The association between Fatigue, Sleep Loss and Simulated Flight Data Measures in Regional Airline Pilots

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ABSTRACT

The impact of fatigue on flight crew performance can be investigated by identifying causal links between fatigue related impairment and embedded performance measures. To investigate the feasibility of recording simulated flight data measures in operational settings, this study sought to identify what key processes need to be in place. In addition, by investigating the association between measures of fatigue and simulated flight data measures, the study also sought to identify if fatigue related changes in flight crew performance are detectable.

Sixteen regional airline pilots, working as eight flight crew, were monitored during a 12 day flight duty period protocol. The protocol consisted of two simulated flights, one which followed four consecutive days where flight duty periods were scheduled (the non-rested condition) and one which followed two consecutive days free from duty (the rested condition). The simulated flights, conducted in a full flight simulator, were representative of normal flights.

Although logistically challenging, the study demonstrated the feasibility of conducting a simulator study in operational settings and that it is possible to record simulated flight data measures from a Simulator Operations Quality Assurance programme. The flight duty period protocol was partially successful. In the non-rested condition, participants initially experienced cumulative sleep debt and ratings of fatigue and sleepiness were significantly higher both before and following each simulated flight. However, following the last sleep opportunity before each simulated flight, there were no flight duty period protocol differences in any sleep related variables aside from cumulative sleep debt and time since sleep. Changes in flight crew performance were identified, with greater variability observed in some initial climb measures during the non-rested condition. Findings were mixed, an increase in time since sleep was associated with reduced variability in some initial climb measures and time taken to complete the go around/missed approach procedure checklist increased with greater time since sleep and with a greater amount of sleep in the previous 48 hour period. Increases in ratings of fatigue and sleepiness were associated with increased variation in some initial climb measures.

Results from this study illustrate that the methodology and the accuracy of simulated flight data measures is sufficient to warrant further investigation into the influence of fatigue on flight crew performance.

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ABBREVIATIONS AND TECHNICAL TERMS

50ft altitude bin	A categorical variable included in some statistical models which indicates if initial climb or go around variables are from one of nine 50ft bins between 300ft and 750ft.
AAL	above aerodrome level
achieved flight duty periods	Flight duty periods flown by line pilots during a roster period.
Actigraphy	A practical and reliable way of recording sleep related variables.
AKL	Auckland International Airport, New Zealand
airspeed in climb	A simulated flight data measure which represents the standard deviation of the absolute difference between airspeed and commanded airspeed during climb between 300ft and 750ft.
airspeed go around	A simulated flight data measure which represents the standard deviation of the absolute difference between airspeed and commanded airspeed during go around between 300ft and 750ft.
autopilot usage during flight	A simulated flight data measure which represents the percentage of each flight where the autopilot is engaged.
autopilot disengagement before landing	A simulated flight data measure which represents the lowest altitude where the autopilot is disengaged prior to landing.
autopilot engagement altitude following go around	A simulated flight data measure which represents the lowest altitude where the autopilot is engaged following go around.
autopilot engagement altitude following take off	A simulated flight data measure which represents the lowest altitude where the autopilot is engaged following take off.
approach	A phase of flight where the aircraft is approaching the runway in preparation for landing.
ATC	air traffic control
ATIS	automatic terminal information service
base leg	Base leg reflects the position of the aircraft before it turns on to the runway extended centreline and approaches the runway to land.
BDS	brief debrief station (software which supports the Operators simulated flight de-briefing process)

BIC	bayesian information criteria
CAANZ	Civil Aviation Authority of New Zealand
CAAUK	Civil Aviation Authority of the United Kingdon
CAE	Canadian Aviation Electronics
CAS	computed airspeed
CHC	Christchurch International Airport, New Zealand
Condition	A categorical variable included in some statistical models. This variable indicates if variables relate to the non-rested condition or rested condition.
Climb	A phase of flight where the aircraft is climbing with flap retracted.
cumulative sleep debt	An accumulation of sleep debt because of restricted sleep over several days.
CWC	crosswind component in relation to the runway
Day	Day 1, 2, 3 or 4: This variable relates to the 24hr period relative to each simulated flight. Day 1 = between 72 and 96 hours, day 2 = between 48 and 72 hours, day 3 = between 24 and 48 hours and day 4 = between 0 – 24 hours.
deg C	degrees centigrade in relation to temperature
deg M	magnetic wind direction
deg T	true wind direction
Degree	In reference to cardinal direction, e.g. 0 degrees (north), 90 degrees (east), 180 degrees (south) and 270 degrees (west).
Descent	A phase of flight where the aircraft is descending toward the runway with flap and gear retracted.
descriptive statistics	The mean, standard deviation, median and range of a dependent variable.
DME	Distance measuring equipment (DME), indicates the aircrafts distance, measured in nautical miles, from a radio navigation aid.
downwind	The aircraft is manoeuvring prior to landing, downwind reflects the position of the aircraft before it turns onto the base leg.
EEG	electro-encephalography (associated with PSG)

EWD	engine warning display (flight deck instrumentation)
FAA	Federal Aviation Administration (United States of America)
fatigue end main sleep	Subjective rating of fatigue at the end of the main sleep period.
fatigue start main sleep	Subjective rating of fatigue at the start of the main sleep period.
fastest 10% of PVT responses	the fastest 10% of psychomotor vigilance task responses (1/reaction time x 1000)
FCOM	flight crew operations manual
FDM	flight data monitoring programme, an alternative name for FOQA
FGCP	flight guidance and control panel (flight deck instrumentation)
FMA	flight management annunciator
FOQA	flight operations quality assurance programme (associated with FOQA)
FRM	fatigue risk management processes (associated with FRMS)
FRMS	fatigue risk management systems
Ft	foot, feet
FTL	flight time limitations, hours of service regulations
GLM	general linear model
go around	A phase of flight where the approach is discontinued, and the aircraft climbs away from the runway.
GS	ground speed
hpa	hectopascals, a unit of pressure
HWC	headwind component in relation to the runway
IAS	indicated airspeed
ICAO	International Civil Aviation Organisation
ILS	instrument landing system, a type of instrument approach
IMC	instrument meteorological conditions

initial climb	A phase of flight where the aircraft is climbing away from the runway with flap extended.
Kg	Kilograms
KSS	Karolinska Sleepiness Scale, a subjective rating of sleepiness.
Kt	Knots
LNAV	lateral navigation, an autopilot mode
Location	A categorical variable included in some statistical models. This variable indicates if the location of the simulated flight is either the Christchurch - Wellington, or Wellington - Christchurch.
MAC	mean aerodynamic chord
main sleep period	The start and end of consolidated sleep during the biological night, as opposed to sleep across the 24 hour period which might be split into two or more sleep periods.
MDA	Minimum descent altitude, associated with an instrument approach. The point at which, if the runway is not visible, a go around must be completed.
MFD	multifunction display (flight deck instrumentation)
MOC	maintenance operations control
NASA	National Aeronautics and Space Administration (United States of America)
NASA-RTLX	NASA Raw Task Load Index, a subjective rating of workload.
Nm	nautical miles
OAT	outside air temperature
Order	A categorical variable included in some statistical models. This variable indicates the order of each simulated flight, i.e. the first or second simulated flight.
paired scenario	A means to group scenarios together. The combination of scenarios from each simulated flight, for comparative purposes.
PF	pilot flying
PFD	primary flight display (flight deck instrumentation)
pitch in climb	A simulated flight data measure which represents the standard deviation of the absolute difference between

	pitch and flight director pitch order during climb between 300ft and 750ft.
pitch go around	A simulated flight data measure which represents the standard deviation of the absolute difference between pitch and flight director pitch order during go around between 300ft and 750ft.
PM	pilot monitoring
post simulated flight sleepiness	Subjective rating of sleepiness at the end of the simulated flight.
post simulated flight fatigue	Subjective rating of fatigue at the end of the simulated flight.
pre simulated flight sleepiness	Subjective rating of sleepiness at the start of the simulated flight.
pre simulated flight fatigue	Subjective rating of fatigue at the start of the simulated flight.
PSG	Polysomnography
PVT	psychomotor vigilance task
PVT response speed	psychomotor vigilance task response speed (1/reaction time x 1000)
PWR MGT	power management selector (flight deck panel)
QAR	quick access recorder, a means to record flight data during flight
QNH	barometric pressure
RA	resolution advisory, associated with the TCAS system
RALT	radio altitude
RAMP	A power lever setting which ensures that engine torque reflects the reserve take off rating engine torque calculated by the flight data acquisition unit.
RNAV	area navigation
roll in climb	A simulated flight data measure which represents the standard deviation of the absolute difference between roll and flight director roll order during climb between 300ft and 750ft.
roll go around	A simulated flight data measure which represents the standard deviation of the absolute difference between roll and flight director roll order during go around between 300ft and 750ft.

RTO	rejected take off
RWY	Runway
SAT	static air temperature
Scenario	A scenario represents an opportunity for the simulator instructor to intervene during the simulated flight, thereby initiating a situation that can be recorded using flight data, at a specific point of interest during a flight.
SCN	suprachiasmatic nucleus
SD	standard deviation
SID	standard instrument departure
simulated flight sleepiness	Pre and post simulated flight subjective ratings of sleepiness.
simulated flight fatigue	Pre and post simulated flight subjective ratings of fatigue.
SMS	safety management system
SOQA	simulator operations quality assurance programme
SP	The Samn-Perelli Crew Status Check, a subjective rating of fatigue.
SQ	a subjective rating of sleep quality
sleep period	A categorical variable included in some statistical models. This variable indicates if the sleep period represents a non-baseline or baseline sleep period.
sleep end	The end of sleep as determined by actigraphy.
sleep start	The start of sleep as determined by actigraphy.
sleepiness end main sleep	Subjective rating of sleepiness at the end of the main sleep period.
sleepiness start main sleep	Subjective rating of sleepiness at the start of the main sleep period.
sleep quality end main sleep	Subjective rating of sleep quality at the end of the main sleep period.
SRC	standard route clearance
slowest 10% of PVT responses	the slowest 10% of psychomotor vigilance task responses (1/reaction time x 1000)
SRM	safety risk management processes (associated with SMS)

STAR	standard arrival route
study flight duty periods	Flight duty periods associated with the flight duty period protocol.
sub scenario	A sub scenario considers other reasonably expected outcomes that could occur during a scenario. It ensures that the scenario is not excluded if the expected outcome does not occur.
TA	traffic advisory, a part of the TCAS system
take off	A phase of flight where the aircraft accelerates prior to becoming airborne.
TAWS/EGPWS	terrain awareness and warning system, enhanced ground proximity warning system
TCAS	traffic collision avoidance system
time in bed	Time in bed during a main sleep period.
timing	A categorical variable included in some statistical models. This variable indicates if subjective ratings of fatigue and sleepiness, or PVT tests were collected before or following each simulated flight.
time taken to complete the go around/missed approach procedure	A simulated flight data measure which represents the time taken to complete the go around/missed approach procedure.
time taken to initiate go around	A simulated flight data measure which represents time taken to initiate go around.
time taken to re-engage the autopilot	A simulated flight data measure which represents time taken to re-engage the autopilot following an un-commanded autopilot disconnection.
time since sleep	Time since sleep as determined by actigraphy.
time since sleep at the start of the post simulated flight PVT test	Time since sleep at the start of the post simulated flight PVT test, as determined by actigraphy.
time since sleep at the start of the pre simulated flight PVT test	Time since sleep at the start of the pre simulated flight PVT test, as determined by actigraphy.
time since sleep at the start of the simulated flight	Time since sleep at the start of the simulated flight, as determined by actigraphy.
top of climb	The point where the aircraft stops climbing, following climb.

TOD	The point where the aircraft descends following the cruise portion of flight.
total sleep in 24hrs	Total sleep in the previous 24 hour period at the start of the simulated flight, as determined by actigraphy.
total sleep in 48hrs	Total sleep in the previous 48 hour period at the start of the simulated flight, as determined by actigraphy.
TWC	tailwind component
type of duty: simulated flight or flight duty period	A categorical variable included in some statistical models. This variable identifies if a dependent variable (e.g. workload) is associated with a flight duty period or if values were associated with a simulated flight.
UCSD scoring algorithm	USCD sleep estimation which computed a weighted sum of the activity in the current minute, the preceding 4 minutes and the following 2 minutes.
VGA	velocity go around
VHF	very high frequency radio communication
VMC	visual meteorological conditions
VmLB 0	flap retraction speed bug
VNAV	vertical navigation, an autopilot mode
Waypoint	a geographical coordinate
WLG	Wellington International Airport, New Zealand
WOCL	window of circadian low
WV	wind direction and velocity
ZFT	zero flight time (in relation to the category of flight simulator)

CHAPTER 1 INTRODUCTION AND RATIONALE

This thesis focuses on identification and measurement of flight crew fatigue in short haul airline operations. It determines the processes needed for, and the feasibility of, using information recorded by a simulator during normal flight operations. It also investigates the association between measures of fatigue and simulated flight data measures from a flight simulator to determine if fatigue related changes in flight crew performance are detectable.

The thesis begins by providing an introduction and rationale. This section starts by outlining the role of fatigue in aircraft incidents and accidents. This is not intended to be alarmist, rather, it is to illustrate the importance of research that highlights the impact of fatigue on pilot performance during normal flight operations. Focus is then placed on providing an overview of sleep, sleep loss, and recovery. The implications of fatigue related performance impairment are also considered to enable cognitive functions, that are sensitive to sleep loss, to be mapped to scenarios that were included in simulated flights. To understand the strengths and weaknesses associated with different approaches to the investigation of the effect of fatigue on pilot simulator performance, several studies involving either in-flight or simulated flights are reviewed. And to illustrate how studies like this can contribute to the overall commercial aviation safety system, a brief introduction to Safety Management Systems and Fatigue Risk Management Systems is provided. The chapter ends by providing rational for the study and introducing the studies aims. Chapter 2 provides an overview of the study methods and key processes including a detailed overview of the flight duty period protocol. Measures of fatigue and performance including simulated flight data measures are also introduced. Chapter 3 introduces the simulated flight protocol, which represents a plan for each simulated flight and provides details on the scenarios included within each simulated flight. Chapters 4, 5 and 6 present results relating to the effect of the flight duty period protocol on measures of fatigue, psychomotor vigilance performance and simulated flight data measures. Chapter 7 discusses results in relation to the literature and provides an overview of the study's limitations. Recommendations are also proposed and opportunities for future research are discussed. The appendices include a broad amount of information which supports content discussed within applicable chapters. Of note, APPENDIX V, APPENDIX W, and APPENDIX X include detailed information on the development of the simulated flight protocol including an overview of two trial simulated flights.

1.1 Flight Crew Fatigue, is it a Problem?

Fatigue within a commercial aviation setting has been defined as:

> A physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties. (International Civil Aviation Organisation, 2015, p. xiii)

Considering fatigue in this way reiterates that fatigue has a physiological cause and that regardless of how engaged and proficient a pilot is, they will be susceptible to it. The definition also illustrates that sleep disruption, the circadian body clock cycle and workload need to be considered when proposing fatigue countermeasures.

Flight crew scheduling practices in combination with human physiology represent the heart of fatigue related problems in commercial aviation (Caldwell, 2005). Work related causes of fatigue in short haul pilots include restricted sleep due to short rest periods and early report times, multiple high workload periods throughout the day, multiple flights within a flight duty period, high density airspace and long flight duty periods (Gander, Gregory, Graeber, et al., 1998). Work related causes of fatigue in night cargo pilots include multiple flights, high workload during circadian low, shorter sleep periods at different times in the circadian cycle, circadian disruption (night work) and during layover, pilots may experience split sleep and short sleep periods (Gander et al., 1996). In long-haul flight operations, work related causes of fatigue include long flight duty periods, extended wakefulness, high workload during circadian low, shorter sleep periods at different times in the circadian cycle, circadian disruption (both due to night work and crossing multiple time zones), split sleep and short sleep periods on layovers and circadian drift following extended tours of duty (Gander, Gregory, Miller, et al., 1998). For short haul pilots, who are the focus of this study, consecutive early starts, multiple flights within a single flight duty period, high workload, long duty periods, late finishes and night work, are key causes of fatigue. The above work related causes of fatigue for short haul, night cargo and long haul pilots represents a summary of factors, identified during NASA field studies, that cause fatigue in flight crew (Gander et al., 1994). This list is not exhaustive (International Civil Aviation Organisation, 2015).

Fatigue created by these patterns of work has a range of consequences. Early research on pilot fatigue demonstrated that in the absence of sufficient sleep a pilot’s response speed and accuracy declines, they accept lower standards of performance. Their ability to integrate information is impaired and their attention is narrowed which contributes to forgetfulness or ignoring tasks associated with aircraft operation (Perry, 1974). More recent research has shown that pilots are susceptible to physiological drowsiness and micro-sleeps[1] (Cabon et al., 1993; Moore-Ede, 1993; Samel et al., 1997) which are common during low workload periods. When sleep loss increases, microsleeps can also occur when workload is higher and more variable (Rosekind, Graeber, et al., 1994). Although pilots may not be immediately aware of micro-sleeps (Wright & McGowan, 2001), over 75% of pilots who responded to a survey acknowledged having nodded off during a flight at some time (Co et al., 1999). Studies have also shown that in two crew situations both pilots can have micro-sleeps simultaneously (Cabon et al., 1993).

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[1] Micro-sleeps are associated with generalised decrements in cognitive tasks (Belyavin & Wright, 1987) and a slowing of response speed (Ogilvie & Simmons, 1992).

Fatigue is often underreported which may result in fatigue risk being underestimated. For example, a survey of 6000 pilots determined that only 20% - 30% would file a fatigue report due to fear of disciplinary action or stigmatization by the employer or colleagues (Tittelbach, 2012). Factors that may contribute to a reduction in reporting may include extra work associated with completing paper work, time taken to complete paper work, scepticism, a lack of trust or confidence in the safety system and a fear of reprisals (Reason, 2016). Confidential incident reporting systems may result in more accurate reporting by guaranteeing anonymity, but unfortunately these systems have not been successful in New Zealand (Forrest, 2006; Sullivan, 2001).

For fatigue to be considered a causal factor in an aircraft incident or accident, performance deficiencies need to be clearly identifiable and consistent with the known effects of fatigue (National Transportation Safety Board, 2007, 2010). This can be challenging as the relationship between incidents, accidents and fatigue in ultra-safe industries[2], such as aviation (Amalberti, 2001), is complex due to the multiple layers of system controls that reduce the likelihood of having an incident, or accident attributable to fatigue (Gander, Hartley, et al., 2011; Goode, 2003; Signal et al., 2022). A further challenge with establishing fatigue as a causal factor is that its true incidence is relatively unknown due to inadequate measures of fatigue, performance (National Transportation Safety Board, 1994), and investigative techniques (Lauber & Kayten, 1988). Despite these challenges, fatigue has been identified as a causal factor in major disasters (Lauber & Kayten, 1988; Rosekind,

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[2] A key feature that distinguishes accidents in a ultra-safe system is that they may occur in the absence of any serious operator error (Gander, Hartley, et al., 2011).

Gander, et al., 1994; Upender, 2022) including incidents and accidents involving aircraft (Civil Aviation Authority of United Kingdom, 2019).

The overall incidence of fatigue as a causal factor in aviation disasters is very low. For example, only 0.22% of all transport category aircraft accidents investigated by the National Transportation Safety Board (NTSB) between 1989 and 2008 identified fatigue as a causal factor (Gander, Graeber, et al., 2011). Aviation mishaps (as opposed to accidents) which involve fatigue or are attributable to fatigue may be higher, at between 4% to 8% (Caldwell, 2005; Kirsch, 1996; Luna, 2003). From a frequency perspective, independent research on pilot fatigue measurement by the Netherlands Aerospace Centre (Civil Aviation Authority of United Kingdom, 2019) identified 20 accidents from the NTSB accident database that occurred between 1980 and 2013. They also identified 10 accidents from the Air Accidents Investigation Branch (AAIB) accident database where fatigue was cited as a contributing factor. In addition, 35 mandatory occurrence reports, between 2009 and 2014 were identified that included fatigue as a contributing factor. Therefore, it is likely that for the reasons mentioned above, the contribution of fatigue in accidents or mishaps is likely under reported.

The focus of the following section is to introduce sleep and the physiological processes that promote both wakefulness and sleep. Individual differences in sleep timing and duration are also introduced to illustrate that approaches to fatigue risk management require flexibility and that a research design should consider the influence of individual variability.

1.1 Defining Sleep

Sleep is “a reversible behavioural state of perpetual disengagement from an unresponsiveness to the environment” (Sullivan et al., 2022, p. 16). Despite recent research on theories of sleep function, it remains unclear if there is a single primary reason why sleep is required. We know many factors influence sleep length and architecture, but we don’t fully understand all the reasons why sleep changes across the life cycle. The traditional approach to sleep medicine has been to focus on and understand disordered or problematic sleep. In contrast, sleep health aims to improve sleep health by focusing on better sleep (Buysse, 2014). Identifying and measuring a positively framed construct like sleep health can advance our understanding of the role of sleep in health and well-being within an occupational setting.

Polysomnography (PSG), which at a minimum includes the recording of cortical brain activity (electro-encephalography; EEG), eye movements, and submental muscle tone, allows the structure of sleep to be summarised. It also provides reliable information on the internal structure of sleep. Two separate sleep states have been defined. Non-rapid eye movement (NREM) sleep represents a relatively inactive, but actively regulating brain in a moveable body whereas rapid eye movement (REM) sleep represents an active brain in a paralysed body (Sullivan et al., 2022). During a normal night of sleep in a healthy adult, sleep is entered through NREM sleep stage N1, and quickly progresses to stage N2 then stage N3 as sleep becomes deeper. REM sleep is unlikely to occur until 80 minutes or longer into the sleep period, after which NREM and REM will alternate during the night. The first NREM/REM cycle typically lasts between 70 - 100 minutes with subsequent cycles lasting between 90 and 120 minutes on average (Sullivan et al., 2022). Between four and five NREM/REM cycles occur during an average eight hour nighttime sleep period. Within a nighttime sleep period of a healthy young adult, N2 sleep accounts for between 45% - 55% of sleep, N3 for between 10% - 20%, REM sleep for 20 - 25% and N1 sleep accounts for between 2% - 5% (Sullivan et al., 2022). Slow wave activity is more predominant during the first third of a sleep period and may not be present in later cycles. This contrasts with REM sleep, which is of short duration earlier in a sleep period, after which it occurs every 90 to 120 minutes in episodes which increase in duration as the sleep period progresses. Arousals can occur spontaneously, or because of an environmental stimulus. An incrementally larger stimulus is required to produce an arousal from N3 sleep than during the lighter stages of NREM sleep or during REM sleep (Sullivan et al., 2022). Transient arousals to a lighter stage of sleep or wakefulness can contribute to fragmentation of sleep structure which reduces the recuperative value of sleep, increases daytime sleepiness and impairs performance (Stepanski, 2002).

1.1.1 Sleep Regulation

Sleep duration and timing are controlled by two separate processes, a circadian process and a homeostatic process (Borbely & Achermann, 1999). The circadian process is controlled by the suprachiasmatic nucleus[3] (SCN) of the anterior hypothalamus. The SCN uses environmental time cues, predominantly the light-dark cycle (Duffy & Wright, 2005) to enable the endogenous period of the circadian body clock cycle to synchronise with the 24 hour day-night cycle. The SCN promotes wakefulness and sleepiness which influences sleep timing, the timing and amount of REM sleep. It also contributes to variation in performance, physical functions,

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[3] The SCN is a group of cells in the brain which produce an internally generated circadian rhythm that is, on average, slightly longer than the 24 hour day/night cycle (Czeisler et al., 1999).

mood, and behaviour. In the absence of time cues, the circadian body clock cycle will continue to oscillate close to the 24 hour day-night cycle (Czeisler et al., 1999). Its timing can be inferred from biological markers including core body temperature, melatonin and cortisol which are tightly controlled by the SCN (Czeisler & Buxton, 2022).

The homeostatic process increases the need for sleep with increasing wakefulness and reduces the desire to sleep following sleep (Achermann, 2004). The homeostatic process can be tracked using slow wave sleep (SWS) as it represents a marker of sleep homeostasis[4]. As time awake increases, the duration of slow wave sleep (SWS) during the first few NREM/REM cycles increases regardless of when that sleep occurs during the circadian body clock cycle. In the young adult, across sleep, the percentage of SWS in each NREM/REM cycle decreases as the pressure for SWS decreases (Sullivan et al., 2022).

The two-process model describes the interaction between the circadian process (process C) and homeostatic process (process S) which produce a compensatory response to variations in sleep need and timing (Borbely, 1982; Daan et al., 1984). The two-process model forms the basis of a bio-mathematical model[5] which can predict the timing and duration of sleep, waking alertness and performance (Akerstedt & Folkard, 1997; Borbely, 1982; Dijk & Skeldon, 2022). The upper and lower threshold of process C defines boundaries for process S. During wakefulness, process S increases until it reaches the upper threshold of process C, it then reduces

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[4] Sleep homeostasis is the ability of an individual to maintain internal biological equilibrium through regulatory mechanisms (Cannon, 1939).

[5] A computer program designed to predict aspects of a schedule that might generate an increase in fatigue risk for the average person, based on scientific understanding of factors that contribute to fatigue (International Civil Aviation Organisation, 2015, p. xii).

during sleep until it reaches the lower boundary of process C, whereby sustained wakefulness occurs and the cycle repeats (Achermann, 2004).

During an average eight hour night-time sleep period, sleep onset occurs approximately five hours before, and wakeup occurs approximately three hours after the core body temperature low point with the drive for REM sleep peaking just after the temperature low point. As core body temperature increases, the circadian body clock cycle increasingly promotes alertness between 09:00 and 11:00, and again during the evening wake maintenance zone. The evening wake maintenance zone occurs a few hours before an individual's bedtime. During these times, it can be very hard to fall or stay asleep. Interaction between the circadian process and homeostatic process results in two periods of increased physiological sleepiness. These being the window of circadian low (WOCL) which occurs between approximately 03:00 and 05:00, and the afternoon nap window which occurs between approximately 15:00 and 17:00.

Sleep inertia can occur immediately after waking from sleep and contributes to cognitive performance impairment, profound sleepiness, disorientation, confusion and grogginess which lasts for a few minutes to between two and four hours (Dinges, 1990). In the absence of major sleep deprivation, recovery is typically complete within 30 minutes of awakening (Lubin et al., 1976). It likely occurs due to differences in the rate of reactivation of different brain regions and the reorganisation of functional connectivity in those regions (Van Dongen et al., 2022). The magnitude of sleep inertia is influenced by prior sleep loss, extended wakefulness, time of day and the depth of sleep / sleep stage prior to awakening (Ferrara & De Gennaro, 2000; Hilditch & McHill, 2019; Riedy et al., 2022). Sleep inertia (process W) is accounted for in the three-process model, proposed in 1987

(Folkard & Akerstedt, 1987) which is an extension of the two-process model. Three process models, although successful at accounting for sleep deprivation, are less successful at accounting for sleep restriction, likely because of a structural inadequacy (Belenky et al., 2003). To improve predictions of alertness and performance during, and following sleep restriction, they propose that in addition to sleep homeostasis, timing and sleep inertia, models should include a fourth factor which represents slow adaption to, and slow recovery from sleep restriction.

1.1.2 Individual Differences

Differences in genetic composition likely contribute to individual differences in sleep need (Drake et al., 2022; Heath et al., 1990; Shaw, 2022) however occupational and personal commitments and social pressure can override genetic (Pack et al., 2022) and circadian influences (Paine & Gander, 2007). Individual differences in the duration of the endogenous circadian body clock cycle represent an important source of circadian related individual differences (Skeiky et al., 2022). Individuals with shorter circadian rhythms typically have a morning chronotype (morningness) as they have been shown to rise earlier, achieve less total sleep and have greater levels of alertness on waking from night time sleep (Carrier et al., 1997). Individuals with longer circadian rhythms typically have an evening chronotype (eveningness) as they stay awake later (Akerstedt & Torsvall, 1981). Morningness or eveningness represents a stable characteristic that is independent of age, gender and socioeconomic position (Paine et al., 2006).

Adults require between seven and nine hours of sleep per day to maintain optimal functioning and health (Hirshkowitz et al., 2015). Sleep duration varies between individuals (Grant & Van Dongen, 2013) with longer nocturnal intervals of melatonin and cortisol likely contributing to increased sleep duration in long sleepers (a sleep duration greater than nine hours) compared with short sleepers (a sleep duration of less than six hours) (Aeschbach et al., 2003). Short sleepers may tolerate higher levels of sleep pressure during wakefulness than long sleepers (Aeschbach et al., 2001).

In the Finish population, when participants were asked "How many hours do you sleep in 24 hours?", 14.5% of participants reported a sleep duration of six hours or less and 13.5% reported a sleep duration of nine hours or more (Kronholm et al., 2006). However, given these estimates are self-reported it is not known if they reflect sleep need or if estimates reflect lifestyle choices, e.g. staying up late even though sleepy. Similar percentages were reported by the National Sleep Foundation (National Sleep Foundation, 2015).

There are considerable individual differences in the response to sleep loss (Van Dongen et al., 2022). For example, individuals who are less vulnerable to sleep loss may have greater cognitive capacity or a greater capacity to engage alternative neural resources (Chee & Asplund, 2013; Goel et al., 2009).

Individual differences in sleep end may relate to differences in the circadian rhythm whereas individual differences in sleep onset may relate to differences in tolerance to sleep pressure (Van Dongen et al., 2005).

Time taken to fall asleep also varies between individuals (Lavie & Zvuluni, 1992). For example, the average sleep latency in 176 adults, as determined by the multiple sleep latency test, was 11 minutes whereas 20% of participants had latencies that were either six minutes or 16 minutes (Clodore et al., 1990; Levine et al., 1988).

Although the average length of the NREM/REM cycle varies between 90 – 110 minutes (Sullivan et al., 2022), the frequency and nature of sleep stage transitions also exhibits individual differences during both baseline and sleep deprived states which has an influence on dynamic sleep structure (Kishi & Van Dongen, 2023).

Age related changes in sleep need include a reduction in the proportion of time spent in slow wave sleep, a decline in nocturnal sleep duration, more awakenings[6] from sleep, an increase in morningness preference with age, and an increase in daytime sleepiness (Crowley et al., 2007; Klerman et al., 2004; Landolt et al., 1996; Miner & Lucey, 2022; Paine et al., 2006).

Individual differences in sleep need can have an operational impact. If group averages are used to estimate the impact of sleep loss on performance, individual differences in the timing and duration of sleep may contribute to a misestimation of that impact (Van Dongen et al., 2006). For example:

> Managers and schedulers need to understand that optimal mission assignments and work/rest schedules cannot be based on traditional, grouped research data, because such averages will paint an overly optimistic picture for some personnel (indicating that they can fly longer missions or sleep less than they actually can) and an overly pessimistic picture for others (resulting in shorter-than-necessary missions for pilots who are capable of flying longer). Similar difficulties would be present in other occupations in which long duty periods and/or shortened sleep episodes threaten to impair operator performance. (Van Dongen et al., 2006, p. 342)

In the following sections, literature is reviewed to provide insights into the causes and prevalence of sleep loss in regional airline pilots. The discussion on recovery

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[6] Although older adults wake more frequently from sleep, they have no greater difficulty in falling back to sleep (Klerman et al., 2004).

following sleep loss is particularly relevant to results regarding sleep loss in participants during the flight duty period protocol. These results are presented in Chapter 4. Circadian disruption, in relation to shift work (as opposed to jet lag) is also discussed, given the prevalence of early starts and lates finishes in regional airline pilot flight duty period pairings.

1.2 Sleep Loss

Sleep loss is a principal physiological source of fatigue (Rosekind, Gander, et al., 1994) which can be acute when is restricted or of poor quality for a single night or total sleep deprivation occurs, or cumulative when sleep is inadequate night after night (Banks et al., 2022; Rosenthal et al., 1993). Most adults sleep about 7.5 hours per night during weekdays and 8.5 hours per night during weekends (Sullivan et al., 2022) which is within the recommended sufficient sleep duration requirement for adults of between seven and nine hours (Hirshkowitz et al., 2015). Regional airline pilots may not achieve this while at work. For example, Co et al. (1999) found that although regional pilots reported an average sleep duration of 7.9 hours when at home during days off and 7.7 hours when at home on call but not called out, on days with flying duties, sleep durations were typically shorter. These averaged 3.3 hours prior to continuous overnight duties and 5.6 hours before reporting for duty when called out. In another example, Spencer and Robertson (2007) found that short-haul pilots' average sleep duration, when it commenced between 21:00 and 01:00, was greater than seven hours. However, duration decreased as the start of sleep was progressively delayed, to an average of 2.5 hours when sleep was started in the late afternoon. Flight duty periods flown by short-haul and regional pilots can result in sleep loss when these involve early starts or overlap with their biological night. Rokicki et al. (1981) investigated the influence of early duties (05:30 report times) and late duties (10:30 – 12:30 report times) on the timing and duration of sleep in trainee Airforce pilots. They found that early duties were associated with reduced sleep duration (6.8 hours) and increases in ratings of fatigue and sleepiness, whereas late duties were associated with increased sleep duration (8.6 hours) and fatigue levels like that observed after a full night's sleep.

To identify additional factors that contribute to sleep loss, Co et al. (1999) asked regional pilots to rate the extent to which 18 factors affected their sleep at home. Pilots mentioned that the most disruptive factors were anxiety and environmental factors (e.g. humidity, temperature, random noise events, and background lighting). Although light is unlikely to contribute to sleep disturbance in aircrew during daytime sleep, noise was shown to reduce the amount of slow wave sleep achieved during the first part of their sleep period (Robertson et al., 2000). Ambient temperature also influences the duration and structure of sleep (Van Someren & Deboer, 2022). For example, when sleep occurs in a warm environment, the duration of wakefulness increases and both REM and NREM sleep duration decrease. In contrast, when sleep occurs in a cool environment, more awakenings occur, less time is spent in stage two sleep and total sleep time reduces.

Sleep restriction is the most common cause of sleep loss in pilots (Signal et al., 2022). It also occurs frequently, For example, during a tour of duty which lasted between three and four days, 67% of short haul pilots reported at least one hour of sleep loss per night and 30% reported two hours of sleep loss per night (Gander, Rosekind, et al., 1998). Flight duty periods that start early restrict sleep since advancing sleep to accommodate an earlier wake up time is difficult due to the evening wake maintenance zone (Kecklund et al., 1997; Lavie, 1986). Four consecutive flight duty periods that start before 07:00 are likely to contribute to a reduction in sleep duration of between 1.5 and two hours (Spencer & Montgomery, 1997). Late evening finishes are not typically associated with reduced sleep duration when shift workers have the ability to sleep in (Drake et al., 2004; Rokicki et al., 1981). However, personal commitments, social pressure (Drake et al., 2022) or early rise times associated with a morningness chronotype (Pilcher & Coplen, 2000) may mean that sleeping following a late evening finish is not practical which could contribute to reduced sleep duration and sleep restriction following a late evening finish.

The effects of sleep restriction are cumulative and dose-related (Belenky et al., 2003). Cumulative sleep loss contributes to elevated ratings of sleepiness, fatigue, confusion, tension, total mood disturbance, mental exhaustion, stress, and impairment in psychomotor vigilance task (PVT) performance. For example, Belenky et al. (2003) showed that when time in bed was restricted to three, five, seven or nine hours' for seven consecutive days, PVT performance in the three hour group declined without stabilising. However, in the five and seven hour group, PVT performance initially declined then stabilised at a reduced level. In a similar study, Dinges et al. (1997) found that PVT performance did not stabilise across a seven day period where sleep was restricted to five hours per night. Van Dongen et al. (2003) also found that restricting sleep opportunities to either four or six hours per night over 14 consecutive days contributed to increasing deficits in cognitive performance that were the equivalent of up to two nights of total sleep deprivation. These results suggest that there is variability in the stabilisation of performance following sleep restriction, which is deserving of further investigation.

Van Dongen et al. (2003) also found that participants may not be aware of their performance impairment. This was on the basis that subjective sleepiness ratings were considerably lower (less sleepy) during sleep restriction when compared with sleepiness ratings during total sleep deprivation. This may explain why chronic sleep restriction is widely tolerated.

1.2.1 Recovery from Sleep Loss

Time taken for complete recovery from extended wakefulness or sleep restriction differs and is dependent on the type of sleep loss (total sleep deprivation or sleep restriction), duration of recovery sleep and the number of consecutive days available for recovery (Banks et al., 2022). The recovery of sleep architecture and baseline performance may occur at different rates with performance impairment lingering following sleep restriction despite the possibility that the individual may report that they have recovered (Banks et al., 2022). Banks et al. (2010) determined that one 10 hour sleep opportunity was not sufficient for PVT performance or subjective sleepiness to recover from five nights of sleep restricted to four hours per night, while two 10 hour sleep opportunities were required to recover from seven nights of sleep restricted to five hours per night (Dinges et al., 1997). A greater number of recovery days is likely needed if the recovery sleep opportunity is reduced. For example, Jay et al. (2007) investigated the recovery of sleep architecture and PVT performance when the recovery opportunity, over a five night period, was either restricted to six hours or extended to nine hours following one night of sleep loss (40 hours of extended wakefulness). They found that one sleep opportunity of nine hours following one night of sleep loss was sufficient to return PVT performance, slow wave sleep, sleep efficiency, and sleep onset latency to baseline levels. However, when the sleep opportunity was restricted to six hours, although slow wave sleep returned to baseline levels following one six hour sleep opportunity, PVT performance, sleep efficiency and sleep onset latency did not return to baseline during the five six hour sleep opportunities. Belenky et al. (2003) reported similar findings in that the performance of participants who had their time in bed restricted to either three, five or seven hours per night, across seven nights, did not recover to baseline following three eight hour periods of recovery sleep. The authors suggest that, because of sleep restriction, longer term changes may occur to the brain which limit its capacity during recovery from sleep restriction, perhaps to limit the possibility of injury because of operating at capacity when exposed to a restricted sleep budget. This limited capacity impairs performance despite three eight hour periods of recovery sleep. Based on their research, it is unknown how long brain capacity is likely to be limited. Following prolonged periods of low level sleep restriction, the return to optimal performance may be a slow process with longer periods of recovery, such as blocks of annual leave, required for full recovery (International Civil Aviation Organisation, 2015). A further consideration is that recovery rates observed within laboratory settings typically occurred following sleep during the biological night, in a quiet and dark environment without distractions or personal commitments / social pressure. Recovery from sleep loss is likely to take longer in operational settings or when recovery sleep occurs at times other than during the biological night. Furthermore, an individual’s recovery from sleep loss is likely to be consistent and trait like (Doran et al., 2001) which suggests that genetic differences may account for individual variation in response to sleep loss (Jagganath et al., 2017).

1.3 Extended Wakefulness

Healthy people can remain awake for extended periods of time with no sleep and following an adequate period for recovery, will have no long term health effects. For example, short periods of extended wakefulness typically occur in individuals who need to meet deadlines whereas longer periods of extended wakefulness exceeding 40 hours likely occur due to atypical work conditions such as military exercises, combat missions or emergency work situations (Thomas et al., 2000). Wakefulness in everyday situations can be further extended when considering commuting time, personal commitments, social pressure and time taken to prepare for sleep or work.

Extended wakefulness represents periods of wakefulness that extend beyond 16 hours. Its effects include reduced cognitive processing speed, impaired constructive thinking, verbal memory, and spatial working memory, creation of false memories, increases in tiredness, sleepiness, and fatigue, changes in mood and emotional processing, as well as reduced stress tolerance and increased reaction to stress (Banks et al., 2022; Sagaspe et al., 2006). Vejvoda et al. (2014) found that short-haul flight duty periods that finished late (00:00 – 01:59) were associated with increased fatigue risk due to long periods of wakefulness in the vicinity of 15 hours at times where the circadian body clock cycle stops promoting alertness. Other studies have also demonstrated that short haul or regional operations have the potential to result in flight duty periods close to or greater than 16 hours, e.g. 15.8 hours (Gander et al., 1994) and 17 hours (Spencer & Robertson, 2000).

An investigation of the relationship between extended wakefulness and 37 aircraft accidents between 1978 and 1990, where flight crew action or inaction was identified as either causal or contributory was undertaken. It found that the median time since sleep was 12 hours for Captains and 9.9 hours for First Officers (National Transportation Safety Board, 1994). Captains and First Officers were placed into one of two groups depending on whether their time since sleep was above or below the median. The high time since sleep group had a median of 14.3 hours awake (13.8 hours for Captains and 13.4 hours for First Officers). Whereas the low time since sleep group had a median of 6.5 hours awake (5.3 hours for Captains and 5.2 hours for First Officers). The high time since sleep group made on average 12.7 errors during the event (40% more errors) compared with 8.7 errors in the low time since sleep group [7].

1.4 Circadian Disruption

Shiftwork may result in sleep occurring when the circadian biological clock is promoting wakefulness and work occurring when the circadian biological clock is promoting sleep. For example, following night shift work there is a limited window for sleep due to the increase in the signal for wakefulness from the brain following the window of circadian low. In addition, prior to a shift that starts early, it may not be possible to fall asleep earlier than usual due to the evening wake maintenance zone. Partial adaption to a night shift work pattern may occur however given the prevalence of environmental and social time cues, an individual is unlikely to acclimatise fully to a night shift pattern (Czeisler & Buxton, 2022). Although some individuals may tolerate shift work (Ritonja et al., 2019), a significant proportion will likely struggle to adapt to shift work (Booker et al., 2018).

Individuals who are unable to tolerate the effects of a shift work schedule typically present with symptoms of excessive sleepiness or insomnia despite adequate time in bed and in the absence of other sleep disorders (Drake et al., 2022). The inability to adapt to shift work can be extreme and constitutes as shift work disorder (SWD). The prevalence of SWD is estimated to be between 14% and 32% of night shift workers and 8% to 26% of rotating shift workers (Drake et al., 2004). A cross-sectional study involving 344 pilots who completed validated questionnaires to

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[7] These were primarily errors of omission (National Transportation Safety Board, 1994).

screen for risk of sleep disorders, fatigue and depression, found that 48.8% of pilots had self-reported insomnia, 38.1% had self-reported impaired sleep quality, 25% reported increased sleepiness and 17.2% were at high risk of having obstructive sleep apnoea (Alzehairi et al., 2021).

The following section discusses workload as it is a factor that both contributes to fatigue and performance impairment in airline pilots.

1.5 Workload

Workload represents the interaction between task related factors (i.e. complexity), individual factors (i.e. experience) as well as time related factors (i.e. time on task) (Casner & Gore, 2010; Hart & Staveland, 1988). Workload is both dynamic and complex and is not totally described by a single measure. For example, heart rate variability may detect differences between the workload of a Captain and a First Officer which might not be evident if solely relying on subjective ratings of workload (Kantowitz & Casper, 1988). In addition, the same task can be relatively easy or very difficult depending on the availability of appropriate tools and procedures (Orlady, 2016). Workload can be managed with knowledge, experience, capability, environmental conditions, regulatory requirements, operating procedures and management of fatigue levels (Warr, 2002) and prior training and experience may allow performance to remain acceptable with increasing levels of workload (Lysaght et al., 1989).

The relationship between workload and fatigue has not been well researched (International Civil Aviation Organisation, 2015), however, it is considered to be a major factor associated with the development of fatigue (Goel et al., 2014; James et al., 1991). The relationship between workload induced fatigue and performance impairment represents an inverted U shape (Gradwell et al., 2017; Klein & Wegmann, 1980; Lysaght et al., 1989) such that when workload is either low or high, fatigue related performance impairment increases (Gaillard, 2000; Rogers et al., 1995; Signal et al., 2022). Low workload may contribute to boredom which can lead to missed signals and instructions (Parasuraman, 1986), micro-sleeps, physiological drowsiness (Cabon et al., 1993; Samel et al., 1997). Due to a lack of stimulation, low workload can unmask fatigue[8]. High workload on the other hand may result in an increase in errors (Ruffell Smith, 1979), unexpected and undesirable performance changes due to task shedding and an inability to perform tasks or maintain task performance (Lysaght et al., 1989).

In a field study involving fatigue ratings made by air traffic controllers, Spencer et al. (1997) found that the effects of workload were more apparent when time since sleep exceeded 12 hours and that time of day variation in fatigue ratings was more pronounced when workload was rated as either low or high when compared with intermediate ratings.

1.5.1 Workload Variation During Flight

Periods of low and high workload are commonly experienced during flight (Graeber, 1988; Laudeman & Palmer, 1995; Ruffell Smith, 1979; Wilson, 2002). Gander et al. (1994) found that during short haul flights, significant increases above mid-cruise heart rate were found for descent and landing, but not for take off. Heartrate increases were greater for the pilot flying than the pilot monitoring and the difference in heartrate increases for the pilot flying and pilot monitoring during

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[8] In an environment stripped of factors that conceal underlying physiological sleepiness, an individual is susceptible to spontaneous uncontrolled sleep and performance impairment associated with sleep loss (Rosekind & Gander, 1996).

descent was greater for first officers than for Captains. Heartrate increases were also greater during take off and descent when in instrument meteorological conditions (IMC) compared with visual meteorological conditions (VMC). These results are consistent with previous studies in than “an increase in heart-rate on take off, greater increases on landing, and greater increases in the pilot flying for all phases of flight” (Gander et al., 1994, p. 55). Factors that may contribute to increases in workload during take off and landing include heightened awareness of an increase in risk of an accident and increases in acceleration (g-forces) (Liu & Lee, 2003).

The following section discusses fatigue related performance impairment and the cognitive functions, that are known to be sensitive to sleep loss. It also establishes that cognitive functions are not impacted equally by sleep loss making some tasks more susceptible to fatigue related performance impairment than others.

1.6 Fatigue Related Performance Impairment

Cognitive performance consists of simple functions (i.e. attention or memory) which form the basis of more complex functions (i.e. multi-tasking). Fatigue related changes in performance can occur without extensive physiological symptoms (Fraser, 1957) and can occur through variation in behavioural functions including affect (e.g. reduced empathy or loss of motivation), cognition (e.g. cognitive slowing or poor decision making, loss of situational awareness) and behaviour (e.g. either overly risk seeking or risk adverse or distractibility) (Banks et al., 2019).

A factor that can influence performance measurement is the willingness of participants to maintain performance. Performance can be protected by applying additional compensatory effort which may decline due to boredom or complacency.

The implication of this is that additional effort may mask fatigue related performance impairment and boredom, or complacency may result in the extent of fatigue related performance impairment being overstated. The sensitivity to sleep loss of a particular task is likely dependent on the willingness of participants to maintain performance (Harrison & Horne, 2000).

Fatigue related impairment in cognitive performance varies as not all facets of performance are impacted equally (Harrison & Horne, 2000; Van Dongen et al., 2022). For example, laboratory studies show that performance in novel and unexpected complex tasks were more severely impaired by sleep loss when compared to either simple tasks (e.g. tasks requiring attention of vigilance) or complex tasks that have been well practiced and have involved training (Harrison & Horne, 2000; Nilsson et al., 2005). An example of how fatigue can impair different facets of cognitive performance is provided by Belenky et al. (1996) who illustrated that during a friendly fire accident in the Gulf War, although fatigue contributed to soldiers loosing situational awareness (a complex cognitive function), they were still able to engage with targets (a simple cognitive function). The following sections provide a brief overview of the effects of fatigue and sleep loss on simple and complex cognitive performance.

1.6.1 Simple Cognitive Performance

Sleep loss contributes to variation in the ability to sustain wakefulness and contributes to an increase in inconsistent performance. Simple cognitive performance functions are elementary in nature and consist of functions such as alertness, vigilance, attention and tracking capacity. These functions are needed to ensure that individuals can sustain alertness and focus attentional resources on tasks which require complex cognitive performance. Real-world tasks that rely on simple cognitive performance (such as driving or flying) are particularly sensitive to increasing levels of sleep loss as responses will slow and brief lapses may occur. Lapses are associated with moment-to-moment variability in brain functioning which reflects the underlying neurobiological mechanism of sleep and wakefulness which use the same neuronal pathway for both rest-mediated recovery processes and cognitive processes (Van Dongen et al., 2011). Lapses which exceed 30 seconds can be described as functional sleep attacks (Lim & Dinges, 2008). In pilots, lapses will likely contribute to abnormally poor performance (Stave, 1977).

The PVT test is a computerised test of reaction time which is used to measure alertness, vigilance and the incidence of lapses (Killgore & Weber, 2014) (see section 2.11.3.1 for an overview of the PVT test). Performance impairment, as a result of sleep loss, on the PVT is characterised by an increase in variability between responses, with an increasing number of slower responses intermixed with normal responses (Doran et al., 2001). During the first 16 hours of wakefulness across the biological day, PVT performance will likely remain mostly stable (Schmidt et al., 2007; Wesensten et al., 2004) due to an increase in sleep pressure being opposed by the circadian drive for alertness. This may explain why studies of alertness and performance find little variation in performance during the waking portion of a normal day (Lim & Dinges, 2008). As wakefulness extends beyond 16 hours, PVT performance becomes increasingly variable as response speed slows and behavioural lapses occur more frequently and become longer (Dorrian et al., 2005; Goel et al., 2009). However, if wakefulness is maintained into the following day, performance will then improve as a result of the circadian biological clock. For example, “after a night of sleep deprivation, when a sleepy person is not lapsing, reaction times are normal, and for much of a 10-min reaction time test there is no cognitive slowing” (Harrison & Horne, 2000, p. 246). This shows that the effects of increasing homeostatic pressure and sleep loss on PVT performance can be masked by the circadian cycle in performance. To illustrate that PVT performance degrades faster at certain times of the day, Wesensten et al. (2004) conducted a study where participants completed a 10 minute PVT test every two hours between 08:00 on day 1 and 22:00 on day 2. By recording average PVT response speed in one minute increments during 10 minute PVT tests, they were able to measure the effect of time on task at different times of the day. Before significant sleep loss, they found that time on task effects were evident between 08:00 and 23:59 on the first day. Of note is that the PVT test undertaken at 22:00 on day 1 exhibited the smallest time on task effect. A comparison of results at 08:00 on days 1 and 2 highlighted that overall performance had reduced and that time on task effects had increased. Of note, is that they also found that PVT performance during the first minute of a test was better than PVT performance during the last minute of the previous test that occurred two hours beforehand. This illustrates that time-on-task effects can be reversed by rest breaks, even following sleep deprivation.

Like attention, vigilance and psychomotor performance, motor tracking shows a decline in performance with an increase in sleep loss (Killgore & Weber, 2014). In addition, sensory processing is impacted however it is not clear if sensory functions are impaired, or if reduced alertness and vigilance impacts sensory perception because of sleep loss.

A factor that may minimise fatigue related performance impairment in simple cognitive tasks relates to motivation and compensatory effort. For example, following sleep loss, simple cognitive performance may reduce if tests are less novel, monotonous or futile, whereas performance may be maintained if tasks are complex, interesting, variable or short (Kjellberg, 1975; Wilkinson, 1991).

1.6.2 Complex Cognitive Performance

Simple cognitive functions contribute to performance in tasks that require complex cognitive performance as those tasks will require sustained, and focused attention. Complex cognitive functions (executive functions) include higher order capacities such as the ability to ignore distractions and sustain focused attention, multi-task, inhibit inappropriate thoughts or behaviours, maintain situation awareness, change a mindset and the ability to think either convergently or divergently (i.e. flexibility in thinking). Executive functions are moderated by central nervous system processes including the circadian body clock cycle, sleep homeostasis and sleep inertia (Achermann & Borbely, 1994; Killgore & Weber, 2014). The interacting effect between central nervous system processes contributes to daily variation in alertness and performance (Riedy et al., 2022). Executive functions are particularly reliant on the prefrontal cortex which some have argued “is the hardest working cortical area during wakefulness” (Harrison & Horne, 2000, p. 246) and has been shown to be sensitive to sleep loss (Thomas et al., 2000). This section will consider the impact of sleep loss on the effects of fatigue and sleep loss on working memory, complex cognitive thinking involving convergent and divergent tasks and cognitive control.

All tasks that require executive functions are reliant on working memory which represents the ability to retain and manipulate information in real time (Goel et al., 2009). Although working memory capacity is impacted by sleep loss, it is not clear if deficits in working memory capacity are due to degraded alertness and attention (“non-executive” aspects) or the ability to manipulate information within the memory buffer (“executive aspects”) (Killgore & Weber, 2014).

The ability to control and regulate mental activity (i.e. cognitive control) includes the ability to both multi-task (i.e. cognitive switching) and to stay focused by dismissing distracting or irrelevant information. For example, fixating on the continuation of an activity beyond a desired point is characteristic of a deficit in the prefrontal cortex as a result of sleep loss (Belenky et al., 2014). Although multi-tasking is impaired by both total sleep deprivation (Couyoumdjian et al., 2010) and sleep restriction (Haavisto et al., 2010), the ability to remain focused by dismissing interference is not impaired by total sleep deprivation (Sagaspe et al., 2006).

