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ATSB TRANSPORT SAFETY REPORT
Aviation Safety Research Grant – B2005/0121

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Abstract

This aim of the study was to provide objective data to inform fatigue risk-management processes by determining the quantity and quality of sleep obtained by airline pilots during transcontinental 'back of clock' operations, and any changes to subjective fatigue and neurobehavioural performance during these sectors. Typical transcontinental back of clock route pairings involve a departure close to midnight Perth local time, with a dawn arrival into an East-coast city such as Melbourne, Sydney or Brisbane. In many instances this first sector is followed by a second sector to another east-coast destination, with sign-off at approximately 0900 Eastern Standard Time. Data were collected by participants during a two-week period of a normal rostered flying for an airline. During each of the 14 days of data collection, participants were required to undertake the following: 1) Wear an activity monitor wristwatch 7 days prior to, and 6 days after, a transcontinental back of clock flight; 2) complete sleep and duty diaries, which record time of sleep, subjective alertness, and time of duty; and 3) complete a simple 5-minute Psychomotor Vigilance Task (reaction time task) during the cruise of each sector, and three times on non-flying days. The results of this study suggest that Australian transcontinental back of clock operations, as operated by the airline involved in this study, differed significantly from a baseline sample of daytime duty periods in a number of important areas with respect to prior sleep, neurobehavioural performance, and subjective fatigue. While there were some significant differences in sleep and subjective fatigue as a function of a single transcontinental sector of back of clock flying, these differences were, on average, of a magnitude that was unlikely to impact on flight crew performance and overall safety. However, when a primary transcontinental sector is followed by an additional east-coast sector, there is evidence of reduced prior sleep, impaired neurobehavioural performance, and high levels of subjective fatigue.

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Sincere thanks goes to the airline that supported this study through access to their crew, and to the many pilots who volunteered as participants for data collection in this study. The authors acknowledge the somewhat onerous nature of the research protocol employed in this study, and we thank all the pilots who approached the study with dedication and professionalism.

Thanks also to the Walter Reed Army Institute of Research, for the use of the Palm PVT software in this research.

ABBREVIATIONS AND DEFINITIONS

Abbreviations

ANOVA	Analysis of variance
ATSB	Australian Transport Safety Bureau
BAC	Blood alcohol concentration
FRMS	Fatigue risk management system
PDA	Personal digital assistant
PVT	Psychomotor vigilance task

Definitions

Actigraphic data	Data from activity monitors that provide information on the level of physical activity/movement of an individual.
Back of clock	Work schedules that involve extended periods of night-work between midnight and dawn.
Duty period	The period between commencement and end of all duties.
Off-blocks	The commencement of a flight sector.
On-blocks	The end of a flight sector.
Polyphasic sleep	Sleep taken in multiple episodes, typically, repeated sleeps of duration between one and four hours.
Red eye flight	A flight with a midnight departure from the west coast of Australia and a dawn arrival into an east coast destination.
Sector	An individual flight.

EXECUTIVE SUMMARY

Work-related fatigue presents a significant risk to aviation safety. Recent incidents involving the Australian transcontinental ‘back of clock’ operations of commercial carriers have been investigated by the Australian Transport Safety Bureau (ATSB), and negative safety outcomes have been attributed to fatigue-related factors. Within the domestic Australian aviation context, transcontinental operations present an area where the effective management of fatigue is critical. This is especially the case with late evening departures from Perth for early morning arrivals on the east coast, with a range of different rostering approaches to building duty structures - the combination of sectors flown, duty periods, and layovers within these city pairings. However, as transcontinental night-work continues because of operational demands, the challenge is to quantify the risks associated with this work, and provide sufficient scientific data to assist in safe rostering practices. Typical transcontinental back of clock route pairings involve a departure close to midnight Perth local time, with a dawn arrival into an east coast city such as Melbourne, Sydney or Brisbane. This sector is colloquially known by some as a *red eye* flight. In many instances this first sector is followed by a second sector to another east coast destination with sign-off at approximately 0900 Eastern Standard Time.

The aim of the study was to provide objective data to inform fatigue risk-management processes by determining the quantity and quality of sleep obtained by airline pilots during transcontinental back of the clock operations, and any changes to subjective fatigue and neurobehavioural performance during these sectors.

Participants in the study were Captains and First-Officers flying for an airline that had given permission for their crew to be invited to participate in the study, and were recruited through an information circular distributed by the airline. The study protocol was approved by the Human Research Ethics Committee at the University of South Australia. A total pool of 82 volunteers was recruited to participate in the study. In total, 37 pilots undertook data collection, yielding 22 complete data sets. The occurrence of operational changes to rosters, where a rostered back of clock operation was not flown due to crew changes, as well as equipment failures, led to a significant proportion of data loss.

Data were collected by participants during a 2-week period of a normal roster of flying for an airline. Data were collected 7 days prior to, during, and 6 days after a transcontinental back of clock sector operated by the participant. During each of the 14 days of data collection, participants were required to undertake the following:

1. Wear an activity monitor wristwatch (7 days prior to, and 6 days after, a transcontinental back of clock flight);
2. Complete sleep and duty diaries, which record time of sleep, subjective alertness, and time of duty; and
3. Complete a simple 5-minute psychomotor vigilance task or PVT (reaction time task) during the cruise of each sector, and three times on non-flying days.

The results of this study suggest that Australian transcontinental back of clock operations, as operated by the airline involved in this study, differed significantly from a baseline sample of daytime duty periods in a number of important areas with respect to prior sleep, neurobehavioural performance, and subjective fatigue. While there were some significant differences in sleep and subjective fatigue as a function of a single transcontinental sector of back of clock flying, on average these differences were of a magnitude that was unlikely to impact on flight crew performance and overall safety.

However, when a primary transcontinental sector is followed by an additional east coast sector there is evidence of reduced prior sleep, impaired neurobehavioural performance, and high levels of subjective fatigue.

During these secondary back of clock sectors, crews had obtained on average significantly less sleep in the 48 hours prior to both take-off and landing, compared with a baseline of daytime sectors. It was observed that on landing crew had a mean level of sleep in the prior 24 hours, and an average across the prior 48 hours, below 5.5 hours per night. This study also demonstrated that subjective fatigue during these second back of clock sectors was significantly higher, compared with baseline levels of day sectors. The finding that over half the crew involved in this study rated their subjective fatigue on landing after a second back of clock sector as “extremely tired” or “completely exhausted” is noteworthy. There was also evidence in reduced neurobehavioural performance during the second back of clock sector in this study. Indeed, the results of this study indicated a mean difference in response speed of 10.2 per cent, with the slowest mean response speed occurring during the second back of clock sector when compared with the baseline performance measure taken between 0600 and 1200 hours.

While the study has demonstrated few significant differences pertaining to the first back of clock sector, and raised some questions with respect to sleep and performance issues pertaining to the second back of clock sector, these findings broadly represent the outcomes of statistical analyses of mean differences between repeated measures. Within any sampled population, there will be variability around the mean, and from the perspective of *risk management*, a safe system of work must be able to manage instances where an individual, for what ever reason, does not obtain “an average” amount of sleep, or feels significantly fatigued on any given day.

Accordingly, within the context of Australian commercial aviation, new approaches to the management of fatigue-related risk have been developed. The defining characteristic of these approaches is that they do not solely depend on prescriptive flight and duty time regulations to provide opportunity for “an average” amount of rest to be obtained by all crew members prior to commencing duty. Rather, these Fatigue Risk Management Systems (FRMS) provide organisations, and the individuals within those organisations, a set of tools to manage the occurrence of fatigue, or possible risk of fatigue, and fatigue-related impairment on a day-to-day basis, in a manner that is able to manage the degree of individual difference found during normal operations.

The conceptual framework for an FRMS proposed by Dawson and McCulloch (2005) is built upon the notion of accident trajectory through absent or failed defences. The model suggests that every fatigue-related incident will be preceded by a fatigue-related error, which in turn will be preceded by behavioural symptoms of fatigue, and an individual work/sleep history that has led to fatigue.

This conceptual framework for an FRMS suggests that the traditional approach to fatigue management, that of prescriptive duty time rule-sets, involves only a single layer of defence at step one of the accident trajectory. According to the conceptual framework for an FRMS, sole reliance on the single layer of defence offered by prescriptive duty time rule-sets, is potentially an inadequate form of defence against fatigue-related risk.

The alternative approach to fatigue risk management suggests that an organisation should develop an FRMS that designs and implements defences at each of the five layers within the accident trajectory. Accordingly, prescriptive rule-sets governing flight and duty time limitations should be bolstered by additional layers of defence, relating to each of the subsequent layers within the accident trajectory.

It is suggested that beyond the development of any revised rule-set governing flight and duty time limitations, the development of additional layers of defences against fatigue-related risk is investigated within the conceptual framework of a FRMS.

1 INTRODUCTION

Work-related fatigue presents a significant risk to aviation safety. Recent incidents involving the Australian transcontinental ‘back of clock’ operations of commercial carriers have been investigated by the Australian Transport Safety Bureau (ATSB), and negative safety outcomes have been attributed to fatigue-related factors (ATSB, 2002, 2004). Work-related fatigue is now recognised in Australian Occupational Health and Safety legislation as an identifiable workplace hazard, and the first essential steps in the process of risk management involves the identification of hazards and quantification of risk.

