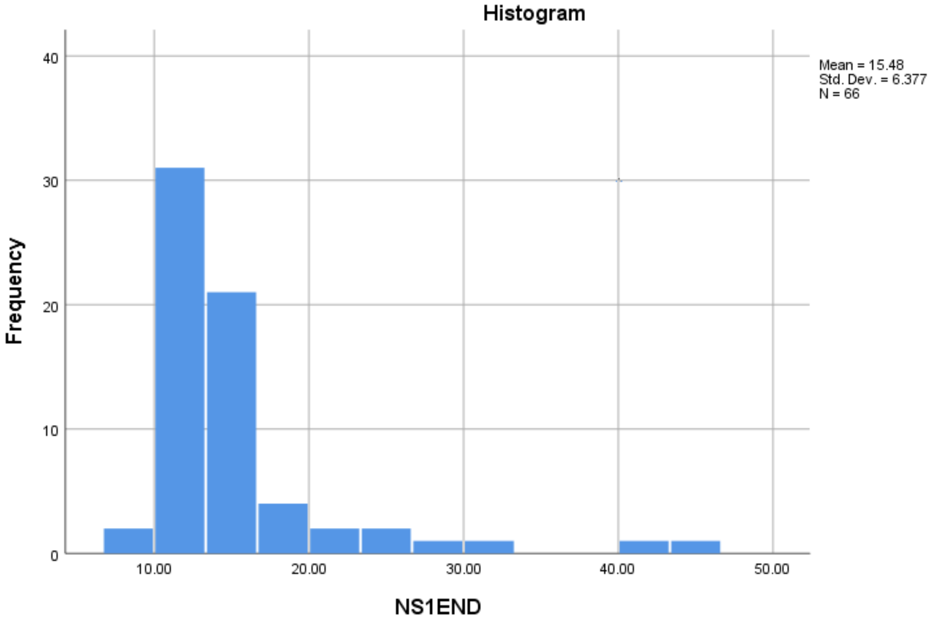


Night Shift 7

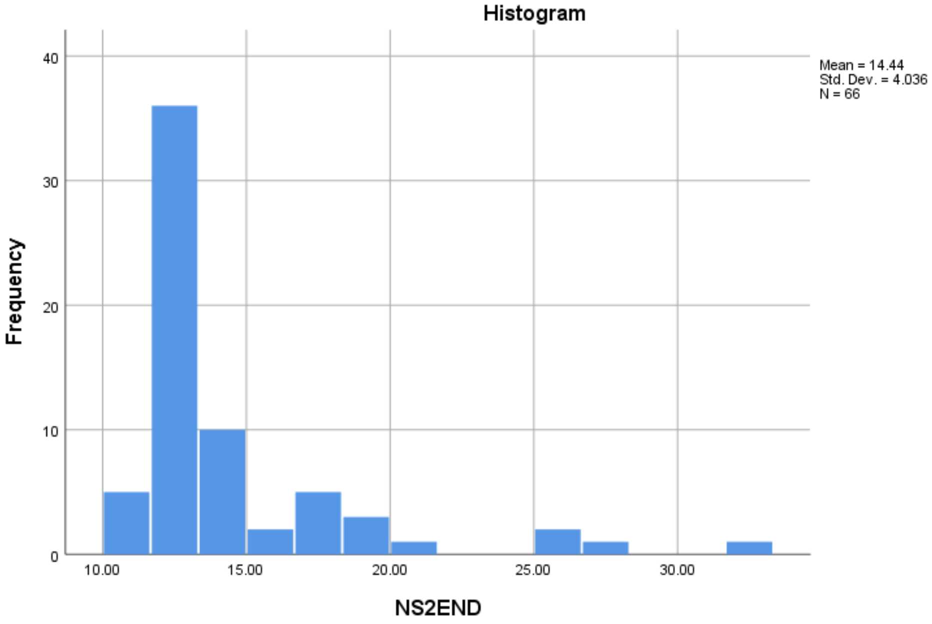


SDSP (7x Night Shifts)