The ability to resolve a problem, including the ability to make decisions is reliant on complex cognitive thinking, requiring either convergent or divergent thinking (Harrison & Horne, 2000). Complex convergent thinking refers to the process of arriving at a solution using logical reasoning and the application of established rules. Tasks which incorporate convergent thinking include critical reasoning, logical well practiced tasks, multitasking, e.g. tasks which include simultaneous vigilance across different sensory modalities[9], tasks which include decision-making elements, and tracking and intercepting tasks. Complex divergent tasks include the ability to appreciate a difficult and rapidly changing situation, undertake risk assessment, anticipate a range of consequences, keep track of events and to be innovative. In addition, they include maintaining the ability to develop, maintain and revise plans, to recall when events occur and retain the ability to control mood and uninhibited behaviour. Importantly, to maintain satisfactory performance during complex divergent tasks, requires an awareness of variation in performance, maintenance of effective communication, and the ongoing avoidance of irrelevant distractions.

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[9] Although these tests are more complex than simple vigilance or reaction time tests, they are not particularly demanding of innovation or require responses to the unexpected (Harrison & Horne, 2000).

Studies that have examined the impact of total sleep deprivation on complex convergent tasks using measures of intellectual functioning including logical deduction, critical reasoning, reading comprehension, grammatical reasoning and nonverbal problem solving, 3D navigation tasks, IQ types of performance test, and logical well practiced tasks, found that these tasks were not significantly affected by short term sleep deprivation (<48hr) (Harrison & Horne, 2000; Killgore & Weber, 2014; Lim & Dinges, 2010; Strangman et al., 2005). A possible reason for this is that practice and training for tasks that require complex convergent thinking may result in the task becoming more routine, less novel and therefore less dependent on the prefrontal cortex (Harrison & Horne, 2000). Tasks requiring complex divergent thinking are highly susceptible to sleep deprivation (Harrison & Horne, 2000). Even a single night of sleep deprivation contributes to fewer creative responses, difficulty in changing strategies, reduced cognitive flexibility, decrements in planning and sequencing capabilities and increases in rule violations (Killgore & Weber, 2014). For example, in relation to decision making:

> If there is a particular need to draw on innovation, flexibility of thinking, avoidance of distraction, risk assessment, awareness for what is feasible, appreciation of one's own strengths and weaknesses at that current time (metamemory), and ability to communicate effectively, then these are the very behaviours that we feel are most likely to be affected by sleep deprivation, not only when people are working alone but also when working in a team. (Harrison & Horne, 2000, p. 246)

The evidence on the effects of sleep restriction on complex cognitive performance, is limited when compared to what is known about the effects of total sleep deprivation on complex cognitive performance. Although Wickens et al. (2015)

identified 28 papers that focused on complex cognitive performance in relation to total sleep deprivation, they only identified five papers[10] that focused on sleep restriction in relation to complex cognitive performance. From their meta-analysis, which included five papers, they identified that complex cognitive performance gradually declines as cumulative sleep debt increases. They identified a considerable difference in performance deterioration between mild sleep restriction (greater than four hours' time in bed per night) and severe sleep restriction (less than four hours' time in bed per night). Although the impact of mild sleep restriction was negligible, severe sleep restriction corresponded to a 7% reduction in complex cognitive performance each night.

Although compensatory effort is unlikely to prevent decrements in complex cognitive tasks that require the prefrontal cortex (Harrison & Horne, 2000), the prevailing view is that "high-level complex skills are relatively unaffected by total sleep deprivation because of the interest they generate and the implicit encouragement for participants to apply compensatory effort to overcome their sleepiness" (Harrison & Horne, 2000, p. 236).

Regional airline pilots operate aircraft that require two pilots (European Aviation Safety Agency, 2025). For this reason, and because flight crew performance is heavily reliant on crew co-ordination, this section introduces fatigue related performance impairment in teams.

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[10] These papers include Balkin et al. (2000), Blagrove et al. (1995), Haavisto et al. (2010), Herscovitch et al. (1980), and Stenuit and Kerkhofs (2008).

1.6.3 Team Performance

Mood and emotional regulation are profoundly influenced by sleep loss which contributes to increases in anxiety, stress, negative mood, willingness to blame others and a reduction in empathy and ability to inhibit inappropriate behaviour. Variation in mood and emotional regulation, as a result of sleep loss can have a detrimental effect on team performance and can influence higher level cognitive functions including judgements on risk assessment and decision making (Killgore & Weber, 2014).

Fatigue likely impacts planning, goal specification, strategy formation, coordination and monitoring of progress, and team members by impairing judgement, decision making and cognitive flexibility (Banks et al., 2019).

Team performance is affected by the level of fatigue in each individual team member. For example, a fatigued individual within a team setting may reduce or conserve their effort if they believe others in the group will make equal or greater contributions (Hoeksema-van Orden et al., 1998). In addition, to conserve energy, reduce effort and complete socially-based tasks sooner, fatigued individuals may break the rules (Nilsson et al., 2005). Fatigue also influences how individuals interact with others. For example, fatigued leaders are more likely impatient, irritable and hostile (Guarana & Barnes, 2017). They may also communicate less and the nature of their communication may become puerile, i.e. more childish, silly or immature (Sparrow et al., 2015). These negative effects may reduce team cohesion, trust, and confidence and may lead to a breakdown in shared understanding and a loss of collective memory of expertise or lessons learnt, which may contribute to further poor performance.

In flight crew, an increase in fatigue disrupts communication between team members by influencing the willingness to communicate which could impair flight crew coordination (Caldwell et al., 2004). In a simulator study that required B-747 flight crew to manage a series of inflight events, Ruffell Smith (1979) found that “high error” crews experienced difficulties in communication, interaction and integration and that, the majority of the flight crew’s problems, were related to a breakdown in crew co-ordination.

The following section moves the focus from fatigue related performance impairment to consideration of the strengths and weaknesses associated with different types of performance measures. This is necessary because they have the potential to influence both the generalisability of findings and the ease of data collection. The section also provides context regarding the ecological validity of the simulated flight data measures used within this thesis research.

1.6.4 Performance Measurement

An additive performance measure may represent simple cognitive tasks which focus on attention, complex attention, processing speed, working memory, short-term memory, reasoning or crystallized intelligence (Lim & Dinges, 2010) or complex cognitive tasks such as decision making tasks, multitasking, tasks that burden working memory and team performance tasks (Wickens et al., 2015). They can be easily implemented within a field setting however they can be intrusive and may interrupt the normal flow of work. In addition, little is known about how an individual’s performance on an additive performance test relates to complex real-world tasks, or to what extent an individual’s performance contributes to overall team performance (Balkin et al., 2004). The extent to which laboratory based additive performance tests relate to real-world tasks is therefore a matter for debate

(Harrison & Horne, 2000). By comparison, ecological performance measures represent data that is collected unobtrusively during work and reflects actual tasks being undertaken. For example, a flight operations quality assurance (FOQA) programme records hundreds of parameters during flight which provides an objective overview of how the aircraft was operated. Simulated performance measures are similar to ecological performance measures however these are acquired from a simulated environment. For example, a zero flight time simulator or a procedural trainer.

A flight simulator offers "greater ecological validity than laboratory tests and greater experimental control than embedded measures within the workplace" (Gander et al., 2017, p. 703) which makes it a sound choice to investigate fatigue related performance impairment in pilots.

The following section reviews studies that investigated fatigue related performance impairment in pilots using recorded flight data during flights or simulated flights. An overview of the strengths and weaknesses associated with the different approaches are summarised which provides a rationale for the design of the flight duty period protocol and simulated flight protocol. These studies also offer an opportunity to place findings from this thesis research within the context of existing literature.

1.7 Studies which Investigate the Association between Fatigue and Pilot Performance

A small number of studies have investigated the association between fatigue and pilot performance, where performance was measured either by using data from a FOQA programme or by using data acquired from a flight simulator. The research design and conclusions differ between these studies when are summarised and discussed below.

1.7.1 Studies which Investigate the Association between Fatigue and Pilot Performance using Data from a FOQA Programme

Rosenkrans (2011) describes a collaborative Ultra Long Haul (ULR) research project between American Airlines, Continental Airlines and Delta Air Lines where each airline used a common protocol and measures (including actigraphy, KSS, SP, and PVT) for assessing fatigue risk associated with ULR flights. The protocol involved B-777 pilots flying routine flights during which sleep/wake patterns were monitored with actigraphy and fatigue status was assessed (using the PVT and ratings of fatigue and sleepiness) at key operational times. FOQA data was provided by American Airlines and Continental Airlines. Analysis of FOQA data provided by American Airlines was used to develop a metric (derived from FOQA data) called “descent unstable landing”. Analysis identified that high fatigue risk crew pairings, which included flights landing during the window of circadian low (03:00 – 05:00), had lower rates of stable approaches compared with low risk crew parings. In addition, FOQA data from routine flights was provided by American Airlines and Continental airlines to explore possible relationships between FOQA data and PVT metrics.

A particular strength of this research was the common protocol and measures used by these airlines for monitoring flight crew fatigue during routine flights. However, due to the research being conducted in a natural setting and the presence of a large number of confounding factors, this research was limited in its ability to detect relationships between variables of interest.

Easy Jet, in collaboration with National Aeronautics and Space Administration (Croft, 2010; Srivastava & Barton, 2012) investigated the 26 day roster period (which included three five day tours of duty (ToD) with variable layover lengths and fatigue characteristics) of 22 pilots in relation to the rosters effect on in-flight pilot performance. The authors found that both the work pattern and ratings of fatigue were good predictors of mean PVT reaction time. However they found no evidence that any of the FOQA events were related to a pilot's degraded PVT performance (Srivastava & Barton, 2012).

Similar to the ULR studies described by Rosenkrans (2011), despite the inclusion of various metrics to assess pilots' fatigue status, the presence of extraneous variables in the natural setting may have masked any associations with FOQA metrics.

Neville et al. (1994) evaluated the effect of extended work hours, reduced sleep hours, night work and time zone changes on subjective ratings of fatigue and pilot performance of five C-141 air crews over a 30 day period during Operations Desert Shield and Desert Storm. To investigate the association between subjective fatigue and pilot performance derived from flight data, pilots were instructed to manually fly ILS approaches and to intercept the localiser as early as possible. Performance measures were calculated as the mean and standard deviation of airspeed and heading during an 80 second segment during final approach before landing. Although no significant associations were found, an increase in subjective fatigue was correlated with an increase in variation of the airspeed measure. Although to a lesser extent, the same was true for the heading measure. The finding that deviations in the performance measures increased as fatigue increased is consistent with previous findings (Hartman, 1967). The authors highlighted that in this naturalistic study, uncontrollable factors such as weather confounded results.

Cabon et al. (2012) sought to evaluate the association between flight data analysis events and crew fatigue risk. Flight data analysis events were categorised by class (class 1 low, class 2 medium and class 3 high). Crew fatigue risk was calculated by categorising individual aircrew schedules over a 12 month period as low, moderate or high fatigue risk using six criteria[11]. Aircrew schedules were then combined for each flight to calculate five levels of crew fatigue risk (low/low, low/moderate, moderate/moderate, high/low and high/high). Cabon et al. (2012) found that the overall frequency of events per 1000 flights, regardless of significance level, decreased with higher fatigue risk. However, when only high significance events were considered, the event rate increased, suggesting that with increasing fatigue risk, more serious flight data analysis events are more likely to occur.

> The flight data monitoring (FDM) data confirm a significant effect of duty schedules. Surprisingly, the frequency of events significantly decreased with the more disruptive schedule. One possible explanation is that tired aircrews tend to rely more on the autopilot and therefore reduce the frequency of Class 1 and 2 events. However, when the risk of fatigue is high, more serious exceedance levels are likely to occur (Cabon et al., 2012, p. 44).

Strengths associated with this research design include the ability to include all flights over a specified period. In addition, no input from participants is needed meaning that the study can be run either periodically or continuously without concerns regarding response rate. A limitation is that the fatigue status of each crew member is unknown, rather it is inferred. The nature of the research design also means that error variance associated with individual differences would not have

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[11] Measures included % of reduced rests, % of split duties, number of “backward” duties, % of duties starting <06:00, %of more than five consecutive duty days and the number of flights per day (Cabon et al., 2012).

been accounted for and given the study's natural setting, the presence of extraneous variables could also mask associations between variables.

De Mello et al. (2008) reviewed the influence of time of day on high significance flight data analysis events (as opposed to low or medium). Events were categorised by time of day and were rated per 100 flight hours to account for flight frequency during six hour blocks. The event rate was highest during the period 00:00 – 05:59 (early morning) where the likelihood of a level 3 event[12] was 50% greater than between 06:00 – 11:59 (morning). A possible weakness of this study is that the measure of fatigue (time of day) is basic compared with aggregate values derived from roster metrics (Cabon et al., 2012) or biomathematical model predictions (European Aviation Safety Agency, 2019).

The European Aviation Safety Agency (EASA) Best Intervention Strategy "Aircrew Fatigue" (European Aviation Safety Agency, 2019) summarised preliminary results from a 2019 research project which investigated the effect of predicted sleepiness on the incidence of FOQA events to assess the impact of fatigue on normal flight operations. Predicted sleepiness was calculated by analysing roster pairings using the Boeing Alertness Model (BAM) algorithm[13]. The study determined that pilots who had a predicted score of six or more on the Karolinska Sleepiness Scale (KSS) had impaired performance prior to and at touchdown. This included critical low speed between 20ft and touchdown, firmer landings, higher speeds when flap was selected, slower taxi speeds, greater use of the autopilot, and higher fuel

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[12] A level 3 event exceeds an operational limit defined by the airline, an instance where an established procedure was not followed or exceedances associated with structural limits defined by the aircraft manufacture (de Mello et al., 2008).

[13] The Boeing Alertness Model is a biomathematical model (BMM). A BMM is defined as a computer program designed to predict crewmember fatigue levels, based on scientific understanding of factors that contribute to fatigue (International Civil Aviation Organisation, 2015).

consumption when compared with pilots predicted to have KSS ratings of less than six.

An advantage of using biomathematical model predictions of pilot' sleepiness instead of actual measures (as used in the collaborative Ultra Long Haul research project, the Easy Jet project and the United Stated Airforce C-141 study) is that a much larger number of flights can be evaluated over a specified period of time. However, predictive models of sleepiness do not consider the individual variability observed in actual measures of sleepiness. Additionally, the presence of extraneous variables during flights may have masked any associations between moderate or low events and predicted sleepiness. A weakness of this study is that it is not clear how the authors determined that sleepy pilots had impaired performance prior to and at touchdown given that the authors highlight that statistical analysis was not undertaken and that validation is required.

1.7.2 Studies which Investigate the Association between Fatigue and Pilot Performance during Flight

There are very few published studies involving experimental manipulation of flight crew fatigue in a naturalistic setting. The following three studies all involved levels of extended wakefulness that would not be expected during normal commercial flight operations.

An example of a study which evaluated the impact of extended wakefulness on in-flight pilot task performance was undertaken by Howitt et al. (1978), where two types of flights with a fatigued pilot were undertaken. Some flights occurred after 30 hours of extended wakefulness and other flights occurred after multiple flights within a single flight duty period. It is not clear at what time the flights following extended wakefulness started or if these flights all started at a similar time. During all flights, a Training Captain was present in the First Officer's seat. The aircraft itself was operated by the Civil Aviation Flying Unit – Telecommunications Flight and no passengers were on board. A total of 18 flights of approximately 1.25 hours in duration were undertaken by one pilot. Eight flights were made as the first flight of the day after a full night's sleep, three flights were undertaken following 30 hours of extended wakefulness, three flights were made following a previous flight the same day and two flights were made as the third flight of the day. Each flight followed the same routine, a standard instrument departure, one lap of the hold, an instrument landing system (ILS) approach, followed by a go around. At the point of go around, the same pattern was flown but without the use of autopilot and flight director. Following the second ILS approach, the aircraft landed which was then followed by a take off with simulated engine failure and visual circuit to land.

During the flights which followed 30 hours of extended wakefulness, the participant said they had no feelings of fatigue once they were in the aircraft. It is possible that the participant's assessment of fatigue may have been underestimated given subjective ratings do not always reliably reflect objective measures of performance, especially when the individual has experienced sleep loss (Belenky et al., 2003). During instrument approaches, there appeared to be no decrement in tracking performance or general instrument flying, a finding which is consistent with similar studies (Adams et al., 1972; Hartman, 1965). However, there was a marked narrowing of attention, a decrement in short term memory, and a tendency for the pilot to make a rare, but gross error in tactics when attention was diverted. In addition, the pilot showed a tendency to lose situational awareness. This was not observed during flights which occurred as a second or third flight of the day, however, on these flights, there was a feeling of boredom and a lack of motivation toward fine accuracy on the instruments. Regarding a gross error in tactics during an otherwise efficiently performed flight, this could be evidence of wake state instability (Dinges & Kribbs, 1991; Dorrian et al., 2005). As noted in section 1.6.1, sleep deprived individuals will experience unpredictable lapses of attention that increase in frequency and duration as the length of extended wakefulness increases (Banks et al., 2022).

The study had high ecological validity since actual flights were operated, and different fatigue conditions were controlled for. However, a limitation is the inclusion of only one pilot. Additionally pilot performance was determined by the safety pilot (Training Captain) who may have had an influence on the participant's performance. For example, intervention by the Training Captain could prevent the incidence or magnitude of gross errors. Their presence may also have provided a false sense of confidence in that the Training Captain would likely have taken control if the participant's performance was unsatisfactory. Other limitations include generalisability and applicability to commercial airline operations.

Although it is acknowledged that substantial differences exist between fixed wing and rotary wing aviation, Lees et al. (1977) field study with helicopter pilots demonstrated the effect of severe sleep restriction[14] on pilot performance during a specific flight manoeuvre. Flight data measures focused on control inputs and stability. Over a five day period, six helicopter pilots flew 13 50-minute flights between 04:30 and 01:00 the following day. Participants time in bed was restricted to 3.5 hours each night. The authors found that the protocol contributed to a progressive increase in subjective ratings of fatigue both between and within days.

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[14] Belenky et al. (2003) defines severe sleep restriction as three hours' time in bed and moderate sleep restriction as between five and seven hours' time in bed.

The authors acknowledge that changes in performance because of sleep restriction was expected, however "the most interesting aspects related to the effect of fatigue on the man-helicopter system, were the shifts, or transitions, in the aviator's control performance observed across the four days of flight" (Lees et al., 1977, p. 429). Although a learning effect was identified during the first day, during subsequent days, shifts, or transitions in the quantity of control inputs influenced helicopter stability. On the second day stability during the flight manoeuvre decreased, and during the third day, aggressive control of the helicopter was observed, whereas on the fourth day, participants applied a passive strategy where they only responded to error in attitude and position. The passive strategy contributed to high levels of observable error and unstable hover performance.

Because few researchers investigating the role of fatigue in performance have the resources to perform simulator versus in-flight comparability evaluations, it is unknown how well findings from a simulator study generalise to the real-world. To investigate this Caldwell and Roberts (2000) combined results from a study which investigated UH-60 helicopter pilot performance during simulated flights (Caldwell et al., 1997; Caldwell et al., 1995) and actual flights (Caldwell & Caldwell, 1997). Ten participants manually flew 14 aircraft handling manoeuvres which were completed in the same order during both simulated and actual flights. During each protocol, a total of 19 flights were flown which consisted of three training flights, three control flights (repeated twice) and five experimental flights (repeated twice). The control flights occurred at 09:00, 13:00 and 17:00 and the experimental flights occurred during the final 23 hour period of 40 hours of continuous wakefulness, at 01:00, 05:00, 09:00, 13:00 and 17:00. During each manoeuvre, participants were required to maintain control over specific flight parameters. A single composite score was calculated based on the flight parameters across 14 manoeuvres.

A comparison of results from both aircraft and simulator studies identified a higher degree of measurement sensitivity during simulated flights. This led the authors to conclude that simulator results may not be as generalisable as expected. The most probable reason for this was that during simulated flights, the influence of weather was absent. During actual flights, the presence of weather had "the net effect of reducing the accuracy of in-flight performance by causing the pilot to constantly correct for deviations which are unpredictably induced by wind gusts or air currents" (Caldwell & Roberts, 2000, p. 288). Other factors which likely contributed to differences in measurement sensitivity include lower participant arousal during simulated flights, inconsistent temperature and light conditions during actual flight, variation associated with air traffic control (ATC) (e.g. delays or pressure / workload variation) and variation in experience levels. High workload is also likely to contribute to reduced measurement sensitivity (Brictson, 1975).

These findings illustrate the benefits of being able to control for real-world factors during simulated flights (i.e. to increase measurement sensitivity). However, a limitation of simulator studies is that they may not establish real-world applicability of findings.

1.7.3 Studies which Investigate the Association between Fatigue and Pilot Performance during Simulated Flight

Although field studies evaluating the impact of sleep loss on pilot task performance during flight possess higher ecological validity, there is a tendency for researchers to rely on flight simulators due to their low relative cost, accessibility, ease of experimental control, and improved safety relative to inflight investigations (Caldwell & Roberts, 2000). The following studies represent research designs which include simulated flights.

Foushee et al. (1986) undertook a similar study to this thesis research. Twenty flight crew operated one simulated flight within a zero flight time simulator. Ten flight crew flew a simulated flight following three days free from duty (pre-duty condition), and the other ten flight crew flew a simulated flight within two ~ three hours of completing a three day high density short-haul duty cycle (post-duty condition). The study differed from this thesis research in that a between-subject design was used, with ten flight crew operating the pre-duty condition and the other ten flight crew operating the post-duty condition. In addition, the simulated flight included an unexpected mechanical abnormality (a non-normal scenario) which resulted in a high level of workload. Measures included expert observer ratings, subjective assessment of workload, aircraft handling data, error analysis and crew communication patterns. A daily logbook was completed by participants which included self-reported sleep wake schedules for each of the four previous nights and subjective ratings of fatigue and sleep quality. Twelve parameters that relate to aircraft configuration and handling were recorded every 15 seconds and were time synchronised with video-taped records. Aircraft handling parameters were utilized primarily for analysis of the approach and landing and for cross checking during the error analysis. Due to the non-normal scenario, the approach was flown at a higher speed onto a short, wet runway with reduced braking effectiveness which increased flight crew workload. Flight crew in the post-duty condition were significantly more fatigued. However, unexpectedly, they also performed significantly better. This was attributed to the post-duty flight crew having more operating experience together which resulted in higher levels of communication and improved crew coordination.

A different methodological approach was taken in the CAA-UK Pilot Fatigue Measurement study (Civil Aviation Authority of United Kingdom, 2019) for investigating the relationship between sleep loss and pilot performance. The study incorporated a between-subject research design which included either one or two simulated flights and unlike the Foushee et al. (1986) study, did not include a rested condition. The study included 36 participants. Of those, 28 were recently qualified and were still affiliated with flight training schools. The other eight participants were airline pilots. All participants undertook a simulated flight using a desktop computer based flight simulator and the airline pilots undertook an additional flight in a high fidelity full flight simulator which reflected the B-747.

Non-airline pilot participants participated in an ambulatory study. For seven consecutive days, they wore an array of ambulatory sensors. Between 08:00 and 22:00, they responded to eight random alarms which prompted completion of a questionnaire and three minute PVT test. A ninth test was undertaken at bedtime and a 10th test was undertaken on waking. They were assigned to one of three groups. During the last four nights, one group was instructed to sleep one hour less, one group was instructed to sleep one hour more, and the third group maintained their habitual sleep schedule.

In addition, all participants undertook a laboratory study which included the simulated flight(s). The purpose of the laboratory study was to investigate the effects of posture, light and skin temperature on vigilance in a controlled environment during 12 30 minute experimental blocks. This occurred on day nine for non-airline pilot participants. Prior to the laboratory study, airline pilots were instructed not to change their sleep wake pattern. Participants arrived at 09:00 and started their first experimental session at 11:00. These were completed at 17:00. The desktop flight simulation started at 18:15 and finished at 19:00. The airline pilots then undertook their second simulated flight in the high fidelity full flight simulator at 20:00 and finished at 22:00.

Scenarios within simulated flights were selected on the basis of analysis of accidents and incidents involving fatigued flight crew with those activities being mapped to a pilot's competency (International Civil Aviation Organisation, 2013). The researchers identified that for accidents and incidents involving fatigue, the most frequently mentioned competencies affected were problem solving and decision making. The desktop flight simulation represented a single pilot operation and started twenty minutes prior to landing. Scenarios within the simulated flight were representative of a normal flight. The simulated flight undertaken in a high fidelity full flight simulator started at 15000ft, 45 nm from the airfield. It included eight scenarios, some of which were not representative of a normal flight. Although the simulated flight was operated by two pilots, one pilot was a confederate who was a part of the research team.

Results identified weak correlations between fatigue measures (PVT and subjective ratings of sleepiness) and pilot competency measures. The researchers concluded that correlations would likely be stronger within an operational environment and recommend further research to investigate crew performance and fatigue over a longer period during normal flight operations. This is inconsistent with other studies that found that measurement sensitivity was greater in the simulated environment (Billings et al., 1975; Caldwell & Roberts, 2000). Given that the airline pilots adhered to their roster and did not change their sleep wake pattern, it is not clear how fatigue was manipulated in this group. It is unknown if the eight participants were operating the same aircraft type or were employed by the same airline. The implication being that these participants may not have been familiar with required standard operating procedures and aircraft type (B-747). The B-747 requires a flight crew of two. Aside from the participant, the second pilot was a confederate pilot. It is unclear if either pilot was type rated on B-747. Because of this, it is unknown if flight crew performance would be representative of line B-747 flight crews.

Caldwell et al. (2004) investigated the effect of up to 37 hours of continuous wakefulness[15] on the performance of F-117 pilots during simulated flights. Ten participants each flew eight simulated flights (three training flights and five testing session flights). During each flight, they hand flew 13 aircraft handling manoeuvres. During each manoeuvre, participants were required to maintain control over specific flight parameters which were recorded twice per second. A score was derived for each manoeuvre by combining scores from three specific flight parameters into a single composite score. Each flight was short in duration and participants had breaks between flights. In addition, participants were prompted to start each manoeuvre. The manoeuvres themselves were considered more alerting than many tasks associated with real-world missions. Despite this, flight performance decreased between 23:00 and 09:00, remained poor from 09:00 to 14:00 and then recovered slightly, although not to baseline levels at 19:00. No one manoeuvre was more sensitive to the effects of extended wakefulness than other manoeuvres. The timing and magnitude of reduced performance was mostly consistent with previous simulator studies undertaken in UH-60 helicopter pilots (Caldwell & Caldwell, 1997; Caldwell et al., 1995). However, the period where performance was most impaired was three to five hours later in F-117 pilots (09:00 – 15:00) than it was in UH-60 helicopter pilots (05:00 – 10:00). The authors attributed this to a difference in work schedules. For example, F-117 pilots reported for work at 10:00 whereas UH-60 pilots reported for work at 06:00. It is apparent

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[15] Although 37 hours of continuous wakefulness is unlikely to occur in commercial pilots, extended wakefulness is possible. For example, a commercial pilot that wakes at 06:00, reports for a 14 hour duty at 20:00. If they do not achieve rest either before or during flight, at the point of landing they could potentially have been awake for 27 hours.

that the timing of maximum performance impairment on flying tasks overlaps with the timing of maximum performance impairment on the PVT (06:00 – 10:00), with both occurring during a zone of maximum vulnerability to degraded alertness and possible performance failure (Skeiky et al., 2022).

Participants demonstrated substantial decrements in the ability to precisely maintain parameters (Caldwell et al., 2004). The most noticeable degradation in performance occurred after 27 hours of continuous wakefulness which was consistent with previous studies in UH-60 helicopter pilots (Caldwell et al., 1997; Caldwell et al., 1995). The authors concluded that "although none of the participants crashed during any of the flight simulations, the clear-cut loss of basic flight control skill suggests that higher-level judgements, decisions, and other aspects of mission readiness would have suffered" (Caldwell et al., 2004, p. 178). The manoeuvres likely represented tasks that required convergent thinking, as they were rule based, logical and procedural in nature. In addition, participants had been trained to asymptotic performance levels to account for practice effects. Given that tasks associated with convergent thinking are generally considered to be unaffected by sleep deprivation (Harrison & Horne, 2000), this could suggest that the participants' ability to undertake tasks that require divergent thinking would have been compromised to a greater extent.

Using the same data set as described by Caldwell et al. (2004) above, Van Dongen et al. (2006) investigated individual variability in performance impairment of F-117 pilots during 37 hours of continuous wakefulness. The study identified statistically significant, systematic individual differences in the effects of sleep deprivation on aircraft handling performance. Up to 50% of the variance after baseline correction was explained by systematic individual differences in impairment levels (Van

Dongen et al., 2006). Visual inspection of the data identified particularly severe performance impairment in some pilots, suggesting a greater vulnerability to sleep deprivation. As such, reliance on averaged group data may entail substantial misestimation of the impact of extended wakefulness on the performance of an individual.

Compared to the aforementioned studies involving F-117 pilots, Previc et al. (2009) not only investigated the effect of sleep deprivation on flying precision but also its effect on pilots' instrument scanning within a gyro flight sustained operations simulator which replicated the T-6 aircraft. Ten pilots undertook ten 19 minute simulated flights over a period of 34 hours of continuous wakefulness. Each simulated flight included seven scenarios that related to aircraft handling. A mirror (reciprocal) flight profile was flown during even numbered flights and spatial disorientation conflicts were introduced during four of the 10 flights. The composite root mean squared error showed a slight improvement in flight performance during the first five flights (12:30 ~ 00:30). It then showed a decrease in flight performance during the next three flights (03:30 ~ 09:30). Performance then levelled off in the vicinity of baseline performance for the remaining two flights (12:30 – 15:30). Overall, a 25% difference in performance existed between peak performance and the maximum deficit in performance. The maximum deficit in performance compared with baseline was 15%, which was relatively small compared with that of 45% observed in F-117 pilots (Caldwell et al., 2004). The authors note that root mean squared error values masked large individual differences. Three pilots showed a slight reduction in composite root mean squared error from the five early to five late flights and two pilots showed decrements over 30%. Following 30 hours of continuous wakefulness, flying precision was degraded and large decreases in vigilance and cognitive capacity were observed. Despite this, instrument scanning was unaffected by sleep deprivation. The authors also investigated variation in airspeed, heading, vertical velocity and roll and found that the change in performance was greatest for vertical velocity and least for roll. The authors suspect that vertical speed was more susceptible to sleep deprivation as these scenarios were associated with prolonged wings-level climb and descent. By comparison, roll was associated with scenarios where the aircraft was turning which indicates pilots may have increased their arousal level to maintain performance. This finding may have some comparability with the driving scenario reported by Matthews and Desmond (2002) where driving performance was more accurate when the car was cornered compared with driving in a straight line. The above findings illustrate that the nature of the task contributes to variation in performance. However, Previc et al. (2009) found that following 30 hours of extended wakefulness, most pilots were able to maintain reasonable flying precision despite a modest increase in fatigue. Leino et al. (2007) and Howitt et al. (1978) reached similar conclusions, in that flight performance during long periods of extended wakefulness did not significantly deteriorate.

The above simulator studies investigated the influence of fatigue on pilot performance associated with aircraft handling, which are aspects of performance that primarily include convergent thinking. Although the studies may have included other performance measures, only those that were informed by continuously recorded parameters acquired from the simulator were reviewed. A study by Thomas et al. (2006) focused on the impact of fatigue on threat and error management and decision making. These aspects of performance primarily involve divergent thinking in flight crew.

Thomas et al. (2006) focused on the impact of fatigue associated with long-haul flying on threat and error management and decision making of B-747 flight crew. This study did not focus on aircraft handling and did not acquire or review continuously recorded parameters from a flight simulator. Sixty-seven flight crew participated in the study. Twenty one flight crew completed a simulated flight in a zero flight time simulator following four consecutive days free from duty (the rested group) and 46 flight crew completed a simulated flight immediately after landing in Sydney following a long-haul flight (the non-rested group). The simulated flight represented a flight from Sydney to Melbourne and included several threats (scenarios) which required pilot intervention. The study utilised trained expert observers to analyse and evaluate flight crew performance. Dependent variables were grouped into categories consistent with Klein's (1993) recognition primed decision model. To assess the impact of fatigue on flight crew performance, crews were allocated to a low, moderate or high fatigue group based on recent duty history, actual sleep, self-rated fatigue or PVT response speed. When grouping flight crew into a low, medium and high fatigue group, Thomas et al. (2006) found that fatigue was associated with an increase in errors and an increase in the mismanagement of both operational threats and errors. As fatigue levels increased, there was also an increase in the likelihood of safety related outcomes due to poor threat and error management. However, fatigue was also associated with enhanced operational performance as crew perhaps anticipated the occurrence of error, and demonstrated improved cross-checking performance, thus making fewer errors in procedural cross checking and an increase in error detection. This is likely an example of compensatory effort to protect performance. Thomas et al. (2006) also found that flight crew took longer to make decisions when sleep opportunity or total sleep in the previous 24 hours was reduced, when high levels of subjective fatigue were experienced and/or had slow PVT response speeds. In addition, flight crew within the high fatigue group also made more conservative decisions which may be associated with a greater aversion to risk.

The simulator studies discussed above represent a mixture of flights that are either representative of normal flights (Thomas et al., 2006), normal flights with non-normal events (Civil Aviation Authority of United Kingdom, 2019; Foushee et al., 1986) and flights which include specific manoeuvres (Caldwell et al., 2004; Previc et al., 2009). In any case, the full flight simulator offers an ideal environment to control for extraneous variables that would be present during in-flight investigations. For example, given that workload varies during flight (Gander et al., 1994), having the ability to control workload within a simulated environment is an advantage. Some studies controlled sleep within a laboratory environment (Caldwell et al., 2004; Previc et al., 2009) but this would likely not be practical in studies with line pilots who have flying duties. Another strength associated with some of these simulator studies is that they incorporated a within-subjects research design (Caldwell et al., 2004; Previc et al., 2009) which allowed for variation associated with individual differences to be accounted for.

Some of the studies (Civil Aviation Authority of United Kingdom, 2019; Foushee et al., 1986) included non-normal scenarios and results may therefore not be generalisable to normal flight operations. Additionally, findings from the simulator studies with military pilots (Caldwell et al., 2004; Previc et al., 2009) are not likely generalisable to regional airline flight operations. However, considering that these manual handing tasks are elementary to the operation of an aircraft, findings from these studies offer a glimpse as to what performance could look like if a regional airline pilot were to operate a flight following sleep deprivation.

The following section shifts the focus to safety management by introducing fundamental safety management system concepts and practices. Safety management systems provide a framework for a performance based approach to fatigue risk management. Flight operations quality assurance is also discussed, so that in combination with fatigue risk management processes, it will be clear how findings from this thesis research can be practically applied within a safety management system.

1.8 Safety Management

1.8.1 Safety Management Systems

Safety is defined as “the state in which the possibility of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and safety risk management” (International Civil Aviation Organisation, 2012, p. 11). Within commercial aviation, the safety process is formalised by a safety management system (SMS) which is defined as “a systematic approach to managing safety, including the necessary organisational structures, accountability, responsibilities, policies and procedures” (International Civil Aviation Organisation, 2015, p. xiv). In addition, considerable focus is placed on the management of risk as a result of change.

Safety science theory[16] provides a framework for SMS which incorporates principles of scientific experimentation, theorizing and logical reasoning and represents an interdisciplinary study of accidents and accident prevention. It postulates that accidents can be scientifically understood and that there is a moral responsibility to

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[16] Safety science theory incorporates concepts borrowed from social science disciplines such as management science, social psychology, industrial psychology, sociology, and anthropology (Dekker, 2019).

develop and apply preventative measures and, in part, lays the basis for emergence of institutions that create and maintain safety rules and practices. For example, it provides flexibility to focus on both accidents and safe operations. In addition, safety science theory allows for the continuous improvement of an SMS in that "the interplay between concerned citizens and scientists, government regulators, and insurers will continue to drive the creation of safety theories and their practical applications into the 20th and 21st centuries" (Dekker, 2019, p. xiv).

Key theories (or models) that are embedded within an SMS (International Civil Aviation Organisation, 2012) include the Swiss Cheese Model of accident causation and the concept of the organisational accident. The theory of practical drift illustrates that safety performance is dynamic because routine operations are continually changing, and the SHELL model is also employed, which reflects interactions between Software, Hardware, the Environment and Liveware (human beings) and explains how mismatches between liveware and the other components contribute to human error. The concept of safety culture acknowledges that organisational culture, professional culture, national culture, reporting culture and just culture can have a profound effect on safety performance. Specifically, processes associated with a just culture allow for an SMS to differentiate between errors, which are unintentional and violations which are deliberate. Finally, the concept of safety space illustrates that the balance between safety and the production of goods (or providing a service) are linked with the extremes of bankruptcy and catastrophe. For example, if production increases and additional resources or process enhancements are not available, safety risk may increase and could eventually result in catastrophe. Whereas, if too much emphasis is placed on safety, the long term outcome could be bankruptcy due to insufficient production.

The main purpose of a safety management system (SMS) is to reduce risk to as low as reasonably practical, because it is acknowledged that it is not practical to eliminate all hazards and associated risks. This is achieved by “the four pillars” of an SMS which include policy, safety risk management, safety assurance and safety promotion (Federal Aviation Administration, 2010; International Civil Aviation Organisation, 2018, 2022; Stolzer et al., 2023). Within these pillars, key elements include defined safety requirements and levels of safety performance which are supported by assurance processes that include safety oversight, safety data collection, analysis, and exchange to identify data driven targeting of areas that may require greater oversight. Safety assurance processes represent the core of an SMS as they inform safety risk management processes that define safety action(s) which illustrates that outputs from SMS are data driven and performance based. Data inputs into an SMS are considerable, and although not exhaustive, may consist of incident and accident reports, improvement reports, hazard reports, investigations, internal and external audits, findings and actions associated with reports, investigations, risks and audits, behavioural based surveys and change management plans. In addition, SMS and in particular safety assurance processes are further enhanced through specialised safety programs that incorporate SMS principals such as flight operations quality assurance and fatigue risk management systems.

The New Zealand Civil Aviation Authority (NZCAA) requires an operator to establish, implement and maintain a system for safety management (Civil Aviation Authority of New Zealand, 2020).

The following section shifts the focus to Flight Operations Quality Assurance (FOQA) because, it is through the analysis of routine flight data, that changes in fatigue risk could potentially be identified as a result of variation in flight data analysis events that have been shown to be reliably linked with fatigue and sleep loss.

1.8.2 Flight Operations Quality Assurance

Flight Operations Quality Assurance is a specialised safety programme that defines processes that allow for flight data to be routinely collected and analysed. Flight data represents a continuous recording of hundreds of parameters during an entire flight from engine start to shut down. It can provide vital information about what happened during a flight.

A FOQA programme is embedded within a SMS and enhances flight safety by improving flight crew awareness, training effectiveness and operational procedures (International Civil Aviation Organisation, 2021). It represents a systematic approach to the proactive identification of risks associated with aircraft operation (Enders, 1993). FOQA software is used to replay, analyse and visualise flight data and report on events, trends and risks identified during analysis. Analysis of flight data identifies events are based on pre-defined event sets. For example, these may include speed and altitude limits, pitch and roll limits, rate of change, warnings, and system limits (i.e. air frame, engines). In addition, specific manoeuvres may be monitored, i.e. go around or rejected take off (Civil Aviation Authority of United Kingdom, 2013). Events are validated by Fleet Data Analysts who represent line pilots. The FOQA programme also complements incident reporting by providing Investigators with additional information. In addition, in the absence of an incident report following a significant safety related event, the gatekeeper process will allow for trusted pilots to contact the pilot in command and recommend that an incident report is submitted.

A FOQA programme could easily be configured to include events or data points that are based on simulated flight data measures included within this thesis research.

Simulator Operations Quality Assurance

The only differences between a Simulator Operations Quality Assurance programme and a FOQA programme, is that the SOQA system replays and analyses simulated flight data and that the event set within a SOQA system will likely reflect the requirements of an operator's training programme. However, the underlying methodology is identical to that of a FOQA programme.

Canadian Aviation Electronics offered SOQA functionality in their CAE 7000 series full flight simulator in 2012 (Fiorino, 2012). Although this functionality was available in earlier CAE full flight simulators, the use of Insight FDM, Insight Analysis and Insight Animation (as discussed in section 2.10.1) in combination with simulated flight data from the CAE 7000 series simulator made this thesis research possible.

The following section introduces two different approaches to the management of fatigue-related safety risks. They are fundamentally different because the flight time limitations approach is based on prescriptive limits, whereas the fatigue risk management systems approach can provide a mechanism to operate outside of those limits if an equivalent level of safety can be demonstrated. Both approaches are discussed because, although fatigue risk management systems represent a new approach, the flight time limitations approach is still very much prevalent within the aviation industry.

1.8.3 Managing Fatigue-Related Safety Risks

The International Civil Aviation Organisation (2022) states that an airline, for the purposes of managing fatigue-related safety risks, shall establish either:

I Flight Time Limitations (FTL) that are within the prescriptive fatigue management regulations established by the Civil Aviation Authority of that airline; or

II A Fatigue Risk Management System (FRMS) for all operations; or

III An FRMS for part of its operations and FTL for the remainder of its operations.

Options II) and III) are only an option if the Civil Aviation Authority of that country makes provisions for FRMS within its regulations. The Civil Aviation Authority of New Zealand has not made provisions for FRMS within the regulations that apply to large aircraft, i.e. part 121 Air Operations Large Aeroplanes (Civil Aviation Authority of New Zealand, 2023). In the absence of FRMS regulation, a New Zealand based airline must use FTL supported by Safety Management Systems (SMS) processes to manage fatigue risk.

Flight time limitations are discussed in the following section, because the operator that facilitated this thesis research uses flight time limitations in conjunction with a fatigue risk management programme based on fatigue risk management system principals, to manage fatigue-related safety risks.

Flight Time Limitations

FTL are a prescriptive, one size-fits-all method for managing fatigue and maintaining flight safety and represent the traditional approach to fatigue risk management. They aim to balance numerous factors such as productivity, investment return, wages, quality of life and safety (Gander, Hartley, et al., 2011) by specifying minimum off duty periods, maximum flight and duty periods and may account for exceptions due to unforeseen operational circumstances, changes in time zone, or reserve status (Dinges et al., 1996). FTL differ between countries and airlines due to differing regulatory requirements or labour agreement requirements. For example, the Civil Aviation Authority of New Zealand (CAANZ) requires operators to establish a scheme for the regulation of flight and duty times which addresses factors[17] that are applicable to the operators flight operation (Civil Aviation Authority of New Zealand, 2023). Although CAANZ includes a suitable FTL scheme within Advisory Circular 119-2 (Civil Aviation Authority of New Zealand, 2022), an operator can establish a different scheme which incorporates labour agreement requirements, as long as this is acceptable to the director. The makeup of an FTL is also influenced by current practice and consideration of legal and economic factors (Dinges et al., 1996). FTL do not represent the best or most acceptable means for crew scheduling as they typically do not take into account time of day in relation to duty length[18], time zone changes, commuting, or behaviour outside of work (Gander, Hartley, et al., 2011; Green & Skinner, 1987). In addition, they may not consider delays, diversions or emergencies (Mohler, 1976). Although

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[17] Potential factors include rest periods before flight, acclimatization, time zones, night operations, maximum number of sectors, single pilot operations, two pilot operations, two pilots plus additional flight crew members, flight crew member qualifications, mixed duties, dead-head transport, reserve or standby period, flight duty period, inflight relief, type of operation, cumulative duty time, cumulative flight time, duty extension, circadian rhythm, days off and record keeping (Civil Aviation Authority of New Zealand, 2023).

[18] Time of day has recently been incorporated into FTL by some regulators; for example CAD 371 (Civil Aviation Department Hong Kong, 2013), Sub part Q of the EU-OPS 1 (Gander, Hartley, et al., 2011), 14 CFR 117.13 (National Archives and Records Administration, 2025) and CAO 48.1 (Civil Aviation Safety Authority, 2013).

recent sleep timing and duration has a greater influence on fatigue than either cumulative flight hours or the duration of recent flights, it is not likely to be accounted for in FTL (Neville et al., 1994).

FTL and labour agreements may create an illusion that fatigue risk has discrete boundaries (Romig & Klemets, 2009) whereas sleep science acknowledges that fatigue risk has a gradient function which is influenced by many factors. Reliance on FTL to reduce fatigue could be considered a function of convenience rather than science (Caldwell, 2012) as focus is placed on work hour limits rather than sleep and circadian factors. Efforts have been undertaken to incorporate scientific principles, guidelines and recommendations into FTL (Dinges et al., 1996; Moebus, 2008) however it is difficult (if not impossible) to design prescriptive rules which account for interactions between duty history, sleep timing and duration, circadian phase and workload. This illustrates that although a flight duty period may be legal, it does not mean that fatigue risk will remain at an acceptable level. It also illustrates why removal from duty, due to fatigue is such a critical fatigue risk mitigation because it acknowledges that FTL cannot account for all factors that contribute to fatigue risk.

Fatigue Risk Management Systems

An FRMS is based on the scientific understanding of the effects of sleep loss and recovery on performance and the influence of the circadian body clock on performance capacity (Signal et al., 2022). It is defined as “a data-driven means of continuously monitoring and managing fatigue-related safety risks, based upon scientific principles and knowledge as well as operational experience that aims to ensure relevant personnel are performing at adequate levels of alertness” (International Civil Aviation Organisation, 2015, p. xiii). Its central concepts are that functional capacity in humans is variable, and that some of that variability is predictable, if previous sleep timing and duration, and circadian phase is known, and that to maintain safety, systems are needed to monitor and mitigate fatigue related performance impairment and its consequences.

An FRMS represents a flexible alternative approach to FTL, and moves the focus of responsibility for safety from the regulator toward operators and individuals (Gander, Hartley, et al., 2011). It is attractive to operators because it may facilitate the ability to replace either part, or all of the existing FTL, if the FRMS provides a level of safety that is equivalent to, or better than that offered by the current FTL. This places an emphasis on the availability of data and a framework to integrate that data within the safety management system. For this reason, FRMS principles and processes have been adapted from SMS specifically for managing fatigue. For example, the four pillars of SMS have been adapted within an FRMS and include policy and documentation, fatigue risk management processes, safety assurance, and promotion (International Civil Aviation Organisation, 2015). The obvious difference being fatigue risk management versus safety risk management, and FRMS safety assurance versus (SMS) safety assurance. Within an FRMS, FRM processes and FRMS Safety Assurance Process are integrated and share common processes. Central to these two processes are fatigue monitoring data and safety performance indicators (SPI) that either identify potential safety hazards or provide a measure of the overall health of the FRMS. SPI may include operational measures that monitor duty related causes of fatigue, reactive measures such as fatigue report frequency or absenteeism, and proactive measures of pilot fatigue, sleep loss and performance that are collected during studies (Gander et al., 2014; International Civil Aviation Organisation, 2015). Criteria for the selection of SPI include scientific validation to confirm construct validity, i.e. that it measures what it claims to measure, that data collection associated with the measure does not interfere with the operation of the aircraft and that the measure is widely used by other operators to allow for meaningful comparison (Gander et al., 2014).

To identify and validate performance measures for use as SPI with an FRMS, Gander et al. (2017) have proposed the following comprehensive research approach which integrates experimental studies that focus on:

1) The effects of sleep restriction on performance and communication.

2) Simulation studies that investigate the impact of fatigued individuals on the performance of workplace teams.

3) Studies that identify causal links between fatigue related impairment of individuals or teams and embedded measures of workplace performance.

4) Thorough investigation and analysis of fatigue related incidents and accidents.

Gander’s comprehensive research approach illustrates how this thesis can contribute to the validation of embedded measures of pilot performance using simulated flight data. If the simulated flight data measures, within this thesis research are reliably associated with fatigue and sleep loss, this would offer an opportunity to routinely monitor these measures, within a FOQA programme. This also illustrates that this thesis research seeks to contribute to the development of SPI for use within a FRMS.

1.9 Rationale and Importance

Considerable research has been published on pilot fatigue, factors that disrupt sleep, and practices that promote good sleep (Gander, Rosekind, et al., 1998; Spencer & Robertson, 2007). However, further research is needed to understand causal links between pilot fatigue and safe aircraft operation. Fundamentally, this thesis research seeks to identify causal links between fatigue related impairment of individuals or teams and embedded measures of workplace performance. To investigate this, a within-subjects research design, in combination with a flight duty period protocol and simulated flight protocol was adopted to structure the collection of measures of fatigue, sleep loss and performance in participants. Although studies with similar research designs have been conducted in operational settings, the research design within this thesis research includes participants undertaking multiple simulated flights within a live operational environment. This could be considered challenging, from a logistics perspective, as the protocol will include subtle manipulation of the participants roster to include fatiguing characteristics and two simulated flights. The feasibility of conducting a within-subjects research design during a normal flight operation is unknown. It is therefore necessary to investigate the feasibility of such an undertaking.

If this thesis research were to identify that measures of fatigue and sleep loss are reliably associated with simulated flight data measures, future research could investigate if measures of fatigue and sleep loss are reliably associated with flight data measures. If future research were to confirm that specific flight data analysis events are significantly associated with measures of fatigue or sleep loss, those events could be routinely monitored as a safety performance indicator within a FRMS.

1.10 Study Aims

The overall aim of this thesis is to evaluate the feasibility of recording performance measures derived from simulated flight data analysis parameters, in combination with measures of fatigue within an operational setting and to determine if those performance measures are associated with fatigue or sleep loss. To achieve this, the following three research questions are addressed:

Question 1: What processes need to be in place to support the use of simulator flight data?

Question 2: How feasible is it to collect simulator flight data?

Question 3: Are fatigue related changes in simulator flight deck performance detectable using simulator flight data?

Specific study objectives and methodology, including secondary research questions can be found in Chapter 2.

1.11 Structure of this Thesis

This thesis, which is structured around a quantitative simulator study is presented as a monograph.

Chapter 2 outlines the study aims and research questions. It also provides a detailed description of the study design and methodology used.

Chapter 3 provides a detailed overview of the development of each simulated flight protocol (one for the Christchurch – Wellington simulated flight and the other for the Wellington – Christchurch simulated flight). Each protocol included specific flight scenarios that were comparable with scenarios in the other simulated flight protocol. Two trial simulated flights were undertaken to refine scenarios and results from a small group discussion involving flight crew from the second trial simulated flight are included. This chapter also provides a detailed overview of parameter validation during each trial simulated flight and an overview of logistical considerations.

Chapter 4 describes the variation in sleep timing and duration and subjective ratings of fatigue, sleepiness, sleep quality during the flight duty period protocol. In addition, workload associated with flight duty periods and simulated flights is considered. Analysis also focused on the influence of sleep related factors on ratings of fatigue, sleepiness, sleep quality and workload with results grouped by research question.

Chapter 5 presents findings from the analysis of PVT data collected before and following each simulated flight. Analysis focused on the influence of sleep related factors on PVT performance. The influence of condition (non-rested or rested), flight order (first or second simulated flight) and test timing (pre or post simulated flight) was investigated. In addition, the relationship between PVT performance and subjective ratings of fatigue and sleepiness was investigated.

Chapter 6 presents findings from the analysis of simulated flight data collected from simulated flights flown by participants and focuses on the influence of sleep related factors and subjective workload on flight crew performance during initial climb, go around, autopilot usage (status) and go around checklist completion accuracy. In addition, the influence of condition (non-rested or rested), flight order (first flight or second flight) and flight location (Christchurch – Wellington or Wellington – Christchurch) was investigated. In addition, the relationship between simulated flight data measures and subjective ratings of fatigue and sleepiness was investigated.

Chapter 7 brings together findings from chapters 3, 4, 5 and 6 and discusses these in detail. Emphasis is placed on the collective meaning of findings and their relationship to previous research. Because this study was undertaken within an operational environment, particular focus is placed on feasibility and relevance of study findings to regional airline operations. Finally, study limitations, recommendations and future research opportunities highlighted by this thesis research are discussed.

CHAPTER 2 METHODOLOGY

2.1 Overview

This chapter provides a detailed overview of the studies aims, study design and methodology.

2.2 Research Questions

Main Research Questions:

In a study that aims to determine if fatigue related changes in simulator flight deck performance are detectable during simulated flight:

- What processes need to be in place to support the use of simulator flight data?
- How feasible is it to collect simulator flight data?
- Are fatigue related changes in simulator flight deck performance detectable using simulator flight data?

Secondary Research Questions:

Flight Duty Period Protocol

- Do participants comply with the flight duty period protocol?

Simulated Flight Protocol

- Do participants comply with the simulated flight protocol?

Workload

- Do workload ratings differ between flight duty period flights and simulated flights?
- Do workload ratings differ between the non-rested and rested simulated flight?
- Do workload ratings differ between the first and second simulated flight?
- Do workload ratings differ between the Christchurch – Wellington and Wellington – Christchurch simulated flight?
- Are workload ratings associated with cumulative sleep debt, time since sleep, or total sleep time in the previous 24hr or 48hr period?

Sleep timing and duration

- Does sleep timing and duration differ between the non-rested and rested condition?
- Does time since sleep differ between the non-rested and rested condition?
- Does sleep timing and duration differ between non-baseline and baseline sleep periods?

Subjective ratings of fatigue and sleepiness

- Do subjective fatigue and sleepiness ratings, prior to and following main sleep periods, and subjective sleep quality ratings, following main sleep periods, differ between the non-rested and rested condition?
- Do subjective fatigue, sleepiness and sleep quality ratings differ between non-baseline and baseline sleep periods?
- Do subjective fatigue and sleepiness ratings across each simulated flight differ between the non-rested and rested condition?

- Are subjective ratings of fatigue and sleepiness across simulated flights associated with cumulative sleep debt, time since sleep or total sleep time?