1.1 Fatigue, shiftwork and performance

The evolution of the so-called “24-hour society” has compelled continuous operations in many industries, including aviation. As a consequence, the prevalence of irregular work hours has increased, and so too has the prevalence of pilots who experience the problems associated with fatigue (Caldwell, 2005).

Fatigue can be defined as the decreased capability to perform mental or physical work, or the subjective state in which one can no longer perform a task, produced as a function of inadequate sleep, circadian disruption, or time on task (Brown, 1994).

1.1.1 Sleep and fatigue

Reduction in either the *quality* or *quantity* of sleep are both significant sources of fatigue when employees are required to work irregular duty schedules (Gillberg, 1995). Research has demonstrated that the timing, duration, and the continuity of sleep each play an important role in the restoration of alertness and performance (Wesensten, Balkin, & Belenky, 1999).

With respect to the relationship between total sleep time and time awake, it has been shown that even moderate amounts of sleep restriction can lead to significant levels of performance impairment. For instance, just one night of restricted sleep, or a single extended period of wakefulness, can have deleterious effects on performance. Sleep fragmentation or disruption has also been shown to impact on the restorative value of sleep (Wesensten, Balkin, & Belenky, 1999).

In order to quantify the effects of sleep restriction on performance in a manner that is readily understood, a number of studies have examined the similarities between fatigue-related impairment and alcohol intoxication. For instance, Dawson and Reid (1997) compared the performance effects of 28 hours of sustained wakefulness and alcohol intoxication. After 17 hours of sustained wakefulness, performance on a tracking task was equivalent to a blood alcohol concentration (BAC) of 0.05 per cent. After 24 hours of sustained wakefulness performance was equivalent to a BAC of 0.10 per cent. These results were replicated by Williamson and Feyer (2000) who found that between 17 and 19 hours of sustained wakefulness produced a performance impairment similar to that associated with a BAC of 0.05 per cent.

1.1.2 Fatigue and circadian disruption

The human sleep wake cycle is regulated by the circadian timing system, which is controlled by endogenous factors, as well as external “zeitgebers”, which are social or environmental cues such as mealtimes, light and dark cycles, and other factors that influence our internal time-keeping systems. Humans are diurnal, and the normal circadian cycle is shaped around daytime wake and restorative sleep during the night.

Irregular patterns of work, especially those that include night work, can lead to significant circadian disruption. Irregular night work frequently involves working at odds to our natural circadian entrainment, and thus working at a time of naturally reduced alertness and performance (Howard, Gaba, Rosekind, & Zarcone, 2002).

Similarly, irregular night work means sleep must be obtained during the day, at a time of normally high levels of alertness and performance. Accordingly, daytime sleep is more difficult to obtain, and is of a lower quality than sleep obtained during the night. The daytime sleep of shiftworkers has been seen to be shorter and less restorative than night time sleep (Lamond et al., 2004) and the level of sleep disturbances in shiftworkers have been likened to those seen in clinical insomnia (Åkerstedt, 1998).

In short, the circadian disruption associated with irregular night work can result in impaired performance, and subsequently impact on safety (DeMoss, Jr.M., Haus, Crain, & Asche, 2004; Lamond & Dawson, 1999).

1.1.3 Consequences of fatigue – performance and safety

For employees required to work irregular duty schedules, the major consequences of fatigue can be described in terms of poorer performance and greater risk of accident, especially during night duty (Harrington, 1994). More specifically, the consequences of fatigue can be isolated in terms of impaired cognitive performance, and include slowed reaction time, impaired vigilance, forgetfulness, lethargy, apathy, and poor decision-making, communication, and mood (Ashberg, Kecklund, Åkerstedt, & Gamberale, 2000; Brown, 1994).

There is considerable evidence to suggest that fatigue has a detrimental impact on safety, and plays a significant role in many accidents within all industries, including aviation (Folkard & Monk, 1979; Lauber & Kayten, 1988). Indeed, Lyman and Orlady analysed 2,006 aircrew error reports and found that 21 per cent of the incidents were fatigue-related, and that these incidents tended to occur between midnight and 0600 hours during the descent, approach, and landing phases of flight. This is not particularly surprising, given that when asked, the majority of commercial pilots complained that fatigue was a problem and that they had felt “extremely tired or washed out during the previous thirty days” (Lyman & Orlady, 1980).

Across all sectors of aviation, pilots are increasingly required to work schedules that include long hours of duty, early departures, late arrivals, and night work (Caldwell, 2005). In other industries, field-based research indicates that people who work during the night-time and sleep during the daytime obtain less sleep than others (Haslegrave, 1998). Furthermore, laboratory-based research clearly indicates that sleep restriction and/or disruption caused by irregular work hours are major contributors to fatigue (Lamond, Dawson, & Roach, 2005). Given that sleep restriction and/or disruption tends to impair neurobehavioural performance, night work poses a higher fatigue risk than day work.

1.2 Transcontinental 'back of clock' operations

Within the domestic Australian aviation context, transcontinental operations present an area where the effective management of fatigue is critical. Routes between Perth and east coast cities in particular are frequently highlighted as problematic, according to evidence from confidential surveys of pilots. This is especially the case with late evening departures from Perth for early morning arrivals on the east coast, with a range of different rostering approaches to building duty structures - the combination of sectors flown, duty periods, and layovers within these city parings. However, as transcontinental night-work continues because of operational demands, the challenge is to quantify the risks associated with this work, and provide sufficient scientific data to assist in safe rostering practices.

Typical transcontinental back of clock route pairings involve a departure close to midnight Perth local time, with a dawn arrival into an east coast city such as Melbourne, Sydney, or Brisbane. This sector is colloquially known by some as a *red eye* flight. In many instances this first sector is followed by a second sector to another east coast destination, with sign-off at approximately 0900 Eastern Standard Time.

Figure 1: Typical transcontinental 'back of clock' route pairings

1.3 Fatigue risk management

In the Australian Occupational Health and Safety legislation, work-related fatigue is now recognised as an identifiable workplace hazard. A key component of any hazard management system is the ability to quantify the hazard. Ultimately, this will lead to the minimisation of risks and errors derived from fatigue.

Consequently, the aim of the proposed project was to provide objective data to inform fatigue risk-management processes by determining the quantity and quality of sleep obtained by commercial aviation pilots during transcontinental back of the clock operations, and any changes to neurobehavioural performance during these sectors.

2 METHODOLOGY

2.1 Participants

Participants were Captains and First Officers flying for an airline that had given permission for their crew to be invited to participate in the study. Participants were recruited through an information circular distributed by the airline.

As all participants were subjected to annual medical certification, they were assumed fit to participate in the study. No other screening mechanisms were used. The study protocol was approved by the Human Research Ethics Committee at the University of South Australia.

A total pool of 82 volunteers was recruited to participate in the study. In total, 37 pilots undertook data collection, yielding 22 complete data sets. The occurrence of operational changes to rosters, where a rostered back of clock operation was not flown due to crew changes, as well as equipment failures, led to a significant proportion of data loss.

2.2 Design and procedure

Data were collected by participants during a two-week period of a normal rostered flying for an airline. Data were collected 7 days prior to, during, and 6 days after a transcontinental back of clock sector operated by the participant.

During each 14 days of data collection, participants were required to undertake the following:

1. Wear an activity monitor wristwatch (7 days prior to, and 6 days after, a transcontinental back of clock flight);
2. Complete sleep and duty diaries, which record time of sleep, subjective alertness, and time of duty; and
3. Complete a simple 5-minute psychomotor vigilance task or PVT (reaction time task) during the cruise of each sector, and three times on non-flying days.

2.3 Materials

2.3.1 Activity monitor

An activity monitor was worn by each participant for the duration of the study period, in order to objectively measure the sleep/wake patterns of participants. The activity monitor is a device worn like a wristwatch, and continuously records body movement – sustained periods of high activity are scored as wake, sustained periods of low activity are scored as sleep, and the degree of movement within a sleep period provides an indication of sleep quality. An activity monitor is illustrated in Figure 2.

Figure 2: Activity monitor

Participants wore an activity monitor at all times, except whilst showering or swimming, as activity monitors are water-resistant, but not waterproof. From the activity monitor recordings, specialised data analysis software was used to objectively determine the quantity and quality of sleep that participants obtained. The activity monitor has been used in a number of previous fatigue studies internationally, in both the commercial and military aviation environment. The activity monitor is currently also being used in a field study with Australian long-haul crew, and has been shown not to interfere with the electronics on board the aircraft.

2.3.2 Sleep and duty diary

In addition to wearing an activity monitor, participants made subjective assessments of their sleep for the duration of the study period using a sleep diary. In the sleep diary, participants recorded self-determined estimates of bed times, sleep quality, and pre- and post-sleep fatigue levels.

2.3.3 Psychomotor vigilance task (PVT)

The PVT is a sustained attention task, in which participants are required to respond as quickly as possible to a visual stimulus. The test lasts 5-minutes, with participants being required to attend to the screen of the device, and respond as quickly as possible by pressing a nominated button with the thumb of their dominant hand each time a visual stimulus appears. The stimulus is presented intermittently to participants across the duration of the 5-minute test.