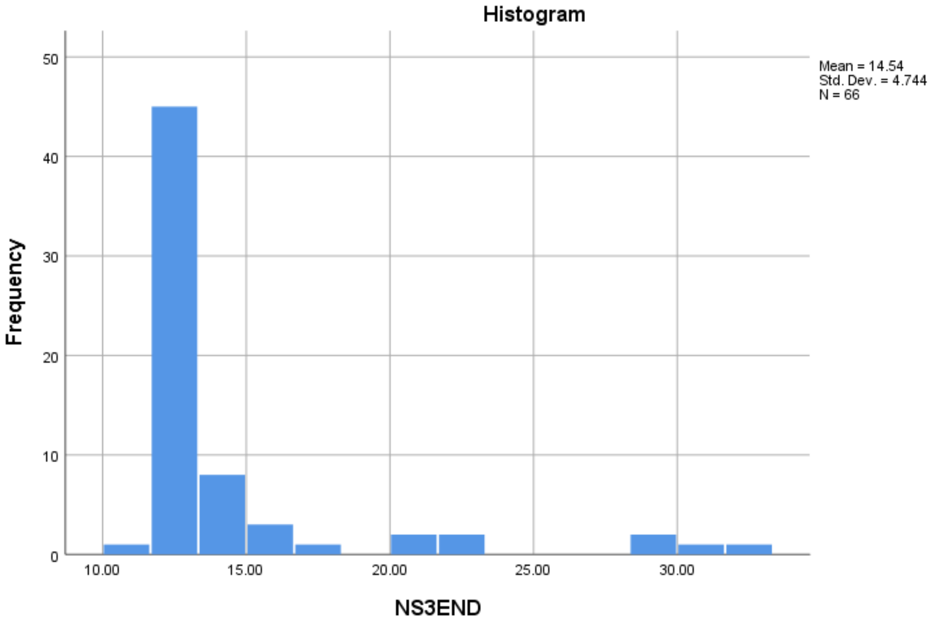
Night Shift 1



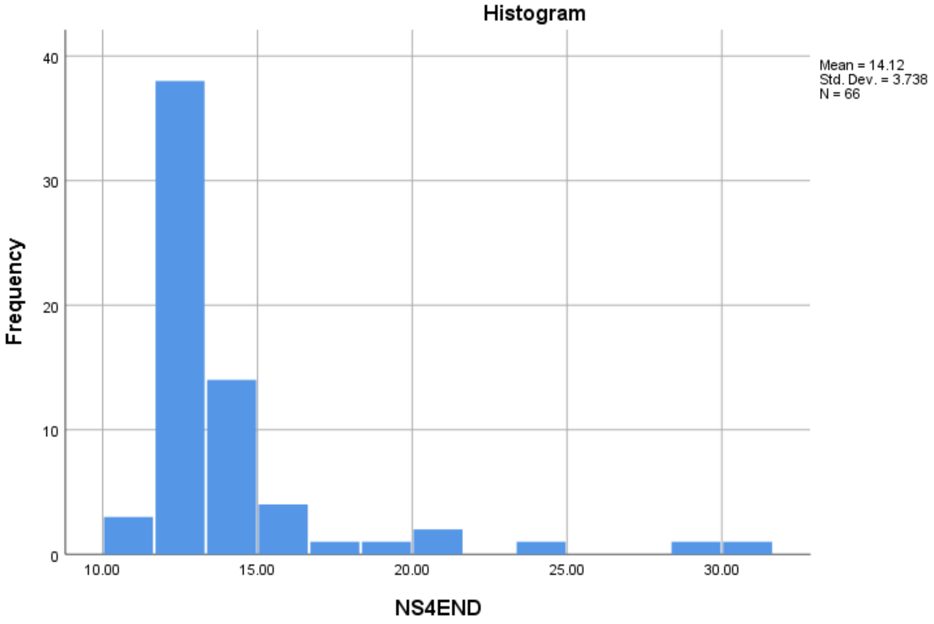
Night Shift 2



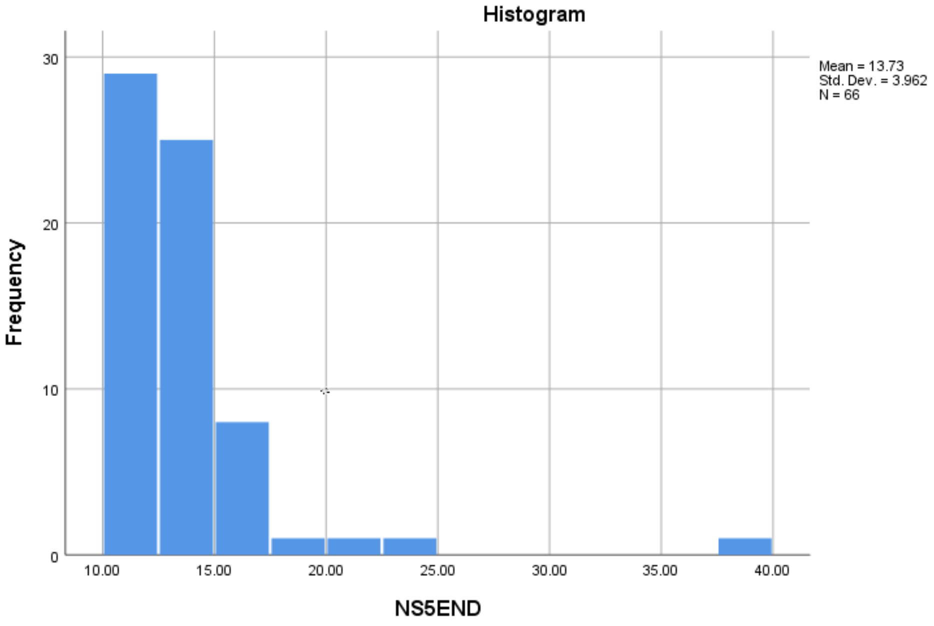
Night Shift 3



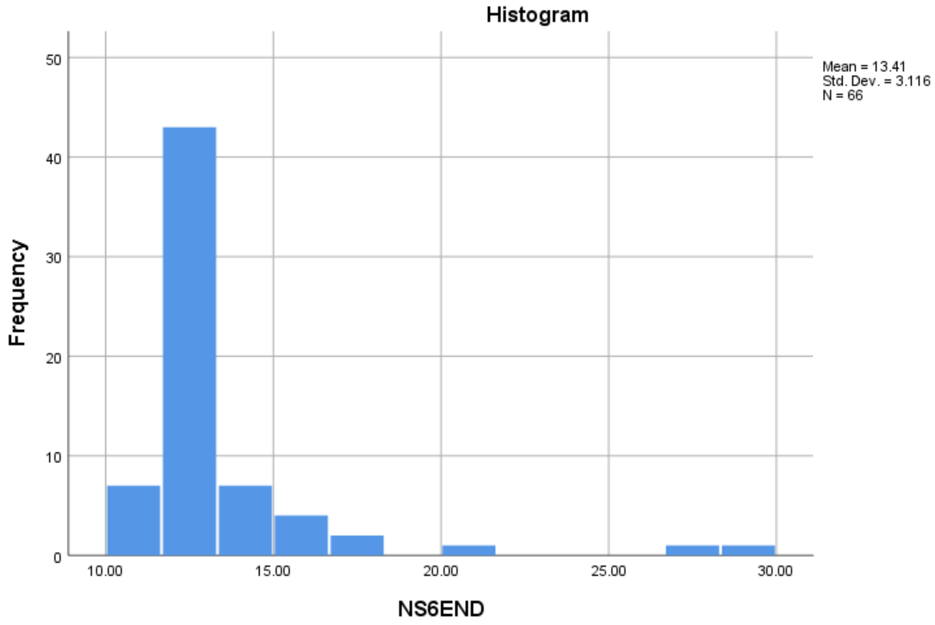
Night Shift 4



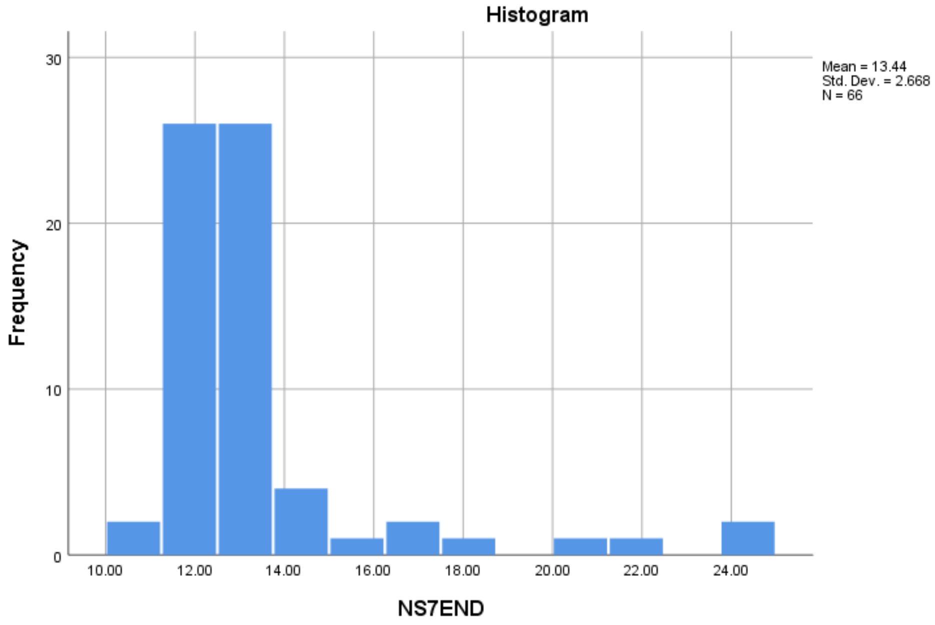
Night Shift 5



Night Shift 6



Night Shift 7



Appendix G: Mixed Model Analysis for SDLP and SDSP Over Seven Consecutive Night Shifts (SPSS output)

SDLP

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables	Number of Subjects
Fixed Effects	Intercept	1		1		
	Nightshift	7		6		
Repeated Effects	Nightshift	7	First-Order Autoregressive	2	ID	65
Total		15		9		

a. Dependent Variable: SDLP.

Information Criteria[a]

-2 Restricted Log Likelihood	-506.491
Akaike's Information Criterion (AIC)	-502.491
Hurvich and Tsai's Criterion (AICC)	-502.464
Bozdogan's Criterion (CAIC)	-492.281
Schwarz's Bayesian Criterion (BIC)	-494.281

The information criteria are displayed in smaller-is-better form.

a. Dependent Variable: SDLP.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	80.632	503.900	.0000
Nightshift	6	348.238	2.125	.0499

a. Dependent Variable: SDLP.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Repeated Measures	AR1 diagonal	.034351	.003592	9.564	.000	.027986	.042164
	AR1 rho	.733732	.029515	24.860	.000	.670390	.786457

a. Dependent Variable: SDLP.

SDSP

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables	Number of Subjects
Fixed Effects	Intercept	1		1		
	nightshift	7		6		
Repeated Effects	nightshift	7	First-Order Autoregressive	2	PN	65
Total		15		9		

a. Dependent Variable: SDSP.