Psychomotor Vigilance Task performance

- Does PVT performance differ between the non-rested and rested condition?
- Does PVT performance change across the simulated flights?
- Does PVT performance differ between the first and second simulated flight?
- Is PVT performance associated with sleep related variables?
- Is PVT performance associated with subjective ratings of fatigue and sleepiness?

Pilot Task performance

- Are simulated flight data measures different between the non-rested and rested condition?
- Are simulated flight data measures different between the first and second simulated flight?
- Are simulated flight data measures different between the Christchurch – Wellington and the Wellington Christchurch flight?
- Are simulated flight data measures associated with cumulative sleep debt, time since sleep and total sleep time?
- Are simulated flight data measures associated with subjective ratings of workload, fatigue or sleepiness?

2.3 Research Design

A within-subjects research design was selected as it reduces the number of participants required and accounts for error variance associated with individual differences (Bordens & Abbott, 2018, p. 323). A disadvantage of this design is the possibility of practice effects (carryover effects) influencing performance and masking the influence of other factors that influence performance. Tasks in each simulated flight were carefully considered to minimise the likelihood of practice effects. To test for the possible influence of practice effects, PVT test order and flight order were included as independent variables in statistical models.

2.4 Ethical Approval

Ethics notification SOA 16/64 – Evaluation of Simulated Flight Data Analysis Events as a Measure of Fatigue Risk in Operational Settings was approved by Massey University Human Ethics committee: Human Ethics Southern A Committee on 18th November 2016 (see APPENDIX A). The notification complied with the code of Ethical Conduct for Research, Teaching and Evaluations involving Human Participants (Massey University, 2014). Post approval, the notification was amended to facilitate data collection associated with trial simulated flights.

2.5 Participants and Recruitment

The study sought to recruit 16 participants. A total of 220 pilots received an invitation via an email from the operator's Pilot Training Manager. The email included a short description of the study with one follow-up email sent after 14 days. An advertisement was also uploaded to the operator's intranet (see APPENDIX B). Two pilots were excluded from participating as they had participated in a trial simulated flight which is described in Chapter 3. No compensation was provided to pilots for participation.

The number of available pilots during each 14 day roster period was estimated to be 40 pilots due to restrictions associated with pairing pilots together. These restrictions include a general requirement that flight crew have the same domicile and that pilots must not have any preassigned days[19] during the flight duty period protocol.

Pilots who showed interest in participation contacted the researcher and were provided with an information sheet (see APPENDIX C) and consent form (see APPENDIX D). On receiving a completed consent form, the researcher provided the pilot's name to the Crew Planner – Training to determine if pilots could be paired together. Information relating to nine pilots who showed an interest in participating, but were unable to participate (primarily due to pairing requirements) was discarded. Pairing details were then passed to the Crew Planner - Rostering who allocated each pair preassigned flight duty periods consistent with the flight duty period protocol. At this time, the researcher also contacted the participant to arrange a suitable time for a training phone call and to arrange for delivery of the study pack five days prior to the start of data collection. The purpose of the call was to reiterate study requirements and the use of equipment. The study pack contained an introductory letter, information sheet, actigraph, a sleep/duty diary and participant training manual/example sleep/duty diary.

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[19] Preassigned days include scheduled simulator details (training or proficiency details associated with the operators training programme); classroom work; annual leave and other planned events or situations.

Eight flight crew (16 participants) consisting of eight Captains and eight First Officers participated in the simulator study. Thirteen participants were domiciled in Christchurch, one in Wellington and two in Auckland. Pilots who participated in this study were not anonymous to the researcher and received no compensation for their participation.

2.6 Management of Fatigue Risk during the Flight Duty Period Protocol

At any point during the protocol, participants were encouraged to remove themselves from duty if they felt fatigued. This was reiterated both in writing and when discussing the protocol with participants. The participant study pack included a PowerPoint presentation containing a FRMS training module to ensure participants could make informed decisions regarding fatigue management during the flight duty period protocol.

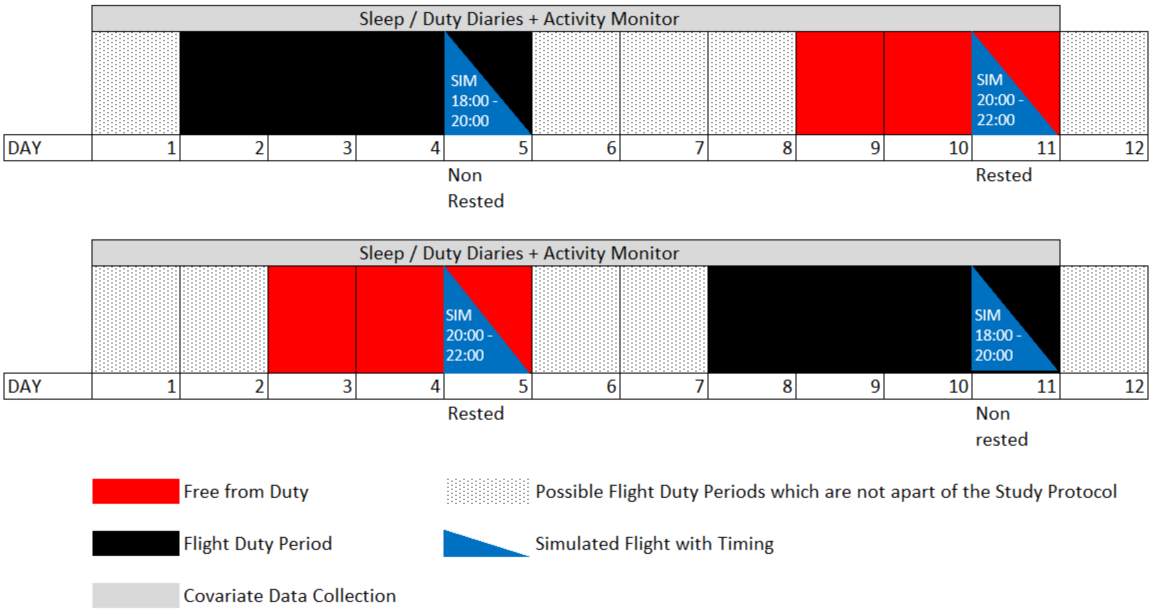
2.7 Flight Duty Period Protocol

This section describes the combination of flight duty periods, off days and simulated flights associated with the non-rested and rested condition that make up the flight duty period protocol. The protocol is outlined in Figure 2-1 and was developed with the following considerations:

- Compliance with all operational and occupational safety requirements.
- Compliance with rostering and scheduling rules.
- To increase the likelihood of participants' experiencing a cumulative sleep debt prior to the non-rested condition.

- To minimise the likelihood of participants' experiencing a cumulative sleep debt prior to the rested condition.
- To ensure that each simulated flight started at a similar time of day.
- To ensure that flight crew operated together, prior to the first simulated flight.
- To ensure that flight crew operated together during the non-rested condition and rested condition.
- To reduce the number of simulator slots required.
- To be able to account for possible effects associated with the order of each simulated flight.

Figure 2-1 Flight Duty Period Protocol



The 12 day protocol included two simulated flights which occurred on days 5 and 11. The order of the non-rested and rested conditions were counterbalanced with half of the participants completing the non-rested condition first. The non-rested condition included four consecutive flight duty periods with the non-rested simulated flight occurring during the latter part of the fourth flight duty period. If flying duties were included during days 0 and 1 (non-rested condition first) or days 6 and 7 (rested condition first), these duties did not include an early start on days 1 or 7. In addition, they did not include a late finish on days 0 and 1 or days 6 and 7. This was to allow for a local night's[20] rest between days 0 and 1 (non-rested condition first) and between days 6 and 7 (rested condition first). The rested condition consisted of two days free from duty, including three local nights rest, prior to the rested simulated flight. If flying duties were included during day 8 (non-rested condition first) or day 2 (rested condition first), these duties did not include a late finish. This was to allow for a local night's rest between days 8 and 9 (non-rested condition first) or between days 2 and 3 (rested condition first).

Flight crew operated flights together before their first simulated flight. Flight crew operated together during days 2 - 5 of the protocol (non-rested condition first) and flight crew operated together during days 1 and 2 of the protocol (rested condition first).

Prior to the non-rested simulated flight, participants not domiciled in the same city as the flight simulator either operated or deadheaded[21] to that city and prior to the rested simulated flight they positioned[22] to that city. To track all flights that occurred during a flight duty period, the flight duty period sector count included operating sectors, deadheading sectors and positioning sectors.

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[20] Local night is defined as a period of eight hours falling between 22:00 and 08:00 local time (Civil Aviation Authority of United Kingdom, 2004).

[21] Deadhead means the air transport of a pilot between one airport and another to position for work mid duty or to return to their domicile following duty.

[22] Position means the air transport of a pilot between one airport and another for the purposes of taking up or returning from flight duties.

Immediately following each simulated flight, they overnighted in a hotel then positioned to their home base the following day on flights departing late in the morning or early afternoon. This ensured that participants had an opportunity to recover from possible sleep loss associated with the timing and/or nature of the preceding flight duty period and/or the simulated flight. For participants domiciled in the city where the simulator was located, the day following each simulated flight was an off day.

The length of each simulated flight was around 70 minutes meaning that two simulated flights could be included within one four hour simulator session. This allowed the number of simulator sessions required to be reduced from 16 to eight.

In the event of flight duty period protocol violations, careful consideration was given to the impact of including or excluding participants. This decision was balanced against the need to have sufficient data. Given that participants operated as a flight crew, excluding one flight crew member would result in the exclusion of that flight crew. See section 4.6.2 which reports on minor flight duty period protocol violations and section 7.3.2 which discusses the impact of those minor violations.

2.8 Inhibited Rostering and Scheduling Rules

Although there was a desire to comply with all rostering and scheduling rules[23], the following rostering rules were not complied with:

- A soft rule[24] which prevents flight duty periods exceeding 09 hrs 40mins. Disabling this rule allowed an additional 1.33 hours of duty time during the last flight duty

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[23] Rostering and scheduling rules prescribe limits on maximum daily, monthly and yearly flight and duty hours, and require minimum breaks within and between duty periods.

[24] A soft rule is a non-contractual rule that influences the roster build process.

period in the non-rested condition so that participants could report for duty at 09:00 local time rather than at 10:20 local time. Participants were still limited to an 11 hour flight duty period.

- A rule that prevents more than five double overnights[25] within 12 roster periods. The double overnight within the protocol was not included in the maximum of five double overnights within 12 roster periods meaning that participants could have a maximum of six double overnights (rather than 5) within 12 roster periods.
- A rule which prevents pilots from being rostered a combination of simulator and aircraft flying within a single duty period. Disabling this rule allowed the simulated flight to occur following aircraft flying at the end of the non-rested flight duty period.
- A rule that ensures pilots are rostered 16 hrs free from duty prior to a flight duty period that includes a simulated flight. Disabling this rule allowed the simulated flight to occur within the non-rested flight duty period.
- A rule that prevents more than two consecutive overnights from being rostered. Agreement was sought from one participant that they would be rostered on four consecutive overnights to allow them to be paired with a participant from another domicile.
- A rule that ensures that each simulator session includes a 90-min pre- briefing and 60-min post briefing. Disabling this rule allowed participants to arrive 45 minutes prior to the simulated flight and depart immediately following completion of the post simulated flight PVT test.

All participants, both pilot unions and the operator were aware that the rules mentioned above would be disabled for the purposes of the study only.

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[25] A double overnight represents two nights away from home base.

2.9 Flight Duty Period Characteristics

Flight duty periods included within the flight duty period protocol were typical of normal flight duty periods with normal rest and duty restrictions applied. The only differences were that flight crew operated together for the entire roster period (14 days)[26] and that one flight duty period included both revenue flights and a simulated flight. Participants were allocated flight duty periods as duty pre assignments by the Crew Planner – Rostering. To increase the likelihood that the non-rested condition would include fatiguing characteristics, the Crew Planner – Rostering was asked to schedule roster duties that started at or before 07:00 and include three or more flights. If this was not possible, flight duty period length should be greater than 09 hrs 40 minutes and the flight duty period should include four or more flights. In addition, the flight duty period which included the non-rested simulated flight should start at or following 09:00 local time and include two or more flights before the non-rested simulated flight.

These guidelines ensured study flight duty periods were likely to have fatiguing characteristics which included either restricted sleep caused by short rest periods and early report times or long duties that included flying multiple sectors, both of which are considered as the main causes of fatigue in day time short haul two pilot flight operations (Gander, Rosekind, et al., 1998).

Flight duty periods differed from one day to the next and from one flight crew pair to the next for the following reasons:

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[26] It would be highly unusual for two pilots to operate together during an entire 14 day roster period.

Flight Schedule: Flights that occurred during the week may not have occurred during the weekend. For example, there were not many pre 08:00 flights departing from Wellington during the weekend, whereas there were during the week.

Flight length: Flight duty periods that included different destinations but have the same number of flights will likely have had different flight lengths. For example, a flight between Nelson and Christchurch was 55 minutes whereas a flight between Nelson and Wellington was 35 minutes.

Home Base: A pilot's home base influences the timing, frequency and/or duration of flights when compared to pilots from a different home base.

Availability of suitable, unallocated flights: The amount of time available to construct flight duty periods was dependent on the amount of time available between participant recruitment and roster publication. A longer time period ensures that more unallocated flights was available to construct suitable flight duty periods.

Workforce / resource levels: Variation in the total number of pilots available during a roster period would contribute to variation in the number of flights operated by pilots during that roster period.

Overnights: Some destinations may have a smaller number of flights, with flights occurring predominantly at the start and end of each day. A flight crew who were rostered an overnight at that destination, may have operated the last flight into that destination, then operated the first flight out of that destination the following morning.

Flight Cancellation: If a flight was cancelled, it may not be possible to replicate the flight duty period in its planned / original form.

Extended duty: A duty may need to be extended if a flight was delayed due to mechanical problems, adverse weather or other unforeseen causes.

Absenteeism: Pilot withdrawal from duty due to sickness or fatigue may have occurred either prior to or during the duty itself. If this did occur, it may not be possible to replicate a flight duty period in its planned / original form.

The above factors illustrate that it would be unrealistic to expect that all participants would have had identical flight duty periods during days 2 - 5 or days 8 - 11 of the non-rested flight duty period protocol. Focus was therefore placed on ensuring that flight duty periods shared similar characteristics, and that guidance provided to the Crew Planning Manager and Crew Planner - Rostering was consistent throughout the data collection period.

2.10 Simulated Flight Protocol

This section provides a description of software that was used to analyse and visualise simulated flight data, it also outlines the make and model of the flight simulator and describes factors that influenced simulated flight timing.

Information about the simulated flight protocol, including an outline of its development, requirements, characteristics and the role of the simulator instructor is described within Chapter 3.

2.10.1 Simulator Operations Quality Assurance (SOQA) Software

Insight Flight Data Monitoring, Insight Analysis and Insight Animation (CAE Flightscape Inc., Ottawa, Canada) were installed on the researcher's computer which allowed configuration of Insight Flight Data Monitoring software to detect simulator flight protocol events during analysis of flight data. This also ensured absolute privacy of recorded flight data.

Insight Flight Data Monitoring

Insight Flight Data Monitoring (Insight FDM) (version 4, Service Pack 5) was used to replay, analyse and display simulated flight data and customise events. Insight FDM includes a fully configurable search engine that populates a secure, transactional database for long term trending, analysis and management of results.

Insight Analysis

Insight Analysis (version 4, Service Pack 5) allows parameters to be viewed in either table or plot windows. It has extensive interactive plotting and data analysis features for studying flight data and can perform a variety of functions including data smoothing, interpolation, differentiation, integration, unit conversions and flight path generations which provides the capability to derive additional parameters.

Some required parameters, depicted on video recordings of the Primary Flight Display, Multifunction Display and Engine Warning Display were not recorded.

These parameters were loaded into Insight Analysis using the data exchange function.

Insight Animation

Insight Animation (version 4 Service Pack 5) is an advanced tool for 3D flight animation which animates aircraft flight. It provides visual context and clarity that flight data in the form of plots or tables cannot. It can display aircraft, high resolution terrain and flight deck instrumentation and incorporates flight related information from multiple sources within one template. The flight path editor function allows the aircraft flight path to be recreated using various data sources. The default animation layout included a 3D flight animation of the aircraft, video files of instrumentation and panels, derived from recorded flight data. Panels were included for flight control inputs, engine controls, flap and gear position and pilot selections on the flight guidance and control panel. Like Insight analysis, Insight animation was used to validate recorded parameters and validate simulated flight data protocol scenarios.

The Flight Simulator

A CAE 7000 series full flight simulator[27] manufactured by CAE Inc., Ottawa, Canada was used to simulate flights for this research. Figure 2-2 shows an internal view of the flight simulator. The computer screen within the red box was used by the simulator instructor to manage the simulated flight protocol.

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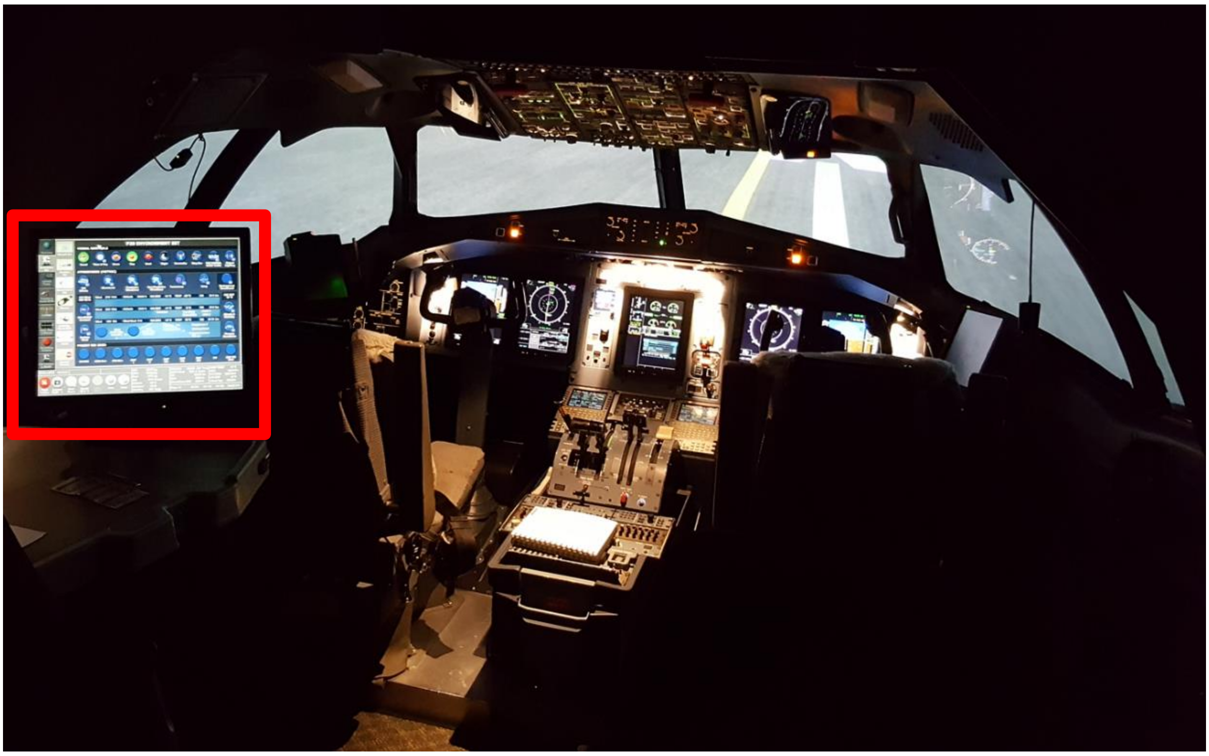
[27] A replica of a specific type, make, model, or series of aircraft. It includes the equipment and computer programs necessary to represent aircraft operations in ground and flight conditions, a visual system providing an out-of-the-flight deck view, a system that provides cues at least equivalent to those of a three-degree-of-freedom motion system and has the full range of capabilities of the systems installed in the aircraft.

Figure 2-2 Flight Simulator Internal View



2.10.2 Timing of Simulated Flights

The following flight duty period protocol considerations were applicable to the timing of simulated flights.

- Compliance with rostering and scheduling rules.
- Assurance that each simulated flight starts at a similar time of day.
- To reduce the number of simulator sessions required.
- Creation of conditions that lead to a mild cumulative sleep debt prior to the non-rested simulated flight and minimisation of cumulative sleep debt prior to the rested condition.

Suitable simulator slots were limited to either S4 (14:00 – 18:00) or S5 (18:00 – 22:00). Simulator slot S5 (18:00 – 22:00) was selected to reduce the likelihood that disruption to the flight schedule (e.g., flight delays) would result in cancellation of a simulated flight. The non-rested simulated flight was scheduled between 18:00 and 20:00 and the rested simulated flight scheduled between 20:00 and 22:00.

2.11 Measures

2.11.1 Monitoring Sleep

Polysomnography (PSG) is recognised as the gold standard for monitoring waking alertness and the structure of sleep and sleep quality (Gander et al., 2017). To measure these variables, it monitors three types of electrical activity: brainwave activity (EEG), eye movements (EOG) and muscle tone (EMG). However, in field studies involving flight crew, it is intrusive, time consuming to set up, expensive and fragile (International Civil Aviation Organisation, 2015)[28]. Although there are situations where detailed information from polysomnography is needed, (e.g., for the validation of the first commercial passenger ultra long-haul flights (Signal et al., 2013), it is unlikely to be suitable for field studies that monitoring sleep patterns across multiple days due to the weaknesses mention above.

2.11.1.1 Actigraphy

Actigraphy has been used extensively in different groups (Ancoli-Israel et al., 2003) including pilots (Gander et al., 2014; Gander et al., 2013; Lowden & Åkerstedt, 1999; Signal et al., 2005; Signal et al., 2024; Vejvoda et al., 2014) and is a recommended measure for monitoring flight crew fatigue (Signal et al., 2022) and is currently the most practical and reliable way to identify if pilots accumulate a sleep debt during multi-day flight duty periods (International Civil Aviation Organisation, 2015).

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[28] Each 30 second recording period needs to be manually scored with a second individual required to double score a percentage of recordings to check for reliability between the two technicians.

Signal et al. (2005) compared actigraphy and polysomnographic recordings in pilots. They found that for both hotel and inflight rest, average sleep durations recorded by actigraphy were similar to average sleep durations recorded by polysomnography. The identified that actigraphy may overestimate or underestimate an individual's polysomnographic sleep duration by more than one hour. The also found that it was not possible to correct estimates of polysomnographic sleep duration using a simple correction factor as actigraphy did not over or underestimate sleep in a systematic manner.

An actigraph is a small device worn on the non-dominant wrist, is unobtrusive and inexpensive compared with polysomnography. It contains an accelerometer for recording movement, typically in one minute epochs. In addition, some models include a light sensor for recording light exposure, and a thermometer that records case temperature to determine when the actigraph is off wrist. Sleep and wake are estimated with a computer-based validated scoring algorithm. The main limitation of actigraphy is that it cannot distinguish between an individual who is asleep and an individual who is awake but not moving. This reduces the reliability of an actigraph to estimate sleep efficiency[29] and sleep latency[30] (Ancoli-Israel et al., 2003).

In this research, the AMI Micro Motion Logger actigraph (Ambulatory Monitoring Inc., Ardsley, New York, USA) was used (Figure 2-3). The actigraph was programmed to record activity, light, and case temperature in one minute epochs and display New Zealand local time to assist participants with the recording of bed and rise times in their sleep/duty diary. Participants were asked to press a button

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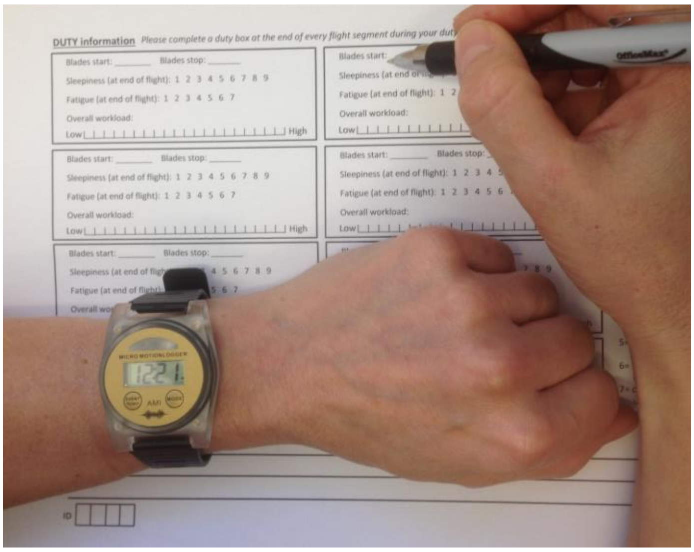
[29] Sleep efficiency represents the percentage of actual sleep obtained during a main sleep period.
[30] Sleep latency represents the time taken to fall asleep.

("event marker") on the actigraph when they started trying to sleep and when they stopped trying to sleep. Actigraphy data, in conjunction with information from the participant's sleep/duty diary, was scored to determine rest interval start and end times and analysed in ActionW2.7 (Ambulatory Monitoring Inc., Ardsley, New York, USA) using a validated scoring algorithm (UCSD scoring algorithm[31]) that estimated, for each epoch, if the participant was awake or asleep (Ancoli-Israel et al., 2003; Jean-Louis et al., 2001).

Figure 2-3 AMI Micromotion Logger



2.11.2 Measuring Sleepiness, Fatigue, and Sleep Quality

The Samn-Perelli Crew Status Check and the Karolinska Sleepiness Scale are recommended for monitoring subjective fatigue and sleepiness in pilots (International Civil Aviation Organisation, 2015) due to their ease of use, ability to be completed at multiple time points, validity, and because they are predictive of objective performance measures (Kaida et al., 2006) and are used widely in

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[31] Each one minute epoch is scored as either sleep or wake. To be identified as a wake epoch, the activity count, plus weighted contributions from surrounding data must exceed a pre-set sensitivity value. The UCSD sleep estimation was used which computes a weighted sum of the activity in the current minute, the preceding four minutes and the following two minutes (Jean-Louis et al., 2001).

commercial aviation. Both scales and the Sleep Quality scale have been used in similar studies which investigate pilot fatigue, sleepiness and sleep quality (Gander et al., 2013; Signal et al., 2013; Signal et al., 2024; van den Berg et al., 2023). A limitation of subjective ratings of fatigue is that they can be skewed by non-fatigue related factors, e.g. concerns regarding job security or over confidence in personal ability (Balkin, 2022). In addition, a response to a subjective question will likely be based on idiosyncratic physical and emotional sensation which may differ from an objective response (Engle-Friedman, 2014).

During the flight duty period protocol, participants were asked to complete, for each sleep period longer than 10 minutes, subjective ratings of fatigue and sleepiness before and after each sleep period and rate their sleep quality after each sleep period. During flight duty periods, participants were asked to complete subjective ratings of fatigue and sleepiness at the start and finish of each flight duty period. During each simulated flight, participants were asked to complete subjective ratings of fatigue and sleepiness before and following each simulated flight.

2.11.2.1 Samn-Perelli Crew Status Check

The Samn-Perelli Crew Status Check is a subjective rating of fatigue. Participants were asked to indicate their level of fatigue, right now, on a 7-point Likert-type scale with verbal labels at each point. These include: 1 (fully alert, wide awake), 2 (very lively, responsive but not at peak), 3 (okay, somewhat fresh), 4 (a little tired, less than fresh), 5 (moderately tired, let down), 6 (extremely tired, very difficult to concentrate), 7 (completely exhausted, unable to function effectively) (Samn & Perelli, 1982). A value of five or greater suggests that although a flight is permissible, it is not recommended (Powell et al., 2007; Samn & Perelli, 1982).

2.11.2.2 Karolinska Sleepiness Scale

The Karolinska Sleepiness Scale is a subjective rating of sleepiness. Participants were asked to indicate how sleepy they feel right now on a 9-point Likert type scale with verbal labels at the following points. These include: 1 (extremely alert), 3 (alert), 5 (neither sleepy nor alert), 7 (sleepy, but no difficulty remaining awake) and 9 (extremely sleepy, fighting sleep) (Akerstedt & Gillberg, 1990). A value of seven and above is associated with the occurrence of very short periods of uncontrolled sleep (Akerstedt & Gillberg, 1990).

2.11.2.3 Sleep Quality

Sleep quality was indicated by a range of values on a scale from 1 (extremely good) to 7 (extremely poor). Previous airline studies have incorporated this scale to evaluate pilots' perceived sleep quality in flight and layover (Signal et al., 2014).

2.11.3 Measuring Performance

2.11.3.1 Psychomotor Vigilance Task

The Psychomotor Vigilance Task (PVT) assesses an individual's reaction time and their ability to sustain attention by measuring how long it takes them to respond to a stimulus during repeated reaction time trials over a 10 minute period (Dinges & Powell, 1985). No choices are made when responding to stimuli. It is particularly sensitive to sleep loss and has been validated as an additive measure of sustained attention (Balkin et al., 2004). However, results are only generalisable to tasks requiring sustained attention or vigilance (Petrilli et al., 2006). Although PVT performance is not a predictor of real-world performance (Dorrian et al., 2005), executive functions likely rely on working memory capacity (Goel et al., 2009) which is, in turn, partially reliant on alertness, attention and psychomotor vigilance

(Killgore & Weber, 2014). In real-world tasks that require attention and timely response, the PVT is well suited "because it taps the ability to sustain attention and respond quickly to salient signals, features of a great many real-world tasks" (Dorrian et al., 2005, p. 59).

The PVT is considered a "gold standard" for measuring fatigue related performance impairment in aviation studies (Lopez et al., 2012) because it is easy to administer, with shorter, three minute and five minute test durations available in addition to the original 10 minute version (Basner & Dinges, 2011; Dinges & Powell, 1985; Roach et al., 2006). It has virtually no learning curve and has been validated as being sensitive to the effects of fatigue due to circadian influences, sleep deprivation and sleep restriction and is recommended by the International Civil Aviation Organisation as a standard measure for use within a FRMS (Gander et al., 2013; International Civil Aviation Organisation, 2015; Vetter et al., 2012). PVT performance has been shown to correlate with simulator pilot performance under different levels of fatigue (Lopez et al., 2012).

In this research, a validated 10 minute version of the PVT test was undertaken on a PVT-192 (Figure 2-4) which was designed and built by Ambulatory Monitoring Inc. During a PVT test, stimuli were presented approximately 10 times per minute with intervals between stimuli varying between two and 10 seconds in two second increments. Participants monitored an LED timer display on the PVT and pressed the response button with their preferred thumb as quickly as possible after the stimulus was presented. In response to the participant's button press, the response time was displayed for 0.5 seconds, providing trial by trial performance feedback (Belenky et al., 2003). Feedback, such as this may contribute to the application of compensatory effort which could contribute to a masking of performance impairment as a result of additional effort to maintain performance by performing normally (Wilkinson, 1961).

Figure 2-4 The PVT-192 Device

Three commonly reported performance metrics from the PVT test were used in this research:

- Response speed (1/reaction time x 1000).
- The fastest 10% of responses (1/reaction time x 1000).
- The slowest 10% of responses (1/reaction time x 1000).

Optimum performance is reflected in the fastest 10% of responses, an overall slowing in responses is reflected in the PVT response speed and an increasing number of slower responses is reflected in the slowest 10% of responses. The reciprocal of average response latency (1/reaction time x 1000) was applied to PVT performance metrics to reduce the influence of delayed responses and emphasise small changes in faster responses (Basner & Dinges, 2011). Mean and median reaction time performance metrics were not included as these outcomes are prone to bias from extreme observations (Basner & Dinges, 2011).

Participants completed a PVT test immediately before and following each simulated flight in the respective simulator briefing room. The rooms were quiet, brightly lit and were free from distractions. Participants were instructed to hold the PVT with both hands and to respond to stimuli with their preferred thumb consistently in all tests. This was reiterated to participants during the training phone call prior to the start of data collection and prior to each test.

2.11.3.2 Simulated Flight Data Measures

In this research, focus was placed on identifying key points of interest during simulated flights. These included snapshots associated with autopilot status and specific checklist items, time stamps associated with the start and end time of the initial climb and go around scenarios and values associated with the validation of parameters associated with simulated flight protocol scenarios. To achieve this, simulated flight data was analysed against customised events that were either system defined or developed by the researcher (see APPENDIX E for a list of customised events developed by the researcher). The following sections describe the simulated flight data measures incorporated within this thesis research.

Initial climb and go around

For both the initial climb[32] and go around[33] scenario, customised events were used to identify snapshot time stamps associated with the start and end point of each scenario. These time stamps were then used to define the start and end point for datasets that contained continuously recorded parameters including airspeed, commanded airspeed, pitch, pitch order, roll, roll order, autopilot status, flap selection, flap position and altitude above aerodrome level. Additional parameters were included within these datasets to allow values to be filtered and to provide context when interpreting results, see APPENDIX F.

The start point for each dataset was 300ft and the end point was 750ft. The start point is dependent on the go around instruction[34] and the end point of 750ft was selected to minimise the likelihood that the autopilot would be engaged[35] or flap retracted[36]. Flap retraction may result in the aircraft momentarily levelling off on reaching acceleration altitude which could result in airspeed and pitch changes. This could contribute to additional variation in those datasets that include flap retraction. Given that not all datasets would include flap retraction, values were excluded from the dataset once flap was selected up below 750ft. During initial climb there were 10 data sets from five flights (31% of flights) where flap was

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[32] Initial climb is a flight phase which occurs immediately following liftoff until the aircraft gear and flap has been retracted. Take off performance calculations suggest a minimum flap retraction altitude of 459ft for WLG16 and 459ft for CHC02.

[33] A go around is a rare but normal flight manoeuvre which requires manual flying skills. It can occur for operational or weather related reasons. A go around can be unexpected. Pilots practice the go around procedure in the flight simulator during training and proficiency details and prepare for a go around by briefing the procedure prior to each approach during each flight flown.

[34] A go around instruction was issued to pilots at 300ft. All aircraft that completed a go around descended slightly below 300ft prior to initiating the go around procedure. This is expected.

[35] During initial climb, the first instance where the autopilot was engaged was at 798ft and during go around, the first instance where the autopilot was engaged was at 752ft.

[36] During initial climb, the first instance where flap was retracted was at 684ft and during go around, the first instance where flap was retracted was at 1450ft.

retracted below 750ft[37]. In addition, values were excluded from the dataset once the autopilot was engaged as initial climb and go around performance measures represented a measure of pilot performance, rather than autopilot performance.

To account for events that occurred during the climb, and to understand how performance changes across the climb, the decision was made to analyse data in 50ft altitude bins. Without this variable, each initial climb and go around measure would include one standard deviation value between 300ft and 750ft, whereas by including this variable, each measure would include nine standard deviation values.

As an aircraft climbs, its rate of climb increases resulting in a reduced number of parameter values per 50ft altitude bin (see APPENDIX G for a count of values within each 50ft altitude bin). Consideration was given to a time bin (e.g., 10 second bins) or a distance bin (e.g., 1 nautical mile bins) however these were considered less meaningful than height based bins.

Initial climb and go around datasets were produced within Insight Analysis then exported as a comma separated value (.csv) dataset. These datasets were loaded into Microsoft Power BI (Microsoft Power BI 2023, Version 2.116.884.0). The Microsoft Power BI group function generated 50ft altitude bins from the recorded parameter Height Above Airfield. Standard deviations were calculated for absolute airspeed delta, absolute pitch delta and absolute roll delta within each 50ft altitude bin. APPENDIX G shows the number of parameter values within each 50ft altitude bin that were used to calculate each respective standard deviation.

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[37] On these flights, flap was selected up at 684ft, 698ft, 718ft, 730ft and 733ft.

Initial climb and go around measures

- Standard deviation of the difference between actual airspeed and commanded airspeed during initial climb.
- Standard deviation of the difference between actual pitch and commanded pitch during initial climb.
- Standard deviation of the difference between actual roll and commanded roll during initial climb.
- Standard deviation of the difference between actual airspeed and commanded airspeed during go around.
- Standard deviation of the difference between actual pitch and commanded pitch during go around.
- Standard deviation of the difference between actual roll and commanded roll during go around.

Autopilot Status

Customised events were used to identify the respective altitude above aerodrome level for autopilot engagement following take off, autopilot engagement following go around and autopilot disconnection prior to landing. In addition, customised events identified the time taken to re-engage autopilot following an un-commanded disconnect and the percentage of autopilot engagement during the flight (all of flight measurement).

Autopilot Status Measures

- Autopilot engagement altitude during initial climb.
- Autopilot engagement altitude following go around.
- Autopilot disconnect altitude prior to landing.
- Time to re-engage autopilot following an un-commanded disconnect (secs).
- Autopilot engagement duration during flight (percentage).

Go around checklist

The operator's go around checklist is included in APPENDIX H. The checklist separates the go around procedure into chronological events, which includes: initiating go around, positive rate of climb, flaps 15 indicated, gear retracted, acceleration altitude, accelerate to the flap retraction speed bug, flap 0 indicated and > 1000ft. Each event may have multiple groups of actions (e.g., initiating go around includes two groups) and each group may have one or multiple actions (e.g., group 1). Within each group, individual actions are outlined for both the pilot flying and pilot monitoring. Go around checklist events, groups and actions are outlined in APPENDIX I.

An action may include an announcement, a check, a verification, a selection, or a manipulation (e.g., manipulating the flight controls). Simulated flight data cannot determine when a pilot makes an announcement or if a pilot checks or verifies that a selection or manipulation was undertaken. For example, although it was not possible to know when the pilot flying said, “going around”, it was possible to observe an outcome because of the announcement, e.g., the power lever go around button has been pushed, the aircraft is rotating to go around pitch attitude and that both power levers are advancing to the RAMP[38]. Likewise, although it was not possible to know if a check or verification was made, e.g., when the pilot monitoring checked that go around [39] was displayed on the flight management annunciator (FMA), it was possible to see when go around was first displayed on the FMA.

Time taken to complete the go around/missed approach procedure was measured in seconds and represents the duration between go around initiation and completion of the checklist. Go around is initiated by a) pushing the power lever go around button, b) rotating to go around pitch attitude on the flight director or c) setting both power levers to the RAMP position. Time taken to initiate go around is determined by subtracting the time stamp associated with the first instance of a, b or c from the last instance of a, b or c.

The go around checklist has nine group sequences and 10 action sequences. Groups one, four, nine and 10 do not include action sequences because there is only one action (groups nine and 10) or because action order is not applicable (groups one and four). Customised events were used to determine time stamps that were used to identify the start and end of each go around checklist group (event group) and the completion of individual actions within each group (see APPENDIX J).

Go around checklist measures focused on a count of correct group sequences and correct action sequences. For a sequence to be correct, the first group or action must be completed before the second group or action starts. Where actions need to be completed simultaneously, the grouped action is not considered complete until all

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[38] During go around, the power levers are physically moved by the pilot flying to the RAMP threshold to ensure that engine torque agrees with the reserve take off rating torque calculated by the flight data acquisition unit.

[39] GA (go around) is an annunciation on the primary flight display which indicates that go around mode is engaged. Go around mode cancels all armed and active flight director modes (Avions de Transport Regional, 2014).

individual actions have been completed. If a group or action was completed out of sequence, it was considered incorrect and was included as an incorrect group sequence.

Go around checklist measures

- Time taken to complete the go around/missed approach procedure.
- Time taken to complete go around initiation.
- Correct group sequences (count).
- Incorrect group sequences (count).
- Correct group sequences (percentage).
- Incorrect group sequences (percentage).
- Correct action sequences (count).
- Incorrect action sequences (count).
- Correct action sequences (percentage).
- Incorrect action sequences (percentage).

2.11.4 Measuring Workload

Workload varies depending on the phase of flight, for example high periods of workload may include preflight, take off and landing whereas low periods of workload may include flight during the cruise (Hart & Hauser, 1987). Flying can, at times, place great cognitive demands on pilots which can lead to errors (Wilson, 2002). At other points during flight, low levels of workload can result in inattention and boredom which can also lead to errors (Dismukes, 2009; Kantowitz & Casper, 1988). Subjective measures of workload are extremely useful in many situations and seem to be the most used technique due to their practicality and validity

(Svensson et al., 1997). There are a range of subjective tools for measuring workload which include the NASA Task Load Index (Hill et al., 1992).

NASA Task Load Index

The NASA Task Load Index (NASA-TLX) was originally developed for use in flight crew (Hart & Staveland, 1988) and has been widely adopted in aviation settings to assess the influence of workload on fatigue in pilots (Liu & Lee, 2003; Vejvoda et al., 2014).

To assess subjective workload, the NASA-TLX includes six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Each dimension includes a 21-point bipolar scale representing 20 intervals which are bound by “low” to “high” except for the performance dimension which is bound by “good” to “poor”. Participants were instructed to mark an “x” on each scale that best indicates their rating for each dimension following each flight duty period and immediately following each simulated flight. Each of the 20 intervals represents a 5 unit increment, meaning each dimension has a possible value of between 0 to 100. For marks placed between points, the value is rounded up to the right hand point. An overall workload index is obtained by adding scores from each dimension then dividing the value by six. If one or more dimensions have a missing rating, an overall workload cannot be calculated. The NASA-TLX includes a weighting component, to account for individual differences in the subjective experience of a task, but it is commonly excluded to reduce participant burden and simplify data entry (Hart, 2006). The modified index is referred to as the raw task load index (NASA-RTLX) and has been shown to be more sensitive, less sensitive or equally sensitive to the original NASA-TLX (Byers et al., 1989; Moroney et al., 1992). For this thesis research, the NASA-RTLX was selected to reduce overall burden on participants and to simplify data entry. Participants were asked to complete the NASA-RTLX, included in the sleep/duty diary, as the end of each flight duty period, and following simulated flights (see APPENDIX K).

2.11.5 Pre-Study Questionnaire

On receiving their sleep/duty diary, participants were asked to complete a pre-study questionnaire which was included within the sleep/duty diary (see APPENDIX K). The intent of the questionnaire was to record demographic information, their experience as pilots and their awareness of fatigue (attendance at training programmes or refreshers). In addition, the questionnaire recorded information relating to the timing, duration and efficacy of a participant's sleep when away from work, and the incidence of daytime napping. Participants were also asked if they had problems with sleep.

2.11.6 Sleep/Duty Diary

The sleep/duty diary was completed by participants during each day of the flight duty period protocol. It was modelled on sleep/duty diaries used in previous aviation studies at the Sleep/Wake Research Centre (Gander et al., 2013; Signal et al., 2013; Signal et al., 2024; van den Berg et al., 2023). The diary included instructions, the pre-study questionnaire, and a look back log where participants recorded flight duty period details for the seven day period prior to the start of data collection. It also included pages for sleep wake diary entries, flight duty period entries and pages relating to each simulated flight, including ratings of fatigue, sleepiness and workload. The sleep/duty diary is included in APPENDIX K.

As the first simulated flight was counterbalanced with half of the participants completing the non-rested simulated flight first, each participant received a sleep and duty diary that reflected their 12 day flight duty period protocol.

2.12 Procedure

Seven flight crew completed data collection within an eight week period between January and February 2019. One flight crew completed their non-rested simulated flight in February 2019 and their rested simulated flight in May 2019[40]. The timing of participants' circadian body clock cycle was not tracked and therefore, it is uncertain if they were acclimatised[41] to New Zealand local time. It is likely that they would be, as the flight simulator was in New Zealand and participants were domiciled in either Auckland, Wellington or Christchurch. Participants did not operate aircraft across multiple time zones or between the hours of 22:00 and 05:00, i.e. back of the clock night flights.

At least five days prior to the start of data collection, participants were sent a study pack. It included a cover letter, information sheet, consent form, confidentiality agreement, actigraph, participant training manual and a sleep/duty diary. A printed FRMS training module, as presented during pilot crew resource management recurrent training, was also included. A training phone call was provided by the researcher to each participant before data collection started. The call included an overview of the studies aims, confidentiality requirements, participant rights,

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[40] A fault with the simulator occurred prior to take off. Time taken to resolve the simulator fault resulted in this simulated flight being rescheduled. Due to simulator availability, this did not occur until May 2019.

[41] A person is acclimatised when their circadian body clock cycle is fully adapted to the local day/night cycle. Desynchronisation between the circadian body clock cycle and the day/night cycle occurs when there is a rapid shift in the day/night cycle caused by trans meridian flight (International Civil Aviation Organisation, 2015).

confirmation of study pack contents, a review of fatigue countermeasures and instructions for completing the sleep/duty diary, completing the PVT and wearing the actigraph. A copy of the training presentation was included within the study pack. The sleep/duty diary also included instructions for correct entry of values. The following points were clarified during the training phone call:

- Participants were instructed to start wearing the actigraph immediately.
- In the event of a safety related incident participants were told that they had the choice of not returning data to the researcher.
- Participants were asked to not drop or swap any flight duty periods associated with the flight duty period protocol.
- Participants were told that the Operations Centre had been instructed to protect the flight duty period protocol from changes during the live roster.
- Participants were instructed to notify the researcher immediately if changes to their roster occurred during the data collection.
- Participants were instructed to manage fatigue as they normally would during the roster period.
- Participants were asked if they were left or right handed to allow the PVT console to be configured.

For each day during the 11-day flight duty period protocol, participants were in structed to complete sleep/duty diary. For each of the four days prior to the non-rested simulated flight, participants completed flight duty period diary entries. On days which included a simulated flight, participants were instructed to meet the researcher and simulator instructor at the pre-flight briefing room 45mins prior to the start of their simulated flight. The researcher collected the participant’s signed confidentiality form and verbally confirmed that participants understood the study's confidentiality requirements. A short briefing was provided in the pre-flight briefing room to reemphasise the importance of operational realism with participants being encouraged to treat the simulated flight as a normal flight. To ensure consistent performance evaluation at both crew positions, participants were told that the captain would perform pilot flying duties and the First Officer, pilot monitoring duties. No additional details about the simulated flight were provided. Participants then undertook the pre simulated flight PVT and then completed the simulator page in their sleep/duty diary. Participants were given flight planning documentation and allocated 30 minutes to complete pre simulated flight planning. Participants entered the flight simulator at either 18:00 (non-rested simulated flight) or 20:00 (rested simulated flight) and immediately proceeded with flightdeck preparation checks. Recording of simulated flight data was initiated by the simulator instructor at engine start and the researcher confirmed that flight data was being acquired by the base station. Recording of simulated flight data was stopped when engines were shut down following flight. After landing, roughly 75 minutes later, participants then went to the postflight briefing room to undertake their post simulated flight PVT test and complete the remainder of the simulator page in their sleep/duty diary. While completing the PVT test, the simulator instructor booked a taxi to take participants to their hotel or the car park. For fatigue mitigation purposes, participants domiciled in Auckland had the option of taking a taxi following each simulated flight. Following the second simulated flight, participants provided the researcher with their completed sleep/duty diary, actigraph and all other applicable study material.

2.13 Data Management and Analysis

Sleep/duty diaries, actigraphy records and flight data were labelled with a unique identification number assigned by the researcher, and all data was stored in a de-identified format. At the completion of data collection, all retained data was copied onto the researcher's personal computer. Copies of these files were backed up on solid state media and stored alongside questionnaires and consent forms in a lockable cabinet at the Sleep/Wake Research Centre. Datasets that included fatigue, sleepiness, sleep quality and sleep related variables were grouped by day to facilitate day-to-day analysis which are described in Section 4.3.2.

2.13.1 Pre-Study Questionnaire and Sleep/Duty Diary

A staff member at the Sleep/Wake Research Centre entered data from sleep/ duty diaries into an MS Access database (Microsoft Access for Microsoft 365 MSO). All diary entries were cross checked by the researcher and entries rectified where necessary. Stat Transfer 14 (2015, Circle Systems, Seattle, WA, USA) was used to control the format of selected output parameters by converting MS Access data tables for use in SPSS (version 26.0, IBM SPSS Statistics for Windows, Armonk, NY, USA). Mean workload scores were calculated in SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA) by adding each of the six subscales then averaging the total score to generate a single overall workload score (Hart, 2006).

Table 2-1 shows the rate of missing data for ratings of fatigue, sleepiness, sleep quality and workload. Rates of missing data was attributed to either a lapse in memory or operational demands that may have interfered with study requirements.

Table 2-1 Subjective Scale Rates of Missing Data

Subjective Scale	Rate of Missing Data (%)
Fatigue Start Main Sleep	1.4%
Sleepiness Start Main Sleep	1.4%
Fatigue End Main Sleep	1.4%
Sleepiness End Main Sleep	1.4%
Sleep Quality	2.4%
Pre Flight Duty Period Fatigue	4.6%
Pre Flight Duty Period Sleepiness	6.2%
Post Flight Duty Period Fatigue	17.8%
Post Flight Duty Period Sleepiness	17.8%
Workload during Flight Duty Periods	0%
Pre Simulated Flight Fatigue	0%
Pre Simulated Flight Sleepiness	0%
Post Simulated Flight Fatigue	6.25%
Post Simulated Flight Sleepiness	6.25%
Workload during Simulated Flights	0%

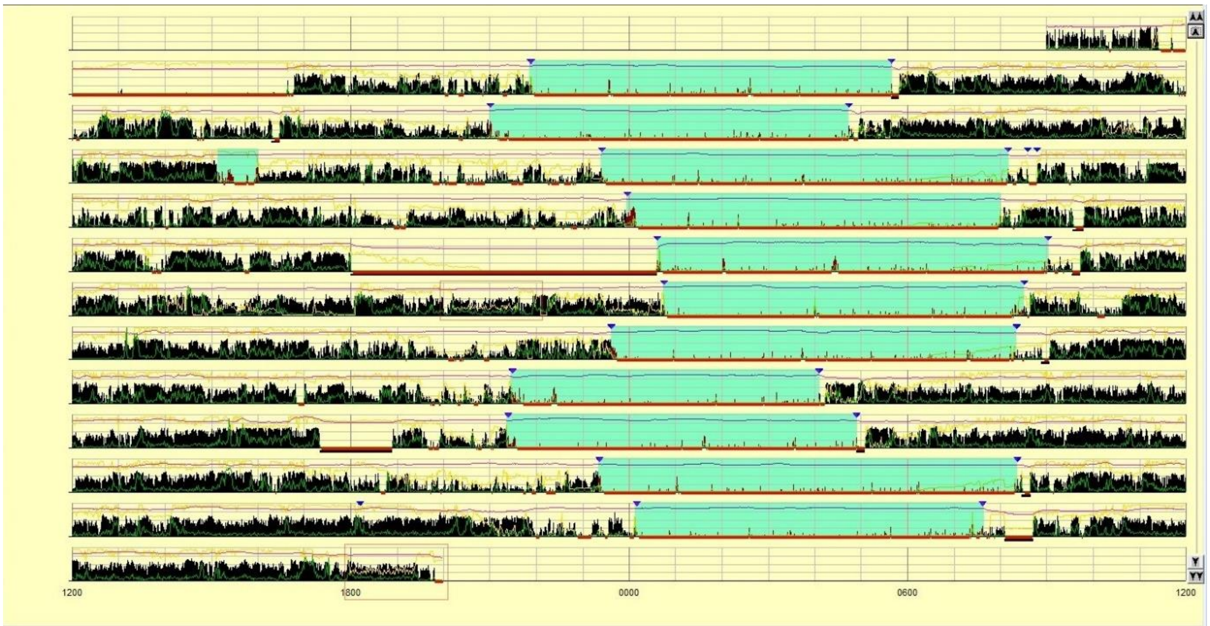
All subjective scale variables were imported to SPSS and SAS for statistical analysis.

2.13.2 Actigraphy

ActionW2.7 (Ambulatory Monitoring Inc., Ardsley, New York, USA) was used to view and score actigraphy records. Prior to scoring, records were trimmed to exclude data before 09:00 on day 1 and following the second simulated flight on day 11. Sleep periods were scored manually by reviewing a change in activity, event marker use and diary information (see APPENDIX L) for additional information on this process. Figure 2-5 shows a participant's scored actigraphy record in ActionW2.7. If a sleep period was split, it was scored as one rest interval when the time between intervals was less than 10 minutes. If the time between intervals was greater than or equal to 10 minutes, two separate rest intervals were scored. If the actigraph was not worn during a rest interval, but the participant had recorded bed and rise times within their sleep/duty diary, the corresponding rest interval was scored as "bad". This enabled metrics for that rest interval to be excluded from analysis.

All actigraphy records were scored by a staff member at the Sleep/Wake Research Centre. To assess the reliability of manually identified rest interval start and end times, 20% of actigraphy records were double scored by the researcher. Differences of more than 15 minutes occurred in 10.5% of rest interval start and end times. These were reviewed, rescored and corrected if needed. An overall agreement of 89.5% between the staff member and the researcher was achieved.

Figure 2-5 Example of a Scored Actigraphy Record



The height of the black vertical bars indicates the amount of movement in one minute intervals. Light blue shading represents each rest interval as determined by manual scoring. The red line below each rest interval represents one minute intervals scored as sleep, as estimated by the software algorithm. A black line represents off wrist periods and the event marker is represented by a blue triangle and the x axis represents time of day (New Zealand local time). Total sleep time was calculated by adding the number of one minute epochs scored as sleep during a sleep interval.

To visualise the placement of sleep periods across the flight duty period protocol in relation to the local night, flight duty periods, and simulated flights, a Darwent plot[42] was constructed using a custom-built MS Excel program (e.g. see Figure 4-11, Figure 4-12, Figure 4-22 and Figure 4-23). The order of records included within Darwent plots were randomised to ensure participant confidentiality.