The 5-minute PVT is a widely accepted measure of neurobehavioural performance in the laboratory. A Palm personal digital assistant (PDA) version of the PVT software was utilised in this study, as developed by the Walter Reed Army Institute of Research (Thorne *et al.*, 2005). The task was completed using a hand held PalmPilot device, as illustrated in Figure 3.

Figure 3: Psychomotor vigilance task on handheld PalmPilot

Participants were required to complete this task during a quiet and low workload period of the cruise phase of each sector, as well as during set times on days where there was no flight duty. Importantly, pilots were instructed that operational requirements will always take precedence over completing the performance task. This protocol has been recently used within other international studies of long-haul crew, and has been subjected to a formal risk assessment process.

2.4 Measures

2.4.1 Prior sleep and wake

Prior sleep and wake were determined using the data from the activity monitors. The actigraphic data[1] were verified using the sleep and duty diaries to determine the times in which the participants attempted sleep.

A number of specific variables were then created for use within the analysis of sleep and performance:

prior sleep in the past 24 hours at the start of a sector (take-off)

prior sleep in the past 24 hours at the end of a sector (landing)

prior sleep in the past 48 hours at the start of a sector (take-off)

prior sleep in the past 48 hours at the end of a sector (landing)

prior wake at the start of a sector (take-off)

prior wake at the end of a sector (landing)

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[1] Actigraphic data: data from activity monitors that provide information on the level of physical activity/movement of an individual.

2.4.2 Duty times

Duty times were determined using the data from the duty diaries completed by the participants. The duty diaries asked participants to record sign-on and sign-off times for each duty period, as well as off-blocks[2] and on-blocks[3] time for every sector flown during the 14 day data collection period.

Two specific variables were then created for use within the analysis of sleep and performance:

sector start time

sector end time

2.4.3 Subjective fatigue

Subjective fatigue was determined from the self-report instrument included in the sleep and duty diary. The self-report instrument utilised the Samn-Perelli Fatigue Checklist, which utilises a seven point scale ranging from "*1 – Fully Alert, Wide Awake*" to "*7 – Completely Exhausted, Unable to Function Effectively*" (Samn & Perelli, 1982).

2.4.4 Neurobehavioural performance

Neurobehavioural performance was determined from the Palm PVT tests completed at regular intervals by the pilots throughout the 14 day period of data collection. From the Palm PVT data, three specific variables were utilised with respect to neurobehavioural performance:

mean reciprocal response time (speed of response)

mean reciprocal response time (speed of response) for the fastest 10 per cent of responses

number of lapses (response time greater than 500 milliseconds)

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[2] Off-blocks: the commencement of a flight sector.

[3] On-blocks: the end of a flight sector.

3 RESULTS

3.1 Prior sleep and wake

The prior sleep and the prior wake of participants was determined for the start and the end of all sectors, effectively corresponding to the critical take-off and landing phases of flight. Repeated measures analysis of variance (ANOVA), with Greenhouse-Geisser correction, were undertaken, with planned comparisons between prior sleep and prior wake at the commencement of first and second back of clock sectors, and 3 day-flying “baseline” measures representing mean prior sleep and prior wake values for departures between the hours: 1) 0600-1200; 2) 1200-1800; and 3) 1800-0000.

Table 1: Summary of actigraphic sleep variables

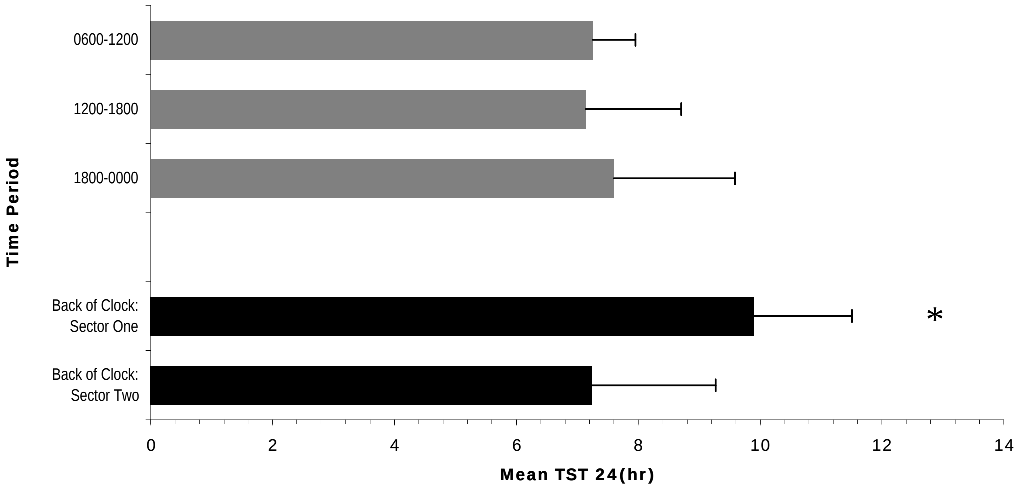
	Back of clock	Day-flying baselines				
	Sector one	0600-1200	1200-1800	1800-0000	F	*p*
Take-off						
TST$_{24}$ (h)	9.89 ±1.62	6.95 ±0.83	7.33 ±1.45	7.95 ±1.93	F(3,36)=11.45	0.001
TST$_{48}$ (h)	15.75 ±1.89	14.81 ±1.73	15.36 ±1.55	15.71 ±2.54	F(3,36)=1.18	n.s.
PW (h)	4.32 ±3.97	3.79 ±0.74	8.47 ±1.14	11.67 ±1.66	F(3,36)=35.47	0.001
Landing						
TST$_{24}$ (h)	7.61 ±2.01	6.80 ±0.91	7.33 ±1.45	7.36 ±1.76	F(3,36)=0.57	n.s.
TST$_{48}$ (h)	12.12 ±2.04	14.62 ±1.80	15.36 ±1.56	14.72 ±2.74	F(3,36)=9.28	0.001
PW (h)	8.23 ±3.81	5.42 ±0.94	10.18 ±1.22	14.17 ±2.63	F(3,36)=29.37	0.001

	Back of clock	Day-flying baselines				
	Sector two	0600-1200	1200-1800	1800-0000	F	*p*
Take-off						
TST$_{24}$ (h)	7.24 ±2.03	7.25 ±0.71	7.14 ±1.56	7.60 ±1.99	F(3,27)=0.17	n.s.
TST$_{48}$ (h)	11.60 ±2.14	15.33 ±1.61	15.41 ±1.75	15.46 ±2.81	F(3,27)=16.50	0.001
PW (h)	9.24 ±4.10	3.77 ±0.78	8.74 ±1.15	12.00 ±1.74	F(3,27)=35.59	0.001
Landing						
TST$_{24}$ (h)	5.34 ±2.04	7.13 ±0.77	7.14 ±1.56	6.85 ±1.58	F(3,27)=3.12	n.s.
TST$_{48}$ (h)	10.70 ±2.01	15.21 ±1.60	15.41 ±1.75	14.21 ±2.87	F(3,27)=17.37	0.001
PW (h)	11.19 ±4.16	5.25 ±0.95	10.51 ±1.19	14.59 ±2.86	F(3,27)=21.55	0.001

3.1.1 Take-off

At the start of sectors, there was a significant difference in the mean amount of sleep in the prior 24 hours, as a function of the type of sector flown. At the start of the first back of clock sector, the mean sleep in the prior 24 hours was 9.89 (SD = 1.62) hours. Planned comparisons showed that this was significantly more than the mean amount of sleep for the 3 day-flying comparison measures of departures between the hours 0600-1200, 1200-1800 and 1800-0000, $F(3, 36) = 11.45$, $p = 0.001$. There was no significant difference between sleep in the prior 24 hours at the start of the second back of clock sector and any of the day-flying comparison measures. The mean amount of sleep in the prior 24 hours at take-off is illustrated in Figure 4.

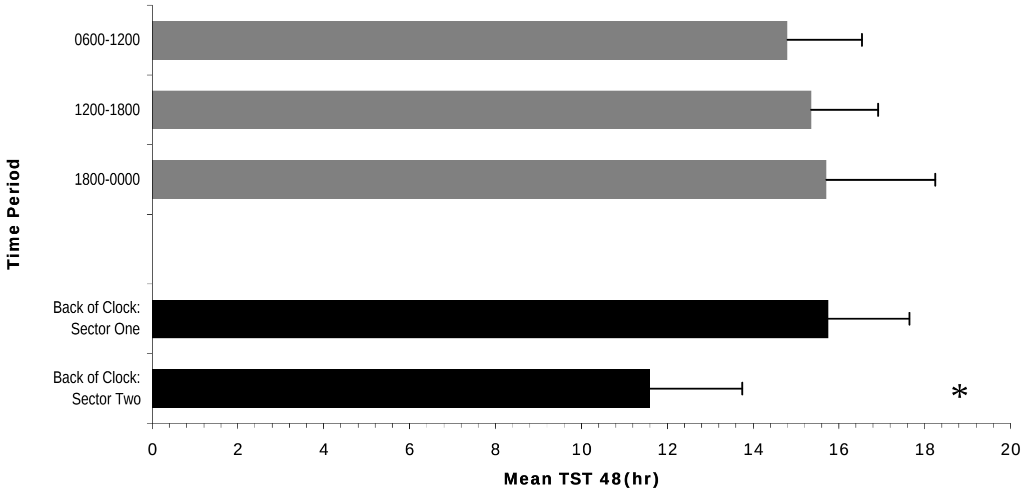
Figure 4: Sleep in prior 24 hours at take-off



Legend: Actigraphic total sleep time in prior 24-hrs (mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

At the start of sectors, there was also a significant difference in the mean amount of sleep in the prior 48 hours, as a function of the type of sector flown. There was no significant difference between sleep in the prior 48 hours at the start of the first back of clock sector and any of the day-flying comparison measures. However, at the start of the second back of clock sector, the mean sleep in the prior 48 hours was 11.60 (SD = 2.14) hours. Planned comparisons showed that this was significantly *less* than the mean amount of sleep for the day-flying comparison measures of departures between the hours 0600-1200, 1200-1800 and 1800-0000, *F*(3, 27) = 16.50, *p*<.001. The mean amount of sleep in the prior 48 hours at take-off is illustrated in Figure 5.