Information Criteria[a]

-2 Restricted Log Likelihood	2097.622
Akaike's Information Criterion (AIC)	2101.622
Hurvich and Tsai's Criterion (AICC)	2101.649
Bozdogan's Criterion (CAIC)	2111.832
Schwarz's Bayesian Criterion (BIC)	2109.832

The information criteria are displayed in smaller-is-better form.

a. Dependent Variable: SDSP.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	74.473	2801.370	.000
nightshift	6	320.403	2.180	.045

a. Dependent Variable: SDSP.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Repeated Measures	AR1 diagonal	9.447985	.931578	10.142	.000	7.787716	11.462209
	AR1 rho	.647971	.037870	17.110	.000	.567516	.716169

a. Dependent Variable: SDSP.

Appendix H: Analysis of practice effects (SPSS output)

SDLP (Start Drives)

Estimates

Measure: SDLP (Start)

nightshift	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	.260	.013	.234	.285
7	.238	.011	.215	.260

Pairwise Comparisons

Measure: SDLP (Start)

(I) nightshift	(J) nightshift	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b] Lower Bound	95% Confidence Interval for Difference[b] Upper Bound
1	7	.022	.008	.230	-.005	.049

SDSP (Start Drives)

Estimates

Measure: SDSP (Start)

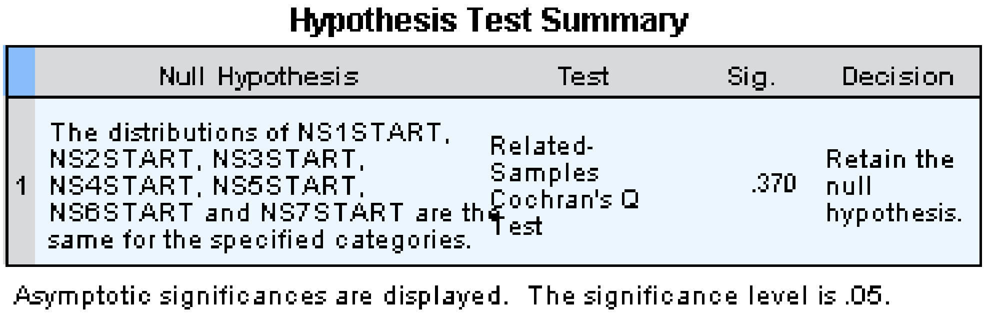
nightshift	Mean	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	12.535	.090	12.355	12.714
7	12.461	.113	12.236	12.686

Pairwise Comparisons

Measure: SDSP (start)

(I) nightshift	(J) nightshift	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a] Lower Bound	95% Confidence Interval for Difference[a] Upper Bound
1	7	.074	.104	1.000	-.257	.404

Proportion Crashing (start drives)

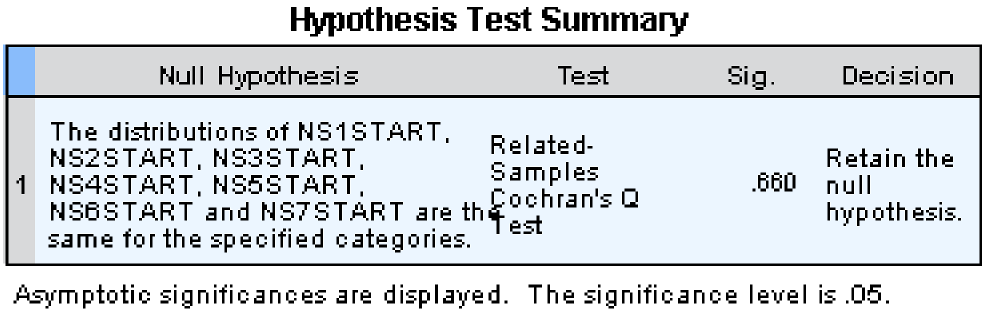


Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distributions of NS1START, NS2START, NS3START, NS4START, NS5START, NS6START and NS7START are the same for the specified categories.	Related-Samples Cochran's Q Test	.370	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Proportion Speeding (start drives)