Actigraphy variables were exported from ActionW2.7 into a custom built program (Actisoft R)[43] in R (R Core Team, 2025) which was used to add the number of one minute epochs scored as sleep during each sleep interval for the following variables:

- Total sleep in the 24hr period prior to the start of the non-rested (18:00) or rested (20:00) simulated flight.
- Total sleep in the 48hr period prior to the start of the non-rested (18:00) or rested (20:00) simulated flight (48 hour interval).
- Total sleep in the 24hr period prior to the start of a baseline or non-baseline sleep period (12:00).
- Cumulative sleep debt.

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[42] Named after Dr David Darwent at the University of Central Queensland, Adelaide, Australia, who generously shared his MS Excel program.

[43] Actisoft R was developed by Edgar Santos-Fernandez, Lora Wu, and Margo van den Berg, Sleep/Wake Research Centre, Massey University, Wellington, New Zealand.

- Time since sleep prior to the non-rested (18:00) or rested (20:00) simulated flight, and prior to the pre simulator PVT test (actual test start time) or post simulator PVT test (actual test start time).

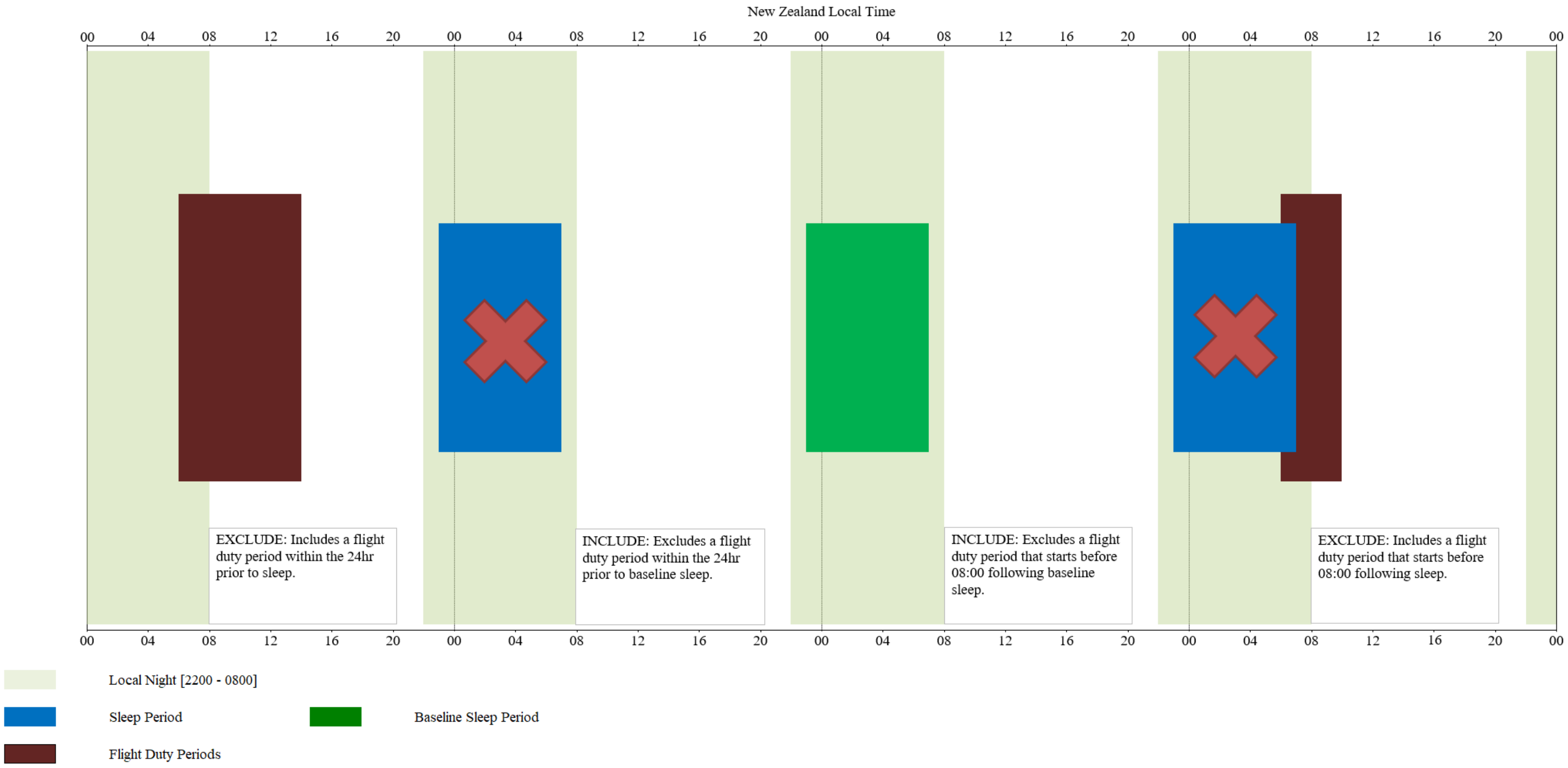
For total sleep in the previous 24 and 48 hour period, this reflected the amount of sleep a participant had achieved in the 24 or 48 hour period before the start of the simulator session. This is consistent with the approach taken in previous flight crew fatigue studies (Gander et al., 2013; Signal et al., 2014; Thomas et al., 2006) and ensures that the period of total sleep time in the previous 24 or 48 hours is consistent between different levels of condition.

To calculate cumulative sleep debt across the four day period prior to the start of each simulated flight, it was necessary to first determine baseline sleep duration for each participant (Gander et al., 1994). Baseline sleep was defined as the total amount of sleep achieved in a 24hr period from midday to midday that was not impacted by work demands, which is consistent with the approach taken by Signal et al. (2014). Baseline sleep periods (see Figure 2-6) were preceded by a 24hr period during which the participant was free from work and included an unrestricted nights rest. This rest period, prior to the baseline sleep period would likely be sufficient to recover from 24 hours of total sleep deprivation (Jay et al., 2007).

For calculating baseline sleep, data was available for an average of 3 days per participant (ranging from: 1 to 4 days). To calculate cumulative sleep debt, each participant's average baseline sleep was subtracted from their total amount of sleep achieved in each 24 hour period. In the non-rested condition, the 24 hour period was 18:00 – 18:00 and in the rested condition, it was 20:00 – 20:00. The difference was summed across the four day period preceding each simulated flight. Based on previous research, it was assumed that sleep could not be stored (Axelsson & Vyazovskiy, 2015; Bonnet & Arand, 1995; Patterson et al., 2019).

Time since sleep variables were calculated as the number of minutes between the end of the sleep interval and the start of the simulator flight or PVT test, which reflects time awake, rather than time since up from bed. The above variables were exported from ActisoftR, then imported to SPSS and SAS for statistical analysis. There was no missing actigraphy data for the above variables.

Figure 2-6 Criteria for Determining Baseline Days



2.13.3 Psychomotor Vigilance Task

Following each simulator session slot, PVT data was immediately downloaded and saved as a REACT PVT file using PVTCOMM for Windows Version 2.9.1 (Ambulatory Monitoring Inc., Ardsley, New York, USA) to minimise potential data loss. REACT PVT files were opened using the REACT program (Ambulatory Monitoring Inc., Ardsley, New York, USA). Summary statistics were generated for each test. These included PVT response speed (1/reaction time x 1000), the fastest 10% of responses (1/reaction time x 1000) and the slowest 10% of responses (1/reaction time x 1000). These variables were exported to MS Excel and then imported into SPSS and SAS for statistical analysis. There was no missing PVT data.

2.13.4 Simulated Flight Data Replay and Analysis Procedure

Following the completion of a simulated flight, the project file[44] was copied to the researcher's computer, then deleted from the SOQA base station computer. Files were then processed and analysed using Insight FDM. Videos of flight deck instrumentation were retained and the project file and associated records with each replay de-identified. Microsoft SQL Server Management Studio 18 was used to query the Insight FDM database and export values for specific customised events. Insight Analysis was used to export datasets which included selected parameters with defined start and end points for the creation of datasets that included either snapshots or continuously recorded parameters. Datasets containing snapshots were combined within a dataset that included participant ID, condition, order, cumulative sleep debt, sleep related variables and subjective ratings of fatigue,

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[44] The project file is generated on the server computer when the recording is initiated by the simulator instructor. It is a file repository which includes the simulated flight data .csv file, video recordings and system files to allow the simulated flight to be replayed by Insight Flight Data Monitoring.

sleepiness and workload. This dataset was loaded into Stat Transfer 14 (2015, Circle Systems, Seattle, WA, USA) to control the format of selected output parameters. Data tables were then loaded into SPSS (version 26.0, IBM SPSS Statistics for Windows, Armonk, NY, USA) to generate descriptive statistics and non-parametric tests. Datasets containing continuously recorded parameters were imported into Microsoft Power BI to calculate standard deviation values. They were then included within a dataset that included participant ID, condition, order, sleep related variables, subjective ratings of fatigue, sleepiness, workload and 50ft altitude bins. Using Stat Transfer 14 (2015, Circle Systems, Seattle, WA, USA), the datasets were converted for use in SPSS (version 26.0, IBM SPSS Statistics for Windows, Armonk, NY, USA) to generate descriptive statistics and SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA) to undertake statistical analysis.

2.14 Statistical Analysis

All data analyses were conducted by the researcher.

2.14.1 Association and Causality

The only way to determine causality is to compare two controlled situations, one where the cause is present and the other where the cause is absent (Field, 2018). The flight duty period protocol allowed for the creation of a controlled situation where fatigue and sleep loss were likely to be present in the non-rested condition and unlikely to be present in the rested condition. A within-subjects research design was selected to reduce error variance associated with individual differences. In addition, the order of simulated flights and condition (the non-rested or rested condition) were counterbalanced and randomly allocated to participants. The simulated flight protocol controlled for flight factors (for example, the effect of weight, wind direction and velocity, temperature, visibility, time and aircraft centre of gravity) and the nature of tasks undertaken by participants while also maintaining ecological validity. Although the study sought to establish causal links between variables, it is acknowledged that this is unlikely given the study was undertaken within a field setting where variables are less controllable compared with a laboratory setting.

2.14.2 Descriptives

SPSS (version 26.0, IBM SPSS Statistics for Windows, Armonk, NY, USA) was used to generate descriptive statistics (means, medians, standard deviations, range, and proportions) and plots (histograms, normal probability plots, detrended probability plots, and box plots). Outliers were checked and retained in the dataset if the observation was valid or, for simulated flight data measures, was considered operationally feasible[45].

2.14.3 Non-Parametric Tests

Non-normally distributed data was analysed using non-parametric tests. The Wilcoxon signed rank test was used to test for differences between two repeated measurements from the same group of participants (Wilcoxon, 1945) and the Mann-Whitney U test was used to test for differences between two independent groups. Effect sizes were calculated from the z-score and the test statistic (Rosenthal, 1984). An effect size below 0.3 was considered to be a small effect whereas an effect which was greater than 0.5 was considered to be a large effect (Field, 2018).

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[45] For an example of outliers that were excluded, see Footnote 87 and Footnote 88.

2.14.4 Linear Mixed Models

SAS software (version 9.4, SAS Institute Inc., Cary, NC, USA) was used to undertake statistical analysis using linear mixed models. The linear mixed model includes both fixed and random effects and uses a likelihood-based estimation method which utilises all available data. An advantage of this method is that it can handle unbalanced and/or missing data (Wolfinger & Chang, 1998). It also enables modelling of variances and covariances so that observations are allowed to be correlated or have non-constant variance. The linear mixed model is particularly well suited for a protocol that incorporates a repeated measures design because data collected from the same participant are likely to be positively correlated due to shared contributions from that participant, and because, data collected from a participant in close succession are typically more strongly correlated than data collected further apart in time. Variances and co-variances were expected to fit either a compound symmetry structure, a first order autoregressive covariance structure or a autoregressive structure with random effect (Littell et al., 2000; Snijders & Bosker, 2012; Stroup et al., 2018). The covariance structure with the smallest Bayesian Information Criteria (BIC) value was selected as lower BIC values are indicative of a better model fit (Field & Miles, 2010). In addition, a model with a smaller number of parameters was preferred (Littell et al., 2000). As such, if a model with a first order autoregressive covariance structure plus a random effect had the same BIC as a model with a first order autoregressive structure, the model without the random effect was selected. Similarly, if a model with a first order autoregressive covariance structure had the same BIC value as a model with a compound symmetry structure, the model with the compound symmetry structure was selected. If the dependent variable was transformed, separate models were rerun to identify the model with the smallest BIC value. To calculate degrees of freedom, the Kenward-

Rodger adjustment was applied to avoid inflation of type I error rates which can occur in repeated measures involving small samples and/or where data was unbalanced (Kenward & Roger, 1997). To check for possible multi-collinearity between pairs of independent variables, correlations, parameter estimates (tolerance values and variance inflation) and collinearity diagnostics (condition index and proportion of variation) were calculated. Where correlation between pairs of independent variables exceeded 70% (0.7) and/or the condition index was greater than 10 with a proportion of variance value greater than 0.5 for at least two independent variables, the independent variable with the highest variance proportion was removed from the model (Tabachnick et al., 2019).

The linear mixed model assumes that the relationship between the dependent and independent variables is linear and that the distribution of studentized residuals is normal with constant variance (Stroup et al., 2018). The Shapiro-Wilk statistic or Kolmogorov-Smirnov statistic in combination with review of the histogram, boxplot and quantile-quantile plot were used to check the normality of studentized residual distribution. Departures from normality were addressed in ungrouped data by removing outliers or applying transformations (Tabachnick et al., 2019). Data transformations are outlined in relation to specific models in Chapters 4, 5 and 6. Residual variance was checked using the Levene's test (Levene, 1960) in combination with the residual vs. predicted mean plot. If in the Levene's test, a categorical variable's p value was less than 0.05, this indicated that the model's residuals were not constant between different levels within that variable. Therefore, a more conservative alpha level of 0.01 was used to determine if the main effect for that variable in the mixed model was significant (Field & Miles, 2010). Where outlying residuals were identified, outliers were removed and the model re-run without outliers. If removing outliers altered the model's findings, outliers were excluded however if the model's findings did not change with outliers removed, outliers were included within the model (Tabachnick et al., 2019). Information about the inclusion or exclusion of outliers in each specific model are reported in the results sections in Chapters 4, 5 and 6. If main effects were significant, post hoc t tests were used to make pairwise comparisons between levels of the significant effect(s). If interactions were significant, simple effect tests were undertaken to determine the effect of a fixed effect at individual levels of the other fixed effect (Stroup et al., 2018). The significance level for post hoc t tests was adjusted to account for inflation of the type I error rate associated with multiple pairwise comparisons. The Bonferroni correction (Dunn, 1961) was used for post hoc pairwise comparisons for ANOVAs and ANCOVAs. Holm's sequentially rejective procedure was used to adjust the level of significance for mixed model repeated measures ANOVAs which included post hoc pairwise comparisons. The Holm's procedure is considered less conservative than the Bonferroni correction meaning that it reduces the type II error rate (Aickin & Gensler, 1996).

The specifics of each linear mixed model are outlined in each of the results chapters (Chapters 4, 5 and 6).

CHAPTER 3 RESULTS: SIMULATED FLIGHT PROTOCOL

3.1 Overview

This chapter provides an overview of steps taken to manage risk associated with the collection of sensitive flight data during simulated flights. Flight data is sensitive because of the regulatory framework in New Zealand. Unlike data recorded on an aircraft's digital flight data recorder, data recorded from other aircraft recording systems or from the flight simulator (SOQA data), which is used for training purposes, is not protected by law in New Zealand and could potentially be used to prosecute a pilot following an accident. This risk is managed through the deidentification of flight data. The chapter also includes a detailed timeline of key events and milestones and provides information regarding the project reference group, which was established to formalise project administration, to facilitate communication between each organisation and to oversee the management of known risks. Information is included about an agreement between the researcher, the operator and each pilot union. An overview of development of the simulated flight protocol is provided to illustrate steps taken to select scenarios for inclusion within the final simulated flight protocol. In addition, parameter validation is discussed. Technical information that may help the reader can be found in APPENDIX T.

3.2 Simulator Study Timeline

This research presented several challenges including access to simulated flight data, pilots, flight simulator slots and the rostering of bespoke flight duty periods. The researcher requested and received approval from the operators Chief Flight

Operations and Safety Officer to undertake this research. To allow the researcher access to simulated flight data focus was initially placed on establishing a temporary agreement relating to SOQA. This was between the researcher, the operators Training Manager and the applicable pilot union Technical Director. With this agreement in place, the researcher requested and received approval from the operators Flight Operations Manager to access pilot resource, simulator slots and develop bespoke flight duty periods with the assistance from the Crew Planning Manager and Crew Planner – Rostering. The researcher then worked closely with the operators Flight Operations Manager, Training Manager and Manager Crew Planning to coordinate simulator slot availability, bespoke flight duty periods and pilot availability. Union Technical Directors acted as an intermediary between the researcher and pilot union councils on all aspects relating to data collection for the study.

Initial work toward this research started in 2012 and involved the researcher discussing the proposed simulator study with Massey University’s Sleep/Wake Research Centre, the operator and pilot unions. On confirmation that both the operator and pilot unions were supportive of the study, the researcher enrolled, part time, in June 2014. To allow access to simulated flight data, the researcher, the operator and the pilot unions discussed processes and procedures needed to support a temporary agreement relating to the SOQA system. This work was started in 2015, and the agreements were signed in 2017. Data collection was delayed multiple times in 2017 and 2018 due to the operator’s workforce requirements. The study was prioritised in 2018, and data collection completed in the first half of 2019. A timeline which includes key points is included in APPENDIX M.

3.3 Project Reference Group

Due to the complex nature of the simulator study and the number of parties involved, a project reference group was initiated by the researcher to ensure that group members from each organisation were informed of the study's content and conduct. Group members had the opportunity to provide comments and advice on information and documents relating to data collection, and when available, a summary of findings and the final report. Group members consisted of representatives from the operator, pilot unions and Massey University. The group met six monthly between 2015 and 2019. For each meeting, an agenda was provided, and minutes recorded. The groups terms of reference are included in APPENDIX N. The Project Reference Group supported the researcher by facilitating discussion between the researcher and Flight Operations, Standards and Training, Crew Resourcing, Fleet Management and the Pilot Unions to address tasks associated with logistics, the flight duty period protocol and the simulated flight protocol.

3.4 Temporary Agreement Relating to Simulator Operational Quality Assurance System

The temporary agreement relating to the Simulator Operational Quality Assurance (SOQA) system represented the primary means to mitigate risk associated with the use of simulated flight data. An agreement was reached between the researcher, the operator and each pilot union in September 2017. The agreement allowed the operator to access and analyse flight data measures via the SOQA system and explore what information can be collected by the SOQA system to support operational safety initiatives. It also allowed the researcher to access and analyse flight data measures for the purposes of the simulator study which was subject to the following requirements:

- Voluntary participation and written informed consent.
- That no individual can be identified.
- Data is stored only on the secure computer server located in the simulator building or on the researcher's computer.
- Data is collected only during specified flight simulations.
- Data collected is only for this study.
- Data cannot be used for any disciplinary, performance, checking, training, or other action.
- No adverse comment, report or action shall be made or taken against any person because of this research.
- The terms of the agreement are in addition to any existing terms and conditions of employment of union members.

The consent form was approved by Massey University's Human Ethics Committee and is included in APPENDIX D. It was modified to include the following two additional dot points at the request of one of the pilot unions:

- I agree to SOQA information being collected during both simulator sessions.
- I agree to participate on the basis that this agreement and my participation in the simulator session is subject to the terms of the Temporary Agreement Relating to Simulator Operational Quality Assurance System Agreement between one of the pilot unions and Cameron Dyer [1st August 2017].

The temporary SOQA agreement had an effective period of one year. In August 2018, the agreement was extended for an additional six months to allow for the completion of data collection. Following March 1st, 2019, the agreement ceased to have effect, and the provisions of the participants collective employment agreement applied as if no agreement had existed. To allow for the collection of simulated flight data measures from one flight crew in May 2019 due to the unserviceability of the simulator during their second simulated flight in February, a verbal agreement was obtained from both pilot unions. In addition to the agreement mentioned above, the operator offered assurances (in the form of a letter) to one pilot union (at the request of that pilot union) that participants were appropriately protected as employees, under the Health and Safety at Work act. In addition, participants were indemnified against any liability of any and all potential consequential adverse outcomes and incidents, both while undertaking the study, and while in transit, before and following the study. The researcher also offered assurances (in the form of a letter) to one pilot union (at the request of that pilot union) that all flight data from the operator’s computers would be deleted after each participant had completed their simulated flight. Data collected from participants would be deidentified and would only be used for the purposes for which it was collected. No other unauthorised or inappropriate use of the data would be made, and that following peer review and examination of the thesis, all data would be deleted.

3.5 Validation of Parameters required for the Simulated Flight Protocol

A parameter represents either a recorded parameter acquired from the flight simulator, a manually entered parameter derived from videos of flight instrumentation or a parameter which is derived from other recorded parameter(s).

Parameter validation relates to confirmation that the parameter is output from the simulator correctly. Parameter validation was only undertaken if values from required parameters had not been observed[46] or if parameter values were suspected of being incorrect. To resolve the issue where values from required parameters had not been observed, one trial simulated flight was undertaken to check recorded parameters and sought to confirm:

- To ensure parameter annunciation (if applicable) or correct operation occurs by comparing recorded flight data parameter values with values depicted in videos of the Primary Flight Display, Multi-Function Display and Engine Warning Display.
- Transfer of simulated flight data and video files from the flight simulator to the SOQA server.
- That simulated flight data is both replayed and analysed correctly by Insight FDM (Flight Data Monitoring) software.

The trial simulated flight was flown by the operators Deputy Training Manager who was provided with a check list to ensure desired parameters were acquired and to note the corresponding timestamp. Knowing when either annunciations occurred or that selections or switch position selections were made, the researcher was able to confirm parameters if were recorded and decoded correctly. If a parameter was not output from the simulator correctly, support was sought from the simulator manufacture. In some instances, corrections were made to the simulator recording frame and subsequent parameter values did record correctly. Updates to the simulator recording frame typically took between three to six months to resolve. No

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[46] A series of flights may include a recorded parameter which depicts a warning (e.g., EGPWS Terrain Ahead 0 = no alert, 1 = alert). If there are no instances within those flights where a value of 1 is recorded, a simulated flight which includes the EGPWS Terrain Ahead warning is required to confirm that a parameter value of 1 is recorded.

scenario included parameters that were suspected of being incorrect, as such, the availability of parameters influenced which scenarios were incorporated within the study. Rather than resolving parameter issues, which was time consuming and required input from the simulator manufacture, alternative scenarios were selected. For example, there had been a desire to capture key stroke data from the flight management system for the paired scenario, holding Pattern (see APPENDIX W, section W7), however required values were not available to be recorded, therefore this scenario was removed.

3.6 Simulated Flight Protocol

A parameter represents a recorded value, for example airspeed, altitude or vertical speed. A scenario represents a situation that has been intentionally initiated by the simulator instructor and will result in a response from the flight crew that can be monitored using parameters. For example, having been instructed to go around, flight crew will initiate actions which are consistent with the go around missed approach procedure. Some of these actions can be monitored using parameters. The simulated flight protocol represents a framework which defines flight characteristics, ensures study requirements (in relation to the protocol) are met and determines which scenarios are included and at what point. The protocol also provides guidance to the simulator instructor and minimises differences between simulated flights in a controlled way which is not possible during actual flight. A flight planning task was included to ensure each simulated flight was realistic.

> The obvious goal is to produce crew performance and behaviour that would be typical for an actual line flight in the same set of circumstances as those developed in the scenario. In keeping with this goal, it is essential that crews

> have access to all the resources they would have on an actual line trip (Lauber & Foushee, 1981, p. 17).

Participants were provided with flight planning documentation[47] which consisted of a weather briefing, NOTAM[48], GPS RAIM[49] predictions, flight plan and alternate flight plan[50]. The weather briefing was constructed using one of the operators packaged weather scenarios. Participant performance was not monitored during flight planning with flight planning documentation being discarded following each simulated flight. ATC, operations control, maintenance operations control and access to weather related information was provided or facilitated by the simulator instructor.

The Captain was pilot flying [51] and the First Officer was pilot monitoring [52] during both simulated flights. The time of departure for all simulated flights was coordinated with New Zealand local time[53]. All departures from each airport occurred during daylight although some flights in the rested condition would land in darkness following the end of evening civil twilight. Two simulated flights were flown by the participants. The flights were counterbalanced, where one flight consisted of a flight from Christchurch (CHC) to Wellington (WLG) and the other

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[47] All flight planning documentation was provided using the Operators forms.

[48] Notice to Airmen (NOTAM) consist of messages relating to the flight and are reviewed by pilots prior to flight.

[49] Global Positioning System Receiver Autonomous Integrity Monitoring is technology developed to assess the integrity of GPS signals in a GPS receiver system.

[50] An alternate flight plan represents the aircrafts planned flight following diversion or enroute diversion whereby landing does not occur at the intended destination.

[51] The pilot flying monitors the aircraft position, the flight path parameters and the autopilot, controls the aircrafts speed, requests checklists, flaps setting and gear extension, selects autopilot modes and announces changes.

[52] The pilot monitoring oversees radio communications, monitors the flight path, aircraft speed, autopilot mode changes, aircraft systems and engines, reads the checklist and selects flap setting and gear extension.

[53] A given crew may report for a simulator duty at 10:00 to conduct a simulated night flight. Although the time is 10:00, simulated time within the simulator could be 02:00. For the purposes of this study, the simulated time within the simulator was coordinated with New Zealand Local time.

flight consisted of a flight from WLG runway to CHC[54]. The order of the flights was counterbalanced with half of the participants operating the CHC – WLG simulated flight first. Each simulated flight included five scenarios which were designed to enable an assessment of factors that relate to crew performance. The scenarios in each simulated flight were as similar as practical to the corresponding scenario in the other simulated flight. Scenarios were unexpected in that their introduction represented a surprise, although the intention was not to startle[55] the crew. The scenarios represented operational problems (speed and height restrictions), environmental problems (tailwind and ice accretion) and an equipment problem (un-commanded autopilot disconnect). Three trial simulator sessions were undertaken. This provided an opportunity for the simulator instructor and researcher to gain experience with how the protocol would flow, to confirm acceptable transfer of simulated flight data and to confirm that simulated flight data was both replayed and analysed correctly using SOQA software.

3.6.1 Simulated Flight Characteristics

The simulated flights within this research were non-jeopardy and were independent from the operators training programme. The simulated flight protocol defines characteristics for each simulated flight. It includes weather conditions, aircraft weight and balance, the location and runway, which standard instrument departure (SID), standard arrival route (STAR) and instrument approach is flown,

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[54] Flights between Wellington (WLG) and Christchurch (CHC) are common in turboprop aircraft with flights between these two cities representing 19% of all flights flown by the operator in the year preceding data collection. The average southbound flight time including taxi to and from the runway was 1hour 1min (min 42min, max 2 hour 54min) and the average northbound flight including taxi was 57mins (min 41min, max 1hour 57min).

[55] Real-life responses to unexpected stimuli during aircraft accidents have suggested that some pilots can be affected by the effects of startle (Martin et al., 2016).

other aircraft / ATC interaction, aircraft system operability, pilot workload, scenarios, and sub scenarios.

3.6.2 Simulated Flight Protocol Requirements

The following requirements ensured that the simulated flight protocol and associated scenarios aligned with the aim and purpose of this research project. These include compliance with operational safety[56] and people safety[57] requirements. That each simulated flight should reflect a normal flight with no abnormal or emergency procedures. That each Christchurch – Wellington simulated flight was as similar as practical to other Christchurch – Wellington simulated flights in this study. That each Wellington – Christchurch simulated flight was as similar as practical to other Wellington – Christchurch simulated flights in this study. That each simulated flight includes scenarios that can be monitored using simulator flight data and that can be aligned with or mapped to cognitive functions that are sensitive to sleep loss. That each simulated flight has both periods of relative inactivity and stress-inducing periods[58], and to minimise practice effects between flights.

3.6.3 The Role of the Simulator Instructor

The simulator instructor was employed by the operator and was known to the participants. The instructor signed a confidentiality form agreeing to keep confidential all information concerning the research project and not retain or copy any information involving the project. The simulator instructor is a pilot who manages the simulated flight from a flight station located behind the captain's seat and to the left of the observer's seat who were responsible for ensuring the

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[56] Requirements associated with New Zealand Civil Aviation Rules or Operator requirements.

[57] Requirements associated with the Health and Safety at Work Act 2015.

[58] Scenarios should include segments where workload is influenced by the sequence, pace and tempo of events (Lauber & Foushee, 1981).

simulated flight protocol was complied with during each simulated flight. The pacing and timing of each scenario should be precisely specified (Lauber & Foushee, 1981) so that the simulator instructor knows exactly when and how to introduce the scenario. A checklist was provided for this purpose (see APPENDIX U). The same instructor was involved with both trial simulated flights and all simulated flights associated with data collection. The benefit of having the same instructor was that they gained experience and familiarity with facilitating the protocol which likely increases consistency between flights compared to flights facilitated by multiple instructors. In case of absence, the instructor provided training to a second instructor.

3.6.4 Simulated Flight Protocol Scenarios

A scenario represents an opportunity for the simulator instructor to intervene during the simulated flight. This intervention will initiate a situation that can be recorded using flight data at a specific point of interest during a simulated flight. Each simulated flight included between five and six scenarios. The start and end of each scenario was determined using flight data. Scenarios included in the first trial flight, second trial flight and final flights are detailed in APPENDIX Q. Scenarios were paired so for example, the go around scenario from the Christchurch – Wellington flight was paired with the go around scenario from the Wellington – Christchurch flight. Comparison with near identical[59] scenarios was preferred over similar scenarios[60]. This places an emphasis on confirming that it is appropriate to compare

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[59] Near identical scenarios represent scenarios that are as identical as reasonably practical. For example, an ice accretion scenario where characteristics are the same in both scenarios, i.e. cloud base and cloud top, temperature, ice accretion rate, time within atmospheric icing conditions, phase of flight and aircraft weight etc.

[60] A similar scenario is not identical however both scenarios share characteristics. For example, an excess energy during approach scenario where each scenario has a different trigger (i.e. excess speed or excess height) however both triggers contribute to the same outcome (i.e. excess energy during approach).

performance measures from scenarios that occur during different flights. Table 3-1, Table 3-2 shows the scenarios that were trialled during trial simulated flights and those that were included in the final simulated flights. Paired scenarios are detailed in Table V 1 (APPENDIX V) (first trial), Table W 1 (APPENDIX W) (second trial) and Table 3-3 (final simulated flight protocol). Performance measures derived from flight data are detailed in Section 2.11.3.2 for scenarios included in the final simulated flight protocol. Due to time constraints, not all scenarios included in the final simulated flight protocol were included in statistical analysis.

Table 3-1 Utilization of Scenarios during Christchurch Wellington Simulated Flights

Scenario	First trial [a]	Second trial [b]	Final flight
Tailwind during Initial Climb	Yes	Yes	Yes
Traffic alert and Collision Avoidance System Resolution Advisory	Yes	Yes	No
Ice accretion during climb and descent	No	No	Yes
Un-commanded autopilot disconnect prior to being established[61] on the ILS/DME RWY 34 instrument approach	Yes	Yes	Yes
Speed restriction during ILS/DME RWY34 instrument approach above 1000ft.	Yes	Yes	Yes
Go around	Yes	Yes	Yes
Holding Pattern	Yes	Yes	No

[a] Changes to scenarios following the first trial are outlined in APPENDIX V, section V2.
[b] Changes to scenarios following the second trial are outlined in APPENDIX X.

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[61] An aircraft is not considered to be established on the localizer until it is within a half scale deflection of the ILS localiser (Aeropath, 2019, ENR 1.5, 4.13.5 (f)).

Table 3-2 Utilization of Scenarios during Wellington Christchurch Simulated Flights

Scenario	**First trial** [a]	**Second trial** [b]	**Final flight**
Aircraft handling following unexpected change to flight path	Yes	No	No
Tailwind during climb	No	No	Yes
Ice Accretion during climb and descent	Yes	Yes	Yes
Un-commanded autopilot disconnect prior to being established on ILS/DME RWY 20	No	Yes	Yes
Height restriction during ILS/DME RWY20 instrument approach	Yes	Yes	Yes
Go Around	Yes	Yes	Yes
Holding Pattern	Yes	Yes	No

[a] Changes to scenarios following the first trial are outlined in APPENDIX V, section V2.
[b] Changes to scenarios following the second trial are outlined in APPENDIX X.

3.6.5 Simulated Flight Protocol Sub Scenarios

A sub scenario considers other reasonably expected outcomes during a scenario and ensures that the scenario is not excluded if the expected outcome did not occur. For example:

> If a scenario incorporates a situation in which a diversion to an alternate airport, although not required, represents a “reasonable” choice, then the scenario designer should plan a sub scenario (sic) that covers the diversion leg. If a diversion is not desirable in each scenario, then steps should be taken to ensure that such a decision is not likely by using weather or operational factors. (e.g., closing the only open runway at the alternate). (Lauber & Foushee, 1981, p. 12)

The final simulated flight protocol included sub scenarios within the following paired scenarios:

- Tailwind during climb
- Excess energy during approach

In the above paired scenarios, a pilot may contact ATC and indicate they cannot comply with the ATC request. For the tailwind during climb scenario, ATC will request the aircraft to level the aircraft off at 2000ft departing Christchurch, or at 4000ft departing Wellington. For the excess energy during approach scenario, ATC will request the aircraft to climb the aircraft and maintain 3500ft.

3.7 Simulated Flight Protocol Development

Two trial simulator sessions consisting of two simulated flights, one from Christchurch to Wellington and one from Wellington to Christchurch contributed to the development of the final simulated flight protocol. Trial simulator sessions also confirmed the satisfactory transfer of simulated flight data and video files to the SOQA server, and that simulated flight data was replayed and analysed correctly by Insight FDM (Flight Data Monitoring) software.

3.8 The Final Simulated Flight Protocol

The final simulated flight protocol represents the protocol that was applied to each simulated flight during data collection. Table 3-3 shows the paired scenarios included in the final simulated flight protocol.

To provide scientific rationale for the inclusion of the following scenarios in fatigue research, scenarios were carefully reviewed to identify cognitive functions that could potentially contribute to anticipated fatigue related changes in flight crew performance. Each scenario will likely require cognitive functions associated with both simple and complex cognitive performance including attention, psychomotor vigilance, tracking, multi-tasking, working memory, convergent thinking and logical deduction, and decision making. See chapter 1, section 1.6 for a detailed overview of fatigue related performance impairment, and chapter 7, section 7.3.3 for a discussion on anticipated fatigue related changes in relation to the simulated flight data measures.

Table 3-3 Comparison of Scenarios During the Final Simulated Flight Protocol

		Christchurch-Wellington	**Wellington – Christchurch**
Paired Scenario	**Scenario Comparability**	**Scenario name**	**Scenario name**
Tailwind during climb	Similar	Tailwind During Initial Climb	Tailwind During Climb
Ice accretion	Near identical	Ice Accretion during Climb and Descent	Ice Accretion during Climb and Descent
Un-commanded autopilot disconnect	Near identical	Un-commanded autopilot disconnect prior to crossing JONAH.	Un-commanded autopilot disconnect prior to crossing CH409.
Excess Energy during Approach	Similar	Speed restriction during ILS/DME instrument approach above 1000ft	Heigh restriction during ILS/DME instrument approach above 1000ft
Go Around	Near identical	Go Around at 300ft due to ATC instruction	Go around at 300ft due to ATC instruction

Paired Scenarios in the Final Simulated Flight Protocol

3.8.1 Paired Scenario: Tailwind during Climb

Tailwind During Initial Climb (Christchurch – Wellington): This scenario is identical to that described in APPENDIX W, section W2: Tailwind During Initial Climb (Christchurch – Wellington).

Tailwind During Climb (Wellington – Christchurch): Before take off, ATC instruct the crew to cross TAXUP at or above 4000ft. The temperature is 20 deg C, cloud base is broken at 4000ft, visibility is greater than 10km with light rain and wind is from the south-west at 10kt. The 2000ft wind is also from the south-west at 15kt. Mean aerodynamic cord (MAC) is 28%[62] and the aircraft take off weight is 22400kg[63]. On passing 2000ft, the wind direction changes to the northwest resulting in a tailwind component of 14kt when passing 2500ft. Pilot intervention is required to ensure the crew comply with the ATC instruction. The tailwind during initial climb scenario included a sub scenario where crew are instructed by ATC to level off at 4000ft if they communicate that they are unable to comply with the 4000ft height restriction. Several outcomes are possible:

- The aircraft flight path is modified, and crew comply with the ATC instruction.
- ATC instruct the aircraft to level off at 4000ft.
- The crew do not contact ATC and do not comply with the SID.

Paired Scenario Compatibility: Mean aerodynamic chord (MAC) is the same, there was a 2 degree difference in temperature and a 200kg difference in take off weight.

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[62] The mean aerodynamic chord (MAC) reflects the aircrafts centre of gravity. It is given as a percentage of the MAC with landing gear extended (Avions de Transport Regional, 2014, 2.01.02 P1)
[63] Maximum take off weight is 23000kg (Avions de Transport Regional, 2014, 2.01.02 P1).

Head wind component (HWC) and cross wind component (CWC) are the same at the surface and within 2000ft of crossing either NUBKA or TAXUP. At take off, the required climb gradient of 8.1% is the same for both scenarios. It is likely that the climb gradient may differ slightly from 8.1% when within 2000ft of TAXUP. For example, the climb gradient between 2000ft and TAXUP during the first trial flight was 7.9% and 7.7% for the second trial flight. Neither trial flight had a tail wind of 12kt between 2500ft and 4000ft meaning that the climb gradient will likely be in the vicinity of 8.1% due to reduced climb performance. When passing 2000ft in Wellington, the aircraft will likely have gear and flap retracted having passed acceleration altitude. In Christchurch, the acceleration altitude will either be delayed or will occur before passing NUBKA. Crew awareness of the need to comply with either the SID or the ATC instruction could differ between scenarios. There is no prompt from ATC to comply with the SID whereas ATC do instruct crew to pass TAXUP at or above 4000ft during prior to take off.

3.8.2 Paired Scenario: Ice Accretion

During the final simulated flight protocol, the ice accretion scenario occurs during both climb and descent for both flights. During cruise, the aircraft is clear of cloud meaning that the checklists mentioned below are required to be completed during climb, and descent.

- Entering icing conditions.
- At first visual indication of ice accretion, and if atmospheric icing conditions exist.
- When leaving icing conditions.
- When the aircraft is visually verified clear of ice.

In addition, the scenario was separated from the tailwind during initial climb scenario to improve comparability between scenarios within the ice accretion paired scenario. The change in environmental conditions paired scenario was removed from the final simulated flight protocol.

Ice Accretion (Christchurch - Wellington): During both climb and descent, the aircraft enters atmospheric icing conditions. Light ice accretion occurs. The scenario requires crew to complete checklists associated with entering icing conditions, ice accretion and leaving icing conditions. Completion of checklists ensures compliance with the aircraft flight crew operating manual (FCOM) requirements for flight within atmospheric icing conditions and ice accretion (Avions de Transport Regional, 2014, p. 2.02.08). Several outcomes are possible:

- A check list is completed correctly at the correct time.
- A check list is completed incorrectly at the correct time.
- A checklist is completed correctly at the incorrect time.
- A check list is completed incorrectly at the incorrect time.

Ice Accretion (Wellington - Christchurch): The ice accretion during climb scenario is identical to that described during the second trial of the initial simulated flight protocol (see APPENDIX W, section W2: Ice Accretion During Climb (Wellington Christchurch). In addition to this, an ice accretion scenario during descent was also included which mirrors that during the climb.

Paired Scenario Compatibility: The two scenarios are near identical. Mean aerodynamic chord (MAC) is the same, there was a 200kg difference in take off weight, a 2 degree difference in temperature at take off and 1 degree difference in temperature at landing. There was a 1000ft difference in altitude when the aircraft enters atmospheric icing conditions during climb and a 700ft difference in altitude when the aircraft exits atmospheric icing conditions during descent. Differences in duration while in atmospheric icing conditions may vary depending on aircraft speed.

3.8.3 Paired Scenario: Un-commanded Autopilot Disconnection

Un-commanded autopilot disconnect when passing JONAH: This scenario is identical to the scenario in the second trial flight (APPENDIX W, section W4).

Un-commanded autopilot disconnect when passing CH409: This scenario is identical to that described in APPENDIX W, section W4 noting that the simulator instructor checklist was updated following the second trial of the initial simulated flight protocol to ensure that the autopilot is available for immediate re-engagement.

Paired Scenario Compatibility: Paired scenario compatibility is identical to that described in APPENDIX W, section W4.

3.8.4 Paired Scenario: Excess Energy during Approach

Speed restriction during Wellington ILS/DME RWY34 instrument approach above 1000ft: The only difference from the scenario described in APPENDIX W, section W6 relates to environmental conditions. The cloud base was increased from 1500ft to 4000ft. The turbulence level was reduced to light, precipitation was reduced from moderate to light and wind speed was reduced from 23kt to 20kt. Windshear was not present.

Height restriction during Christchurch ILS/DME RWY20 instrument approach above 1000ft: The only difference to the scenario described in APPENDIX W, section W6 relates to environmental conditions. The overcast cloud base at 1500ft was removed, noting that the broken cloud layer at 1000ft was retained. All other environmental conditions remained the same.

Paired Scenario Compatibility: Paired scenario compatibility is identical to that described in APPENDIX W, section W6.

3.8.5 Paired Scenario: Go Around

Go around following Wellington ILS/DME RWY34 instrument approach: During approach to land, the aircraft should be stable at 1000ft. The surface headwind component is 19kt and the crosswind component, 3kt. The 2000ft headwind component is 15kt and the crosswind component, 12kt. Cloud base is 4000ft and visibility 7000m in light rain. Turbulence is light with no windshear reported or present. Temperature is 16 degrees. On reaching 300ft, ATC instruct the aircraft to go around. The scenario requires the crew to complete the go around/missed approach procedure which requires the crew to press the Go Around push button which disconnects the autopilot and requires the pilot flying to manually fly the aircraft. The scenario offers an opportunity to monitor the order of go around/missed approach procedure checklist items and to monitor the accuracy of hand flying during the go around procedure.

Go around following Christchurch ILS/DME RWY20 instrument approach: The aircraft should be stable at 1000ft. The surface headwind component is 17kt and the crosswind component, 10kt. The 2000ft headwind component is 12kt and the crosswind component, 21kt. Cloud base is 1000ft and visibility 6000m in light rain. Turbulence is light. Temperature is 15 degrees. No windshear is reported or present. On reaching 300ft, ATC instruct the aircraft to go around. The go around /

miss approach procedure is required to be completed. The scenario offers an opportunity to monitor the order of go around / miss approach procedure checklist items and to monitor the accuracy of hand flying during the go around procedure.

Paired Scenario Compatibility: The scenarios are near identical. The height or speed restriction that preceded the go around scenario should have been resolved prior to the aircraft passing 1000ft during the approach. The expectation would be that if the aircraft was not stable, that a go around / miss approach would be initiated when passing 1000ft. Weather conditions were similar, cloud base differs by 3000ft, visibility by 1000m and temperature by 1 deg C. Headwind component differs by 3kt at 2000ft and 2kt at the surface and the crosswind component differs by 9kt at 2000ft and 7kt at the surface. Aircraft configuration and centre of gravity should be the same. Aircraft weight should differ by roughly 140kg at the point where the go around is initiated. Both the cause of the go around and the time that crew become aware of the need to go around is the same in both scenarios. With the absence of windshear, the same go around/missed approach procedure should be undertaken.

CHAPTER 4 RESULTS: SLEEP, FATIGUE, SLEEPINESS, SLEEP QUALITY AND WORKLOAD DURING THE FLIGHT DUTY PERIOD PROTOCOL

4.1 Overview

This chapter presents findings from the analysis of sleep related variables (sleep timing, duration, time since sleep, and cumulative sleep debt) and subjective ratings of workload, fatigue, sleepiness and sleep quality across the four days leading up to, and before, and after each simulated flight. A key focus of this chapter is the influence of the flight duty period protocol condition (rested or non-rested), flight order (first flight or second flight) and location (Christchurch – Wellington or Wellington – Christchurch) and timing (pre simulated flight or post simulated flight) on dependent variables. There was also a focus on whether or not sleep was influenced by work demands and if workload differed by the type of flight undertaken (flight duty period flights or simulated flights). Analyses were also undertaken to investigate the influence of sleep related variables on subjective ratings of fatigue, sleepiness, sleep quality and perceived workload. Analyses and results are grouped by research question.

4.2 Research Questions

The following research questions are addressed.

Flight Duty Period Protocol

Question 1: Do participants comply with the flight duty period protocol?

Subjective Ratings of Workload

Question 2: Do workload ratings differ between flight duty period flights and simulated flights?

Question 3: Do workload ratings differ between the non-rested and rested simulated flight?

Question 4: Do workload ratings differ between the first and second simulated flight?

Question 5: Do workload ratings differ between the Christchurch – Wellington and Wellington – Christchurch simulated flight?

Question 6: Are workload ratings associated with cumulative sleep debt, time since sleep, or total sleep time in the previous 24 hour or 48 hour period?

Sleep timing and duration

Question 7: Do sleep timing and duration differ between the non-rested and rested condition?

Question 8: Does time since sleep differ between the non-rested and rested condition?

Question 9: Does sleep timing and duration differ between non-baseline and baseline sleep periods?

Subjective Ratings of Fatigue and sleepiness

Question 10: Do subjective fatigue and sleepiness ratings, prior to and following main sleep periods, and subjective sleep quality ratings, following main sleep periods, differ between the non-rested and rested condition?

Question 11: Do subjective fatigue, sleepiness and sleep quality ratings differ between non-baseline and baseline sleep periods?

Question 12: Do subjective fatigue and sleepiness ratings across each simulated flight differ between the non-rested and rested condition?

Question 13: Are subjective ratings of fatigue and sleepiness across simulated flights associated with cumulative sleep debt, time since sleep, or total sleep time?

4.3 Method

4.3.1 Measures

Workload

Overall workload rating on the raw NASA Task Load Index was measured either post flight duty period or post simulated flight[64].

Sleep Timing and Duration

Cumulative Sleep Debt: the amount of sleep debt (in minutes) accrued by the end of day 4, the final 24 hour period prior to the non-rested (18:00) or rested simulated flight (20:00 – 22:00).

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[64] Calculation of overall workload rating on the NASA Task Load Index is defined in section 2.11.4.

Time Since Sleep: the duration of time since sleep at the start of the simulated flight, or the time since sleep at the start for the pre or post simulated flight PVT test.

Total sleep in 24hrs: Total sleep in the previous 24 hour period prior to the non-rested (18:00 – 18:00) or rested simulated flight (20:00 – 20:00). For comparisons between baseline and non-baseline sleep periods, total sleep in the previous 24 hour period (12:00 – 12:00) was used.

Total sleep in 48hrs: Total sleep in the previous 48 hour period prior to the non-rested (18:00 – 18:00) or rested simulated flight (20:00 – 20:00).

Sleep start: Represents the start of sleep during the main sleep period, not the start of the rest interval. It was measured in minutes since 00:00.

Sleep end: Represents the end of sleep following the main sleep period, not the end of the rest interval. It was measured in minutes since 00:00.

Time in Bed: Time in Bed represents the duration between the start and end of the main sleep period (rest interval, not sleep) start and end times. It represents the time where participants were trying to sleep.

Fatigue, Sleepiness and Sleep Quality

Samn Perelli fatigue rating: Ratings were recorded prior to and following each simulated flight (pre simulated flight fatigue, post simulated flight fatigue or simulated flight fatigue)[65] and at the start and end of each main sleep period (fatigue start main sleep or fatigue end main sleep).

Karolinska Sleepiness Scale rating: Ratings were recorded prior to and following each simulated flight (pre simulated flight fatigue, post simulated flight fatigue or simulated flight fatigue)[66] and at the start and end of each main sleep period (sleepiness start main sleep or sleepiness end main sleep).

Sleep Quality: Ratings were recorded following each main sleep period.

Independent Variables

The following variables were included in linear mixed models, which are described in further detail below.

Type of Duty: Simulated Flight or Flight Duty Period: This variable identifies if dependent variable values were recorded during a flight duty period or were recorded immediately before or following a simulated flight.

Non-rested or rested condition: This variable identifies if dependent variable values are from the non-rested or rested condition.

Location: This variable identifies if dependent variable values are from the Christchurch – Wellington or Wellington - Christchurch simulated flight.

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[65] This represents a dataset which includes pre and post simulator fatigue ratings. These can be grouped by condition, order or timing.

[66] This represents a dataset which includes pre sim and post sim sleepiness ratings which can be grouped by condition, order or timing.

Flight order: This variable identifies if dependent variable values are from the first or second simulated flight.

Day: This variable identifies which 24 hour period prior to the start of each simulated flight, sleep related dependent variable values are from. Day 1 (between 72 hours and 96 hours), day 2 (between 48 hours and 72 hours), day 3 (between 24 hours and 48 hours) and day 4 (between zero hours and 24 hours) before each simulated flight.

Non-baseline or baseline sleep period (sleep period): This variable identifies if dependent variable values are associated with non-baseline or baseline sleep periods.

4.3.2 Day-to-Day Analyses

Day-to-day analyses were undertaken to determine if, during the four day period prior each simulated flight, sleep timing and duration as well as subjective ratings of fatigue, sleepiness and sleep quality differed by day (e.g., day 1 compared with day 2) and/or between conditions (e.g., day 1 in the non-rested condition compared with day 1 in the rested condition). For each day, the main sleep period was defined as sleep occurring predominantly during the biological night[67]. If multiple sleep episodes occurred during the main sleep period (i.e., sleep was split by more than 10 consecutive minutes of waking activity), then sleep durations were summed across the main sleep period. Additionally, sleep start time and pre-sleep fatigue and sleepiness ratings from the first sleep episode and sleep end time, and post-sleep

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[67] Biological night reflects the circadian phase when the individual is habitually exposed to darkness (Mason et al., 2022).

ratings of fatigue, sleepiness and sleep quality from the last sleep episode were used for analyses.

4.3.3 Statistical Analyses

Descriptive statistics (mean, standard deviation, median, and range) are provided for each dependent variable. Linear mixed models were used to investigate the association between dependent and independent variables. Where studentized residuals were not normal, Mann-Whitney U tests were used to test for significant differences between variables.

Collinearity

For linear mixed models that included continuous independent variables (cumulative sleep debt, time since sleep, total sleep in 24hrs or 48hrs, sleep start, sleep end and time in bed) collinearity between variables was checked. Total sleep in 24hrs or 48hrs were found to be colinear and were therefore not included in the same model. Further collinearity tests indicated no redundancy between the remaining variables. For workload and pre and post simulated flight ratings of fatigue and sleepiness, two separate models were run which included the following variables:

- Cumulative sleep debt, time since sleep, total sleep in 24hrs.
- Cumulative sleep debt, time since sleep, total sleep in 24hrs.

Transformations

Details on dependent variable transformation are included as a foot note in the model results table. Where transformations were undertaken, differences in parameter estimates from the transformed model were not reported, however relative relationships were.

4.4 Data Management

The pre-study questionnaire, sleep/duty diary and actigraphy data were available from each participant with each of the datasets being complete aside from a small number of missing responses within the sleep/duty diary. Missing responses did not appear systematic in nature and the total number of responses for each variable is included within the applicable table.

4.5 Participant Demographics

A total of 16 pilots consisting of 8 Captains (7 males) and 8 First Officers (6 males) participated in the study. Only 2 Captains had check or training experience. Table 4-1 Participant Demographic Information includes descriptive statistics for participant age, total flight time, aircraft flight time, short haul experience and time with the operator. Captains had significantly more total flight time ($U = 53$, $z = 2.893$, $p = .002$), short haul flight experience ($U = 57$, $z = 2.626$, $p = .007$) and a longer tenure with the operator ($U = 64$, $z = 3.363$, $p = <.001$) than First Officers. Age ($U = 48.5$, $z = -1.762$, $p = .83$) and time on aircraft type ($t(8.56) = -2.272$, $p = .051$) were not significantly different. Fifteen participants had either attended fatigue refresher courses, received training in fatigue awareness and/or fatigue management or attended seminars or similar. Table 4-2 summarises information about participants' usual sleep at home during days away from work and shows normal individual variability among participants. On average, participants went to bed at 22:35, they took 21 minutes to fall asleep and woke on average, 1.5 times per night. Their average final wake up time was 07:27, having slept for 7 hours and 55 minutes. Additional information on participants' sleep at home during days away from work is summarised in Figure 4-1, Figure 4-2, Figure 4-3 and Figure 4-4.