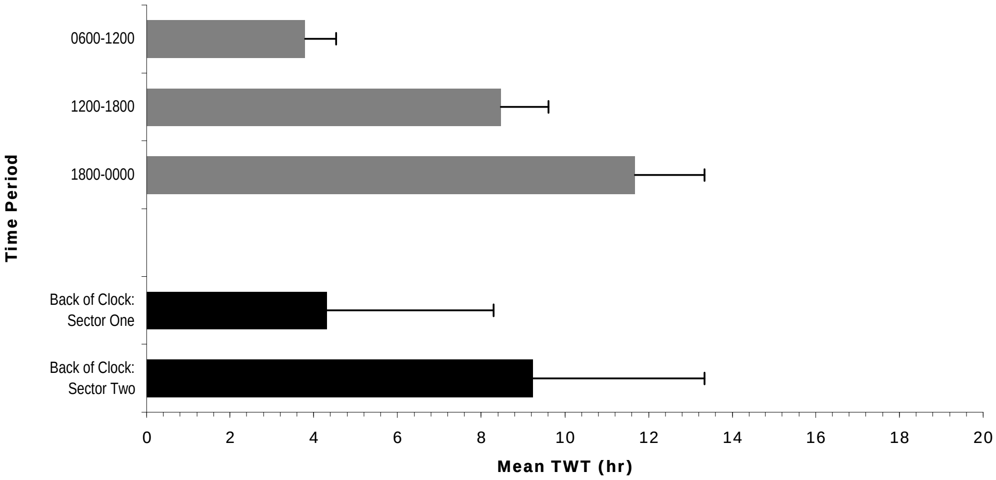
Figure 5: Sleep in prior 48 hours at take-off



Legend: Actigraphic total sleep time in prior 48-hrs (mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

At the start of sectors, there was also a significant difference in the mean amount of prior wake, as a function of the type of sector flown. At the start of the first back of clock sector, the mean prior wake was 4.32 (SD = 3.97) hours and at the start of the second back of clock sector, the mean prior wake was 9.24 (SD = 4.10) hours. Planned comparisons showed that these prior wake values for the back of clock sectors were not *consistently* less or more than the mean amount of prior wake for the day-time comparison measures. Significant variability of prior wake was found to occur across the day, with an increase in prior wake for afternoon and evening departures. The mean amount of prior wake at take-off is illustrated in Figure 6.

Figure 6: Prior wake at take-off

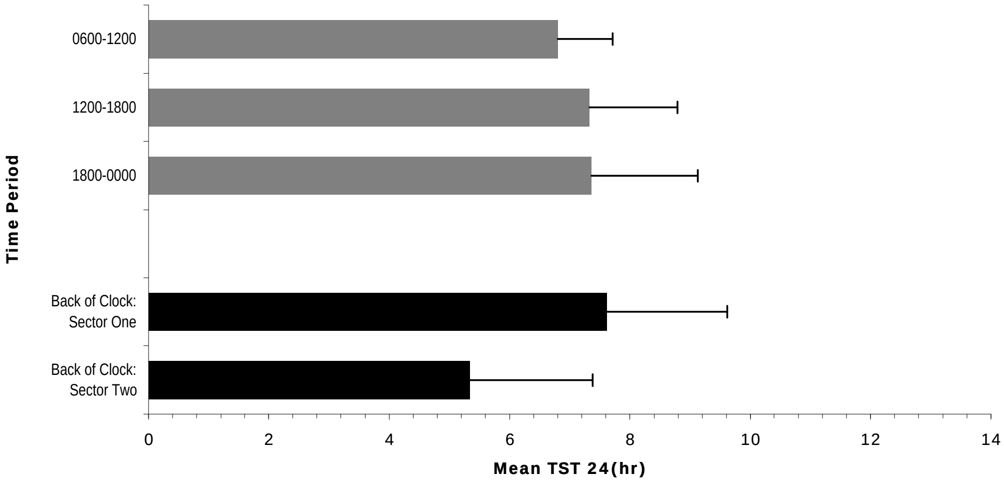


Legend: Actigraphic prior wake (mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

3.1.2 Landing

At the end of sectors, there was no significant difference in the mean amount of sleep in the prior 24 hours, as a function of the type of sector flown. The mean amount of sleep in the prior 24 hours at landing for the second back of clock flight was 5.34 (SD = 2.04) hours. While this figure was less than the mean amount of sleep in the prior 24 hours for any of the day-flying comparison measures, the difference was not significant. The mean amount of sleep in the prior 24 hours at landing for each type of sector flown is illustrated in Figure 7.

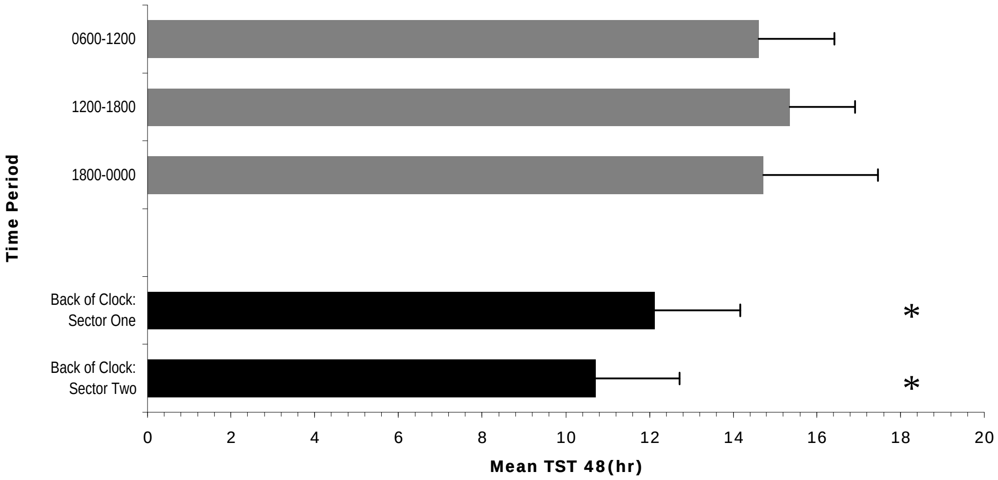
Figure 7: Sleep in the prior 24 hours at landing



Legend: Actigraphic total sleep time in prior 24-hrs (mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

At the end of sectors, there was a significant difference in the mean amount of sleep in the prior 48 hours, as a function of the type of sector flown. At the start of the second back of clock sector, the mean sleep in the prior 48 hours was 12.12 (SD = 2.04) hours. Planned comparisons showed that this was significantly less than the mean amount of sleep for the day-flying comparison measures of departures between the hours 0600-1200, 1200-1800 and 1800-0000, *F*(3, 36) = 9.28, *p*<.001. Similarly, at the start of the second back of clock sector, the mean sleep in the prior 48 hours was 10.70 (SD = 2.01) hours. Planned comparisons showed that this was also significantly less than the mean amount of sleep for the day-flying comparison measures of departures between the hours 0600-1200, 1200-1800 and 1800-0000, *F*(3, 27) = 17.37, *p*<.001. The mean amount of sleep in the prior 48 hours at landing for each type of sector flown is illustrated in Figure 8.