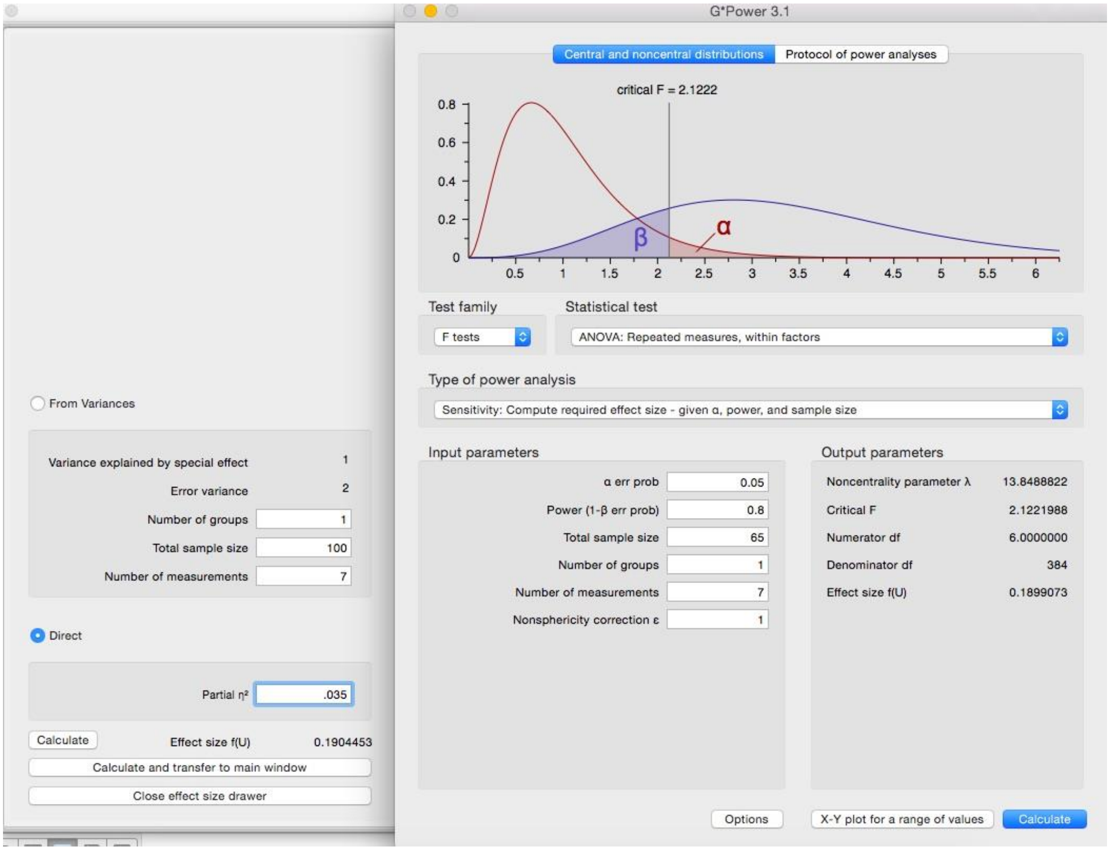


Hypothesis Test Summary

	Null Hypothesis	Test	Sig.	Decision
1	The distributions of NS1START, NS2START, NS3START, NS4START, NS5START, NS6START and NS7START are the same for the specified categories.	Related-Samples Cochran's Q Test	.660	Retain the null hypothesis.

Asymptotic significances are displayed. The significance level is .05.

Appendix I: Power Analysis



○ From Variances

Variance explained by special effect	1
Error variance	2
Number of groups	1
Total sample size	100
Number of measurements	7

● Direct

Partial η² .035

Effect size f(U) 0.1904453

Test family: F tests

Statistical test: ANOVA: Repeated measures, within factors

Type of power analysis: Sensitivity: Compute required effect size - given α, power, and sample size

Input parameters

α err prob	0.05
Power (1-β err prob)	0.8
Total sample size	65
Number of groups	1
Number of measurements	7
Nonsphericity correction ε	1

Output parameters

Noncentrality parameter λ	13.8488822
Critical F	2.1221988
Numerator df	6.0000000
Denominator df	384
Effect size f(U)	0.1899073