Table 4-1 Participant Demographic Information

Variable	Captain					First Officer					
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N	p
Age	39.1	8.6	37	31 – 56	8	33[a]	7.6	31	26 – 46	8	.083[c]
Total Flight Time (hours)	8135	5679.7	6310.5	3600 – 21500[b]	8	3309.2	1106.5	2800	1730 - 4600	7	.002[c]
Aircraft Flight Time (hours)	1993.3	1177.6	1604.0	500 – 4000	8	995.7	395.9	1141.5	277 - 1400	8	.051[d]
Short Haul Experience (years)	10.6[a]	7.64	7.7	4.8 – 28.8[b]	8	4.1[a]	5.83	2.2	.58 – 18.3[b]	8	.007[c]
Time with operator (years)	8.31	6.71	5.83	4.83 – 24.58[b]	8	1.89	.879	1.91	.75 – 3.25	8	<.001[c]

a not normally distributed; [b] includes 1 outlier; [c] Mann-Whitney U test; [d] independent t test.

Table 4-2 Participants usual Sleep Timing and Duration during days away from work

Variable	Mean	SD	Median	Range	N
Bed time on days off work (local time; hh:mm)	22:35	00:48	22:30	21:00 - 00:00	16
Time taken to fall asleep on days of work (minutes)	21	10	20	10 – 45	16
Number of awakenings during the night at home	1.5	.89	1	0 – 3	16
Rise time on days off work (local time; hh:mm)	07:27	00:43	07:30	06:00 - 08:30	16
Total amount of sleep at night at home (hours)	7.91	1.08	8.00	6.00 – 10.00	16

Figure 4-1 Overall what kind of sleeper would you consider yourself to be?

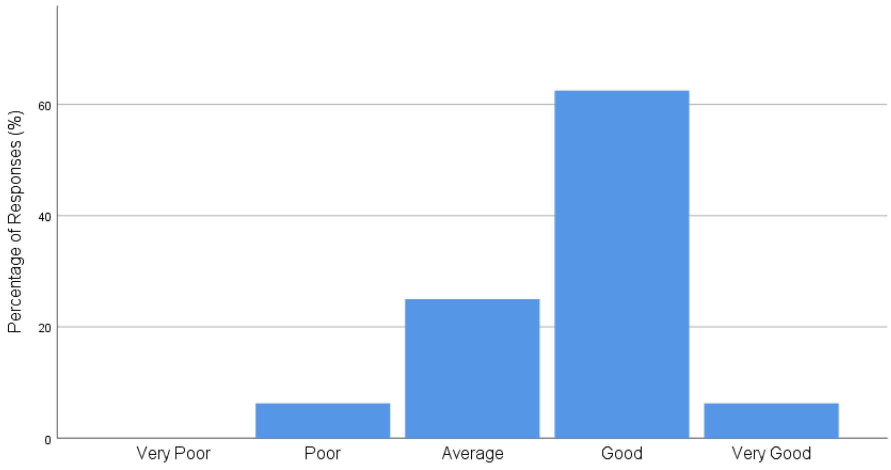
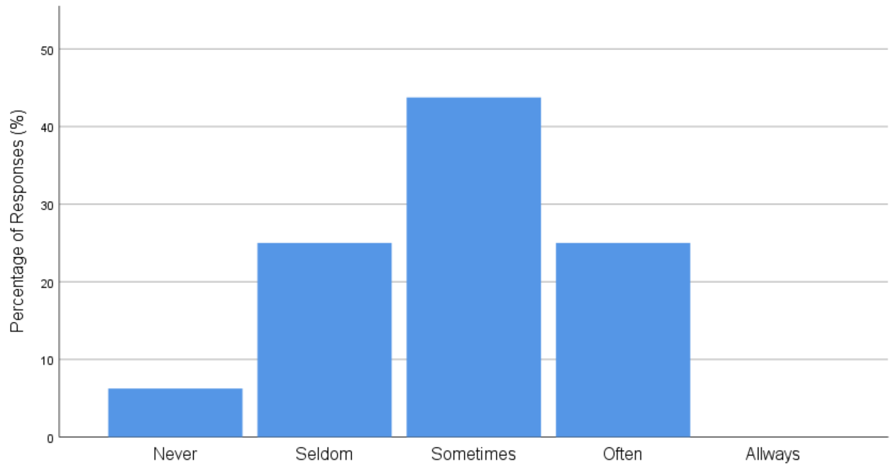


Figure 4-2 shows that 43% of participants report that they sometimes (one – three times per month) had problems falling to sleep at night. They reported that this was due to one of the following reasons: difficulty switching off following a busy day, being over tired, the room temperature, dietary considerations, i.e. sweet foods or caffeine shortly before bedtime, anxiety about having to wake early or not getting enough sleep and conversation with their partner.

Figure 4-2 When sleeping at home, do you have problems getting to sleep at night?



If participants wake during the night, they reported this being due to one of the following: noise, needing to use the toilet, room temperature, children or their partner. Figure 4-3 shows that 56% of participants indicate that it is reasonably easy to get back to sleep if they wake during the night.

Figure 4-3 If you wake during the night, on average, how difficult is it to go back to sleep?

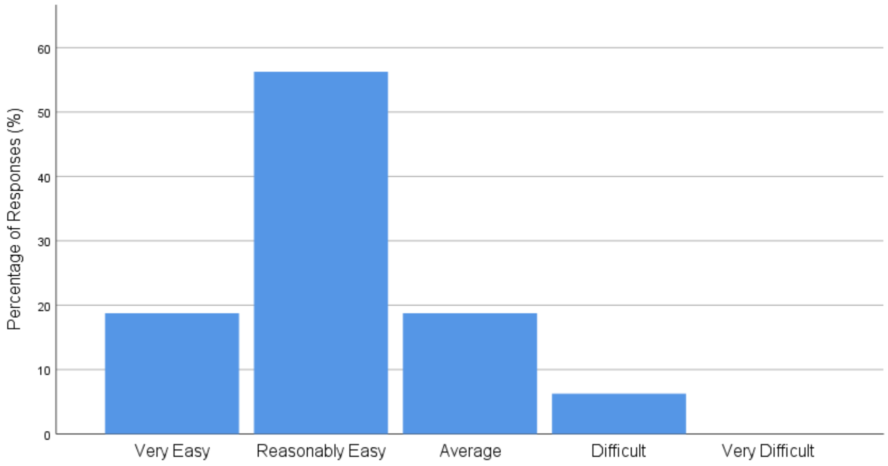
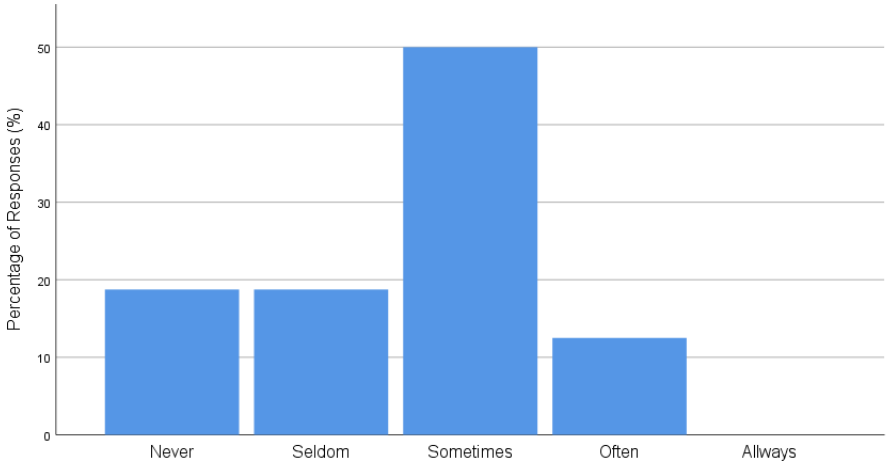


Figure 4-4 Napping during the daytime while at home



No participants reported taking anything to help with sleep. One participant reported having a sleep problem that related to the nature of duties rostered, such as irregular start and finish times and overnighting in different locations with different sleep environments. The sleep problem had not been diagnosed and did not stop the participant from working.

4.6 Flight Duty Period Protocol

In the day-to-day analyses, day 1 - 4 refers to the four days leading up to either the non-rested or rested simulated flight, where day 4 includes the final main sleep period before the non-rested or rested simulated flight. This section includes results for the following research question:

Q1: Do participants comply with this flight duty period protocol?

4.6.1 Flight Duty Period Protocol Test Details

Table 4-3 shows descriptive statistics for duty start and end time, length and sectors flown during each of the four days prior to the simulated flight. One hundred and eight flight duty periods were achieved which included 337 flights and 832.6 hours of duty time.

Table 4-3 Flight Duty Periods prior to the Non-rested and Rested Simulated Flight

Day Duty Period Occurs	**Variable**	**Non-rested condition**					**Rested condition**				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Day 1	Duty Start	07:58	03:28	06:52	05:00 – 15:42	16	08:37	03:12	07:05	05:39 – 12:20	9
	Duty End	16:36	02:28	16:30	12:52 – 20:29	16	17:18	04:11	15:35	12:09 – 21:54	9
	Duty Length (hours)	8.6	2.1	8.8	2.3 – 10.9	16	8.6	1.4	9.0	6.5 – 10.8	9
	Sectors	3.75	1	4	1 – 5	16	3.89	.782	4	3 – 5	9
Day 2	Duty Start	06:49	01:50	06:01	05:35 – 12:45	15	13:12	00:24	13:12	12:55 – 13:30	3
	Duty End	14:38	02:52	14:55	08:24 – 18:42	15	20:42	02:20	20:48	18:19 – 23:00	3
	Duty Length (hours)	7.8	2.3	8.8	2.0 – 10.2	15	6.3	2.1	6.3	4.8 – 7.9	3
	Sectors	3.53	1.24	3	1 – 5	15	1.67	1.52	2	0 – 3	3
Day 3	Duty Start	08:35	02:56	07:38	05:39 – 14:29	16	11:05	02:00	11:05	09:40 – 12:30	2
	Duty End	16:51	03:02	15:44	12:29 – 20:26	16	16:31	03:29	16:31	14:03 – 18:59	2
	Duty Length (hours)	8.2	1.2	9.6	5.0 – 9.6	16	5.4	1.4	5.45	4.4 – 6.5	2
	Sectors	3.69	.602	4	2 – 4	16	.50	.707	.50	0 – 1	2
Day 4 [a]	Duty Start	10:46	00:36	10:39	09:55 – 12:04	16	15:57	01:32	16:07	13:15 – 19:00	16
	Duty End	19:57	00:16	19:55	19:37 – 20:26	16	21:36	00:45	21:49	19:39 – 22:04	16
	Duty Length (hours)	9.1	0.7	9.28	7.5 – 10	16	5.6	1.1	5.8	2.7 – 6.5	16

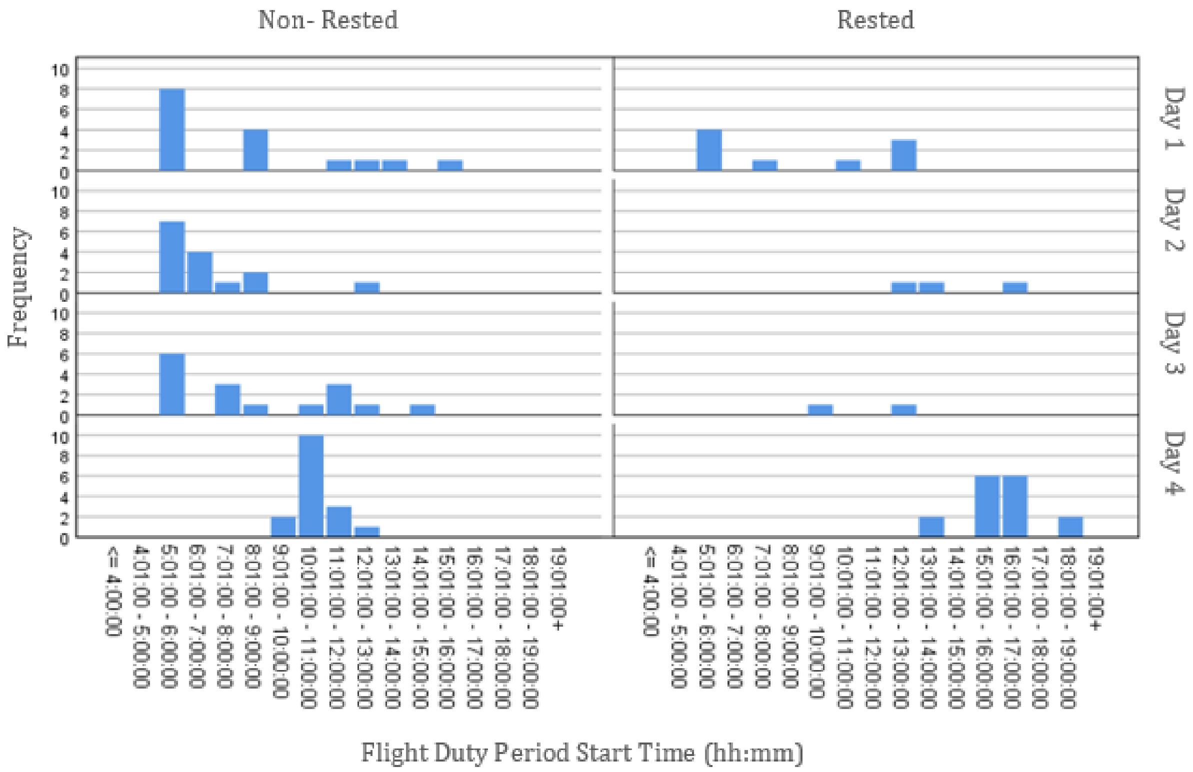
Day Duty Period Occurs	**Variable**	**Non-rested condition**					**Rested condition**				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
	Sectors	3.25	.683	3	2 – 4	16	1.88	.342	2	1 – 2	16

a Day 4 includes either the non-rested simulated flight (18:00 – 20:00) or the rested simulated flight (20:00 – 22:00).

Flight Duty Period Start Time

Figure 4-5 shows the frequency of flight duty period start times grouped in one hour bins between 04:00 – 19:00. In the non-rested condition, during days 1, 2 and 3, most flight duty periods started between 05:01-07:00. During day 4, all flight duty periods started between 09:01-13:00, with 62.5% starting between 10:00-11:00. The later start on day 4 was required due to the operator's 10 hour flight duty period length limitation. During day 4 of the rested condition, 37.5% of flight duty periods started between 15:01 – 16:00 with another 37.5% starting between 16:01 -17:00. Eighty seven percent of participants needed to position from their respective home base prior to operating the rested simulated flight.

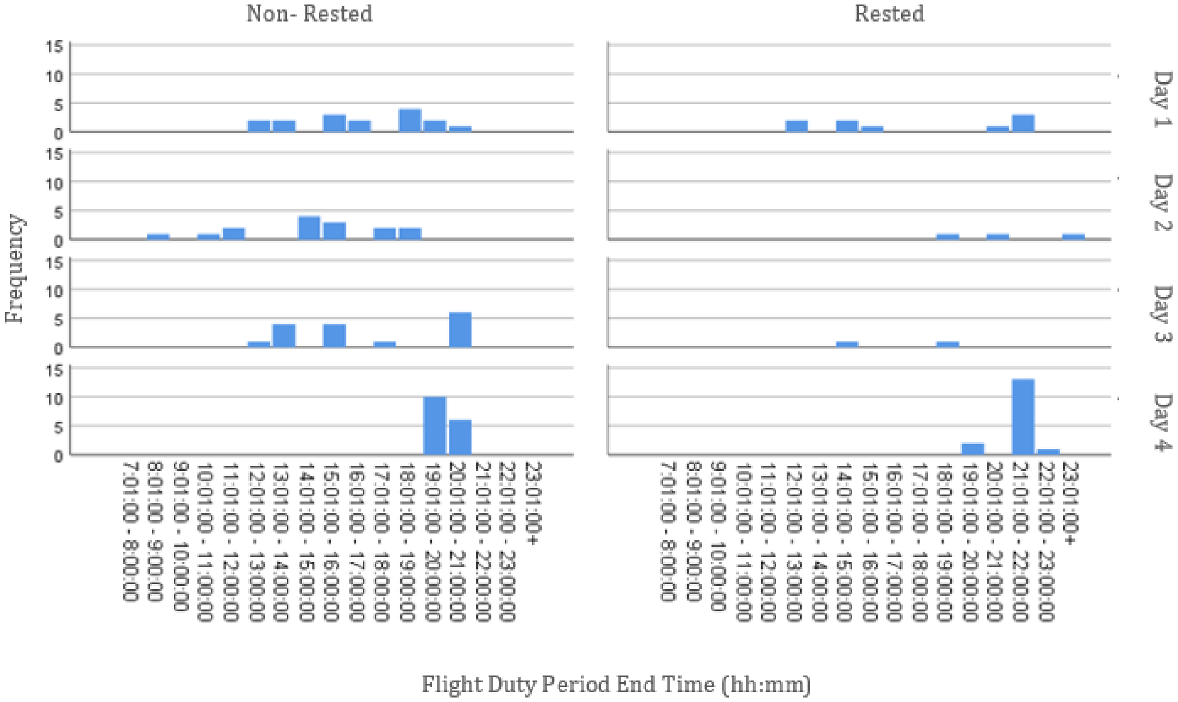
Figure 4-5 Flight Duty Period Start Times during Days 1 - 4 grouped by Condition



Flight Duty Period End Time

Figure 4-6 shows the frequency of flight duty period end times grouped in one hour bins between 04:00 and 19:00. End times were variable, aside from those associated with simulated flights during day 4. During the rested condition, two duty periods finished after 22:00.

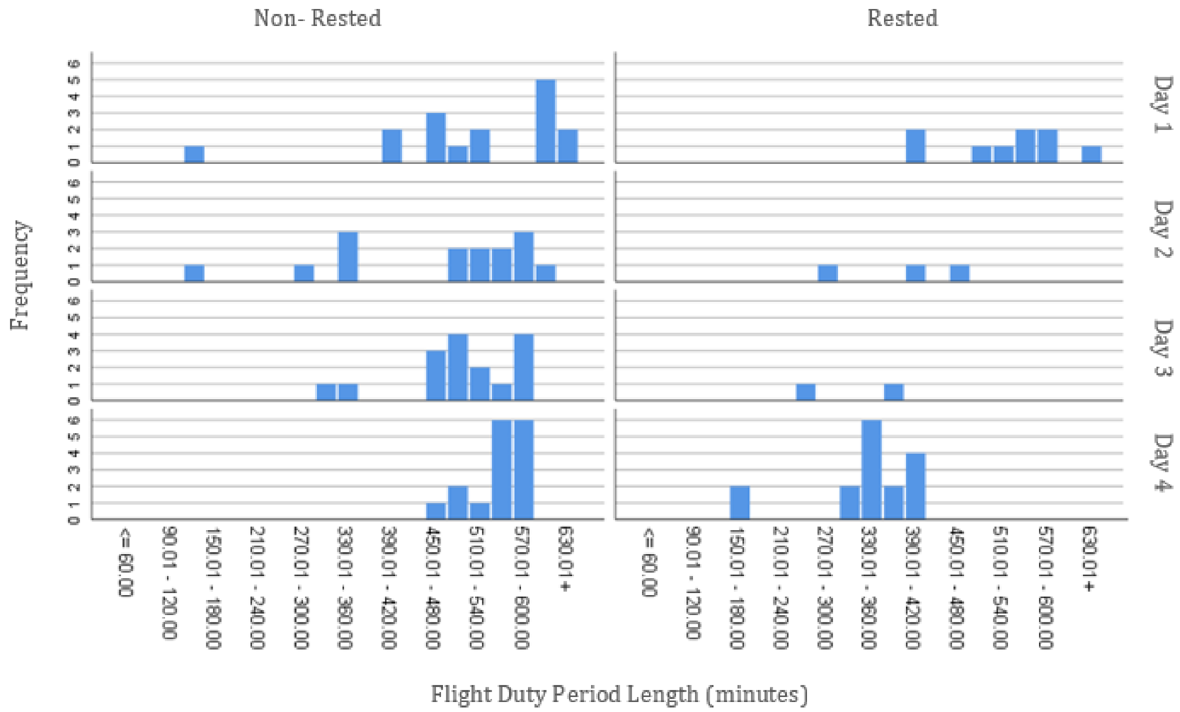
Figure 4-6 Flight Duty Period End Time during Days 1 - 4 grouped by Condition



Flight Duty Period Length

Figure 4-7 shows flight duty period length grouped in 30 minute bins, between 60 and 630 minutes (one hour – 10.5 hour). In the non-rested condition, during day 1, 44% of duties were longer than 10 hours. This reduces to 7% in day 2 and in day 3 and 4, no duties exceeded 10 hours. In the rested condition, 11% of duties were longer than 10 hours during day 1, however, no duties exceeded 10 hours during day 2, 3 or 4. The mean duty length on day 4 in the non-rested condition was 9 hours 10 minutes compared with 5 hours 40 minutes in the rested condition.

Figure 4-7 Flight Duty Period Length during Days 1 - 4 grouped by Condition



Number of Sectors During Flight Duty Periods

Figure 4-8 shows the number of sectors flown during each flight duty period. To track all flights that occurred during a flight duty period, the sector count includes flights flown by participants, positioning flights where the participant is a passenger and simulated flights that were flown by participants. In the non-rested condition, during day 1, 68% of duties had four or more sectors compared with 40% during day 2, 75% during day 3 and 37.5% during day 4[68]. In the rested condition, during day 1, 66% of duties had four or more sectors. During days 2 and 3, two duties had zero sectors[69] and three duties had one sector. During day 4, 87.5% of duties included a positioning sector as 14 of the 16 participants needed to position to the city where the flight simulator was located prior to

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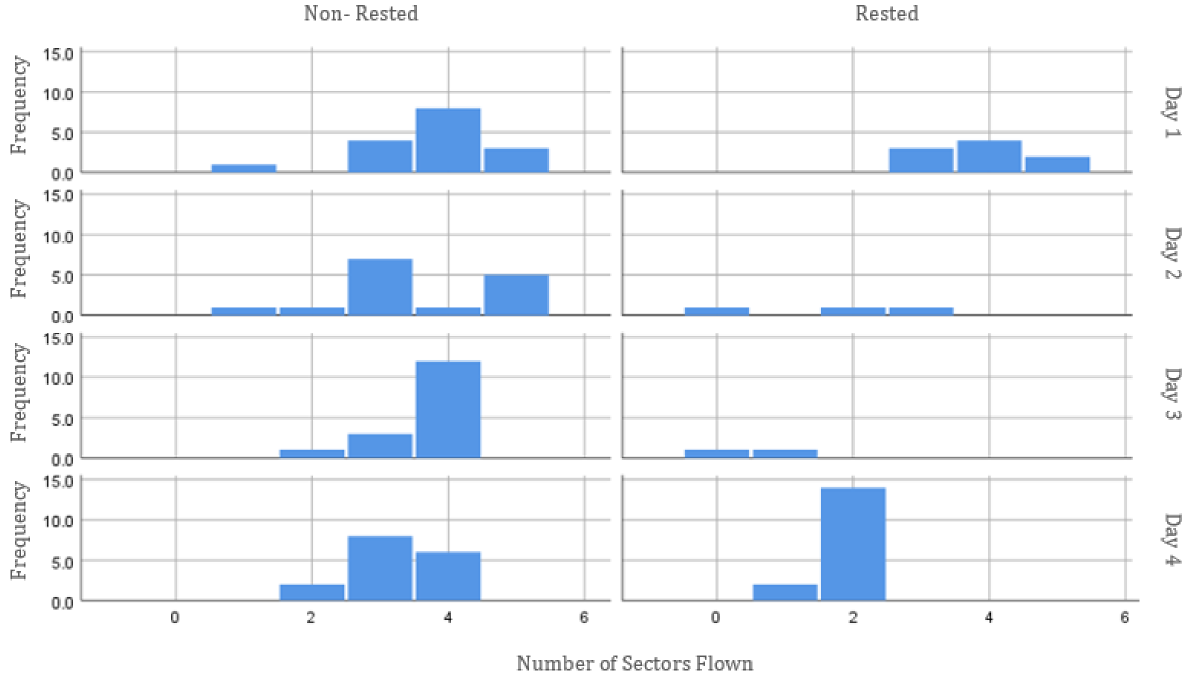
[68] Prior to their non-rested simulated flight, eight participants operated flights immediately prior to the simulated flight, six participants positioned to the city where the flight simulator was located, and two participants positioned to an airport where they then operated a flight to the city where the flight simulator was located.

[69] These duties included simulated flights that were not associated with this study.

operating their rested simulated flight. No sectors were operated by participants on the day of their rested simulated flight.

Figure 4-8 Sectors Count during the Flight Duty Period Protocol during Days 1 - 4 grouped by Condition



Comparison of Published Flight Duty Periods with Study Flight Duty Periods

To determine if flight duty periods in the present study were representative of flight duty periods operated by pilots, comparisons were made between study flight duty periods and achieved flight duty periods that were operated by pilots during a 14-day roster period that overlapped with data collection. A total of 108 study flight duty periods and 1463 achieved flight duty periods were compared. Duties on day four were excluded from this comparison as they included a simulated flight. Table 4-4 shows that study flight duty periods started earlier (U = 65781.500, z = -3.348, p = 0.001), were longer (U = 38145, z = -4.124 p = 0.000) and included more sectors (U = 39193, z = -4.028, p = 0.00) than flight achieved flight duty periods.

Figure 4-9 shows that 42% of study flight duty periods start before 07:00 compared with 26% of achieved flight duty periods. Figure 4-10 shows that 29.5% of study flight duty periods are 9.5 hours or longer compared with 12% of achieved flight duty periods.

Figure 4-9 Flight Duty Period Start Times (excluding day 4).

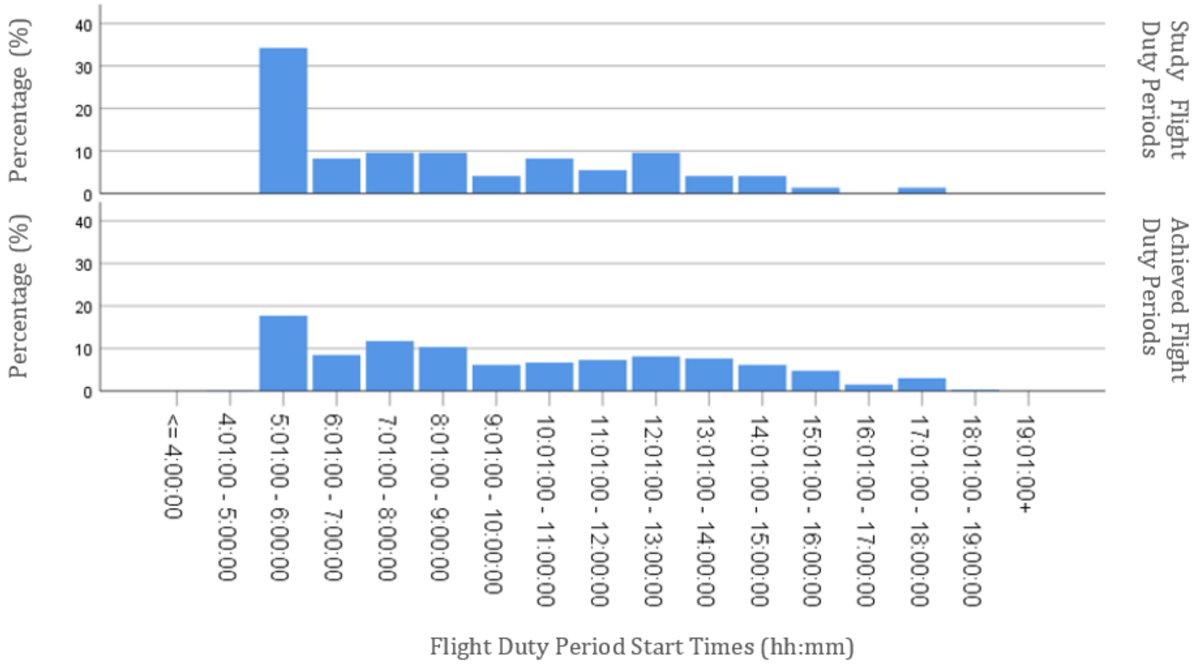


Figure 4-10 Flight Duty Period Duty Length (excluding day 4)

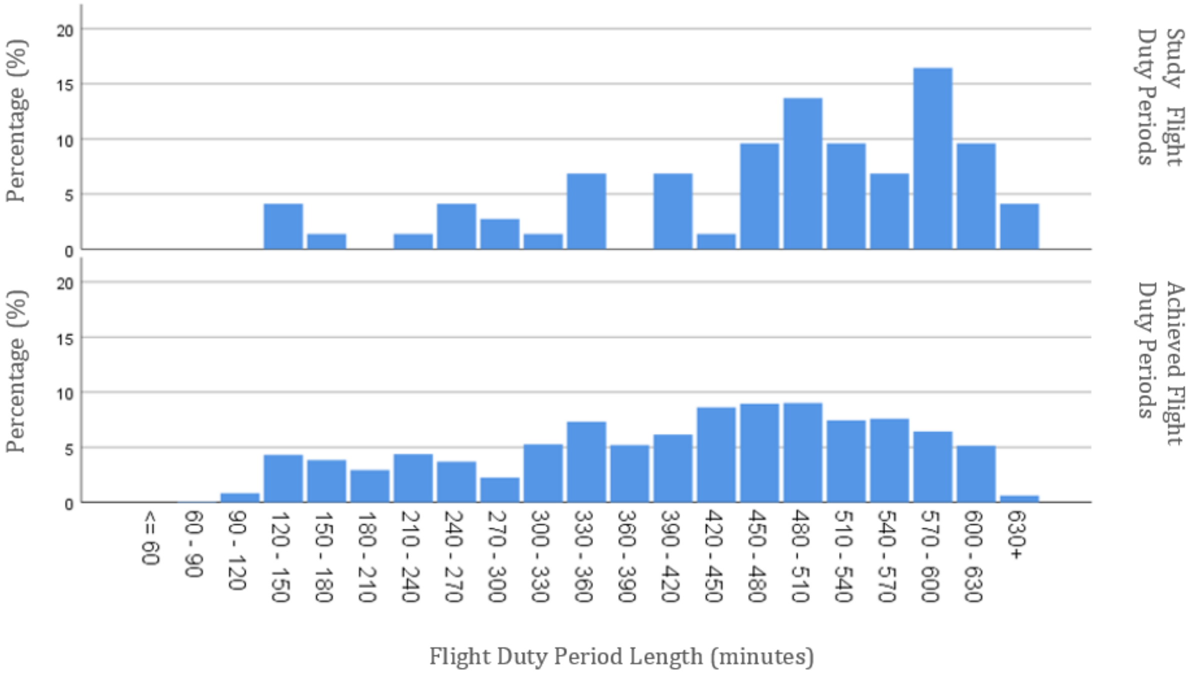


Table 4-4 Comparison of Study Flight Duty Periods with Achieved Flight Duty Periods (excluding day 4)

Variable	**Study flight duty periods**					**Achieved flight duty periods**					
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N	P[a]
Duty Start (hh:mm)	08:36	3:13	07:50	05:00 – 17:30	73	09:56	3:29	09:20	0430 – 18:55	1463	0.01
Duty End (hh:mm)	16:29	3:26	15:36	08:25 – 21:55	73	16:45	3:32	17:26	07:25 – 22:28	1463	0.51
Duty Length (hours)	7.8	2.2	8.3	2.0 – 10.9	73	6.8	2.3	7.25	1.25 – 11.0	1463	0.00
Sectors	3.49	1.05	4	1 – 5	73	3.02	1.02	3	1 – 5	1463	0.00

a Mann-Whitney U test.

4.6.2 Results

Flight Duty Period Protocol Violations

All data collected from participants, including data collected during flight duty period protocol violations, was included for analyses described within this chapter and within Chapters 5 and 6. Each flight duty period violation was carefully reviewed, and consideration given to the impact of including or excluding a dataset (see Section 2.7).

Non-rested Condition

Figure 4-11 shows that 15 participants operated four consecutive flight duty periods, and that one participant operated two consecutive flight duty periods prior to their non-rested simulated flight. The participant that did not work during day 2, removed themselves from duty, prior to the start of duty because of fatigue[70, 71].

Rested Condition

Figure 4-12 shows that during the rested condition, three flight duty periods were operated during day 2 and two flight duty periods were operated during day 3. These flight duty periods were operated by three participants who were not rostered to operate these duties, rather, they were requested by Operations Control to operate the duties to cover unforeseen circumstances. Two of the flight duty periods involved simulator duties not related to this study. One of these simulator flight duty periods encroaching the local night due to its late finish (23:00). Table 4-5 shows descriptive statistics for start, end,

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[70] Removal from duty due to fatigue is a key fatigue risk mitigation. It was reiterated to participants that removal from duty would in no way jeopardize the study and that if fatigue was experienced, that removal from duty was expected.

[71] The participant had been rostered to operate a four sector duty with a sign on time of 07:50 and a sign off time of 17:55. The previous day, they signed on at 05:37 and signed off at 16:30 having flown five sectors. At the completion of the duty on day 1, they removed themselves from duty.

length and the number of sectors flown for each of those five flight duty periods described above.

Table 4-5 Flight Duty Periods flown during Day 2 and 3 of the Rested Condition

Flight duty period	**Variable**			
	Duty Start	Duty End	Duty Length (hh:mm)	Sectors
Day 2	13:30	18:20	04:50	2
Day 2 [b]	12:55	20:49	07:54	3
Day 2 [a, c]	16:30	23:00	06:30	0
Day 3 [b]	09:40	14:40	04:24	1
Day 3 [a, c]	12:30	19:00	06:30	0

a This duty represents a flight simulator detail associated with the operators training programme; b Operated by the same participant; c Operated by the same participant.

Flight Crew Familiarity

The flight duty period protocol was designed to ensure that flight crew (consisting of two pilots) operated together prior to their first simulated flight while also ensuring that they operated together during the four day period prior to the non-rested simulated flight. Table 4-6 shows that seven of eight flight crew flew a minimum of four flights together before the first simulated flight and that all flight crew flew a minimum of six flights together before the non-rested simulated flight. Flight crew rostered to complete their rested simulated flight first had a reduced opportunity to operate together. Of those four flight crews, one flight crew did not operate together (flight crew A) due to training programme requirements, two flight crew operated one flight duty period together and one flight crew operated two flight duty periods together. All flight crew flew together prior to their non-rested simulated flight with six flight crew operating four consecutive flight duty periods during the non-rested condition. One flight crew operated three flight duty periods together and one flight crew (flight crew A) operated two flight duty periods together which was the only time this crew operated together during their flight duty period protocol.

Table 4-6 Flight Crew Familiarity prior to the First Simulated Flight

Variable	**Study duty periods**				
	Mean	SD	Median	Range	N
Sectors flown as crew prior to first simulated flight	8	3.03	9	4 – 12	7
Minutes flown as crew prior to first simulated flight	589.5	235.1	636	254 – 900	7
Sectors flown as crew prior to the non-rested simulated flight	10.12	2.98	10	6 – 14	8
Minutes flown as crew prior to the non-rested simulated flight	747	218	750	406 – 1043	8

Simulated Flight Timing

Figure 4-11 shows that all non-rested simulated flights occurred between 18:00 and 20:00 and Figure 4-12 shows that one flight crew completed their rested simulated flight between 18:00 and 20:00. These participants had their rested simulated flight rescheduled as the simulator was unserviceable. Retiming this simulated flight allowed these participants to report for their next flight duty period earlier. For all other participants, there rested simulated flight occurred between 20:00 and 22:00

Figure 4-11 Flight Duty Periods and Sleep Periods across the Four Days Prior to the Non-rested Simulated Flight

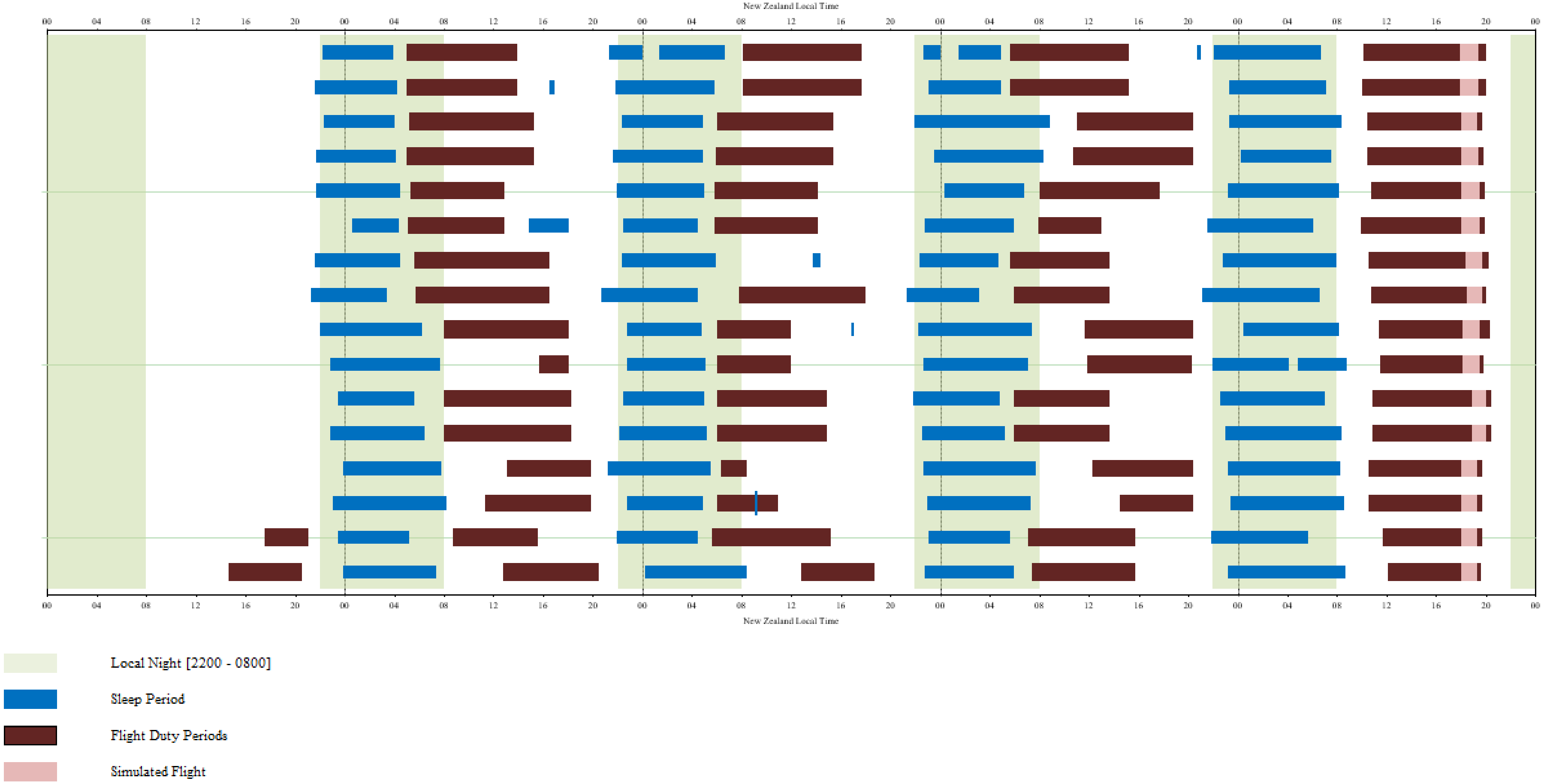
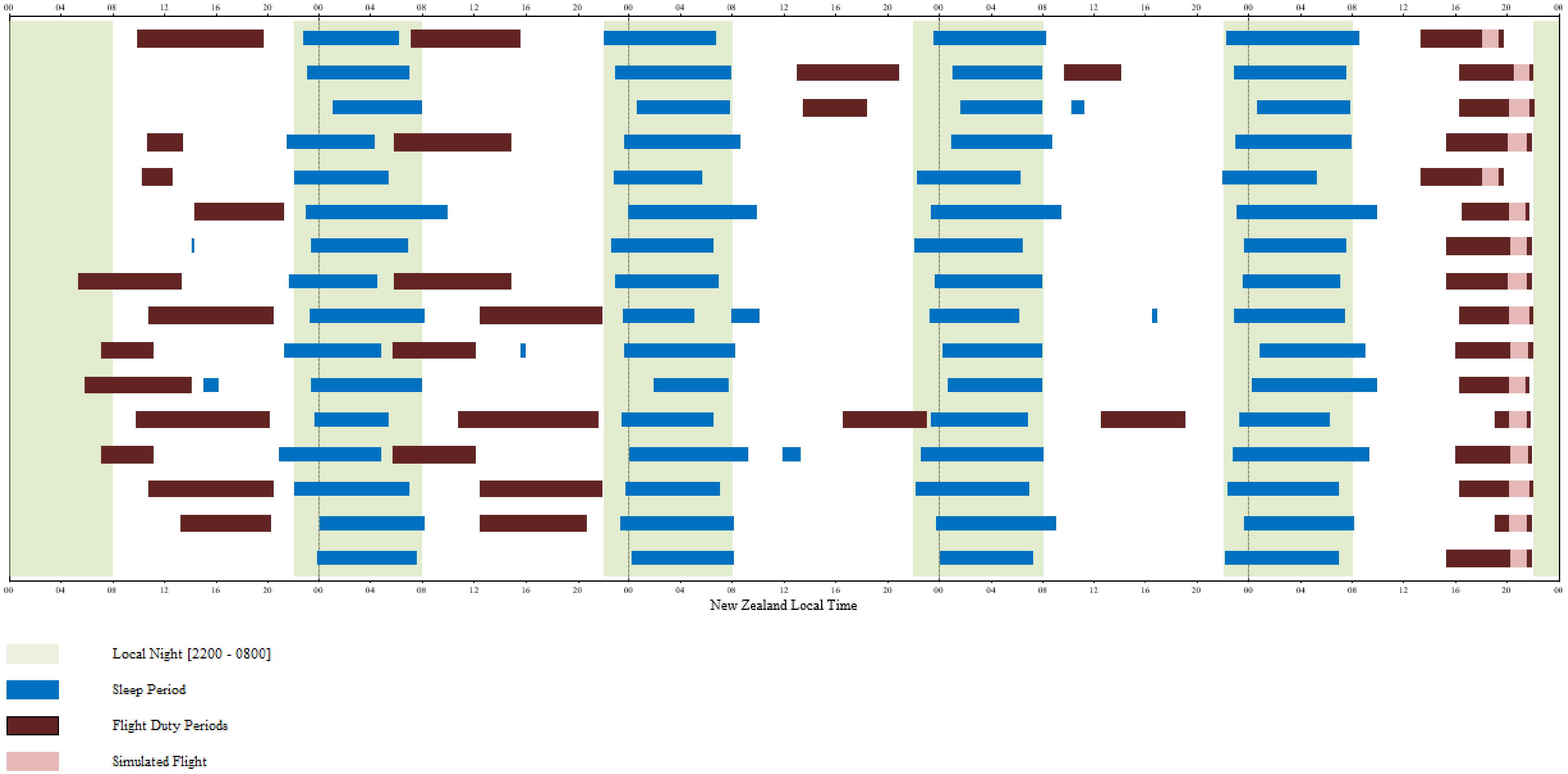


Figure 4-12 Flight Duty Periods and Sleep Periods across the Four Days Prior to the Rested Simulated Flight



4.7 Subjective Ratings of Workload

4.7.1 Test Details

Workload ratings were recorded following flight duty periods during days 1 - 4 and following simulated flights. Of the 96 possible ratings, 95 were recorded. Distributions for workload ratings following flight duty periods and simulated flights, the non-rested and rested condition, the first and second simulated flight and the Christchurch – Wellington and Wellington Christchurch simulated flight are presented in Figure 4-13 - Figure 4-16. Descriptive statistics for workload ratings are outlined in Table 4-7 (flight duty periods during days 1 - 4), Table 4-8 (flight duty periods versus simulated flights), Table 4-9 (condition), Table 4-10 (order) and Table 4-11 (location). No outliers were identified. Although workload ratings were not normally distributed, see Figure 4-13 - Figure 4-20, where applicable, studentized residuals associated with mixed model ANOVA were transformed to normalise their distribution, see Table 4-12 and Table 4-13.