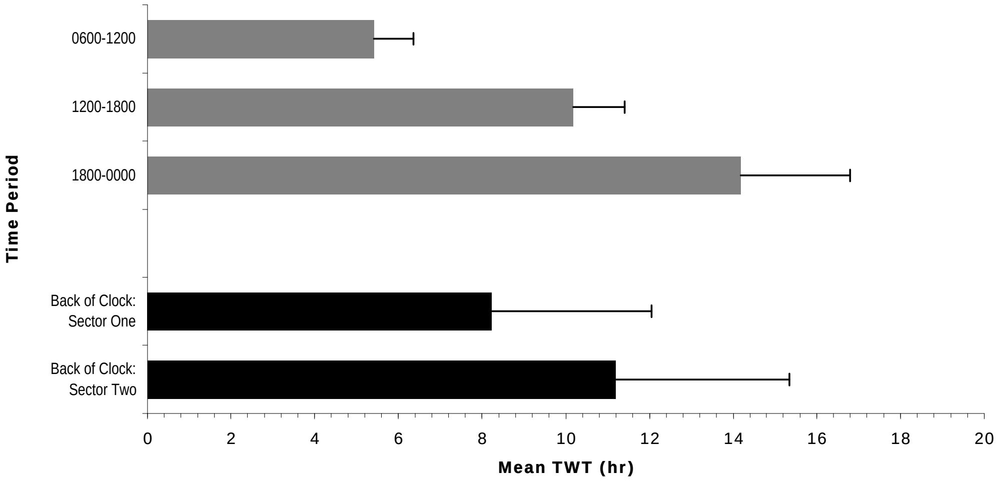
Figure 8: Sleep in the prior 48 hours at landing



Legend: Actigraphic total sleep time in prior 48-hrs (Mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

At the start of sectors, there was also a significant difference in the mean amount of prior wake, as a function of the type of sector flown. At the end of the first back of clock sector, the mean prior wake was 8.23 (SD = 3.81) hours and at the end of the second back of clock sector, the mean prior wake was 11.19 (SD = 4.16) hours. Planned comparisons showed that these prior wake values for the back of clock sectors were not *consistently* less or more than the mean amount of prior wake for the day-time comparison measures. Significant variability of prior wake was found to occur across the day, with an increase in prior wake for afternoon and evening departures. The mean amount of prior wake at landing is illustrated in Figure 9.

Figure 9: Prior wake at landing



Legend: Actigraphic prior wake (mean ±SD) for the two back of clock sectors and the three baseline departure times. * *p*<.05

3.1.3 Summary

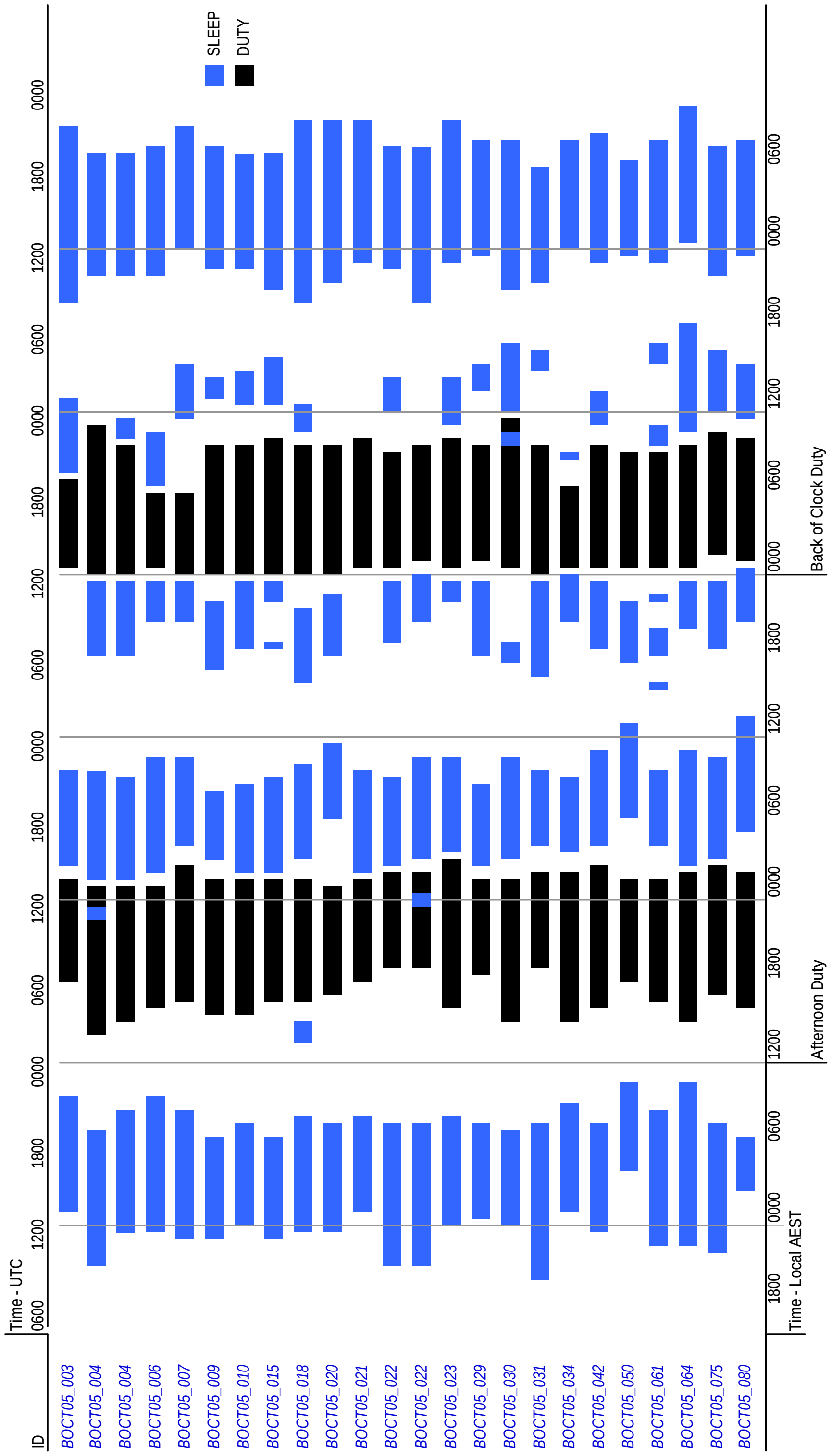
In summary, the first back of clock sectors were typically associated with significantly more sleep in the 24 hours prior to the start of duty, and significantly less sleep in the prior 48 hours on landing when compared with baseline measures from flights that occurred during daytime duties. Similarly, the second back of clock sectors were associated with significantly less sleep in the prior 48 hours, both at take-off and landing.

These findings are associated with a general pattern of sleep obtained by crew in response to the particular timing of work-rest cycles in the back of clock duty pattern.

As illustrated in Figure 10, the duty prior to the back of clock sector consistently involved an afternoon duty, followed by a 24 hour layover. This pattern provided an opportunity for two sleep periods between duties. The first of these sleep periods was typically taken during the local night, and at an appropriate time with respect to the crew-members’ circadian phase. The second sleep period was observed to be an early evening sleep obtained prior to the sign-on for the back of clock sector. While not all crew were observed to obtain this second sleep period, the majority did, and accordingly this led to greater amounts of prior sleep and less prior wake at take-off for these flights.

In contrast, where a crew-member flew a second back of clock sector, as an additional east coast flight after the transcontinental flight, less prior sleep and more prior wake were observed, when compared with baseline measures from flights that occurred during daytime duties. Again, this is due to the particular positioning of flight duties with respect to sleep opportunities, with the end of the second back of clock sector corresponding to the end of the previous main sleep period 24 hours prior.

Figure 10: Sleep in prior 24 hours at take-off

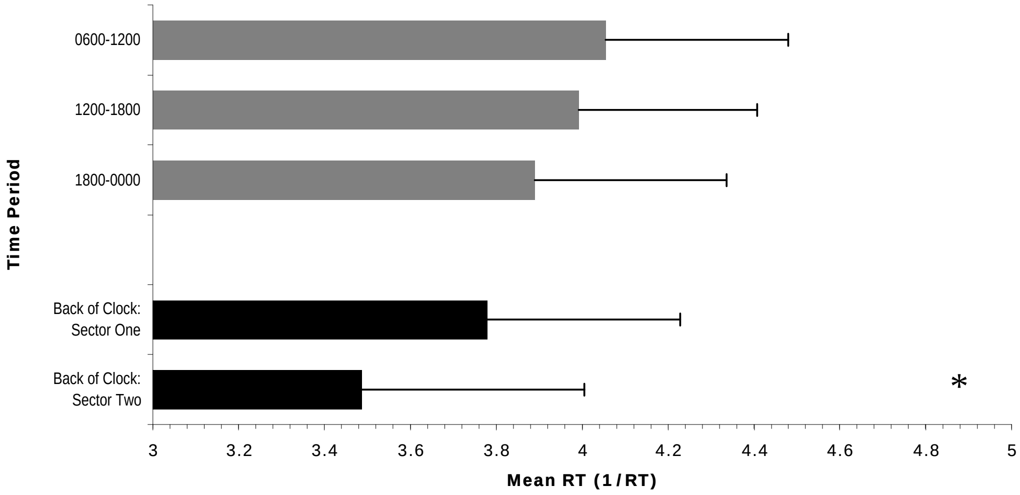


3.2 Neurobehavioural performance

Neurobehavioural performance was assessed using a 5-minute Palm PVT test. Repeated measures ANOVA, with Greenhouse-Geisser correction, were undertaken, with planned comparisons between PVT performance during the cruise of the first and second back of clock sectors, and 3 day-time “baseline” measures representing mean performance for tests undertaken between the hours: 1) 0600-1200; 2) 1200-1800; and 3) 1800-0000.

With respect to PVT reciprocal response time, there was a significant difference found as a function of the time of the test. Planned comparisons showed that performance during the first back of clock sector was significantly slower than performance during the 0600-1200 and 1200-1800 test times *F*(3, 42) = 8.053, *p*<.05. Similarly, performance during the second back of clock sector was significantly slower than performance during any of the baseline test times *F*(3, 42) = 33.391, *p*<.01. The mean reciprocal response time for each test time is illustrated in Figure 11.

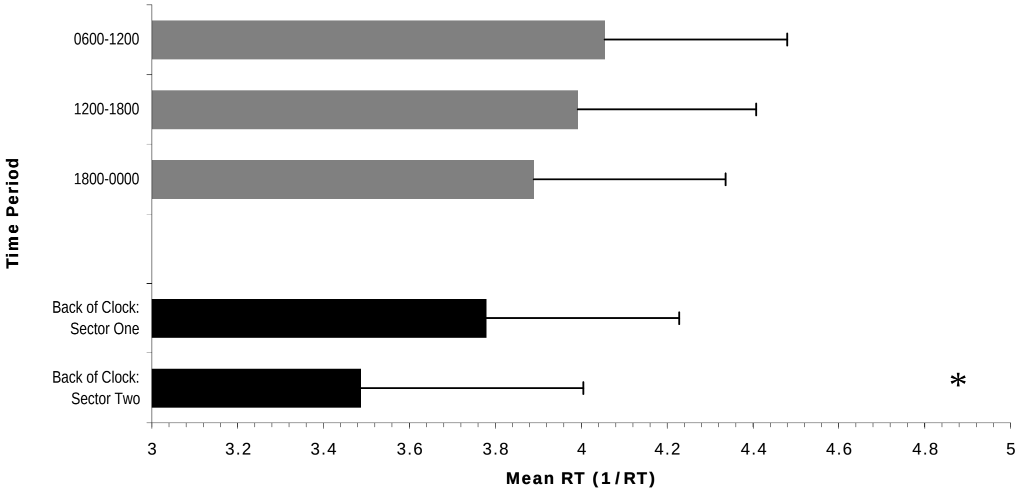
Figure 11: PVT reciprocal response time



Legend: PVT reciprocal response time (mean ±SD) for the two back of clock sectors and the three baseline testing times. * *p*<.05

A significant difference in PVT reciprocal response time for the fastest 10 per cent of responses was also found as a function of the time of the test. Planned comparisons showed that performance during the first back of clock sector was significantly slower than performance during the 0600-1200 and 1200-1800 test times *F*(3, 42) = 7.359, *p*<.05. Similarly, performance during the second back of clock sector was significantly slower than performance during any of the baseline test times *F*(3, 42) = 22.212, *p*<.01. The mean reciprocal response time for each test time is illustrated in Figure 12.

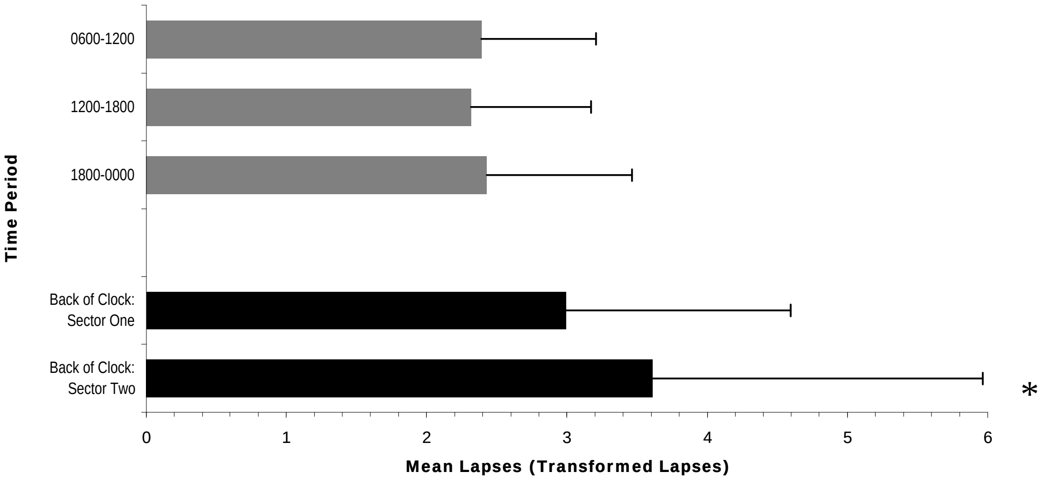
Figure 12: PVT reciprocal response time (fastest 10 per cent of responses)



Legend: PVT reciprocal response time - fastest 10 per cent of responses (mean ±SD) for the two back of clock sectors and the three baseline testing times. * *p*<.05

With respect to PVT Lapses, there was a significant difference found as a function of the time of the test. Planned comparisons showed that performance during the first back of clock sector was not significantly different from any of the baseline test times. However, performance during the second back of clock sector was significantly worse than performance during any of the baseline test times $F(3, 42) = 7.546$, $p<.05$. The mean number of lapses for each test is illustrated in Figure 13.

Figure 13: PVT transformed lapses



Legend: PVT transformed lapses - fastest 10 per cent of responses (mean ±SD) for the two back of clock sectors and the three baseline testing times. * *p*<.05

3.3 Subjective fatigue

Subjective fatigue was analysed using self-report ratings at the start and end of every sector, effectively corresponding to the critical take-off and landing phases of flight. The self-report instrument utilised the Samn-Perelli Fatigue Checklist, which utilises a seven point scale ranging from *"1 – Fully Alert, Wide Awake"* to *"7 – Completely Exhausted, Unable to Function Effectively"* (Samn & Perelli, 1982). Repeated measures ANOVA, with Greenhouse-Geisser correction, were undertaken, with planned comparisons between prior sleep and prior wake at the commencement of first and second back of clock sectors, and three day-flying "baseline" measures representing mean Samn-Perelli ratings for departures between the hours: 1) 0600-1200; 2) 1200-1800; and 3) 1800-0000.

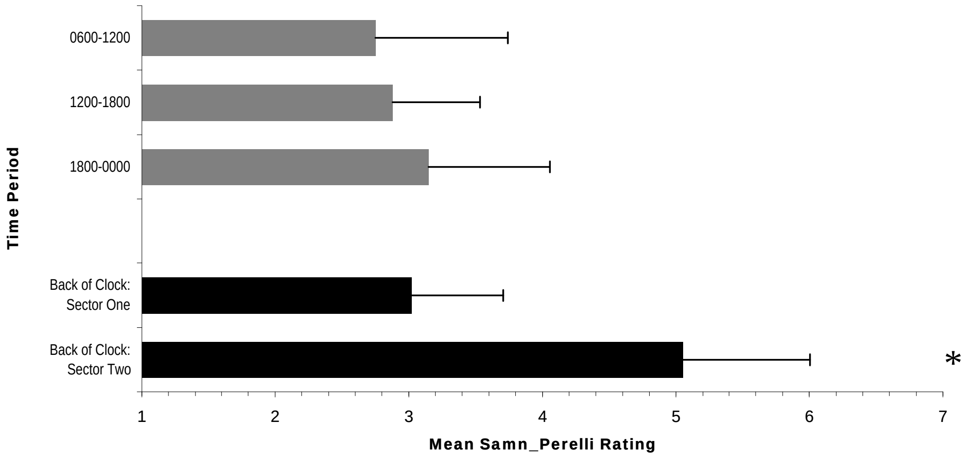
3.3.1 Take-off

The mean Samn-Perelli ratings of crew at the start of three day-flying "baseline" measures ranged from 2.75 (SD = 0.99) to 3.15 (SD = .91) demonstrating subjective fatigue between *Very Lively* and *Okay*.

The mean rating at the start of the first back of clock sector was 3.02 (SD = 0.67), not significantly higher than any of the 3 day-flying "baseline" measures.

However, the mean Samn-Perelli rating at the start of a second back of clock sector was 5.05 (SD = 0.96), demonstrating subjective fatigue at a *Moderately Tired* level. This mean Samn-Perelli rating at the start of a second back of clock sector was significantly higher than any of the 3 day-flying "baseline" measures $F(3, 27) = 26.676$, $p<.001$. The mean Samn-Perelli ratings of crews at the start of sectors is provided in Figure 14.

Figure 14: Mean Samn-Perelli ratings at sector start



Legend: Samn-Perelli ratings (mean ±SD) for the two back of clock sectors and the three baseline testing times. * $p<.05$

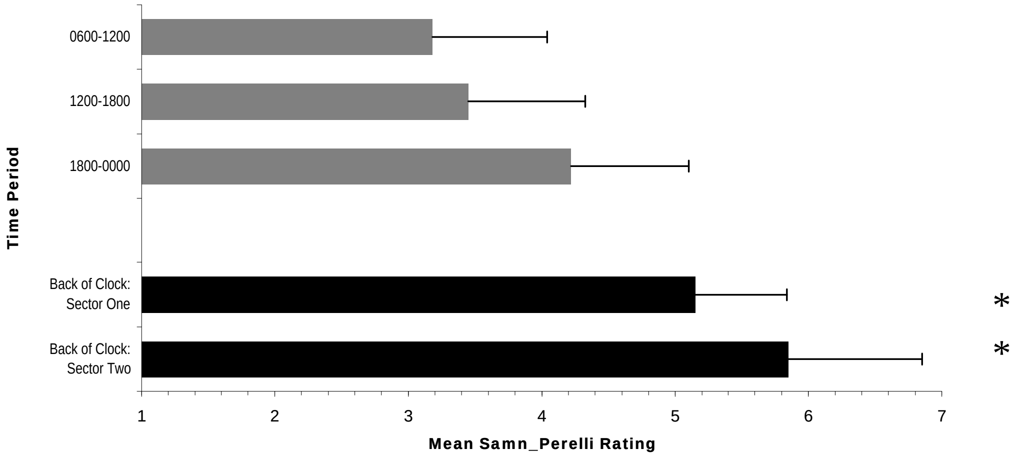
3.3.2 Landing

The mean Samn-Perelli ratings of crew at the start of three day-flying “baseline” measures ranged from 2.75 (SD = 0.99) to 3.15 (SD = .91) demonstrating subjective fatigue between *Very Lively* and *Okay*.