Figure 4-13 Workload Following Flight Duty Periods and Simulated Flights

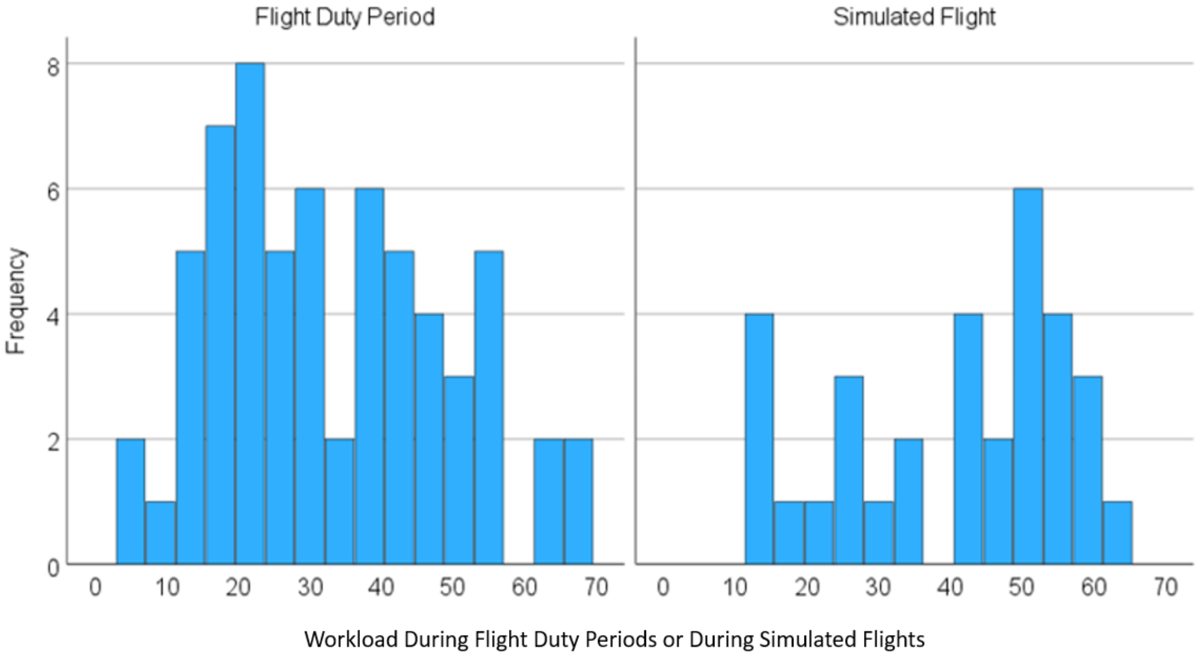


Figure 4-14 Workload Following Simulated Flights grouped by Condition

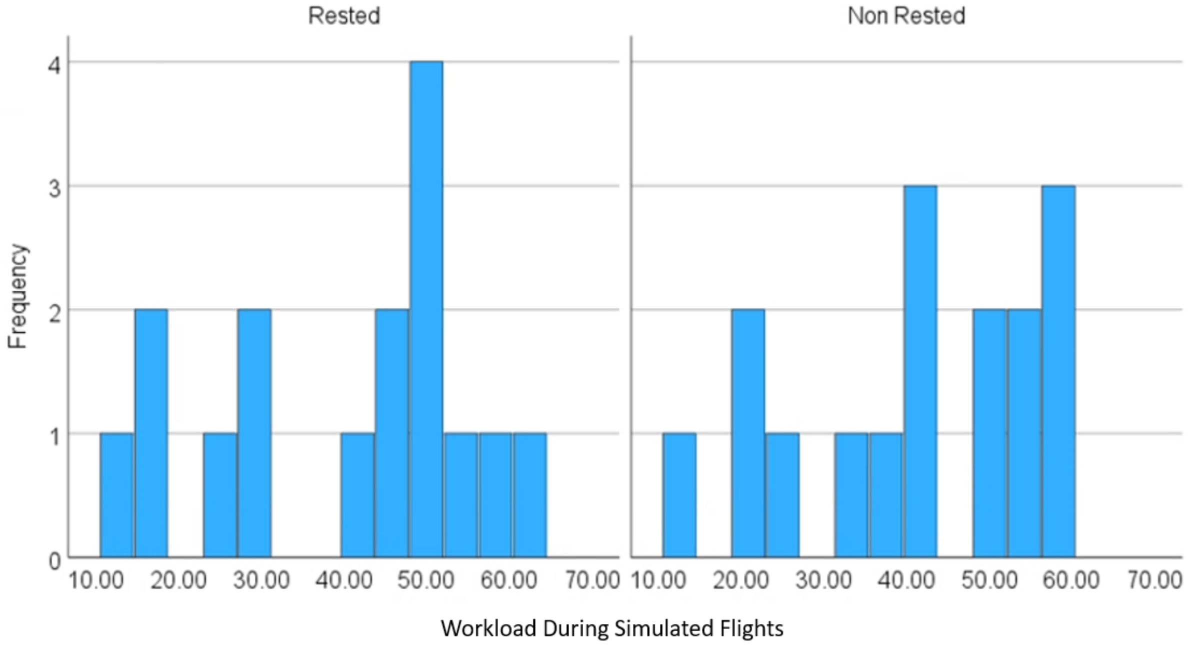


Figure 4-15 Workload grouped by Order

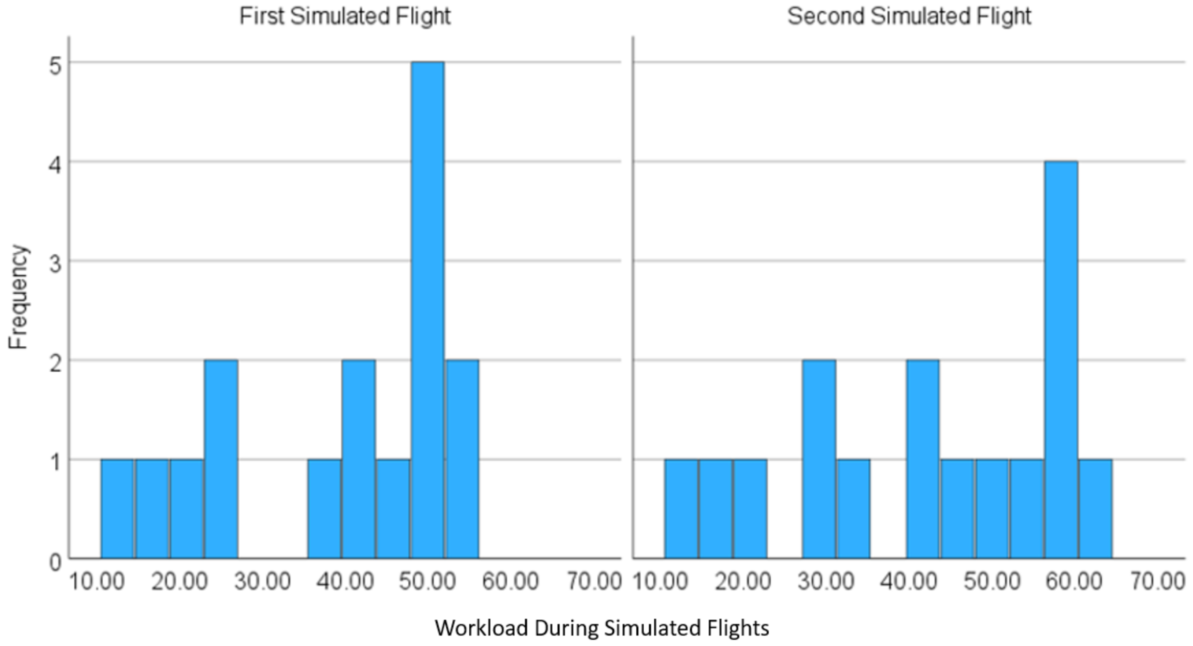


Figure 4-16 Workload grouped by Location

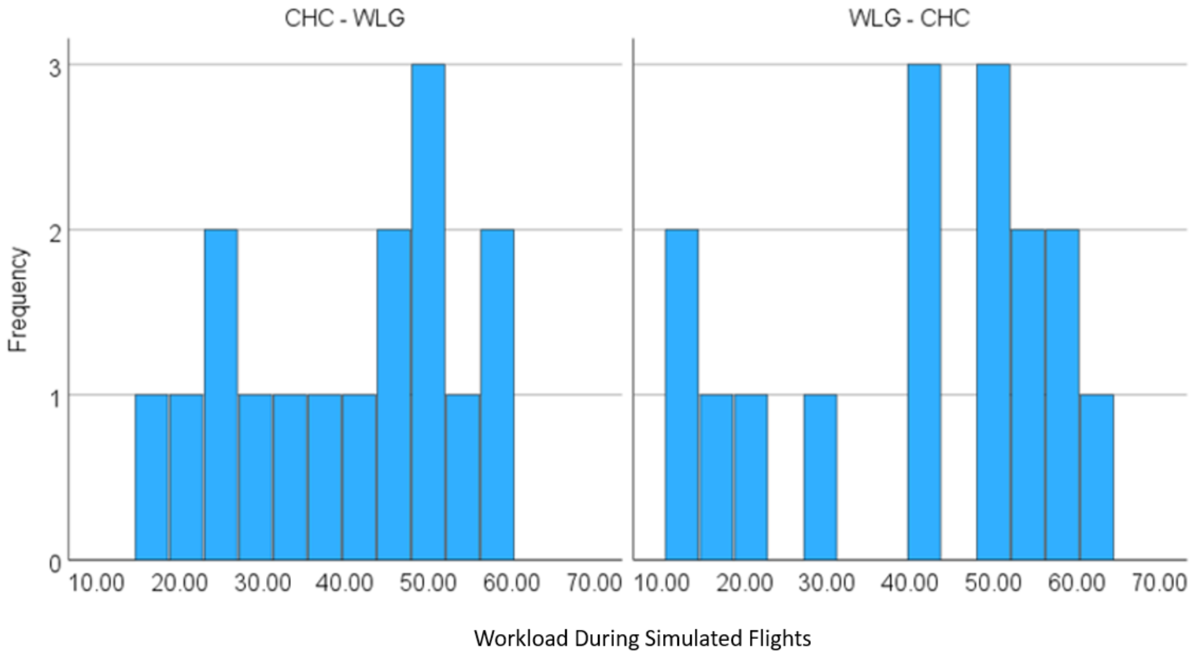


Figure 4-17 Workload during the Flight Duty Period on Day 1

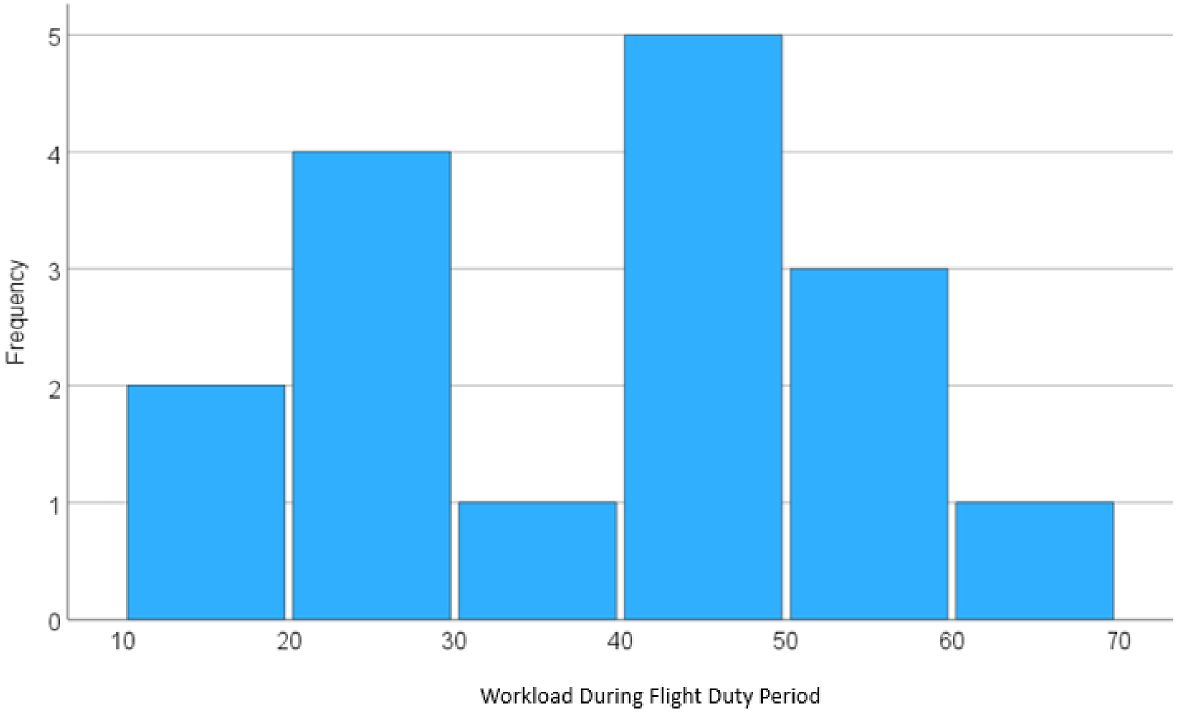


Figure 4-18 Workload during the Flight Duty Period on Day 2

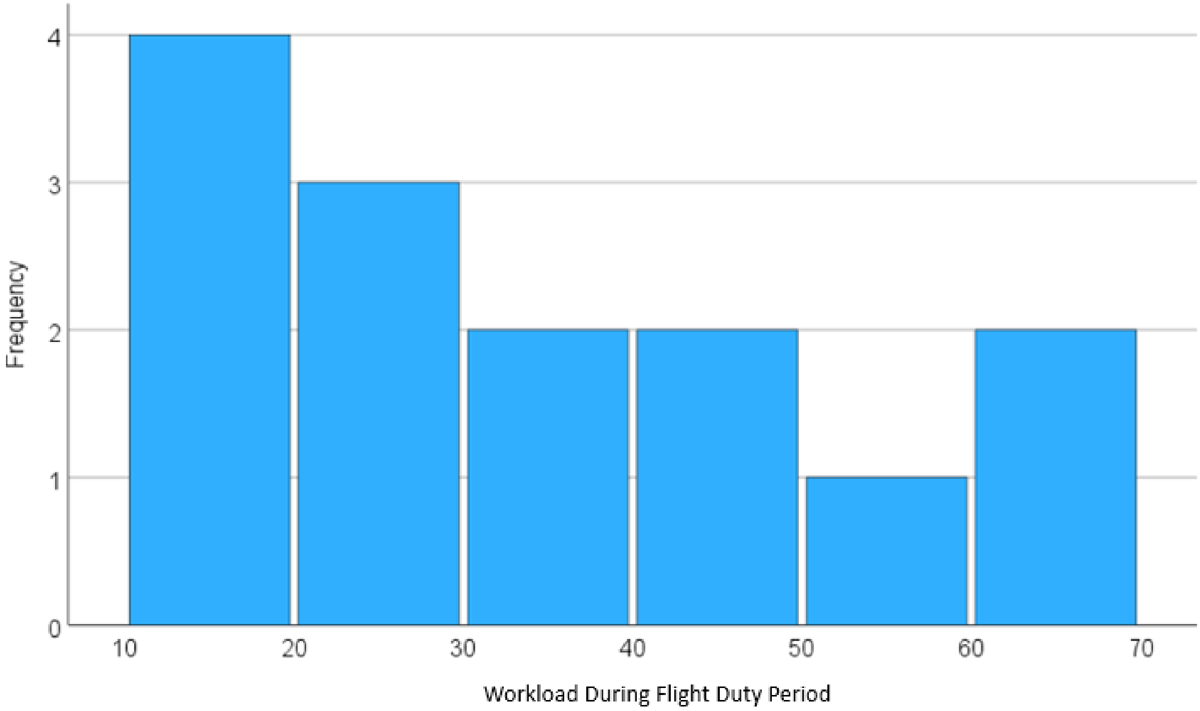


Figure 4-19 Workload during the Flight Duty Period on Day 3

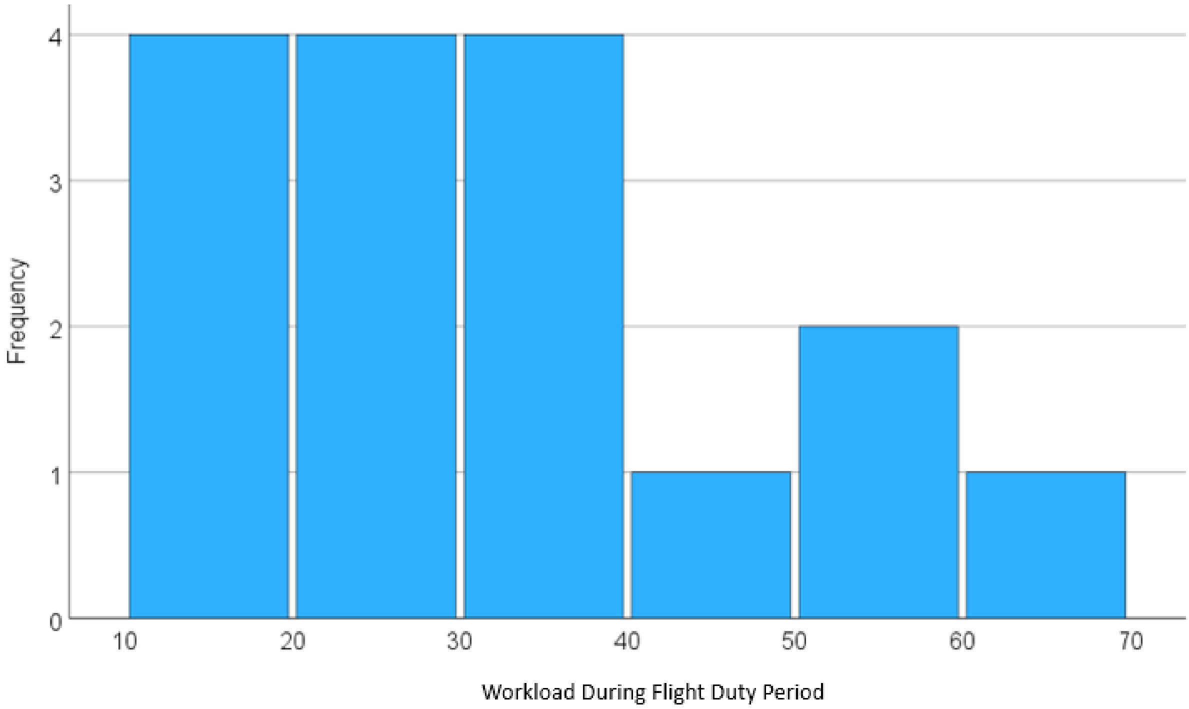


Figure 4-20 Workload during the Flight Duty Period on Day 4

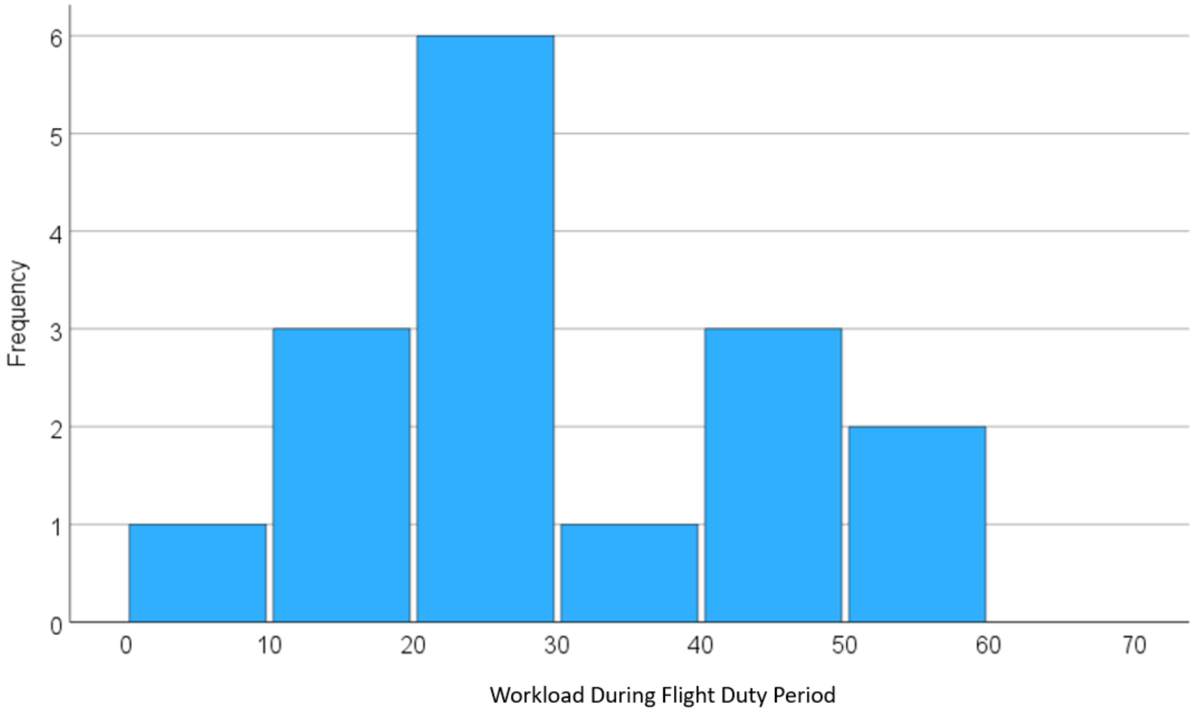


Table 4-7 Mean, Standard Deviation, Median and Range of Workload during Flight Duty Periods on Days 1 - 4

Variable	**Flight duty period**				
	Mean	SD	Median	Range	N
Workload on Day 1	38.4	15.9	40.8	52 (16 – 68) [a]	16
Workload on Day 2	31.33	18.5	29.1	61 (7 – 68)	15
Workload on Day 3	31.4	16	25.8	53 (12 – 65)	16
Workload on Day 4	30.2	15	27.9	52 (5 – 57) [a]	16

[a] Not normally distributed.

Table 4-8 Mean, Standard Deviation, Median and Range of Workload during Flight Duty Periods and Simulated Flights

Variable	**Flight duty period**					**Simulated flight**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Workload	32.9	16.3	29.1	63 (5 – 68) a	63	40.6	15.8	45	49 (13 – 62) [a]	32

[a] Not normally distributed.

Table 4-9 Mean, Standard Deviation, Median and Range of post Simulated Flight Workload grouped by Condition

Variable	**Non-rested condition**					**Rested condition**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Workload	41.45	15.5	42.5	47.5 (12.5 – 60) [a]	8	39.8	16.5	47.5	48.3 (13.3 – 61.6)	8

[a] Not normally distributed.

Table 4-10 Mean, Standard Deviation, Median and Range of Simulated Flight Workload Ratings grouped by Order

Variable	**First flight**					**Second flight**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Workload	39.2	15.1	45	43 (12.5 – 55.8)	16	42	16.8	45	48.3 (13.3 – 61.6)	16

Table 4-11 Mean, Standard Deviation, Median and Range of Simulated Flight Workload grouped by Location

Variable	**CHC – WLG**					**WLG – CHC**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Workload	40.31	14.5	45	45 (15 – 16)	16	40.98	17.5	45.83	49.17 (12.5 – 61.6)	16

4.7.2 The Effect of Flight Duty Periods and Simulated Flights on Workload

This section includes analysis and results for the following research question:

Q2: Do workload ratings differ between flight duty period flights and simulated flights?

4.7.2.1 Analysis

Descriptive statistics for workload following simulated flights and workload following flight duty periods are outlined in Table 4-8. Table 4-12 lists a summary of results for the effect of type of duty on ratings of workload.

Table 4-12 Results of mixed model ANOVA for the effect of Type of Duty: Simulated Flight or Flight Duty Periods on Workload Ratings

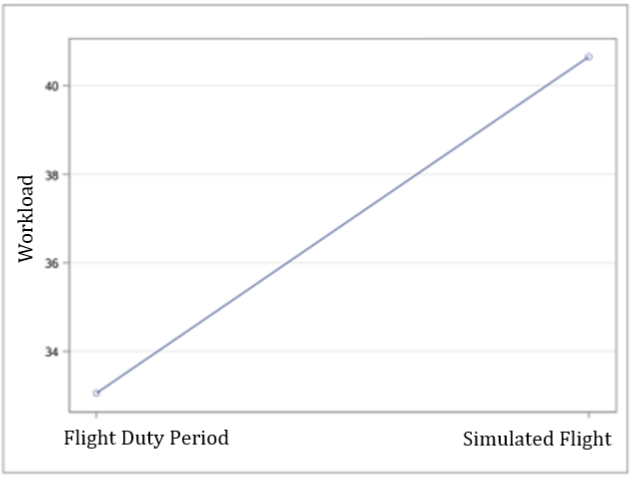
Dependent variable	Independent variable	DF	F-value	P(F)
Workload [a, b]	Type of Duty: Simulated Flight or Flight Duty Period	1, 78	7.05	.0096

[a] The number of observations used: 95/95, [b] Studentized residuals normally distributed.

4.7.2.2 Results

Figure 4-21 shows that ratings of workload during the simulated flights were significantly higher (estimated mean = 40.6) than ratings of workload during flight duty periods (estimated mean = 33.0).

Figure 4-21 LS-means Estimates for the Effect of Type of Duty: Simulated Flight or Flight Duty Periods on Workload Ratings



4.7.3 The Effect of Condition, Order and Location on Workload

This section includes analysis and results for the following research questions:

Q3: Do workload ratings differ between the non-rested and rested simulated flight?

Q4: Do workload ratings differ between the first and second simulated flight?

Q5: Do workload ratings differ between the Christchurch – Wellington and Wellington – Christchurch simulated flight?

4.7.3.1 Analysis

The purpose of this analysis was to identify if workload ratings differ significantly by condition, location or order. Table 4-13 lists a summary of results for the effect of the non-rested or rested condition, the Christchurch – Wellington or Wellington – Christchurch flight and the first or second simulated flight on ratings of workload. Descriptive statistics for workload by condition, location, and order are outlined in Section 4.7.1.

Table 4-13 Results of mixed model ANOVA for the effect of Condition, Location and Order on Simulated Flight Workload Ratings

Dependent variable	Independent variable	DF	F-value	P(F)
Workload [a, b]	Condition	1,13	0.02	.9005
	Location	1,13	0.14	.7147
	Order	1,13	2.25	.1578

[a] The number of observations used: 32/32; [b] REFL LOG transformation applied to normalise studentized residual distribution.

4.7.3.2 Results

As shown in Table 4-13, workload ratings were not significantly different between the non-rested and rested condition, the first and second simulated flight or the Christchurch – Wellington or Wellington – Christchurch simulated flights.

4.7.4 The Effect of Sleep Related Variables on Workload

This section includes analysis and results for the following research question:

Q6: Are workload ratings associated with cumulative sleep debt, time since sleep, or total sleep time in the previous 24 hour or 48 hour period?

4.7.4.1 Analysis

Table 4-14 lists results for the effect of cumulative sleep debt, time since sleep at the start of the simulated flight and total sleep in 24hrs and 48hrs on ratings of workload during simulated flights. Descriptive statistics for the variables mentioned in Table 4-14 are included in Section 4.8.1.1. Table 4-15 shows the direction of association between dependent and independent variables.

Table 4-14 Results of mixed model ANOVA for the effect of Sleep Related Variables on Workload during Simulated Flights

Dependent variable	Independent Variable	DF	F-value	P(F)
Workload [a b c]	Cumulative Sleep Debt	1,25.7	1.67	.2076
	Time Since Sleep	1,27.9	0.41	.5288
	Total Sleep in 24hrs	1,23.7	0.32	.5757
Workload [a b c]	Cumulative Sleep Debt	1,25.4	1.64	.2121
	Time Since Sleep	1,26.6	0.21	.6467
	Total Sleep in 48hrs	1,23.5	0.08	.7793

[a] The number of observations used: 32/32; [b] REFL LOG transformation applied to normalise distribution; [c] includes 1 outlier.

Table 4-15 Direction of Association between Subjective Ratings of Workload and Sleep Related Variables

Dependent Variable	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs
Workload	▲	▼	▼	⬛
Workload	▲	▼	⬛	▼

▲	Increase in IV = Increase in DV
▼	Increase in IV = Decrease in DV
🟦	Significant Association
☐	Non-significant trend
⬛	Independent variable not included within the model

4.7.4.2 Results

Cumulative sleep debt, time since sleep at the start of the simulated flight and total sleep in the previous 24 hour period or 48 hour period were not significantly associated with ratings of workload.

4.8 Sleep Timing, Duration and Time Since Sleep

4.8.1 Test Details

Total sleep in 24hrs, cumulative sleep debt, the start of sleep, the end of sleep and time in bed were calculated across the four day period (day 1 - 4) prior to each simulated flight. In addition, at the start of the simulated flight, total sleep in 48hrs, and time since sleep at the start of the simulated flight was calculated. Similarly, the time since sleep at the start of the pre and post simulated flight PVT test were calculated. A descriptive summary of sleep periods is provided in Section 4.8.1.1 and a descriptive summary of sleep timing and duration in non-baseline and baseline sleep periods is provided in Section 4.8.1.2. Participants' flight duty periods, sleep periods and baseline sleep during their participation in the study are shown in Figure 4-22 for 11 nights prior to the non-rested simulated flight and in Figure 4-23 for 11 nights prior to the rested simulated flight. Flight duty periods are represented by dark brown bars, estimated sleep periods by light blue bars[72], actigraphically recorded sleep periods by dark blue bars, baseline sleep periods by dark green bars and each simulated flight by light pink bars. Each row represents a participant's data, with white columns representing each day of the study and light green columns representing each local night (22:00 – 08:00). Row order has been randomised so that data for each flight crew are not necessarily plotted together.

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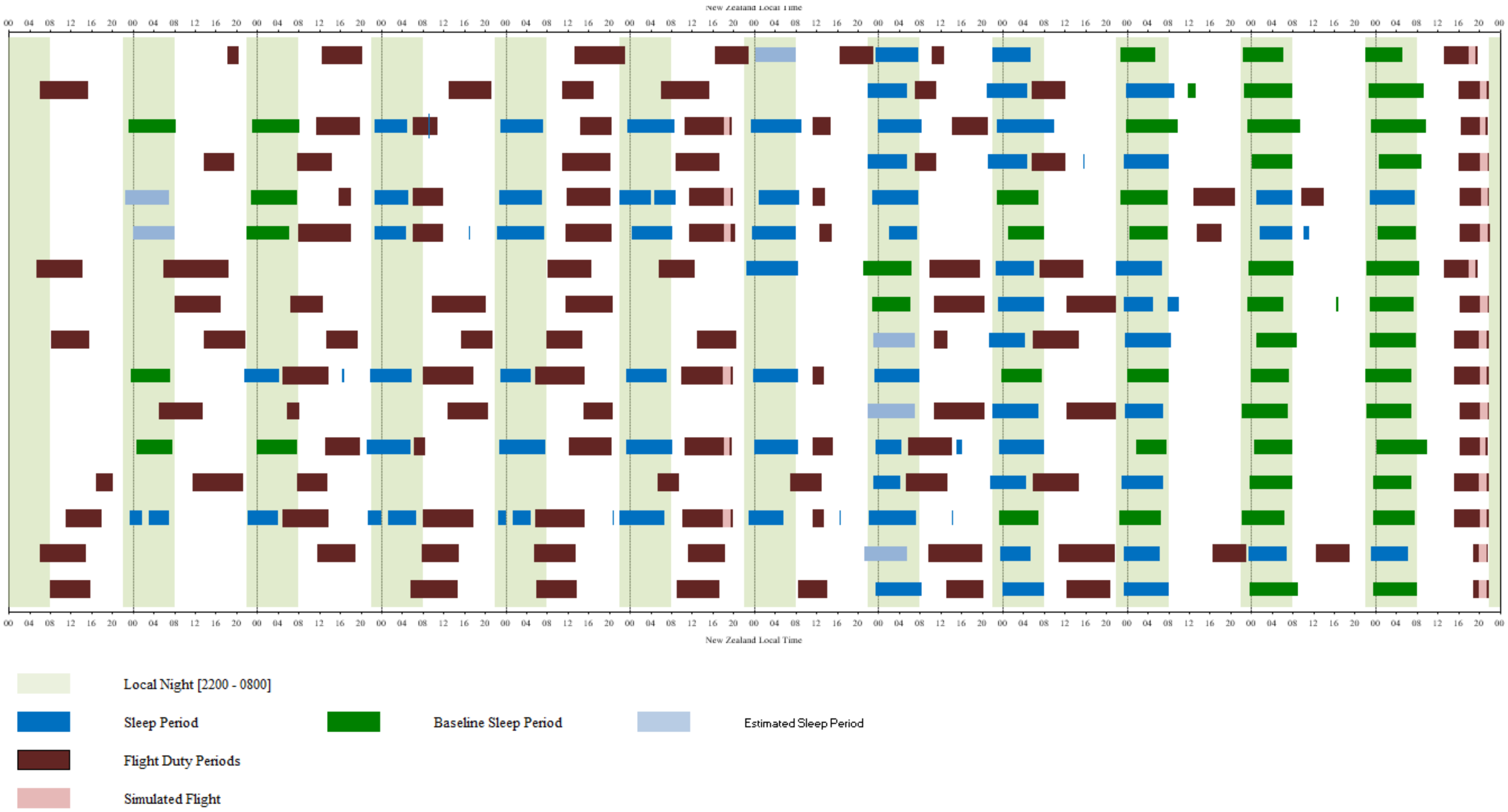
[72] In the absence of actigraphically derived sleep records, sleep periods were estimated using sleep diary entries. Subjective estimates of sleep duration correlate highly with polysomnography (Signal et al., 2005).

Figure 4-22 Flight Duty Periods, Sleep Periods and Baseline Sleep Periods across 11 Days Prior to the Non-Rested Simulated Flight

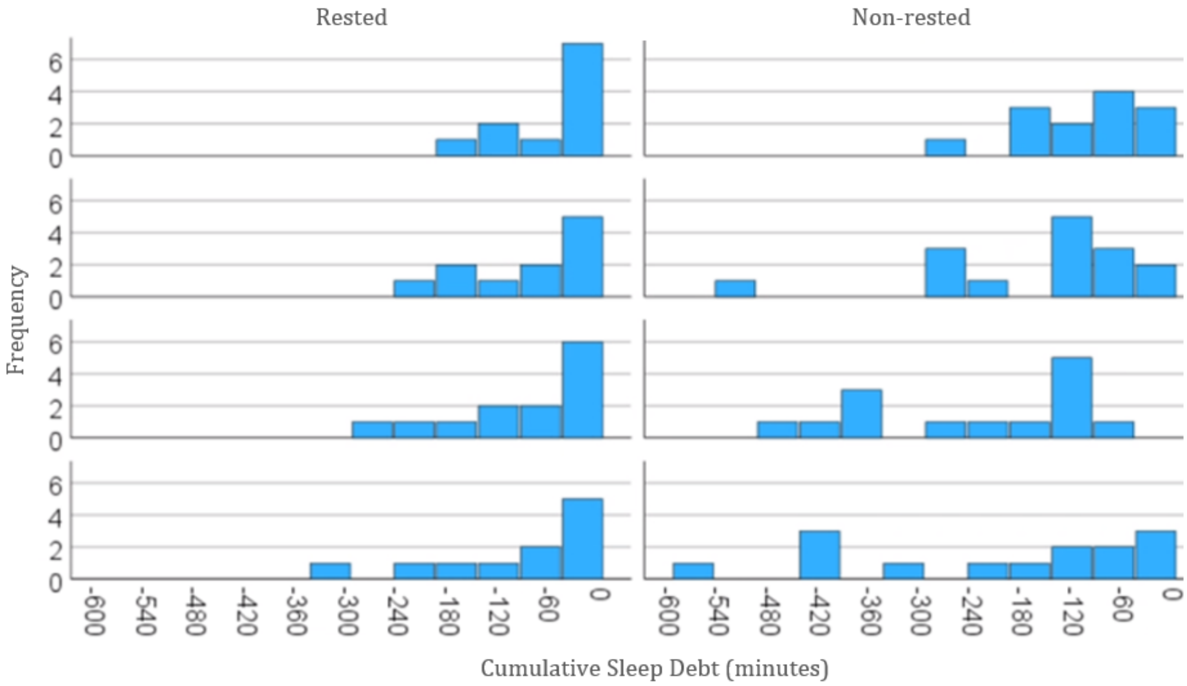
Figure 4-23 Flight Duty Periods, Sleep periods and Baseline Sleep Periods across 11 days prior to the Rested Simulated Flight



4.8.1.1 Sleep Timing and Duration during Day 1 - 4 grouped by Condition

One hundred and twenty eight actigraphy recordings (100% of the recordings available) were used to calculated variables of interest. The distribution for each variable during day 1 - 4 are presented in Figure 4-24 (cumulative sleep debt), Figure 4-25 (total sleep in 24hrs), Figure 4-26 (sleep start), Figure 4-27 (sleep end) and Figure 4-28 (time in bed). Table 4-16 lists the mean, standard deviation, median and range for each variable.

Figure 4-24 Cumulative Sleep Debt grouped by Condition[73]



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[73] A value of zero represents zero cumulative sleep debt (i.e. sleep is equal to or greater than baseline). A larger negative value represents an increasing amount of cumulative sleep debt.

Figure 4-25 Total sleep in 24hrs grouped by Condition

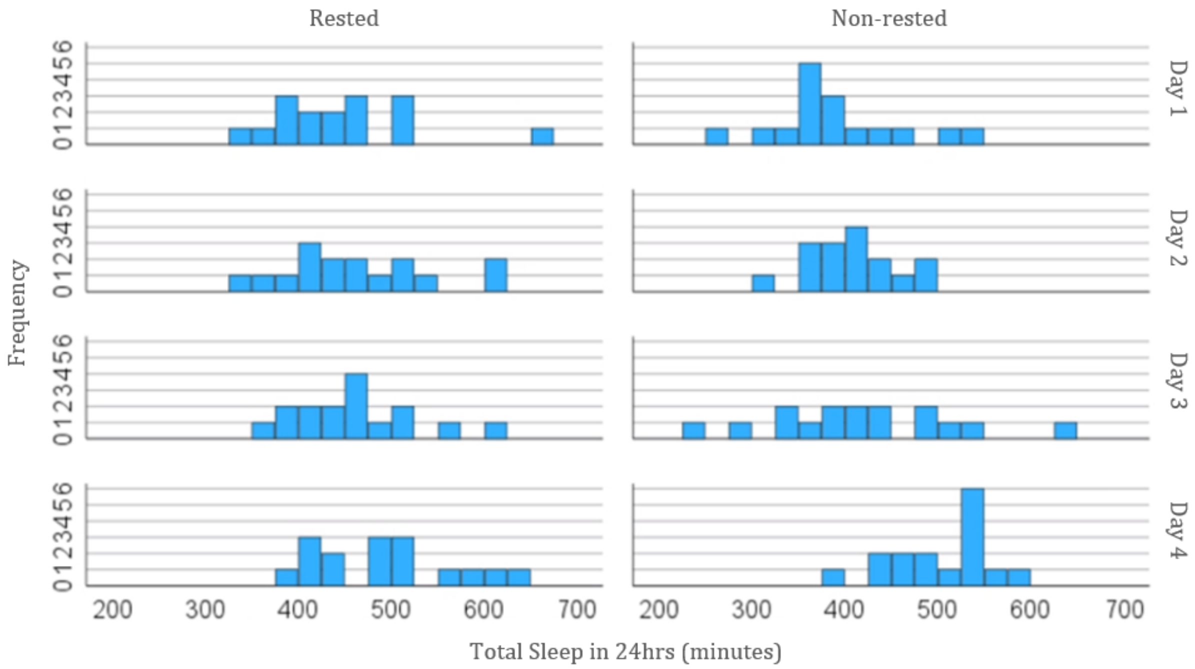

Figure 4-26 Sleep Start grouped by Condition

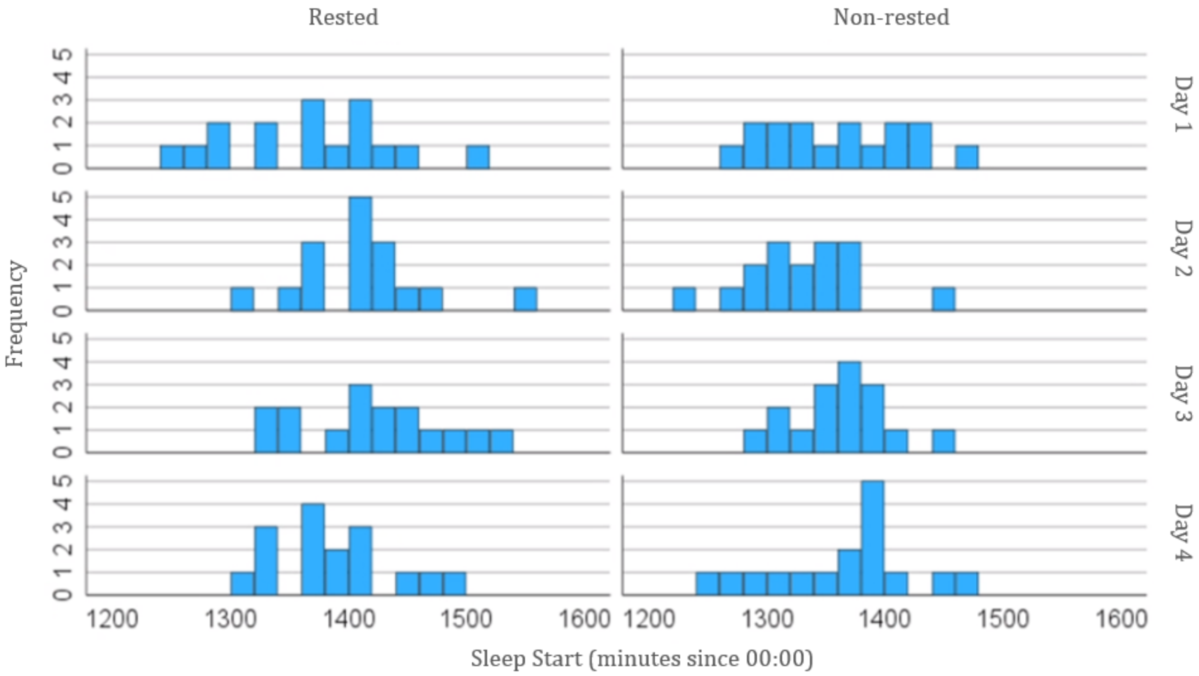

Figure 4-27 Sleep End grouped by Condition

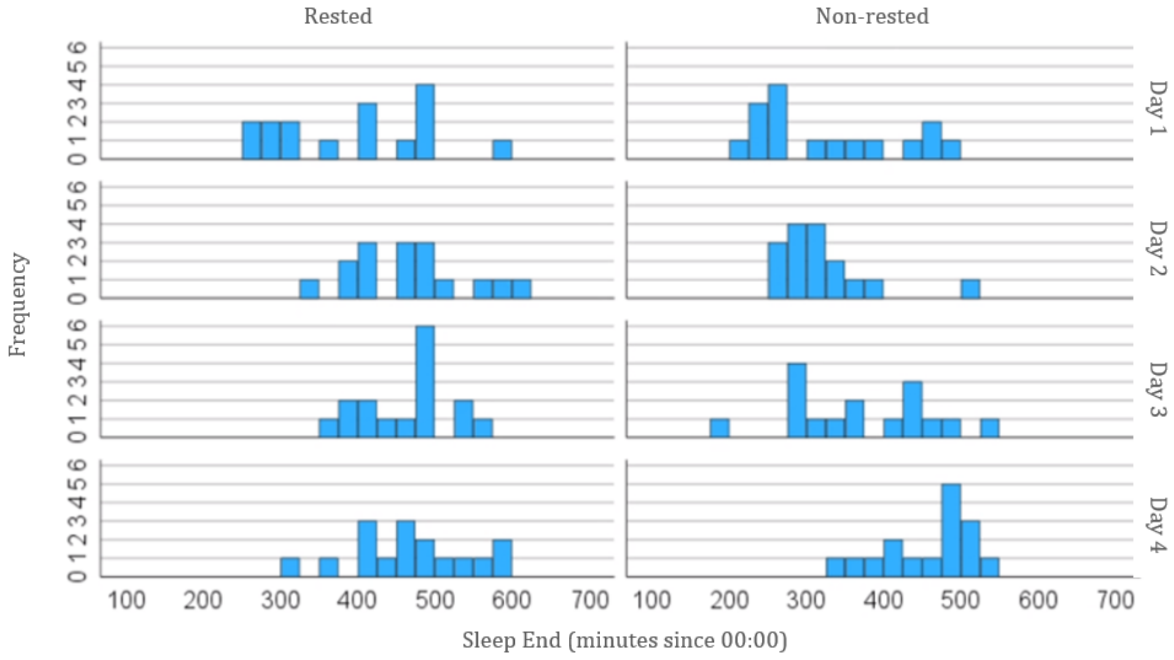

Figure 4-28 Time in Bed grouped by Condition

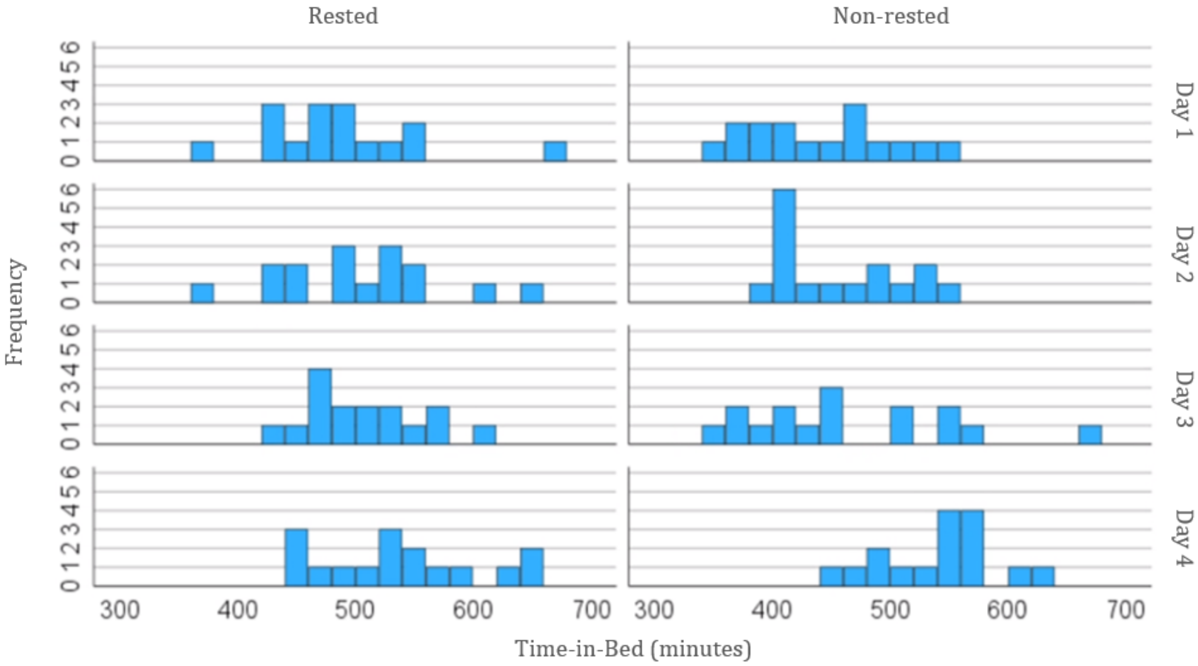

Table 4-16 Sleep Timing and Duration in the Non-rested or Rested Condition

Day Duty Period Occurs	Variable	Non-rested condition					Rested condition				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Day 1	Cumulative Sleep Debt (minutes)	-84.9	78.45	-59.4	284 (-284 – 0)	16	-38.75	52.9	-13.5	155 (-155 – 0) [a]	16
	Total Sleep in 24hrs (minutes)	393.5	72.52	380	274 (268 – 542) [a]	16	449.8	76.5	438	311 (342 – 653) [a]	16
	Sleep Start[74] (min since 00:00)	1359.9	59.98	1354	201 (1276 – 1477)	16	1366	68.7	1377	250 (1255 – 1505)	16
	Sleep End[75] (min since 00:00)	328.3	95.22	290.5	283 (207 – 490)	16	395	97.9	416	333 (259 – 592) [c]	16
	Time in Bed (minutes)	439.5	62.18	437.7	200 (357 – 557)	16	486.6	67.2	484	292 (371 – 663) [a]	16
Day 2	Cumulative Sleep Debt	-152.6	133.4	-115.25	512 (-512 – 0) [a, c]	16	-57.11	67.3	-27.75	206 (-206 – 0)	16
	Total Sleep in 24hrs	410.2	46.3	415.5	173 (324 – 497)	16	462.5	78.2	458	270 (343 – 613)	16
	Sleep Start	1330	48.5	1335	216 (1238 – 1454) [a]	16	1411	54.2	1409	236 (1318 – 1554) [a]	16
	Sleep End	321.6	60.2	302.5	238 (267 – 505) [b]	16	467.8	74.6	470	271 (336 – 607)	16
	Time in Bed	453.6	53.7	442.5	159 (389 – 548)	16	505.1	70.6	508.5	285 (360 – 645)	16
Day 3	Cumulative Sleep Debt	-212	157.9	-147	493 (-493.1 – 0) [c]	16	-77	82.6	-48.25	251 (-251 – 0)	16
	Total Sleep in 24hrs	421.9	98.2	404	388 (245 – 633)	16	459.3	64	460.5	241 (359 – 600)	16
	Sleep Start	1360.9	41.4	1363	178 (1281 – 1459) [a]	16	1420	63.3	1418	211 (1326 – 1537) [c]	16

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[74] For example, 13.59.9 = 22:39.

[75] For example, 328.3 = 05:28.

Day Duty Period Occurs	**Variable**	**Non-rested condition**					**Rested condition**				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
	Sleep End	370.6	92.6	359	340 (190 – 530)	16	462.1	57.2	477.5	196 (369 – 565)	16
	Time in Bed	462.3	86.2	442	302 (359 – 661) [c]	16	506	51.4	497	189 (422 – 611)	16
Day 4	Cumulative Sleep Debt	-194.1	187.7	-136	577 (-577 – 0) [c]	16	-65.3	98.4	-12.75	329 (-329 – 0) [a]	16
	Total Sleep in 24hrs	503.5	54.6	516	200 (385 – 585)	16	491.2	77.8	494.5	263 (384 – 647) [c]	16
	Sleep Start	1364.3	62.4	1384	223 (1243 – 1466)	16	1389	50.6	1380.5	167 (1318 – 1485)	16
	Sleep End	457.6	58	482.5	183 (342 – 525)	16	470.6	76.8	462.5	283 (312 – 595)	16
	Time in Bed	542.8	50.1	554	187 (451 – 638)	16	536.1	67	526.5	207 (445 – 652) [c]	16

[a] Includes 1 outlier; [b] Includes 1 extreme outlier; [c] Not normally distributed.

Total Sleep in 48hrs

The distribution for total sleep in 48hrs is presented in Figure 4-29 and Table 4-17 lists the mean, standard deviation, median and range.

Figure 4-29 Total Sleep in 48hrs grouped by Condition

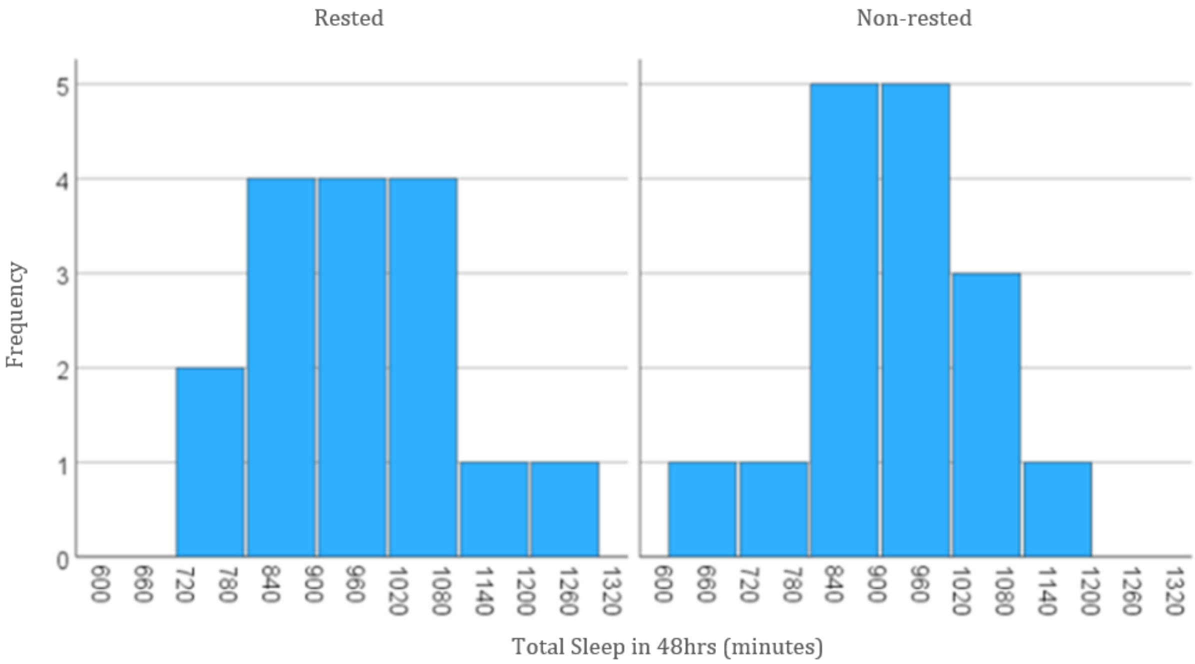

Table 4-17 Mean, Standard Deviation, Median and Range of Total Sleep in 48hrs grouped by Condition

Variable	**Non-rested condition**					**Rested condition**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Total Sleep in 48hrs (minutes)	925	124	916	480 (683 – 1163) [a]	16	950	131	928	478 (769 – 1247)	16

[a] Includes 1 outlier.

4.8.1.2 Sleep Timing and Duration in Baseline and Non-Baseline Sleep Periods

This section focuses on differences in sleep related variables between baseline and non-baseline sleep periods. The dataset included 51 baseline sleep periods and 117 non-baseline sleep periods. Figure 4-30 (Total sleep in 24hrs), Figure 4-31 (Sleep Start), Figure 4-32 (Sleep End) and Figure 4-33 (Time in Bed) show box and whisker plots for sleep related variables. Table 4-18 lists the mean, standard deviation, median and range for the applicable variables.

Figure 4-30 Total sleep in 24hrs for Baseline and Non-baseline Sleep Periods

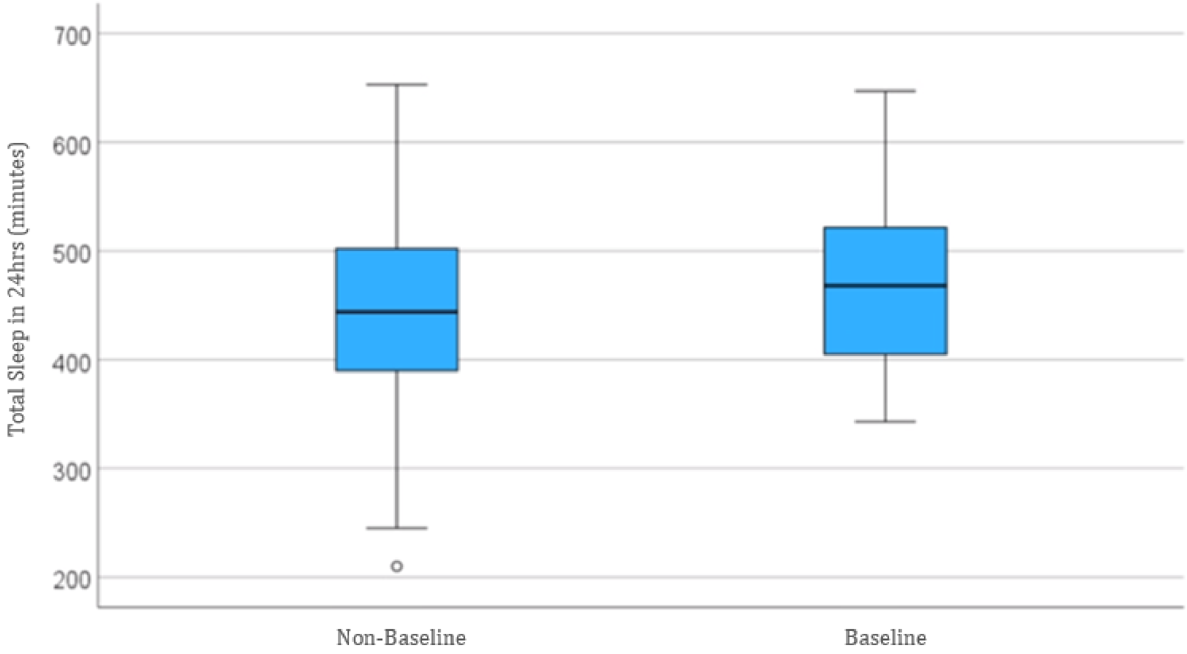

Figure 4-31 Sleep Start for Baseline and Non-baseline Sleep Periods

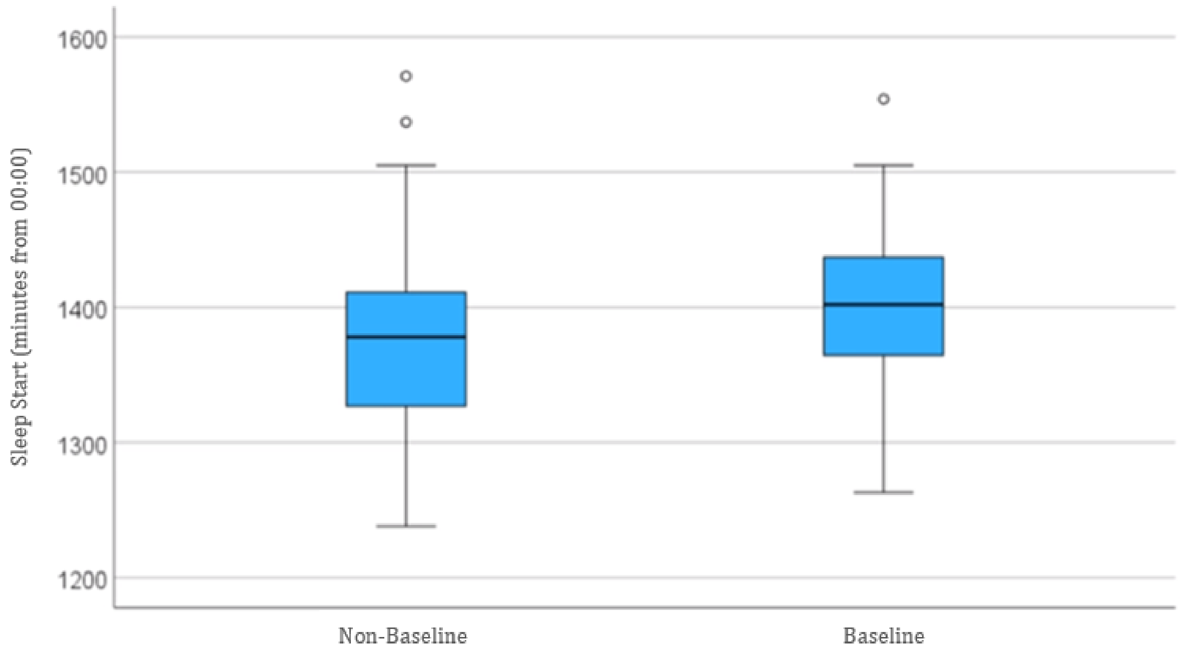

Figure 4-32 Sleep End for Baseline and Non-baseline Sleep Periods

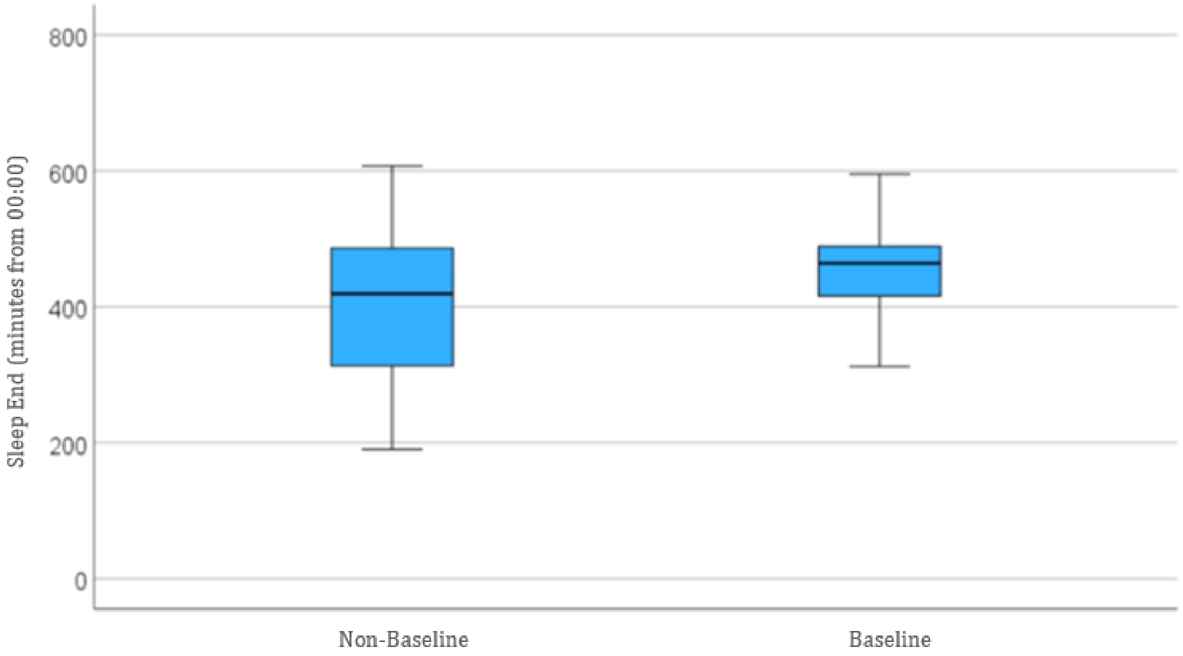

Figure 4-33 Time in Bed for Baseline and Non-baseline Sleep Periods

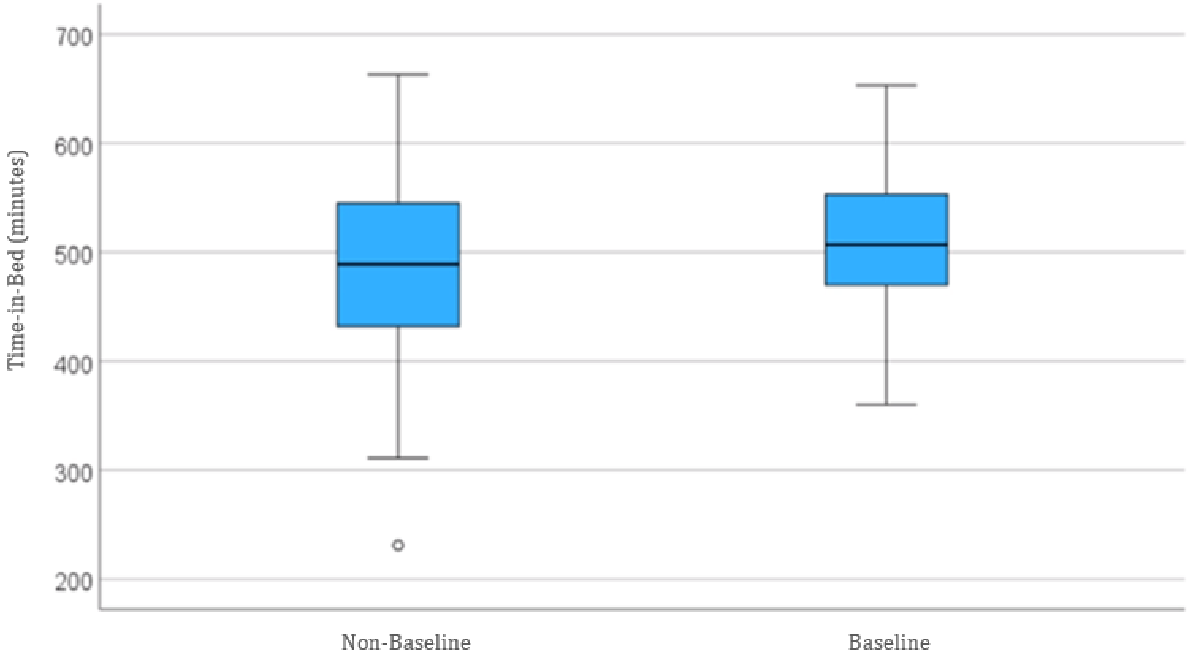

Table 4-18 Mean, Standard Deviation, Median and Range of Total Sleep in 24hrs, Sleep Start, Sleep End and Time in Bed for Baseline and Non-baseline Sleep Periods

Variable	**Baseline**					**Non-baseline**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Total Sleep in 24hrs (min)	465	75	468	304 (343 – 647)	51	445	82	444	443 (210 – 653) [a]	117
Sleep Start[76] (min from 00:00)	1400	58	1402	291 (1263 – 1554) [a]	51	1374	62.7	1378	333 (1238 – 1571) [b]	117
Sleep End[77] (min from 00:00)	456	67	464	283 (312 – 595)	51	403	98	419	417 (190 – 607) [c]	117
Time in Bed (min)	513	65	507	293 (360 – 653)	51	485	79	489	432 (231 – 663) [a]	117

[a] Includes 1 outlier; [b] Includes 2 outliers; [c] Not normally distributed.