The Samn-Perelli rating at the end of a first back of clock sector was 5.15 (SD = 0.69), demonstrating subjective fatigue at a *Moderately Tired* level. This mean Samn-Perelli rating at the end of a first back of clock sector was significantly higher than any of the three day-flying “baseline” measures $F(3, 36) = 21.809$, $p<.001$.

Similarly, the mean Samn-Perelli rating at the end of a second back of clock sector was 5.85 (SD=1.00), demonstrating subjective fatigue at a *Moderately Tired* to *Extremely Tired* level. This mean Samn-Perelli rating at the end of a second back of clock sector was significantly higher than any of the three day-flying “baseline” measures $F(3, 27) = 24.626$, $p<.001$. The mean Samn-Perelli ratings of crews at the end of sectors are provided in Figure 15.

Figure 15: Mean Samn-Perelli ratings at sector end

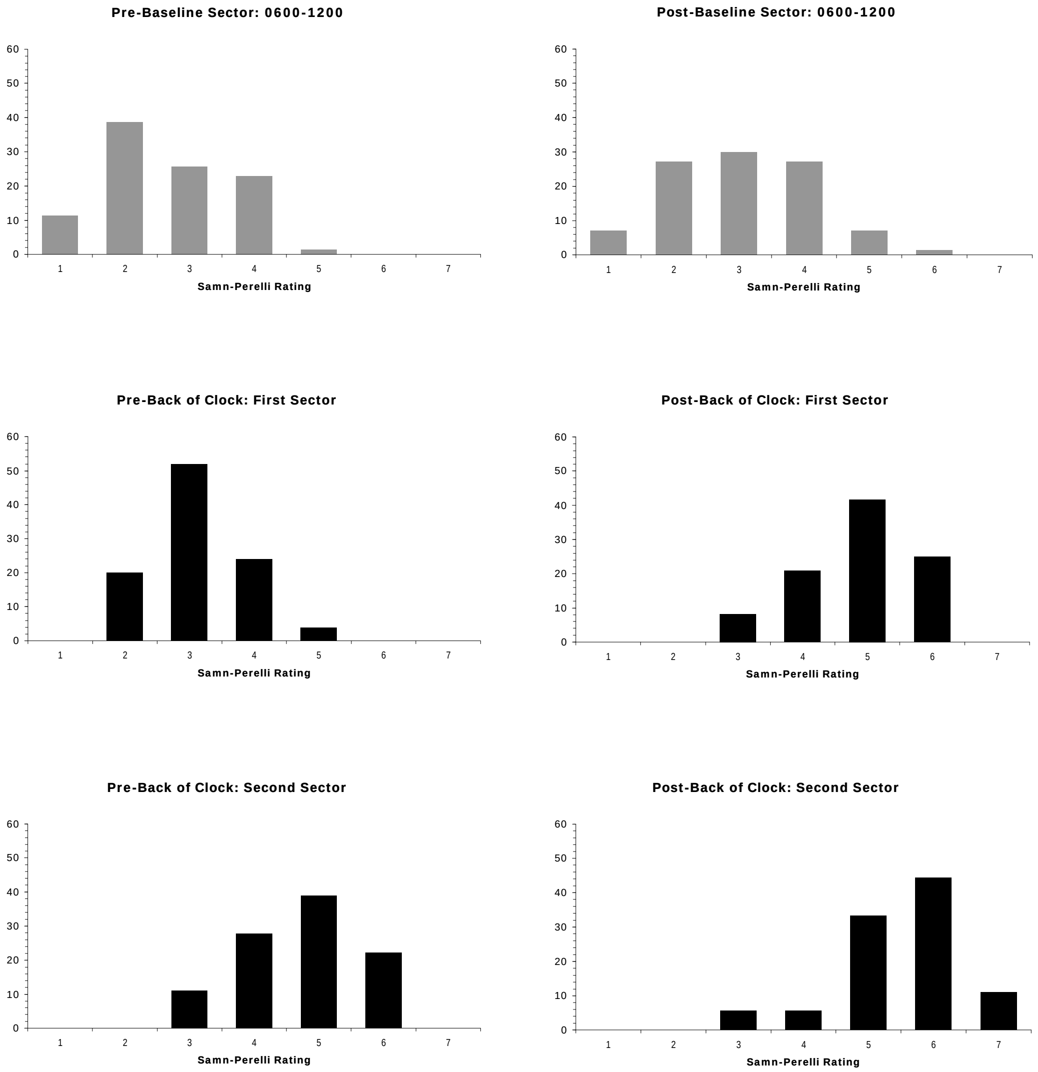


Legend: Samn-Perelli ratings (mean ±SD) for the two back of clock sectors and the three baseline testing times. * $p<.05$

To summarise the findings with respect to subjective fatigue, the results of this study suggest that there is a significant increase in subjective fatigue across the day, with both the first and second back of clock sectors being associated with significantly higher levels of subjective fatigue.

Analysis of the overall distribution of Samn-Perelli ratings highlight that at the end of the second back of clock sector, 55.5 per cent of the pilots reported subjective fatigue levels of *Extremely Tired* or *Completely Exhausted*, compared with only 1.4 per cent of pilots reporting similar levels of fatigue during the baseline day-time measures between 0600 and 1200 hours. Details of the distribution of Samn-Perelli ratings are given in Figure 16.

Figure 16: Distribution of Samn-Perelli ratings


Pre-Baseline Sector: 0600-1200

Post-Baseline Sector: 0600-1200

Pre-Back of Clock: First Sector

Post-Back of Clock: First Sector

Pre-Back of Clock: Second Sector

Post-Back of Clock: Second Sector

Legend: Distribution of Samn-Perelli ratings for the two back of clock sectors and the baseline testing times of 0600-1200 hours.

4 DISCUSSION

4.1 Back of clock operations, sleep, and performance

The results of this study suggest that Australian transcontinental ‘back of clock’ operations, as operated by the airline involved in this study, differed significantly from a baseline sample of daytime duty periods in a number of important areas with respect to prior sleep, neurobehavioural performance, and subjective fatigue.

Primary back of clock sectors

The results of this study suggest that while there are some significant differences in sleep and subjective fatigue as a function of a single transcontinental sector of back of clock flying, on average these differences were of a magnitude that were unlikely to impact on flight crew performance and overall safety.

Indeed, due to the structure of the overall roster pattern flown by the crew involved in this study, on average, crews departed the west coast with significantly more sleep in the prior 24 hours than was observed during the daytime baseline measures. Analysis of flight crew sleep patterns prior to the back of clock duty indicate a general polyphasic sleep[4] strategy, where the main night-time sleep the night before the back of clock duty is augmented by a late afternoon sleep prior to sign-on around midnight.

From the perspective of neurobehavioural performance, which was utilised in this study as a generic measure of potential performance impairment associated with fatigue, there was no evidence of a significant decline in performance during the first back of clock sector. While it would be anticipated that some performance decline would be observed purely as a time of day effect, the results of this study suggest that the sleep obtained by crew prior to sign-on for the back of clock duty is sufficient to sustain performance through the primary transcontinental back of clock sector.

Secondary back of clock sectors

When a primary transcontinental sector is followed by an additional east coast sector, there is evidence of reduced prior sleep, neurobehavioural performance impairment, and high levels of subjective fatigue.

During these secondary back of clock sectors, crews had obtained, on average, significantly less sleep in the 48 hours prior to both take-off and landing, compared with a baseline of daytime sectors. It was observed that on landing crews had a mean level of sleep in the prior 24 hours, and an average across the prior 48 hours below 5.5 hours per night.

Laboratory studies that have restricted night-time sleep to this level indicate performance impairment after just one night of restricted sleep. For instance, a study of restricting sleep to an average of 4.98 hours over a seven night period, found significant performance impairment after the first night of restricted sleep (Dinges *et al.*, 1997).

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[4] Polyphasic sleep: sleep taken in multiple episodes, typically, repeated sleeps of duration between one and four hours.

This study also demonstrated that subjective fatigue during these second back of clock sectors was significantly higher, compared with baseline levels of day sectors. Of note is the finding that over half the crew involved in this study rated their subjective fatigue on landing after a second back of clock sector as “extremely tired” or “completely exhausted”. Most likely a consequence of the combination of reduced prior sleep and the effects of a long duty-period during a time when the crew would normally be asleep. This finding illustrates overall high levels of subjective fatigue during the second back of clock sectors.