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[76] For example, 1400 = 23:20.

[77] For example, 456 = 07:36.

4.8.1.3 Time Since Sleep at the Start of the Simulated Flight and Psychomotor Vigilance Task grouped by Condition

Of the possible 32 recordings for time since sleep at the start of either the simulated flight or at the start of the pre or post simulated flight PVT test, 32 values were available for each variable. The distribution for these variables is presented in Figure 4-34, Figure 4-35. Figure 4-36 and Table 4-19 lists the mean, standard deviation, median and range. Distributions for these variables are positively skewed in the non-rested condition and negatively skewed in the rested condition.

Figure 4-34 Time Since Sleep at the Start of the Simulated Flight grouped by Condition

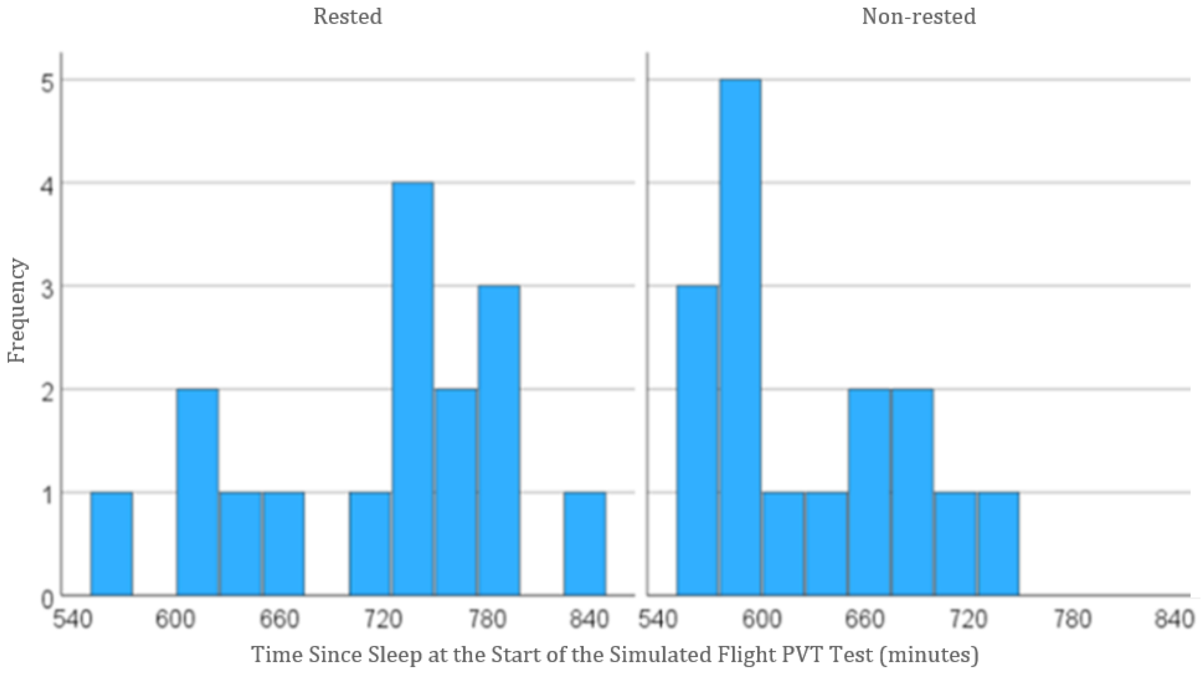


Figure 4-35 Time Since Sleep at the Start of the Pre Simulated Flight PVT grouped by Condition

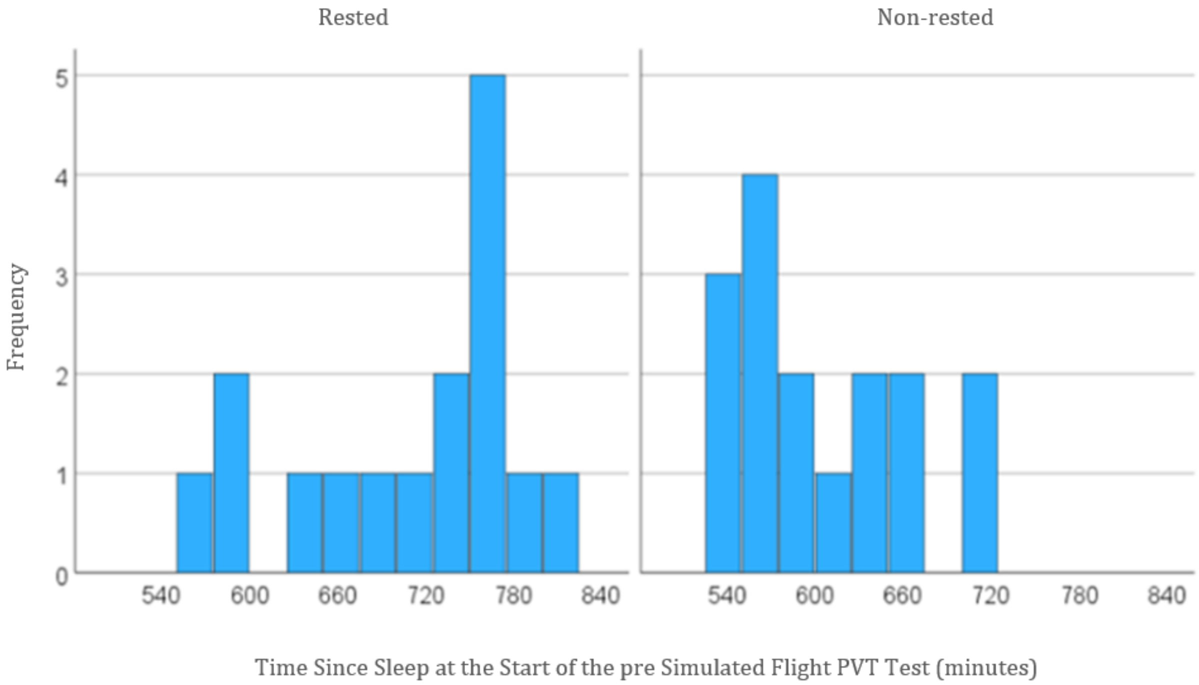


Figure 4-36 Time Since Sleep at the Start of the Post Simulated Flight PVT Test grouped by Condition

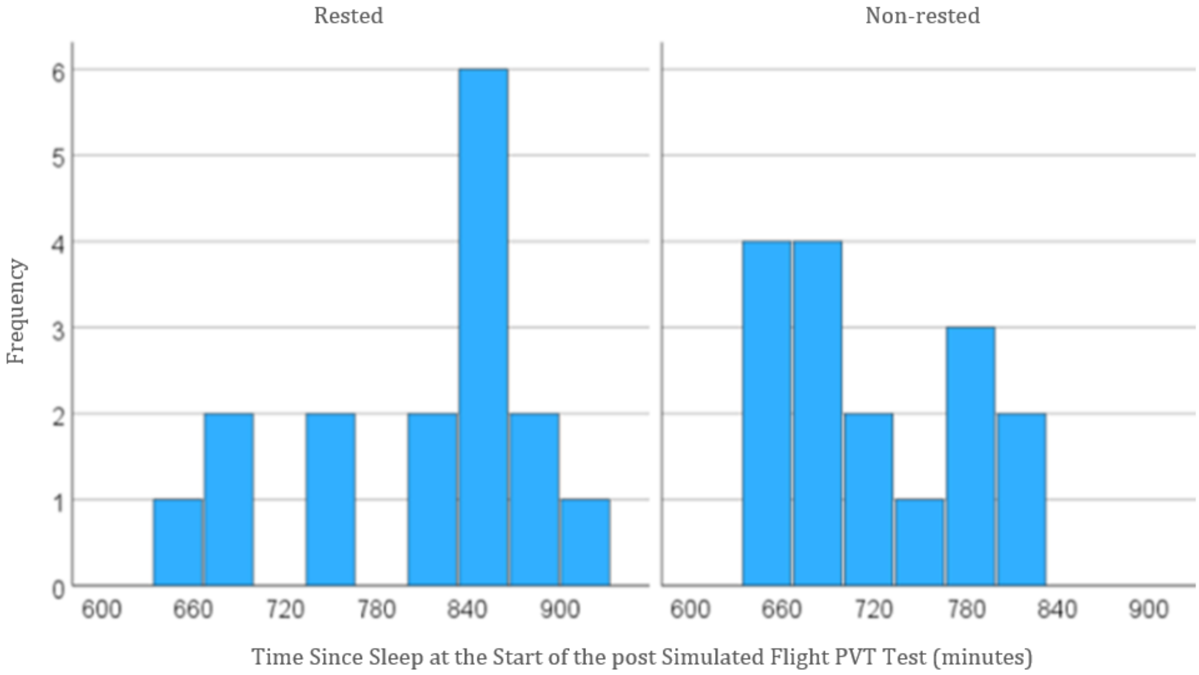


Table 4-19 Mean, Standard Deviation, Median and Range for Time Since Sleep at the start of the Simulated Flight, and at the start of the Pre or Post Simulated Flight PVT grouped by Condition

Variable	Non-rested condition					Rested condition				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Time Since Sleep at the Start of the Simulated Flight (minutes)	622	58	597	183 (555 – 738)	16	714	75	737	258 (569 – 827)	16
Time Since Sleep at the Start of the pre Simulated Flight PVT Test (minutes)	604	57	581	177 (543 – 720)	16	706	76	736	262 (553 – 815)	16
Time Since Sleep at the Start of the post Simulated Flight PVT Test (minutes)	715	60	695	177 (642 – 819)	16	809	77	837	265 (657 – 922)	16

4.8.2 The Effect of Condition and Day on Sleep Related Variables

This section includes analysis and results for the following research question:

Q7: Do sleep timing and duration differ between the non-rested and rested condition?

4.8.2.1 Analysis

Table 4-20 lists results for the effect of condition and day on total sleep in 24hrs and 48hrs, cumulative sleep debt, sleep start, sleep end and time in bed prior to the simulated flight. If main effects were significant, post hoc t tests were used to make pairwise comparisons between levels of the significant effect(s). If interactions were significant, simple effect analyses were undertaken to determine the effect of a fixed effect at individual levels of the other fixed effect. Descriptive statistics for the variables mentioned in Table 4-20 are outlined in Section 4.8.1.1.

Table 4-20 Results of mixed model ANOVA for the effect of Day and Condition on Sleep Related Variables.

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
Cumulative Sleep Debt [e, f, g, h]	Day	3, 83.2	13.95	**<.0001**
	Condition	1,30.3	8.42	**.0068**
	Day x Condition	3,83.2	3.37	**.0224**
Total Sleep in 24hrs [a, b, c]	Day	3, 66.8	14.50	**<.0001**
	Condition	1,30.2	3.02	.0924
	Day x Condition	3,66.8	3.45	**.0213**
Sleep Start [a, b]	Day	3, 85.3	1.55	.2080
	Condition	1,34.6	11.18	**.0020**
	Day x Condition	3,85.3	3.88	**.0118**
Sleep End [a, i]	Day	3, 90	14.47	**<.0001**
	Condition	1,30	16.41	**.0003**
	Day x Condition	3,90	6.03	**.0009**
Time in Bed [a, b]	Day	3, 61.5	18.71	**<.0001**
	Condition	1,29.7	6.50	**.0162**
	Day x Condition	3,61.5	3.00	**.0374**
Total Sleep in 48hrs [c, d]	Condition	1, 15	1.05	.3225

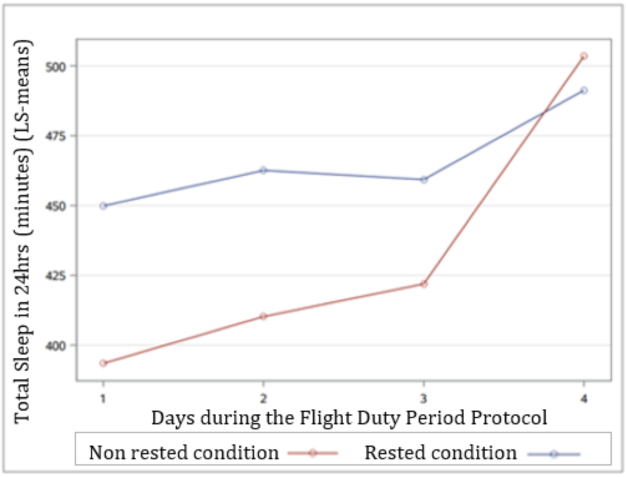
[a] Number of observations used: 128/128; [b] Autoregressive covariance structure with random variance components; [c] includes 1 outlier; [d] Number of observations used: 32:32; [e] Number of observations used: 122/122; [f] Autoregressive covariance structure; [g] excluded 6 outliers; [h] includes 2 outliers; [i] Compound symmetry covariance structure.

4.8.2.2 Results

Total Sleep in 24hrs

The interaction between condition and day was significant. Simple effect tests showed that total sleep in 24hrs was significantly shorter in the non-rested condition during day 1 (p = .0305) and 2 (p = .0442), see Figure 4-37. In the rested condition, participants obtained nearly one hour of additional sleep compared with the non-rested condition during both day 1 (449 minutes versus 393 minutes) and day 2 (462 minutes versus 410 minutes). The difference in total sleep in 24hrs between the non-rested and rested condition was not significantly different during day 3 (p = .1480) or 4 (p = .6333).

Figure 4-37 LS-means Estimates of Total sleep in 24hrs for the Interaction: Condition x Day



Simple effect tests show that in the non-rested condition, total sleep in 24hrs before the non-rested simulated flight was significantly higher (503 minutes) during day 4 compared with day 3 (421 minutes), 2 (462 minutes) and 1 (449 minutes), see Table 4-21.

Table 4-21 Simple Effect Comparisons for Condition x Day for Total Sleep in 24hrs

Simple Effect Level	Day	Day	Adj P
Non-rested	1	2	.8512
Rested	1	2	1.000

Simple Effect Level	**Day**	**Day**	**Adj P**
Non-rested	1	3	.3316
Rested	1	3	1.000
Non-rested	1	4	**<.0001**
Rested	1	4	.1651
Non-rested	2	3	.8512
Rested	2	3	1.000
Non-rested	2	4	**<.0001**
Rested	2	4	.5374
Non-rested	3	4	**.0009**
Rested	3	4	.5374

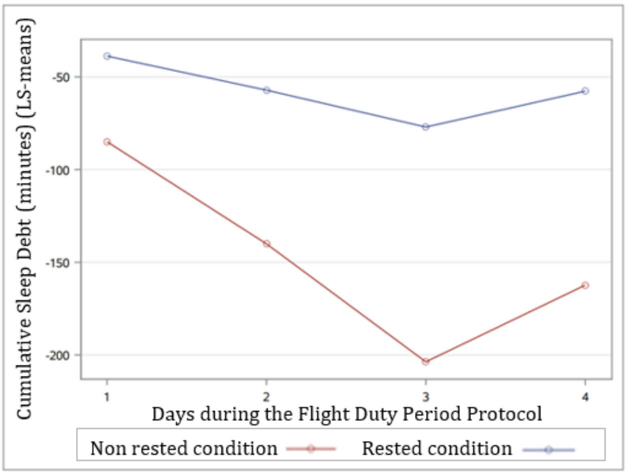
Total sleep in 48hrs

The difference in total sleep in the previous 48 hour period prior to the start of each simulated flight was not significant between the non-rested and rested condition.

Cumulative Sleep Debt

For cumulative sleep debt the interaction between condition and day was significant. Simple effect tests showed that cumulative sleep debt was significantly higher in the non-rested condition than in the rested condition during day 2 (p = .0199), day 3 (p = .0006) and day 4 (p = .0045), see Figure 4-38. Compared to the rested condition, participants in the non-rested condition incurred higher levels of cumulative sleep debt during day 2 (140 minutes versus 57 minutes), day 3 (203 minutes versus 77minutes) and day 4 (162minutes versus 57minutes). The difference in cumulative sleep debt between the non-rested and rested condition was not significantly different for day 1 (p = .1828).

Figure 4-38 LS-means Estimates of Cumulative Sleep Debt for the Interaction: Condition x Day



In the non-rested condition, simple effect tests showed that cumulative sleep debt was significantly lower during day 1 (84 minutes) compared with day 2 (140 minutes) and 3 (203 minutes). In addition, cumulative sleep debt was significantly lower in day 2 (140 minutes) and 4 (162 minutes) compared with day 3 (203 minutes). All other simple effect tests that compared cumulative sleep debt between different levels of condition and day were not significant (see Table 4-22).

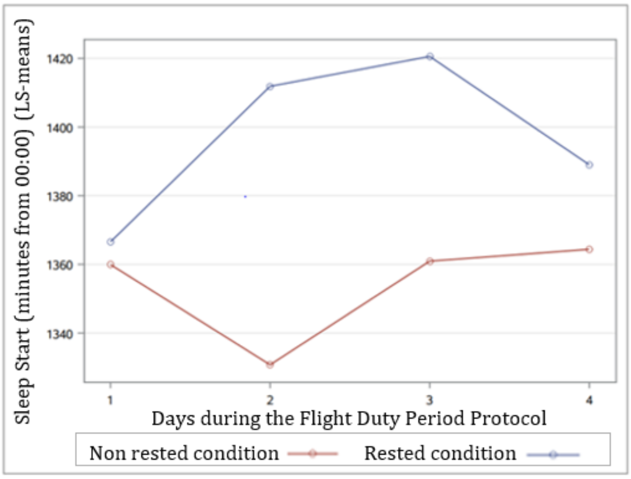
Table 4-22 Simple Effect Comparisons for Condition x Day for Sleep Start

Simple Effect Level	Day	Day	Adj P
Non-rested	1	2	**.0006**
Rested	1	2	.7097
Non-rested	1	3	<**.0001**
Rested	1	3	.2340
Non-rested	1	4	**.0029**
Rested	1	4	.7767
Non-rested	2	3	<**.0001**
Rested	2	3	.7097
Non-rested	2	4	.2569
Rested	2	4	.9766
Non-rested	3	4	**.0129**
Rested	3	4	.7097

Sleep Start

The interaction between condition and day was significant for sleep start. Simple effect tests showed that the start of sleep was significantly later in the rested condition during day 2 (23:30 versus 22:10, p = .0001) and 3 (23:40 versus 22:40, p = .0039), see Figure 4-39. Differences in sleep start were not significantly different between different levels of condition during day 1 (p = .7434) or 4 (p = .2253).

Figure 4-39 LS-means Estimates of Sleep Start for the Interaction: Condition x Day



In the rested condition, simple effect tests showed that the start of sleep during day 1 (22:46) was significantly earlier than the start of sleep during day 2 (23:31) and 3 (23:40). All other simple effect tests that compared the start of sleep between different levels of condition and day were not significant (see Table 4-23).

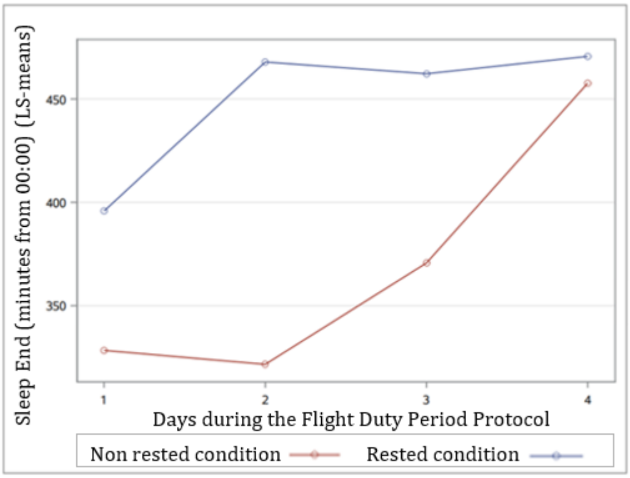
Table 4-23 Simple Effect Comparisons for Condition x Day for Sleep Start

Simple Effect Level	Day	Day	Adj P
Non-rested	1	2	.4192
Rested	1	2	**.0361**
Non-rested	1	3	1.000
Rested	1	3	**.0332**
Non-rested	1	4	1.000
Rested	1	4	.7007
Non-rested	2	3	.4192
Rested	2	3	.7007
Non-rested	2	4	.4192
Rested	2	4	.7007
Non-rested	3	4	1.000
Rested	3	4	.2332

Sleep End

The interaction between condition and day was significant for sleep end. Simple effect tests show that the end of sleep was significantly later in the rested condition during day 1 (06:35 versus 05:28, p = .0169), 2 (07:46 versus 05:21, p = <.0001) and 3 (07:42 versus 06:10, p = .0014), see Figure 4-40. The end of sleep was not significantly different between conditions during day 4 (p = .6396).

Figure 4-40 LS-Means Estimates of Sleep End for the Interaction: Condition x Day



In the rested condition, simple effect tests show that the end of sleep during day 1 (06:35) was significantly earlier than the end of sleep during day 2 (07:47), 3 (07:42) and 4 (07:50). In the non-rested condition, the end of sleep was significantly later during day 4 (07:37) compared with day 1 (05:28), 2 (05:21) and 3 (06:10). All other simple effect tests that compared the end of sleep between different levels of condition and day were not significant (see Table 4-24).

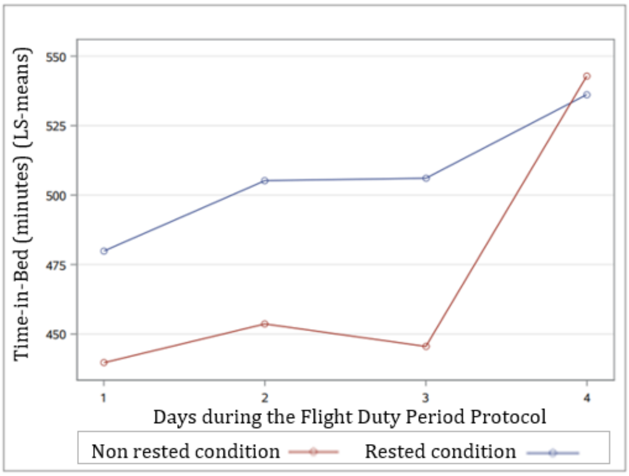
Table 4-24 Simple Effect Comparisons for Condition x Day for Sleep End

Simple Effect Level	**Day**	**Day**	**Adj P**
Non-rested	1	2	.7650
Rested	1	2	**.0094**
Non-rested	1	3	.1267
Rested	1	3	**.0161**
Non-rested	1	4	<.0001
Rested	1	4	**.0076**
Non-rested	2	3	.0957
Rested	2	3	1.000
Non-rested	2	4	<**.0001**
Rested	2	4	1.000
Non-rested	3	4	**.0008**
Rested	3	4	1.000

Time in bed

The interaction between condition and day was significant for time in bed. Simple effect tests found that time in bed was significantly shorter in the non-rested condition during day 2 (505 min versus 453 min, p = .0181) and 3 (506 min versus 445 min, p= .0064), see Figure 4-41. However, it was not significantly different between different levels of condition for day 1 (p = .0669) and 4 (p = .7556).

Figure 4-41LS-means Estimates of Time in Bed for the Interaction: Condition x Day



In the non-rested condition, simple effect tests found that time in bed during day 4 (9 hours 2 minutes) was significantly longer than day 1 (7 hours 19 minutes), 3 (7 hours 33 minutes) and 3 (7 hours 25 minutes). In the rested condition, time in bed during day 4 (8 hours 56 minutes) was significantly longer than day 1 (7 hours 59 minutes). All other simple effect tests that compared time in bed between different levels of condition and day were not significant (see Table 4-25).

Table 4-25 Simple Effect Comparisons for Condition x Day for Time in Bed

Simple Effect Level	**Day**	**Day**	**Adj P**
Non-rested	1	2	1.000
Rested	1	2	.4520
Non-rested	1	3	1.000
Rested	1	3	.4289
Non-rested	1	4	<**.0001**
Rested	1	4	**.0150**
Non-rested	2	3	1.000
Rested	2	3	.9660
Non-rested	2	4	<**.0001**
Rested	2	4	.2617
Non-rested	3	4	<**.0001**
Rested	3	4	.4367

4.8.3 The Effect of Condition on Time Since Sleep

This section includes analysis and results for the following research question:

Q8: Does time since sleep differ between the non-rested and rested condition?

4.8.3.1 Analysis

Table 4-26 lists results for the effect of condition and order on time since sleep. Descriptive statistics for the variables mentioned in Table 4-26 are included in Section 4.8.1.3.

Table 4-26 Dependent and Independent Variables Included within Analyses.

Dependent variable	Independent variable	DF	F-value	P(F)
Time Since Sleep at the Start of the pre Simulated Flight PVT Test [a]	Condition	1,14	41.24	<**.0001**
	Order	1,14	1.26	0.2805
Time Since Sleep at the Start of the post Simulated Flight PVT Test [a]	Condition	1,14	36.51	<**.0001**
	Order	1,14	0.81	0.3845
Time Since Sleep at the Start of the Simulated Flight [a] [b]	Condition	1,14	40.07	<**.0001**
	Order	1,14	0.94	0.3476

[a] Number of observations used: 32/32; [b] Interaction Condition x Order removed from the final model as it was not significant.

4.8.3.2 Results

After controlling for order, time since sleep was significantly shorter in the non-rested condition for the pre simulator PVT test (estimated mean = 10 hours 3 minutes versus 11 hours 45 minutes), the simulated flight (estimated mean = 10 hours 21 minutes versus 11 hours 54 minutes) and the post simulator PVT test (estimated mean = 11 hours 54 minutes versus 13 hours 28 minutes).

4.8.4 Comparing Non-baseline and Baseline Sleep Periods

This section includes analysis and results for the following research question:

Q9: Does sleep timing and duration differ between non-baseline and baseline sleep periods?

4.8.4.1 Analysis

Table 4-27 lists results comparing total sleep in 24hrs, sleep start, sleep end and time in bed between baseline and non-baseline sleep periods. Descriptive statistics for the variables mentioned in Table 4-27 are included in Section 4.8.1.2.

Table 4-27 Results of mixed model ANOVAS for the effect of Non-baseline and Baseline Sleep periods on Sleep Related Variables.

Dependent variable	Independent variable	DF	F-value	P(F)
Total Sleep in 24hrs [a b]	Baseline versus Non-baseline sleep period	1, 154	3.40	.0670
Sleep Start [a c]	Baseline versus Non-baseline sleep period	1, 156	5.47	**.0206**
Sleep End [a, b, d]	Baseline versus Non-baseline sleep period	1, 155	9.53	**.0024**
Time in Bed [a b]	Baseline versus Non-baseline sleep period	1, 157	4.67	**.0321**

a Number of observations used: 168/168; b Includes one outlier; c Includes three outliers; d REFL SQRT transformation applied to normalise distribution.

4.8.4.2 Results

For baseline sleep periods, the start (23:18 versus 22:54) and end of sleep (07:31 versus 06:42) was significantly later and time in bed was longer (8 hours 53 minutes versus 8 hours 4 minutes) than for non-baseline sleep periods. However, total sleep in 24 hours was not significantly different between non-baseline and baseline sleep periods (7 hours 24 minutes versus 7 hours 45 minutes).

4.9 Subjective Ratings of Fatigue, Sleepiness and Sleep Quality

4.9.1 Test Details

4.9.1.1 Subjective Ratings of Fatigue, Sleepiness before Main Sleep Periods and Subjective Ratings of Fatigue, Sleepiness and Sleep Quality following Main Sleep Periods

Ratings of fatigue and sleepiness were recorded before and following main sleep periods and ratings of sleep quality were recorded following main sleep periods during days 1 - 4 before simulated flights. The distribution for each subjective rating is presented in Figure 4-42 (fatigue start main sleep), Figure 4-43 (sleepiness start main sleep), Figure 4-44 (fatigue end main sleep), Figure 4-45 (sleepiness end main sleep) and Figure 4-46 (sleep quality). Table 4-28 lists the mean, standard deviation, median and range for each subjective rating.

Figure 4-42 Fatigue before Main Sleep Periods grouped by Condition and Day

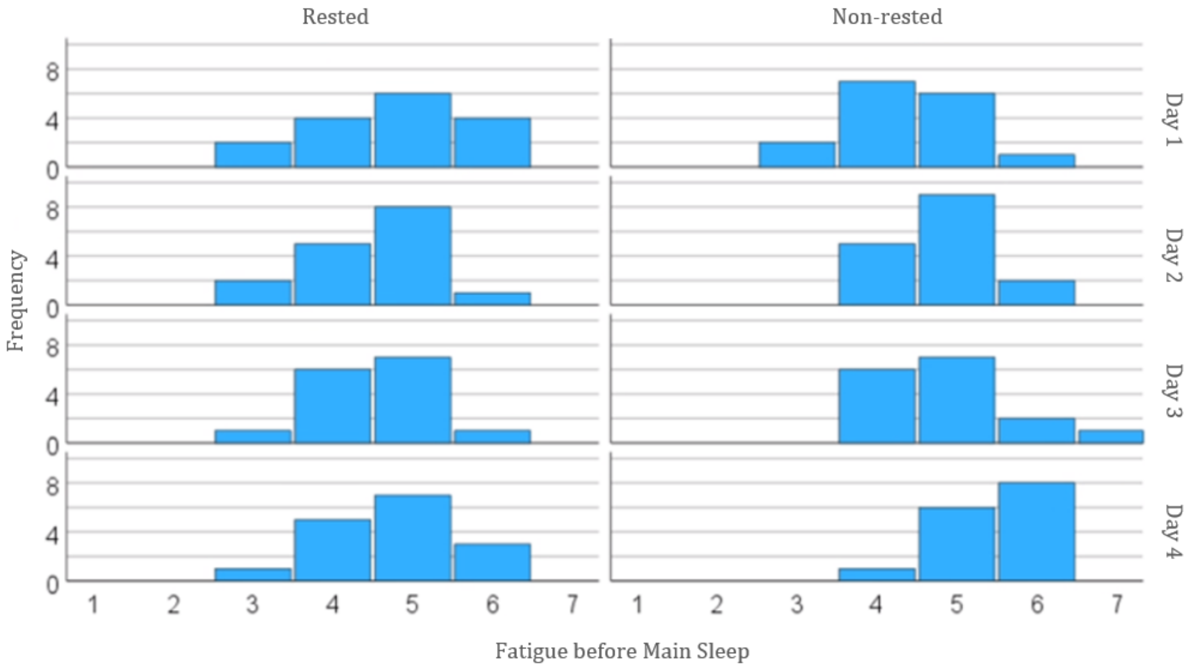


Figure 4-43 Sleepiness before Main Sleep Periods grouped by Condition

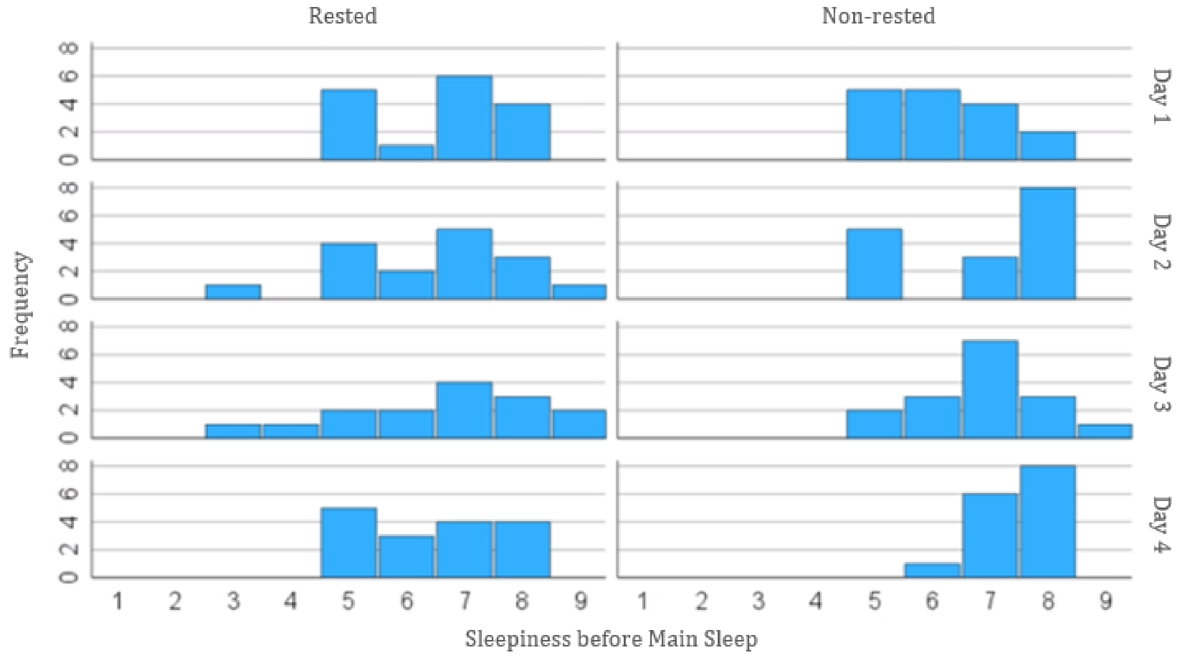


Figure 4-44 Fatigue following Main Sleep Periods grouped by Condition

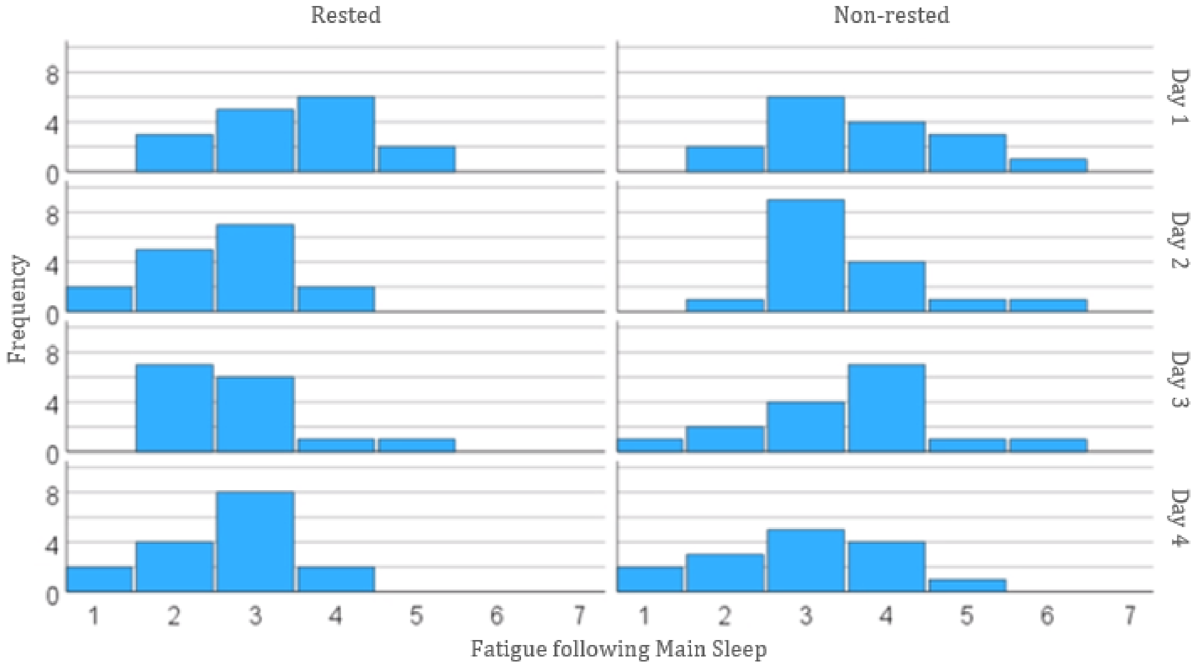


Figure 4-45 Sleepiness following Main Sleep Periods grouped by Condition

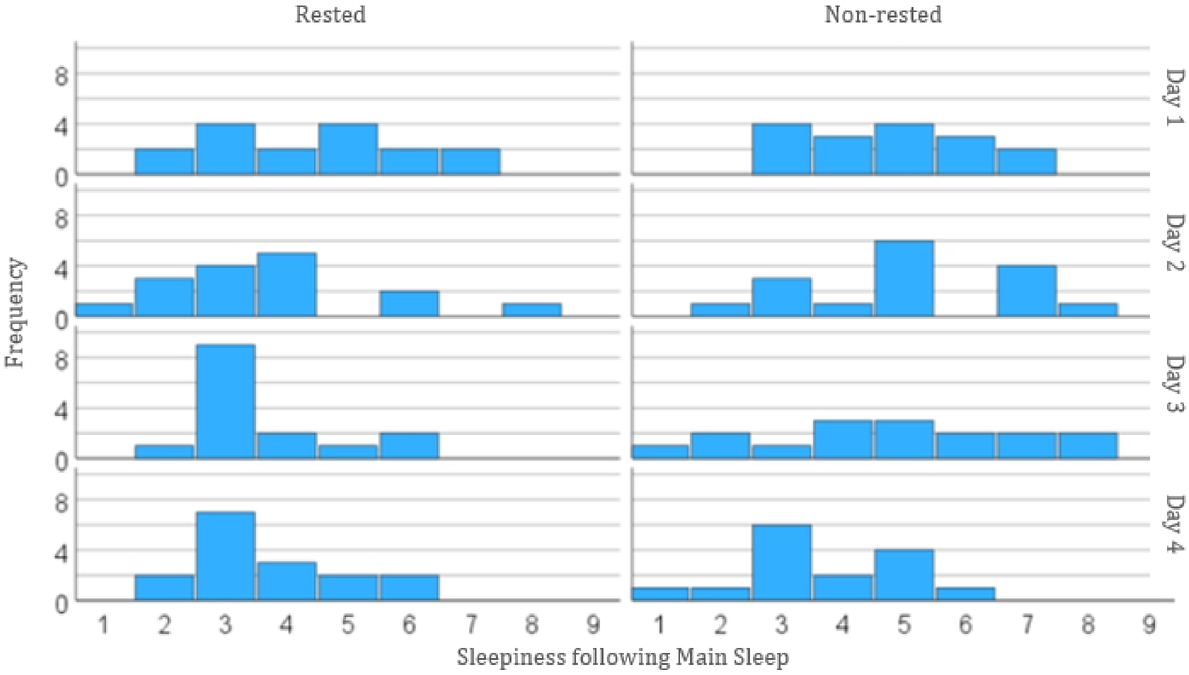


Figure 4-46 Sleep Quality ratings following Main Sleep Periods grouped by Condition

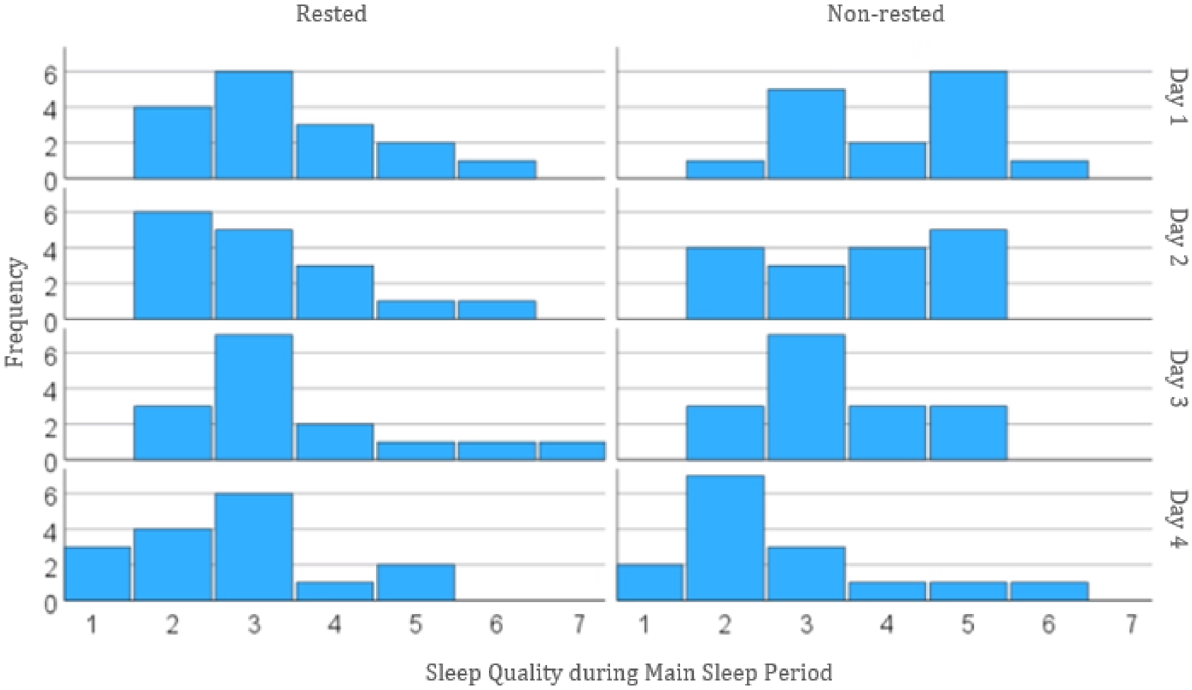


Table 4-28 Fatigue and Sleepiness before Main Sleep Periods and Fatigue, Sleepiness and Sleep Quality following Main Sleep Periods

Day Duty Period Occurs	**Variable**	**Non-rested condition**					**Rested condition**				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Day 1	Fatigue Start Main Sleep	4.4	.82	4	3 (3 – 6)	15	4.75	1	5	3 (3 – 6)	16
	Sleepiness Start Main Sleep	6.2	1.08	6	3 (5 – 8)	15	6.56	1.2	7	3 (5 – 8) [c]	16
	Fatigue End Main Sleep	3.73	1.16	4	4 (2 – 6)	15	3.44	.96	3.5	3 (2 – 5)	16
	Sleepiness End Main Sleep	4.73	1.43	5	4 (3 – 7) [c]	15	4.38	1.62	4.50	5 (2 – 7) [c]	16
	Sleep Quality	4.07	1.16	4	4 (2 – 6) [c]	15	3.38	1.20	3	4 (2 – 6)	16
Day 2	Fatigue Start Main Sleep	4.81	.65	5	2 (4 – 6)	16	4.5	.81	5	3 (3 – 6)	16
	Sleepiness Start Main Sleep	6.88	1.36	7.50	3 (5 – 8) [c]	16	6.44	1.54	7	6 (3 – 9)	16
	Fatigue End Main Sleep	3.5	.96	3	4 (2 – 6) [a]	16	2.56	.89	3.0	3 (1 – 4)	16
	Sleepiness End Main Sleep	5.06	1.76	5	6 (2 – 8) [c]	16	3.69	1.77	3.50	7 (1 – 8) [a,c]	16
	Sleep Quality	3.63	1.20	4	3 (2 – 5)	16	3.13	1.20	3	4 (2 – 6) [c]	16
Day 3	Fatigue Start Main Sleep	4.88	.88	5	3 (4 – 7) [a,c]	16	4.53	.74	5	3 (3 – 6)	15
	Sleepiness Start Main Sleep	6.88	1.08	7	4 (5 – 9)	16	6.6	1.76	7	6 (3 – 9)	15
	Fatigue End Main Sleep	3.5	1.21	4	5 (1 – 6) [b]	16	2.73	.88	3	3 (2 – 5) [a,c]	15
	Sleepiness End Main Sleep	4.81	2.13	5	7 (1 – 8)	16	3.6	1.18	3	4 (2 – 6) [b,c]	15

Day Duty Period Occurs	**Variable**	**Non-rested condition**					**Rested condition**				
		Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
	Sleep Quality	3.38	1.02	3	3 (2 – 5)	16	3.53	1.45	3	5 (2 – 7) [b c]	15
Day 4	Fatigue Start Main Sleep	5.47	.64	6	2 (4 – 6) [c]	15	4.75	.85	5	3 (3 – 6)	16
	Sleepiness Start Main Sleep	7.47	.64	8	2 (6 – 8) [c]	15	6.44	1.2	6.5	3 (5 – 8)	16
	Fatigue End Main Sleep	2.93	1.16	3	4 (1 – 5) [c]	15	2.63	.88	3	3 (1 – 4)	16
	Sleepiness End Main Sleep	3.67	1.34	3	5 (1 – 6)	15	3.69	1.25	3	4 (2 – 6)	16
	Sleep Quality	2.67	1.39	2	5 (1 – 6) [b c]	15	2.69	1.25	3	4 (1- 5) [b c]	16

[a] Includes 1 outlier; [b] Includes 2 outliers; [c] Not normally distributed.

4.9.1.2 Subjective Ratings of Fatigue, Sleepiness and Sleep Quality in Baseline and Non-baseline sleep periods

During the flight duty period, 117 non-baseline and 51 baseline sleep periods were identified. The distribution of fatigue and sleepiness ratings before and following main sleep periods and sleep quality ratings following main sleep periods is outlined in Figure 4-47 and Figure 4-51. Table 4-29 lists the mean, standard deviation, median and range.