There was also evidence in reduced neurobehavioural performance during the second back of clock sector in this study. Indeed, the results of this study indicated a mean difference in response speed of 10.2 per cent, with the slowest mean response speed occurring during the second back of clock sectors when compared with the baseline performance measure taken between 0600-1200 hours. While this difference does not represent levels of performance impairment that warrant undue concern, there is clear preliminary evidence of reduced performance during secondary back of clock sectors – most likely associated with restricted prior sleep, the length of time on task, and time of day effects.

Inter-individual variability

One critical finding with respect to sleep and performance during Australian transcontinental “back of clock” flying is that there is a large degree of inter-individual variability, both in terms of the sleep obtained prior to the back of clock duty, and the flow-on effects on subjective fatigue and performance.

To this end, while the study has demonstrated few significant differences pertaining to the first back of clock sector, and raised some questions with respect to sleep and performance issues pertaining to the second back of clock sector, these findings broadly represent the outcomes of statistical analyses of mean differences between repeated measures. Within any sampled population, there will be variability around the mean, and from the perspective of *risk management*, a safe system of work must be able to manage instances where an individual, for whatever reason, does not obtain “an average” amount of sleep, or feels significantly fatigued on any given day.

Accordingly, within the context of Australian commercial aviation, new approaches to the management of fatigue-related risk have been developed. The defining characteristic of these approaches is that they do not solely depend on prescriptive flight and duty time regulations to provide opportunity for “an average” amount of rest to be obtained by all crew members prior to commencing duty. Rather, these FRMS provide organisations, and the individuals within those organisations, a set of tools to manage the occurrence of fatigue, or possible risk of fatigue and fatigue-related impairment on a day-to-day basis.

4.2 Fatigue risk management systems (FRMS)

Fatigue risk management systems (FRMS) can be defined as the application of the principles of safety management systems, to the management of fatigue-related risk. To this end, rather than relying on compliance with prescriptive hours of service (HOS) rule-sets in order to manage the safety-related risks of fatigue, an FRMS develops and employs multiple strategies to manage fatigue, such that each strategy forms an additional layer of defence against fatigue.

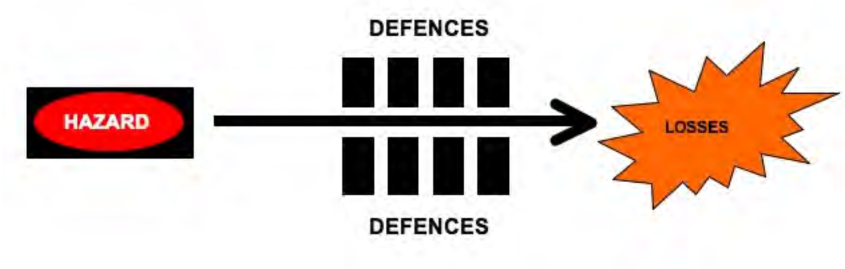
The prescriptive rule-sets governing flight and duty time limits, such as those that form the basis of the Australian regulation Civil Aviation Order 48 can be best described as a single-layered defence within the language of a fatigue risk management system.

Traditionally, fatigue has been managed through compliance with an agreed set of rules broadly governing the hours of work. In contrast to this traditional *prescriptive* approach of "flight and duty time limits", recent research and policy initiatives have suggested that improved safety, and greater operational flexibility, might be achieved through the development of more sophisticated *fatigue risk management systems* (Dawson & McCulloch, 2005).

A FRMS builds upon the developments in safety management in the latter half of the 20th century, and adopts the concept of "defences in depth".

The concept of "defences in depth" stems from the work of James Reason (1997), and applies the original battlefield philosophy of multiple lines of different types of defences to the process of safety management. According to this model, the most effective way that an organisation can manage a specific hazard, is through the development of multiple layers of defences.

Figure 17: Multiple defences against a safety hazard (after Reason, 1997)



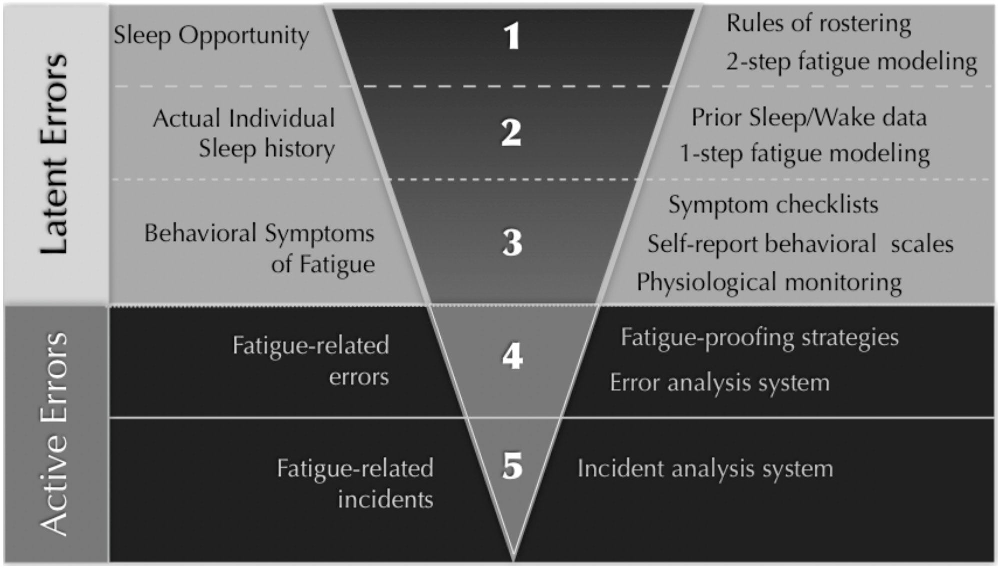
The concept of "defences in depth" acknowledges that each layer of defence might not be perfect, and accordingly, any system achieves maximum protection through multiple layers of defence. For instance, it is acknowledged that a prescriptive rule set governing flight and duty time limitations cannot provide a perfect defence against fatigue, but can only ensure that adequate *opportunity* for sleep is provided between duty periods. Accordingly, in instances where sleep opportunity has not translated into actual sleep, for whatever reason, an additional layer of defence is required to ensure fatigue-related risk is adequately managed.

An alternative conceptual framework for FRMS has been proposed recently (Dawson & McCulloch, 2005). This model emphasises an integrated approach to the design and implementation of defences in depth against fatigue-related risk.

The conceptual framework for an FRMS proposed by Dawson and McCulloch (2005) is built upon the notion of accident trajectory through absent or failed defences. The model suggests that every fatigue-related incident will be preceded by a fatigue-related error, which in turn will be preceded by behavioural symptoms of fatigue, and an individual work/sleep history that has led to fatigue.

This trajectory is illustrated in Figure 18 below, which also introduces the concept of layers of defence at each of the five levels of the fatigue-related incident trajectory.

Figure 18: Multiple defences against a fatigue as an identifiable hazard (Dawson and McCulloch, 2005)



This conceptual framework for an FRMS suggests that the traditional approach to fatigue management, that of prescriptive duty time rule-sets, involves only a single layer of defence at step one of the accident trajectory. According to the conceptual framework for an FRMS, sole reliance on the single layer of defence offered by prescriptive duty time rule-sets, is potentially an inadequate form of defence against fatigue-related risk.

The alternative approach to fatigue risk management suggests that an organisation should develop an FRMS that designs and implements defences at each of the five layers within the accident trajectory. Accordingly, prescriptive rule-sets governing flight and duty time limitations should be bolstered by additional layers of defence, relating to each of the subsequent layers within the accident trajectory.

It is suggested that beyond the development of any revised rule-set governing flight and duty time limitations, the development of additional layers of defences against fatigue-related risk is investigated within the conceptual framework of a FRMS.

5 CONCLUSIONS

Airline pilots operating ‘back of clock’ sectors differed significantly from the baseline sample of pilots whose duty covered daytime flights across many of the measures examined here (prior sleep, neurobehavioural performance and subjective assessments of fatigue). For pilots operating a single back of clock sector, levels of prior sleep and wake were similar to, or in some cases were better, than for the daytime sample, suggesting fatigue risks were being managed effectively and flight safety is unlikely to be compromised. However, the results were significantly poorer for pilots who operate an additional sector after a ‘red eye’ flight. Airlines need to consider the additional fatigue risks posed by scheduling crews for sectors subsequent to an overnight transcontinental flight.

Moreover, the study also demonstrates that differences between individuals are significant, and in some cases may be a more important factor. This issue has the potential to complicate fatigue-risk management strategies for airlines and demonstrates the limits of applying a ‘one size fits all’ approach to managing fatigue risks. Accordingly, this study highlights the need for systematic approaches to the management of fatigue-related risk that move beyond simple prescriptive flight and duty time limitations.

The results of the study support strategies for fatigue-risk management that take account of individual sleep patterns, and can respond to instances where low levels of prior sleep, periods of excessive wake, and instances of high levels of subjective fatigue are systematically managed in order to reduce the overall risk of fatigue-related error, incidents or accidents in commercial aviation.

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