Figure 4-47 Fatigue before Main Sleep Periods grouped by Sleep Period

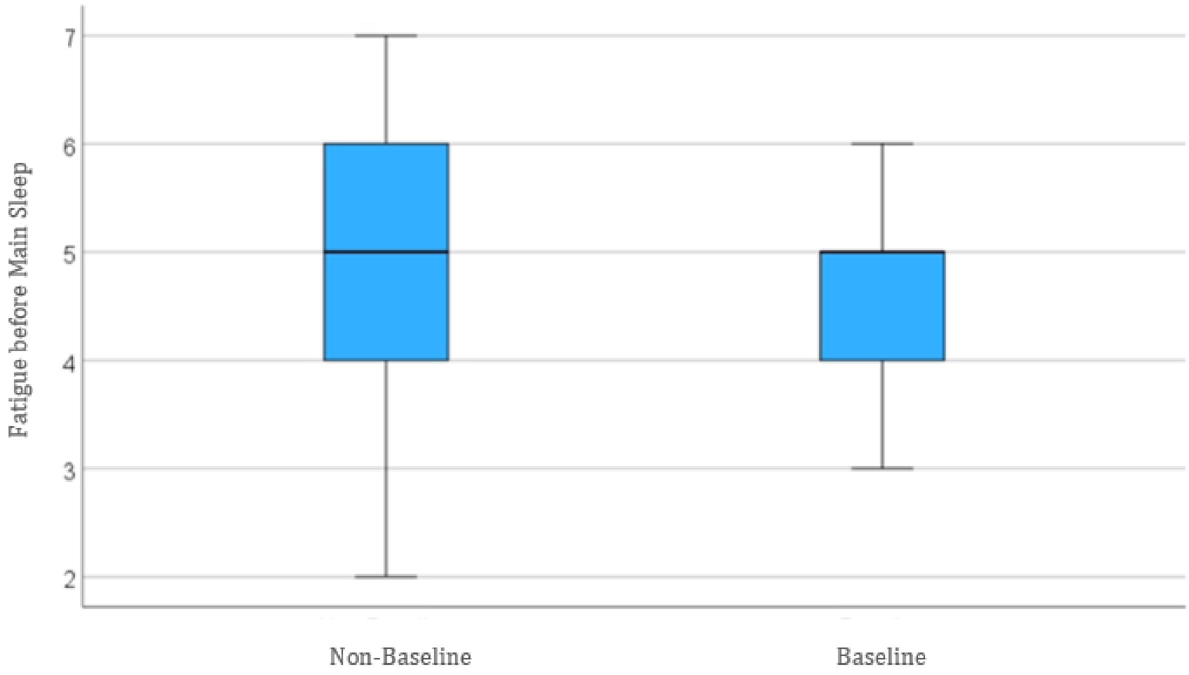


Figure 4-48 Fatigue following Main Sleep Periods grouped by Sleep Period

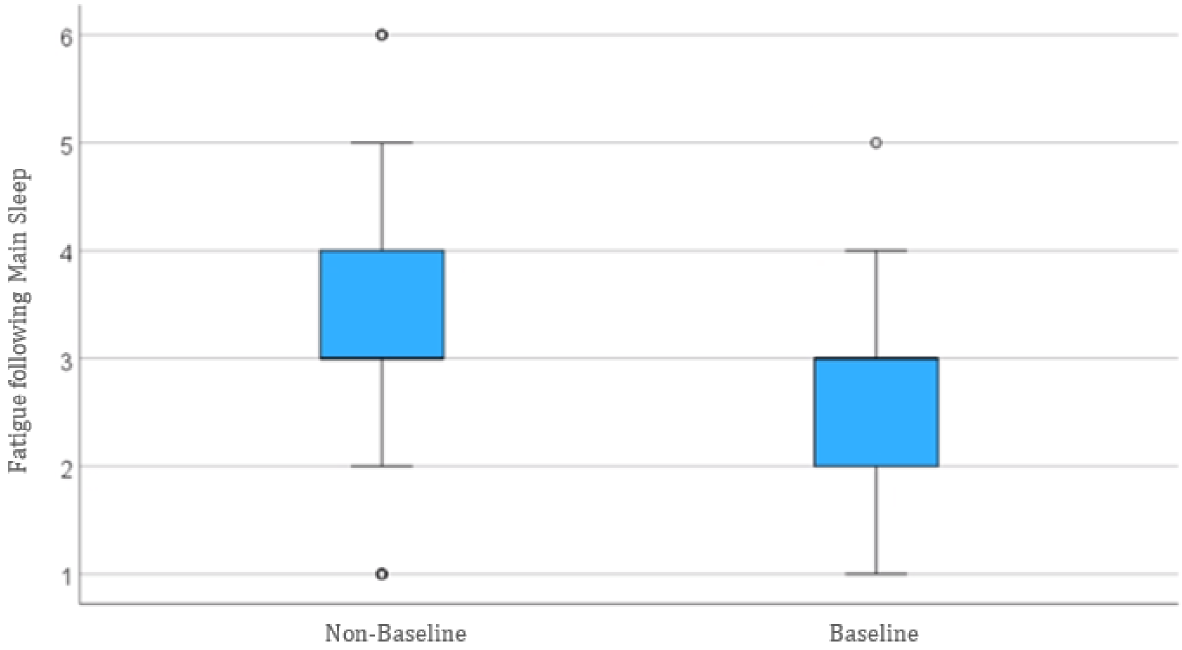


Figure 4-49 Sleepiness before Main Sleep Periods grouped by Sleep Period

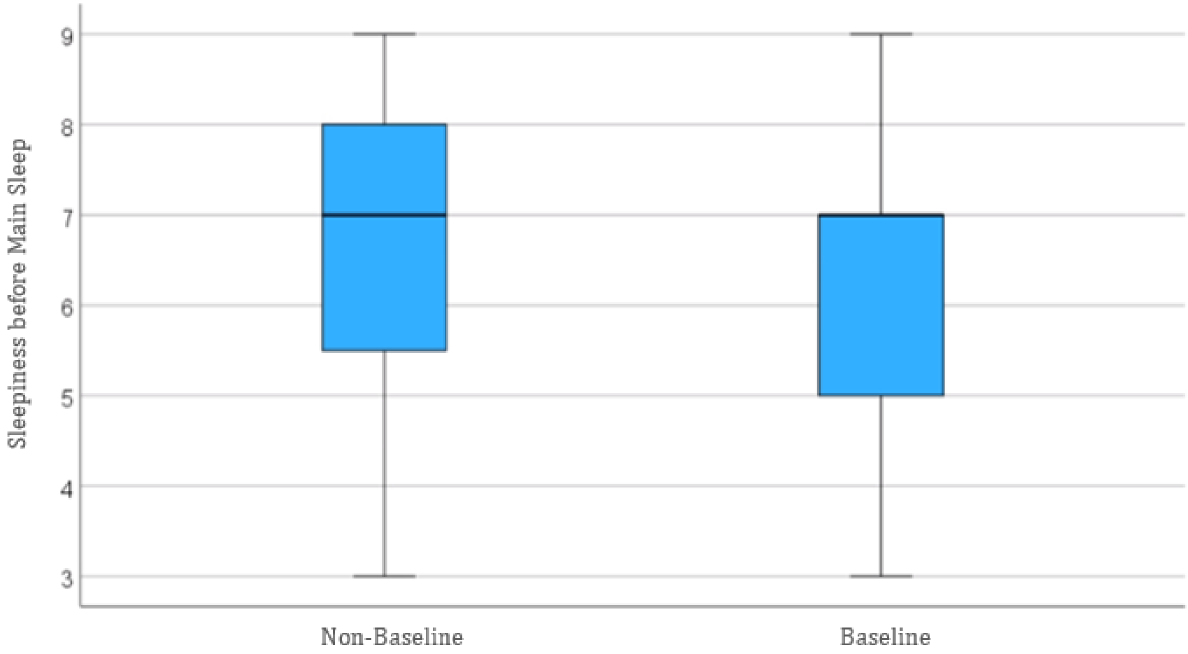


Figure 4-50 Sleepiness following Main Sleep Periods grouped by Sleep Period

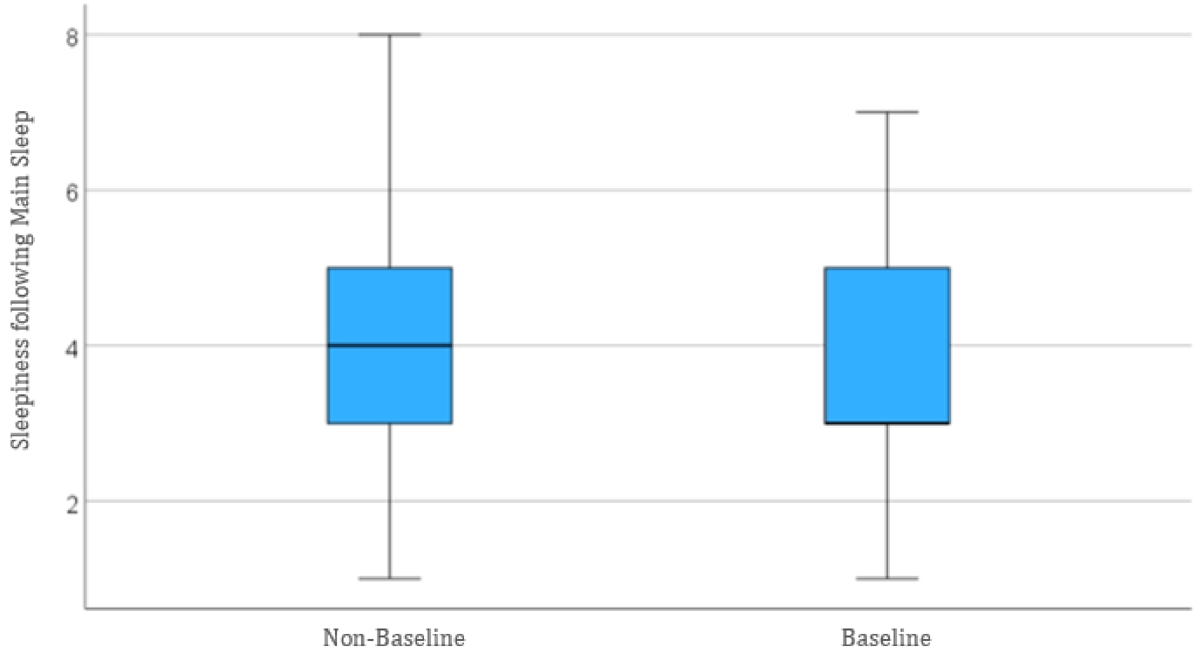


Figure 4-51 Sleep Quality ratings at the end of Baseline and Non-baseline Sleep Periods

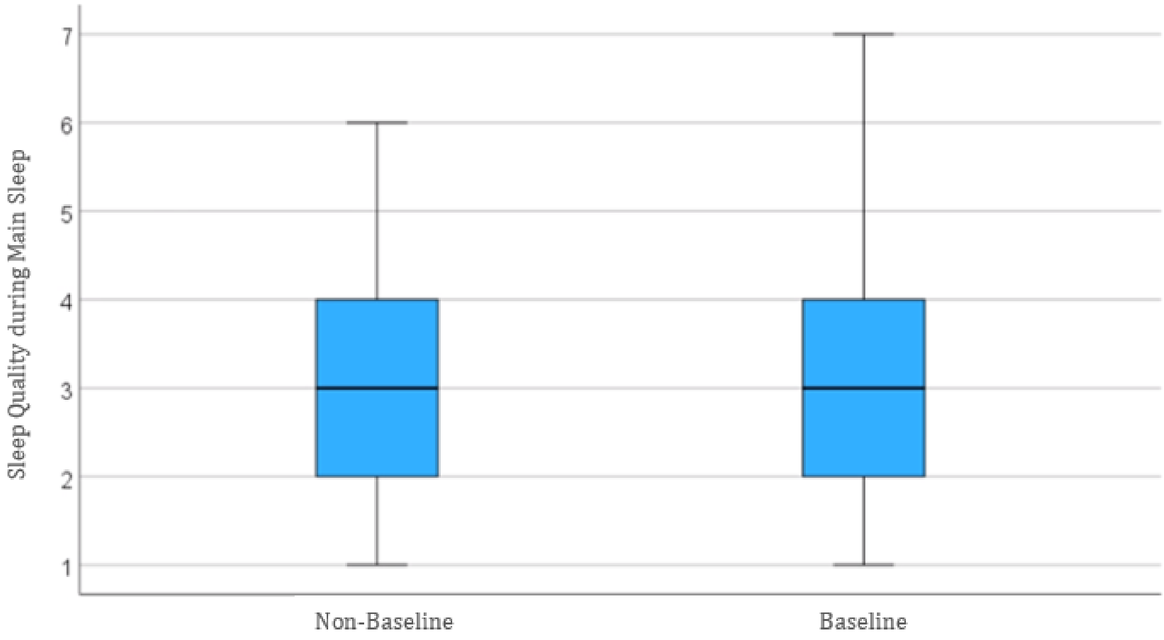


Table 4-29 Mean, Standard Deviation, Median and Range of Fatigue and Sleepiness ratings before and following Non-Baseline and Baseline Main Sleep Periods.

Variable	Baseline sleep period					Non-baseline sleep period				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Fatigue Start Main Sleep	4.53	.84	5	3 (3 – 6)	49	4.86	.89	5	5 (2 – 7)	116
Sleepiness Start Main Sleep	6.53	1.27	7	6 (3 – 9)	49	6.69	1.36	7	6 (3 – 9)	116
Fatigue End Main Sleep	2.78	.91	3	4 (1 – 5) [a]	49	3.3	1.06	3	5 (1 – 6) [b]	116
Sleepiness End Main Sleep	3.84	1.57	3	6 (1 – 7)	49	4.39	1.63	4	7 (1 – 8)	116
Sleep Quality	3.10	1.31	3	6 (1 – 7)	49	3.42	1.27	3	5 (1 – 6)	116

[a] Includes 1 outlier; [b] Includes 5 outliers.

4.9.1.3 Fatigue and sleepiness ratings prior to and following simulated flights

Fatigue and sleepiness ratings were recorded immediately before and following each simulated flight. The distribution of variables is presented in Figure 4-52 (fatigue ratings) and Figure 4-53 (sleepiness ratings). Descriptive statistics including the mean, standard deviation, median and range are presented in Table 4-30.

Figure 4-52 Fatigue Ratings during Simulated Flights grouped by Condition and Timing

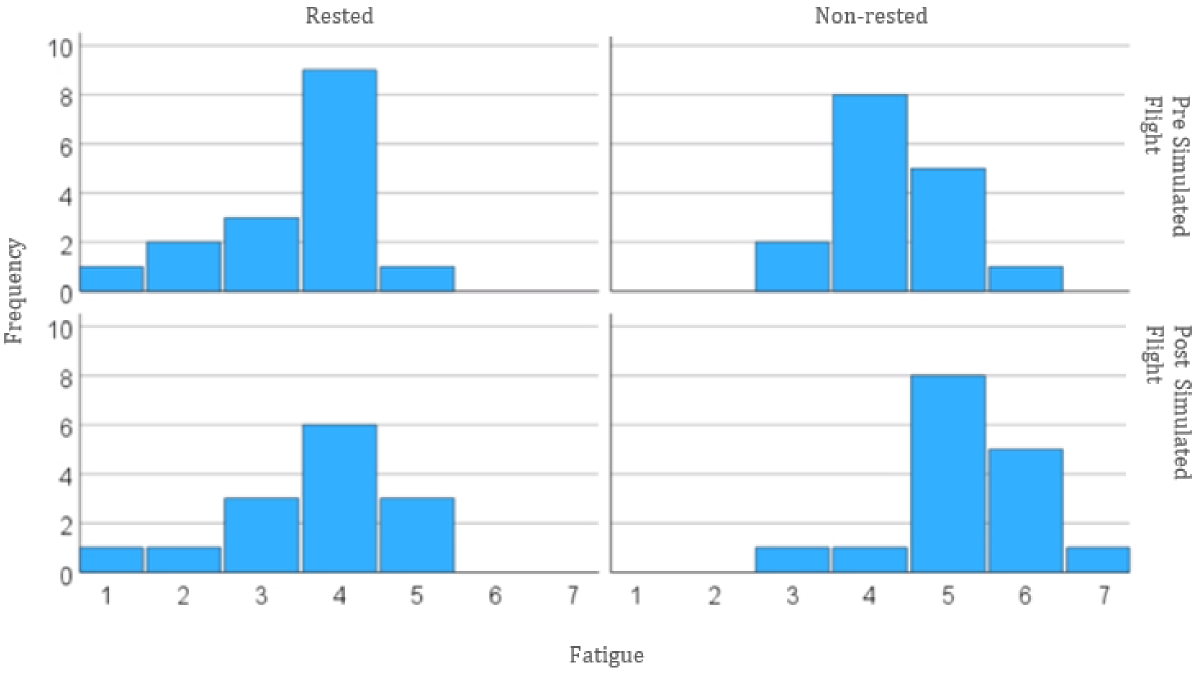


Figure 4-53 Sleepiness Ratings during Simulated Flights grouped by Condition and Timing

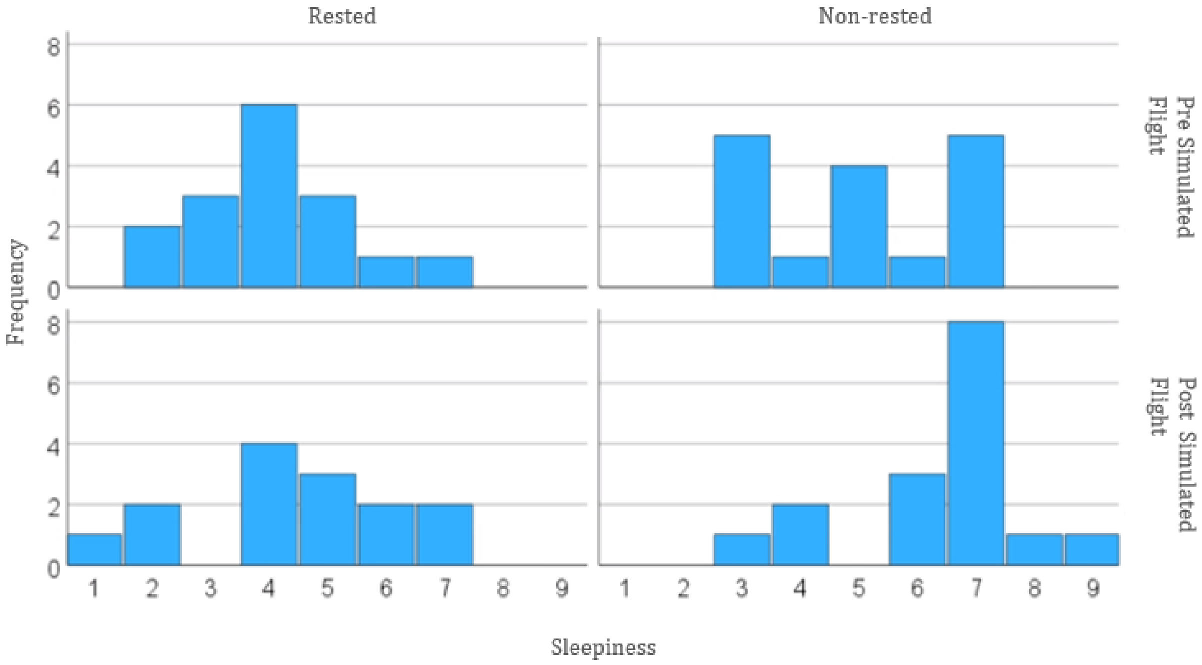


Table 4-30 Mean, Standard Deviation, Median and Range of Fatigue and Sleepiness Ratings grouped by Condition and Timing

Variable	**Non-rested condition**					**Rested condition**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Pre Simulator Fatigue Rating	4.31	.793	4.00	3 – 6	16	3.44	1.03	4	1 – 5 [a]	16
Post Simulator Fatigue Rating	5.25	.931	5.00	3 – 7 [a]	16	3.64	1.15	4	1 – 5 [a]	14
Pre Simulator Sleepiness Rating	5.00	1.67	5.00	3 – 7 [c]	16	4.06	1.34	4	2 – 7	16
Post Simulator Sleepiness Rating	6.38	1.54	7	3 – 9 [c]	16	4.43	1.82	4.5	1 – 7	14

[a] Includes 1 outlier; [b] Includes 4 outliers; [c] Not normally distributed

4.9.2 The Effect of Condition and Day on Fatigue, Sleepiness and Sleep Quality

This section includes analysis and results for the following research question:

Q10: Do subjective fatigue and sleepiness ratings, prior to and following main sleep periods, and subjective sleep quality ratings, following main sleep periods, differ between the non-rested and rested condition?

4.9.2.1 Analysis

Table 4-31 lists results for the effect of condition and day on ratings of fatigue, sleepiness and sleep quality. If main effects were significant, post hoc t tests were used to make pairwise comparisons between levels of the significant effect(s). If interactions were significant, simple effect analyses were undertaken to determine the effect of a fixed effect at individual levels of the other fixed effect. Descriptive statistics for the variables mentioned in Table 4-31 are outlined in Section 4.9.1.1.

Table 4-31 Results of Mixed Model ANOVA for the Effect of Day and Condition on Subjective Ratings of Fatigue, Sleepiness and Sleep Quality

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
Fatigue Start Main Sleep [a b c]	Day	3, 87.4	3.38	**.0219**
	Condition	1, 28.9	1.49	.2326
	Day x Condition	3, 87.4	3.10	**.0308**
Sleepiness Start Main Sleep [a b d e]	Day	3, 91.2	1.61	.1918
	Condition	1, 29.9	0.69	.4128
Fatigue Main Sleep End [b c e f]	Day	3, 91.7	4.49	**.0055**
	Condition	1, 30.3	5.29	**.0285**
Sleepiness Main Sleep End [b f g]	Day	3, 87.1	3.19	**.0276**
	Condition	1, 30.5	4.83	**.0357**
	Day x Condition	3, 87.1	3.56	**.0174**
Sleep Quality [b, e, h, i]	Day	3, 90.8	5.92	**.0010**
	Condition	1, 30	0.92	.3458

[a] Number of observations used: 126/128; [b] Compound Symmetry covariance structure; [c] includes 1 outlier; [d] REFL SQRT transformation applied to normalise distribution; [e] the non-significant (NS) interaction Condition x Day was removed from the final model; [f] Number of observations used: 124/126; [g] excludes 2 outliers; [h] Number of observations used: 125/128; [i] SQRT transformation applied to normalise distribution.

4.9.2.2 Results

Fatigue at the Start of Main Sleep Periods

The interaction between condition and day was significant. Simple effect tests show that ratings of fatigue, at the start of the main sleep period during day 4 were significantly higher (p = .0210) in the non-rested condition (estimated mean = 5.43) compared with the rested condition (estimated mean = 4.75), see Figure 4-54.

Figure 4-54 LS-means Estimates for Fatigue Start Main Sleep for the Interaction: Condition x Day

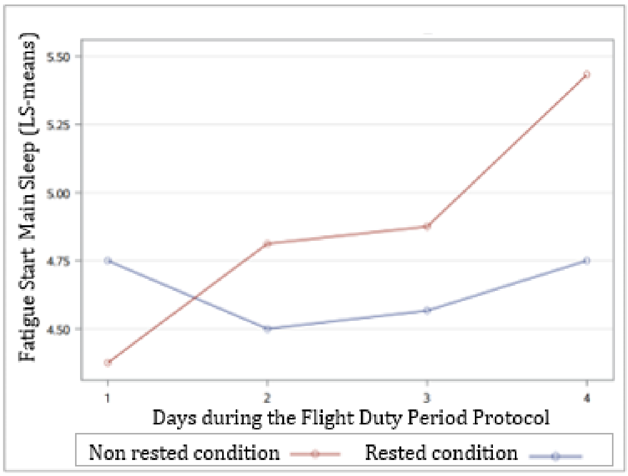


Table 4-32 shows that in the non-rested condition, ratings of fatigue at the start of sleep during day 4 (estimated mean = 5.43) were significantly higher than day 1 (estimated mean = 4.37).

Table 4-32 Simple Effect Comparisons for Condition x Day for Fatigue at the Start of the Main Sleep Period

Simple Effect Level	Day	Day	Adj P
Non-rested	1	2	.1645
Rested	1	2	1.000
Non-rested	1	3	.1428
Rested	1	3	1.000
Non-rested	1	4	**.0004**
Rested	1	4	1.000
Non-rested	2	3	.8023
Rested	2	3	1.000
Non-rested	2	4	.0825
Rested	2	4	1.000
Non-rested	3	4	.1222
Rested	3	4	1.000

Sleepiness at the Start of Main Sleep Periods

The interaction between condition and day was not significant. In the reduced model, condition and day did not contribute to significant differences in sleepiness ratings at the start of sleep.

Fatigue at the End of Main Sleep Periods

The interaction between condition and day was removed from the model as it was not significant. Independent of day, ratings of fatigue at the end of the sleep period were significantly higher in the non-rested condition (estimated mean = 3.40) compared with the rested condition (estimated mean = 2.83). Fatigue was significantly lower following the main sleep period during day 4 (estimated mean = 2.77) compared with day 1 (estimated mean = 3.65), see Table 4-33.

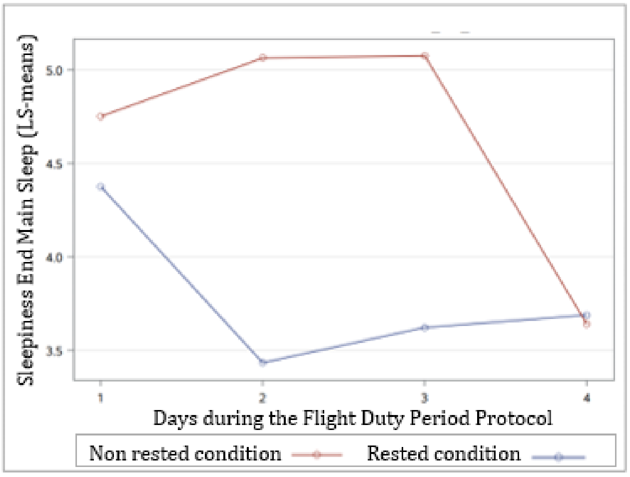
Table 4-33 Simple Effect Comparisons of Fatigue Ratings at the End of Main Sleep Periods for different Levels of Day

Day	Day	Adj P
1	2	.0828
1	3	.1819
1	4	**.0032**
2	3	.6974
2	4	.4908
3	4	.3378

Sleepiness at the End of Main Sleep Periods

The interaction between condition and day was significant for sleepiness ratings at the end of the main sleep period. Simple effect tests showed sleepiness ratings were significantly higher in the non-rested condition during day 2 (5.06 versus 3.43, p = .0033) and 3 (5.07 versus 3.62, p = .0093), see Figure 4-55. The difference in sleepiness ratings was not significant during day 1 (p = .4831) or 4 (p=.9301).

Figure 4-55 LS-means Estimates for Sleepiness at the End of Main Sleep Periods for the Interaction: Condition x Day



In the non-rested condition, simple effect tests showed that sleepiness was significantly lower during day 4 (3.64) compared with day 3 (5.07), 2 (5.06) and 1 (4.75), see Table 4-34.

Table 4-34 Simple Effect Comparisons for Condition x Day for Sleepiness at the End of Main Sleep Periods during Days 1 - 4.

Simple Effect Level	Day	Day	Adj P
Non-rested	1	2	1.000
Rested	1	2	.1920
Non-rested	1	3	1.000
Rested	1	3	.4241
Non-rested	1	4	**.0479**
Rested	1	4	.4336
Non-rested	2	3	1.000
Rested	2	3	1.000
Non-rested	2	4	**.0087**
Rested	2	4	1.000
Non-rested	3	4	**.0087**
Rested	3	4	1.000

Sleep Quality

The interaction between condition and day was removed from the model as it was not significant. Sleep quality ratings were not significantly different between levels of condition. Post hoc t tests showed that ratings of sleep quality were significantly higher during day 4 (untransformed estimated mean = 2.67) compared with day 3 (untransformed estimated mean = 3.43), see Figure 4-56 and Table 4-35.

Figure 4-56 Untransformed LS-means for Sleep Quality for Different Levels of Day

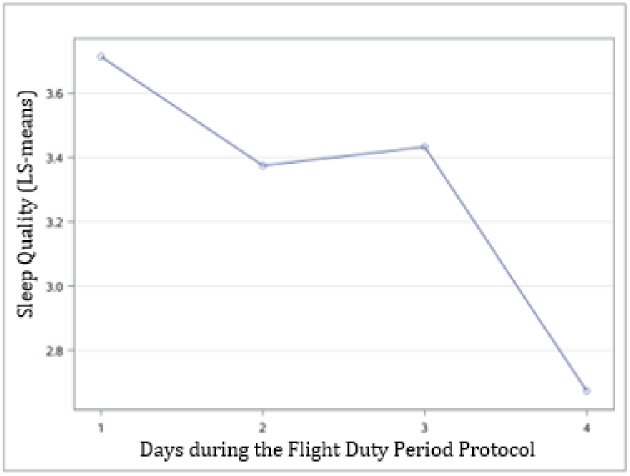


Table 4-35 Simple Effect Comparisons of Sleep Quality for Different Levels of Day

Day	Day	Adj P
1	2	.6894
1	3	.6894
1	4	**.0008**
2	3	.8234
2	4	**.0229**
3	4	**.0161**

4.9.3 The Effect of Non-baseline and Baseline Sleep Periods on Fatigue, Sleepiness and Sleep Quality

This section includes the analysis and results for the following research question:

Q11: Do fatigue, sleepiness and sleep quality ratings differ between non-baseline and baseline sleep periods?

4.9.3.1 Analysis

Table 4-36 lists the results for the effect of non-baseline and baseline sleep periods on ratings of fatigue, sleepiness and sleep quality. Descriptive statistics are included in Section 4.9.1.2.

Table 4-36 Results of mixed model ANOVA for the Effect of Non-baseline and Baseline sleep periods on Subjective Ratings of Fatigue, Sleepiness and Sleep Quality

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
Fatigue Start Main Sleep [a b c]	Sleep Period [g]	1, 153	6.64	**.0109**
Sleepiness Start Main Sleep [a b]	Sleep Period [g]	1, 152	1.16	0.2823
Fatigue End Main Sleep [a c d]	Sleep Period [g]	1, 153	6.57	**.0113**
Sleepiness End Main Sleep [a d e]	Sleep Period [g]	1, 153	1.97	.1628
Sleep Quality [d f]	Sleep Period [g]	1, 152	2.56	.1112

[a] Number of observations used: 166/168; [b] REFL SQRT transformation applied to normalise distribution; [c] includes 1 outlier; [d] LOG transformation applied to normalise distribution; [e] includes 2 outliers; [f] Number of observations used: 165/168; [g] Levels of sleep period include non-baseline and baseline sleep periods.

4.9.3.2 Results

Fatigue ratings at the start and end of main sleep periods were significantly different between non-baseline and baseline sleep periods. In baseline sleep periods, fatigue ratings were significantly lower at the start (untransformed estimated mean = 4.51

versus 4.86) and end (untransformed estimated mean = 2.82 versus 3.27) of main sleep periods. Sleepiness ratings before and following the main sleep period and sleep quality ratings following the main sleep period were not significantly different.

4.9.4 The Effect of Condition, Timing and Order on Fatigue and Sleepiness before and following Simulated Flights

This section includes analysis and results for the following research question:

Q12. Do fatigue and sleepiness ratings across each simulated flight differ between the non-rested and rested condition?

4.9.4.1 Analysis

Table 4-37 lists results for the effect of condition, timing and order on ratings of fatigue and sleepiness. If interactions were significant, simple effect analyses were undertaken to determine the effect of a fixed effect at individual levels of the other fixed effect. Descriptive statistics for the variables mentioned in Table 4-37 are outlined in Section 4.9.1.3.

Table 4-37 Results of mixed model ANOVA for the Effect of Condition, Timing and Order on Subjective Ratings of Fatigue and Sleepiness before and following Simulated Flights

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
Simulated Flight Fatigue [a b]	Condition	1, 37.4	41.27	<**.0001**
	Timing	1, 37.4	13.63	**.0007**
	Order	1, 37.4	0.61	.4412
	Condition x Timing	1, 38.6	4.39	**.0427**
Simulated Flight Sleepiness [c d]	Condition	1, 43.3	18.94	<**.0001**
	Timing	1, 43.3	8.83	**.0048**
	Order	1, 43.3	2.18	.1471

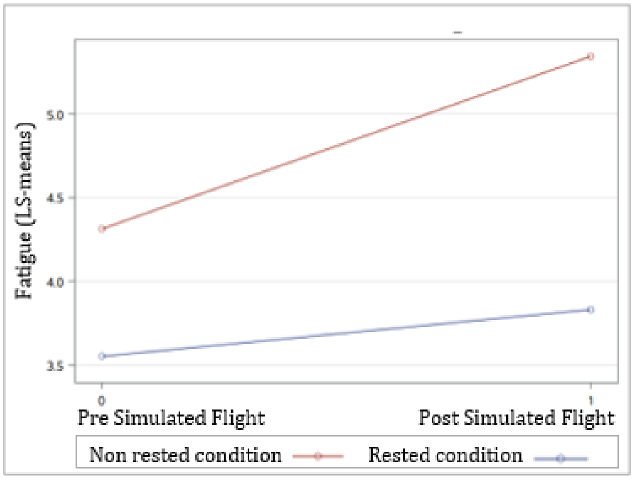
[a] Number of observations used 59/61; [b] Excludes 3 outliers; [c] Number of observations used: 62/64; [d] Interaction Condition x Timing removed from the final model as it was not significant.

4.9.4.2 Results

Simulated Flight Fatigue

The interaction between condition and timing was significant. Simple effect tests show that pre simulated flight fatigue ratings were significantly higher (p = .0034) in the non-rested condition (estimated mean = 4.31 versus 3.55) compared to the rested condition. In addition, fatigue ratings following simulated flights were significantly higher (p = <.0001) in the non-rested condition (estimated mean = 5.34 versus 3.83) than the rested condition, see Figure 4-57.

Figure 4-57 LS-means Estimates for Fatigue before and Following Simulated Flights for the Interaction: Condition x Timing



Simple effect tests showed that fatigue ratings in the non -rested condition were significantly higher (p = .0001) post simulated flight compared with pre simulated flight ratings (estimated mean = 5.34 versus 4.31). The difference between pre and post simulated flight fatigue ratings in the rested condition were not significantly different.

Simulated Flight Sleepiness

The interaction between condition and timing for sleepiness ratings was removed from the model as the effect was not significant. In the reduced model, sleepiness ratings were significantly higher in the non-rested condition (estimated mean = 5.68 versus 4.31) compared to the rested condition. In addition, sleepiness was significantly higher following simulated flights (estimated mean = 5.46 versus 4.53) compared to ratings before simulated flights.

4.9.5 The Effect of Sleep Related Variables on Fatigue and Sleepiness

This section includes analysis and results for the following research question:

Q13. Are subjective ratings of fatigue and sleepiness across simulated flights associated with cumulative sleep debt, time since sleep, or total sleep time?

4.9.5.1 Analysis

Table 4-38 lists results for the effect of cumulative sleep debt, time since sleep at the start of the simulated flight and total sleep in 24hrs and 48hrs on ratings of fatigue and sleepiness before and following simulated flights. Descriptive statistics for the variables mentioned in Table 4-38 are included in Section 4.8.1.1 and Table 4-39 shows the direction of association between dependent and independent variables.

Table 4-38 Results of Mixed Model ANOVA for the Effect of Sleep Related Variables on Subjective Ratings of Fatigue and Sleepiness before and following Simulated Flights

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
Pre Simulated Flight Fatigue [a]	Cumulative Sleep Debt	1, 27.7	7.35	**.0114**
	Total Sleep in 24hrs	1, 26.5	14.08	**.0009**
	Time Since Sleep at the Start of the pre Simulated Flight PVT Test	1, 25	4.25	**.0497**
Pre Simulated Flight Fatigue [a b]	Cumulative Sleep Debt	1, 25.5	5.44	**.0279**
	Total Sleep in 48hrs	1, 23	4.94	**.0363**
	Time Since Sleep at the Start of the pre Simulated Flight PVT Test	1, 25	0.31	.5851
Pre Simulated Flight Sleepiness [a b]	Cumulative Sleep Debt	1, 25.2	6.35	**.0185**
	Total Sleep in 24hrs	1, 24.3	8.62	**.0072**
	Time Since Sleep at the Start of the pre Simulated Flight PVT Test	1, 27.4	0.45	.5088
Pre Simulated Flight Sleepiness [a]	Cumulative Sleep Debt	1, 25.4	5.71	**.0246**
	Total Sleep in 48hrs	1, 23.3	1.58	.2212
	Time Since Sleep at the Start of the pre Simulated Flight PVT Test	1, 25.5	0.15	.7024
Post Simulated Flight Fatigue [a]	Cumulative Sleep Debt	1, 25.7	3.00	.0951
	Total Sleep in 24hrs	1, 24.7	2.36	.1373
	Time Since Sleep at the Start of the post Simulated Flight PVT Test	1, 24.8	7.00	**.0139**
Post Simulated Flight Fatigue [a]	Cumulative Sleep Debt	1, 25.70	3.23	.0842
	Total Sleep in 48hrs	1, 22.5	6.45	**.0185**
	Time Since Sleep at the Start of the post Simulated Flight PVT Test	1, 22.6	10.03	**.0044**
Post Simulated Flight Sleepiness [c]	Cumulative Sleep Debt	1, 23.1	5.28	**.0309**
	Total Sleep in 24hrs	1, 22.7	9.32	**.0057**

Dependent variable	**Independent variable**	**DF**	**F-value**	**P(F)**
	Time Since Sleep at the Start of the post Simulated Flight PVT Test	1, 25.9	6.48	**.0172**
Post Simulated Flight Sleepiness [a]	Cumulative Sleep Debt	1, 25.4	6.41	**.0179**
	Total Sleep in 48hrs	1, 22.5	6.46	**.0184**
	Time Since Sleep at the Start of the post Simulated Flight PVT Test	1, 23.6	4.31	**.0489**

[a] Number of observations used 32/32; [b] Includes 1 outlier; [c] Number of observations used 30/32.

Table 4-39 Direction of Association between Subjective Ratings of Fatigue and Sleepiness and Sleep Related Variables

Dependent Variable	**Cumulative Sleep Debt**	**Time Since Sleep**	**Total Sleep in 24hrs**	**Total Sleep in 48hrs**
Pre Simulated Flight Fatigue	🟦 ▲	🟦 ▼	🟦 ▼	⬛
Pre Simulated Flight Fatigue	🟦 ▲	▼	⬛	🟦 ▼
Pre Simulated Flight Sleepiness	🟦 ▲	▼	🟦 ▼	⬛
Pre Simulated Flight Sleepiness	🟦 ▲	▲	⬛	▼
Post Simulated Flight Fatigue	▲	🟦 ▼	▼	⬛
Post Simulated Flight Fatigue	▲	🟦 ▼	⬛	🟦 ▼
Post Simulated Flight Sleepiness	🟦 ▲	🟦 ▼	🟦 ▼	⬛
Post Simulated Flight Sleepiness	🟦 ▲	🟦 ▼	⬛	🟦 ▼

▲	Increase in IV = Increase in DV
▼	Increase in IV = Decrease in DV
🟦	Significant association
⬜	on-significant trend
⬛	Independent variable not included within the model

4.9.5.2 Results

Cumulative Sleep Debt

Cumulative sleep debt was significantly associated with pre simulated flight fatigue ratings and both pre and post simulated flight sleepiness ratings (see Table 4-38). For pre simulated flight fatigue ratings, each one hour increase in cumulative sleep debt, resulted in an increase in model estimates of 0.16 units in the model which accounted for total sleep in 24hrs, and an increase of 0.15 units in the model which accounted for total sleep in 48hrs. Similar increases were found for pre and post simulated flight sleepiness ratings, as summarised in Table 4-40. Cumulative sleep debt was not significantly associated with post simulated flight fatigue ratings.

Table 4-40 Model Estimates for Subjective Ratings of Fatigue and Sleepiness in Models that have a Significant Association between Subjective Ratings of Fatigue or Sleepiness and Cumulative Sleep Debt

Dependent Variable	Model Estimate	Model which includes:
Pre Simulated Flight Fatigue	0.16	Total Sleep in 24hrs
Pre Simulated Flight Fatigue	0.15	Total Sleep in 48hrs
Pre Simulated Flight Sleepiness	0.24	Total Sleep in 24hrs
Pre Simulated Flight Sleepiness	0.25	Total Sleep in 48hrs
Post Simulated Flight Sleepiness	0.26	Total Sleep in 24hrs
Post Simulated Flight Sleepiness	0.29	Total Sleep in 48hrs

Time Since Sleep

Time since sleep was significantly associated with fatigue ratings recorded before simulated flight in the model which accounted for total sleep in 24hrs and all models which included ratings of fatigue and sleepiness (see Table 4-38) following simulated flights. For each additional hour of wakefulness, the pre simulated flight fatigue rating estimate in the model which accounted for total sleep in 24hrs decreased by 0.24 units. Similar decreases were found for fatigue and sleepiness ratings following simulated flight, as summarised in Table 4-41. Time since sleep was not significantly associated with pre simulated flight fatigue ratings in the model which accounted for total sleep in 48hrs or pre simulated flight sleepiness ratings.

Table 4-41 Model Estimates for Subjective ratings of Fatigue and Sleepiness in Models that have a Significant Association between Subjective Ratings of Fatigue or Sleepiness and Time Since Sleep

Dependent Variable	Model Estimate	Model which includes:
Pre Simulated Flight Fatigue	-0.24	Total Sleep in 24hrs
Post Simulated Flight Fatigue	-0.5	Total Sleep in 24hrs
Post Simulated Flight Fatigue	-0.48	Total Sleep in 48hrs
Post Simulated Flight Sleepiness	-0.65	Total Sleep in 24hrs
Post Simulated Flight Sleepiness	-0.48	Total Sleep in 48hrs

Total Sleep in 24hrs

Total sleep in 24hrs was significantly associated with pre simulated flight fatigue and sleepiness ratings and post simulated flight sleepiness ratings (see Table 4-38). For each additional hour of sleep during the previous 24 hour period, pre simulated flight fatigue rating estimates decreased by 0.64 units. Similar decreases were found for pre and post simulated flight sleepiness ratings, as summarised in Table 4-42. Total sleep in 24hrs was not significantly associated with post simulated flight fatigue ratings.

Table 4-42 Model Estimates of Fatigue and Sleepiness in Models that have a Significant Association between Subjective Ratings of Fatigue or Sleepiness and Total Sleep in 24hrs

Dependent Variable	Model Estimate	Model which includes:
Pre Simulated Flight Fatigue	-0.64	Total Sleep in 24hrs
Pre Simulated Flight Sleepiness	-0.79	Total Sleep in 24hrs
Post Simulated Flight Fatigue	-1.01	Total Sleep in 24hrs

Total Sleep in 48hrs

Total sleep in 48hrs was significantly associated with pre simulated flight fatigue ratings and post simulated flight fatigue and sleepiness ratings (see Table 4-38). For pre simulated flight fatigue ratings, for each additional hour of sleep during the previous 48 hour period, model estimates decreased by 0.20. Similar decreases were found for pre and post simulated flight sleepiness ratings, as summarised in

Table 4-43. Total sleep in 48hrs was not significantly associated with pre simulated flight sleepiness ratings.

Table 4-43 Model Estimates of Fatigue and Sleepiness in Models that have a Significant Association between Subjective Ratings of Fatigue or Sleepiness and Total Sleep in 48hrs

Dependent Variable	Model Estimate	Model which includes:
Pre Simulated Flight Fatigue	-0.20	Total Sleep in 48hrs
Post Simulated Flight Fatigue	-0.29	Total Sleep in 48hrs
Post Simulated Flight Sleepiness	-0.43	Total Sleep in 48hrs

4.10 Summary

Flight Duty Period Protocol

The flight duty period protocol required that participants complete their non-rested simulated flight between 18:00 – 20:00 and their rested simulated flight between 20:00 and 22:00. Participants were also required to operate together before their first simulated flight, operate four consecutive flight duty periods prior to the non-rested simulated flight, and that they had two days free from duty and three local nights' rest prior to their rested simulated flight. Although these requirements were not complied with in a small number of cases, data collected from all participants was included within analysis .

Workload

Ratings of workload were significantly higher following simulated flights than following flight duty periods, however workload did not differ significantly between the non-rested and rested condition, between the first and second simulated flight or during the Christchurch – Wellington or Wellington – Christchurch simulated flight. Workload ratings were not significantly associated with sleep related variables.

Sleep Timing, Duration and Time Since Sleep

The effect of Flight Duty Period Condition and Day on Sleep Related Variables: Compared with the rested condition, cumulative sleep debt was significantly higher in the non-rested condition during days 2, 3 and 4. In the non-rested condition, cumulative sleep debt was significantly higher during day two compared with day 1 and in day three compared with day 2. When compared with day 3, cumulative sleep debt was significantly lower during day 4.

Time since sleep was significantly shorter in the non-rested condition when compared with the rested condition at the start of the pre simulated flight PVT, the start of the simulated flight and the start of the post simulated flight PVT.

Compared with the rested condition, total sleep in 24hrs was significantly shorter in the non-rested condition during days 1 and 2. In the non-rested condition, total sleep in 24hrs was significantly longer during day 4, compared with day 3.

Total sleep in 48hrs prior to the simulated flight was not significantly different between the non-rested and rested condition.

The start of sleep was significantly later in the rested condition, compared with the non-rested condition during days 2 and 3 and it was significantly earlier in the rested condition during day 1 compared with day 2.

The end of sleep was significantly later in the rested condition, compared with the non-rested condition during days 1, 2 and 3 and it was significantly earlier during the rested condition during day 1 compared with day 2. In addition, it was significantly earlier during the non-rested condition during day 3 compared with day 4.

Time in bed was significantly shorter during the non-rested condition during day 2 and 3. In addition, it was significantly shorter during the non-rested condition during day 3, when compared with day 4.

The effect of non-baseline and baseline sleep periods on sleep related variables:

During baseline sleep periods, the start and end of sleep was significantly later, and time in bed was significantly longer. However, total sleep over the 24 hour period starting at 12:00 was not significantly different when compared with non-baseline sleep periods.

Subjective Ratings of Fatigue, Sleepiness and Sleep Quality

The effect of condition and day on subjective ratings of fatigue, sleepiness and sleep quality:

Ratings of fatigue at the start of sleep were significantly higher in the non-rested condition during day 4. However, there were no significant differences in fatigue ratings between days in either the non-rested or rested condition.

Ratings of sleepiness at the start of sleep were not significantly different between the non-rested and rested condition or between different levels of day.

Ratings of fatigue at the end of sleep were significantly higher during the non-rested condition and although fatigue ratings were significantly different between different levels of day, there were no significant differences in meaningful comparisons.

Subjective sleepiness ratings at the end of sleep were significantly higher in the non-rested condition during days 2 and 3, and in the non-rested condition, sleepiness ratings were significantly higher during day 3, compared with day 4.

Sleep quality was not significantly different between the non-rested and rested condition, however, it was significantly higher during day 4, compared with day 3.

The effect of non-baseline and baseline sleep periods on subjective ratings of fatigue, sleepiness and sleep quality:

During baseline sleep periods, ratings of fatigue were significantly lower during both the start and end of sleep. Sleepiness and sleep quality did not differ significantly between levels of condition.

The effect of condition, timing and order on subjective ratings of fatigue and sleepiness before and following simulated flights:

The interaction between condition and timing was significant for pre and post simulated flight ratings of fatigue. Fatigue ratings were significantly higher in the non-rested condition and following simulated flight. Sleepiness ratings were significantly higher in the non-rested condition compared and were significantly higher following simulated flight.

The effect of sleep related variables on pre simulated flight and post simulated flight subjective ratings of fatigue and sleepiness:

An increase in cumulative sleep debt was associated with a significant increase in ratings of fatigue and sleepiness. Time since sleep was associated with a significant decrease in pre simulated flight ratings of fatigue in the model which accounted for total sleep in 24hrs and a significant decrease in post simulated flight ratings of fatigue and sleepiness. An increase in total sleep in 24hrs was associated with a significant decrease in fatigue and sleepiness ratings prior to the start of simulated flights and post simulated flight ratings of sleepiness whereas. An increase in total sleep in 48hrs was associated with a significant decrease in ratings of fatigue prior to the start of the simulated flight and a decrease in both ratings of fatigue and sleepiness following flight.

CHAPTER 5 RESULTS: PSYCHOMOTOR VIGILANCE TASK

5.1 Overview

This chapter presents findings from the analysis of PVT test data collected before and following each simulated flight. Analysis focused on the influence of sleep related factors on PVT performance. In addition, the influence of condition (non-rested or rested), flight order (first or second simulated flight) and test timing (pre simulated flight or post simulated flight) was investigated. Analyses and results are grouped by research question.

5.2 Research Questions

The following research questions are addressed.

Question 1. Does PVT performance differ between the non-rested and rested condition?

Question 2. Does PVT performance change across the simulated flight?

Question 3. Does PVT performance differ between the first and second simulated flight?

Question 4. Is PVT performance associated with sleep related variables?

Question 5. Is PVT performance associated with subjective ratings of fatigue and sleepiness?

5.3 Method

5.3.1 Measures

Dependent Variables

The following dependent variables were utilised:

PVT response speed: The mean response speed for all valid responses (reaction times ≥ 100ms). Depending on the comparisons made, this measure is reported as either: PVT Response Speed, Pre-Simulator PVT Response Speed or Post-Simulator PVT Response Speed.

The fastest 10% of responses: The fastest 10% of responses for all valid responses (reaction times ≥ 100ms). Depending on the comparisons made, this measure is reported as either: Fastest 10% of Responses, Pre-Simulator Fastest 10% of Responses or Post-Simulator Fastest 10% of Responses.

The slowest 10% of responses: The slowest 10% of responses for all valid responses (reaction times ≥ 100ms). Depending on the comparisons made, this measure is reported as either: Slowest 10% of Responses, Pre-Simulator Slowest 10% of Responses or Post-Simulator Slowest 10% of Responses.

The following independent variables were utilised in this chapter.

Independent Variables

The following variables were included in linear mixed models, which are described in further detail below.

Condition (non-rested or rested condition): Identifies if PVT variables are from the non-rested or rested condition.

Flight order (first flight or second flight): Identifies if PVT variables are from the first or second simulated flight.

Timing (pre simulated flight or post simulated flight): Identifies if PVT variables are from the pre or post-simulator PVT test.

Sleep Related Variables

Cumulative Sleep Debt: the amount of sleep debt (in minutes) accrued by the end of day 4, the final 24 hour period prior to the non-rested (18:00) or rested simulated flight (20:00 – 22:00).

Time Since Sleep: the duration of time (in minutes) between end of sleep and the start of either the pre or post simulated flight PVT test.

Total sleep in 24hrs: Total sleep in the previous 24 hour period prior to the non-rested (18:00 – 18:00) or rested simulated flight (20:00 – 20:00).

Total sleep in 48hrs: Total sleep in the previous 48 hour period prior to the non-rested simulated flight (18:00 – 18:00) or rested simulated flight (20:00 – 20:00).

Samn Perelli fatigue rating: Depending on the comparisons made, this measure is reported as either pre or post simulated flight fatigue rating.

Karolinska Sleepiness Scale rating: Depending on the comparisons made, this measure is reported as either pre or post simulated flight sleepiness rating.

5.3.2 Statistical Analyses

Descriptive statistics (mean, standard deviation, median, and range) are provided for each dependent variable. Linear mixed models were used to investigate the association between dependent and independent variables.

Collinearity

For linear mixed models that included continuous independent variables (cumulative sleep debt, time since sleep, total sleep in 24hrs and 48hrs, fatigue ratings and sleepiness ratings) collinearity between variables was checked. Total sleep in 24hrs and 48hrs were found to be colinear and were therefore not included in the same model. Similarly, fatigue and sleepiness were also collinear and not included within the same model. Further collinearity tests indicated no redundancy between the remaining variables. For each PVT variable, four separate models were run which included the following variables:

- Cumulative sleep debt, time since sleep, total sleep in 24hrs and pre or post simulated flight fatigue.
- Cumulative sleep debt, time since sleep, total sleep in 24hrs and pre or post simulated flight sleepiness.
- Cumulative sleep debt, time since sleep, total sleep in 48hrs and pre or post simulated flight fatigue.
- Cumulative sleep debt, time since sleep, total sleep in 48hrs and pre or post simulated flight sleepiness.

Transformations

Post-simulator fastest 10% of responses was the only PVT variable that required transformation. Differences in parameter estimates from the transformed model were not reported however relative relationships were. Details for each transformation are included as footnotes in tables which include linear mixed model results.

5.3.3 Test Details

Sixteen participants each completed 4 PVT tests (two in each condition), resulting in a total of 64 completed tests. Each PVT test had an average of 94 valid reaction time values (range 85 – 103 responses). The average start time of the pre-sim PVT in the non-rested condition was 17:41 (range 17:27 – 17:49) whereas the average start time in the rested condition was about two hours later at 19:36 (range 17:41 – 20:10). Similarly, there was almost a two hour difference between the average start time for the post-sim PVT in the non-rested condition (mean = 19:33, range 19:21 – 19:46) and the rested condition (mean = 21:19, range 19:27 – 21:49). Three outliers were identified[78]. All PVT tests were included within this analysis. Figure 5-1 shows variation in PVT start times and Table 5-1 includes descriptive statistics for PVT start times.

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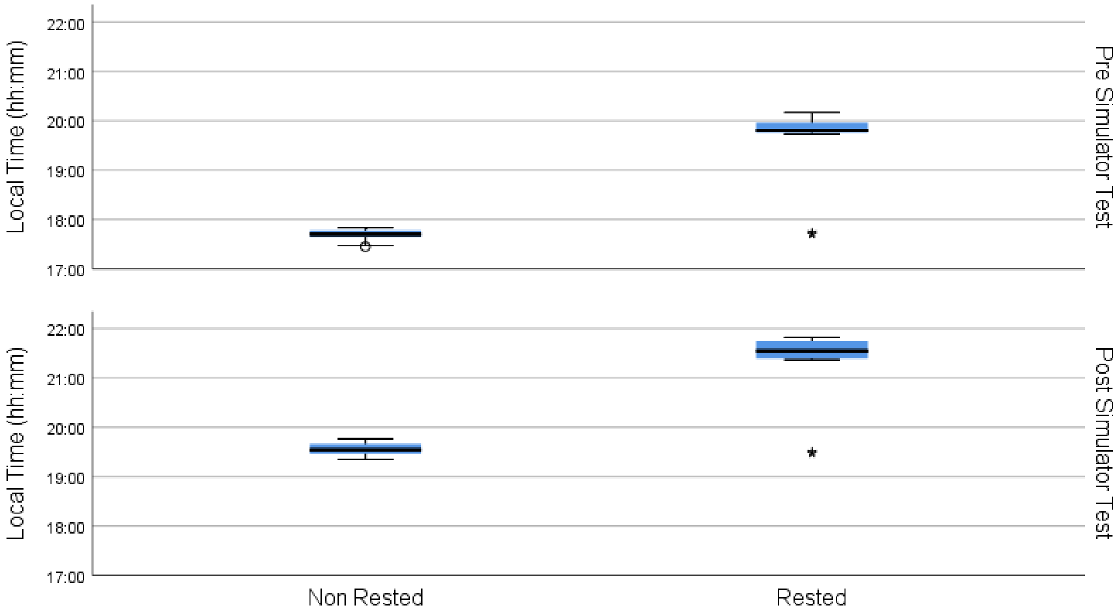
[78] In the non-rested condition, one participant started their pre-sim PVT test at 17:27. Two participants completed their rested simulated flight between 18:00 – 20:00 rather than 20:00 – 22:00. These are depicted in Figure 5-1 as extreme values (asterisks) rather than outliers (open circles).

Figure 5-1 PVT start times during the non-rested and rested condition



The duration between the pre-sim PVT and the simulated flight's taxi out time varied widely between participants (average = 39 minutes; range 28-84 minutes). Some participants needed to wait longer for the flight simulator to become available, whereas others took longer to complete pre-departure checklists. For that reason, to determine time since sleep, the PVT start time was used instead of the flight's taxi out time. By comparison, there was much less variability between the end of the simulated flight and the start of the post-sim PVT (average 6 minutes, range 1 – 19 minutes). Nevertheless, for consistency, to calculate time since sleep for the post simulated flight PVT test, the start time of this test was also used instead of the simulated flights on blocks arrival time. The mean, standard deviation, median and range for PVT response speed, fastest 10% of responses and slowest 10% of responses grouped by the non-rested or rested condition are outlined in Table 5-2. For slowest 10% of responses, one outlier was identified in the non-rested condition.

Table 5-1 Mean, Standard Deviation, Median and Range of PVT Timing for Non-rested and Rested Simulated Flights.

Variable	**Non-rested**					**Rested**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Pre-Simulator PVT Test start time	17:41	0:06	17:41	17:27 – 17:49 [a]	16	19:36	0:45	19:48	17:41 – 20:10 [b]	16
Post-Simulator PVT Test start time	19:33	0:08	19:32	19:21 – 19:46	16	21:19	0:44	21:33	19:27 – 21:49 [b]	16

[a] Includes 1 outlier; [b] Includes 2 extreme outliers.

Table 5-2 Mean , Standard Deviation and Range of PVT Variables grouped by Condition and Timing

Variable	**Non-rested**					**Rested**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Pre-Simulator PVT Response Speed	4.21	.470	4.31	3.18 – 4.91	16	4.26	.443	4.18	3.76 – 5.04	16
Pre-Simulator Fastest 10% of Responses	5.32	.497	5.35	4.39 – 6.18	16	5.31	.449	5.38	4.72 – 6.07	16
Pre-Simulator Slowest 10% of Responses	2.80	.398	2.89	1.97 – 3.48	16	2.97	.410	2.83	2.47 – 3.77	16
Post-Simulator PVT Response Speed	4.09	.532	4.29	2.80 – 4.77	16	4.18	.422	4.09	3.63 – 5.10	16
Post-Simulator Fastest 10% of Responses	5.22	.495	5.24	4.46 – 5.96	16	5.27	.405	5.25	4.52 – 5.94	16
Post-Simulator Slowest 10% of Responses	2.75	.545	2.97	1.39 – 3.32	16	2.87	.469	2.83	2.33 – 3.83	16

5.4 The Effect of Condition, Timing and Order on PVT Performance

This section includes analyses and results for the following research questions:

Q1. Does PVT performance differ between the non-rested and rested condition?

Q2. Does PVT performance change across the simulated flight?

Q3. Does PVT performance differ between the first and second simulated flight?

5.4.1 Analysis

Table 5-3 summarises the linear mixed model results for the effect of the non-rested or rested condition, the pre-flight or post-flight test timing and the first simulated flight or second simulated flight order on the PVT variables response speed, fastest 10% of responses and slowest 10% of responses. The interaction between condition and timing was not significant for any of the PVT variables examined and was therefore removed from final models. Figure 5-2, Figure 5-3 and Figure 5-4 show LS-means estimates for PVT variables grouped by timing and condition.

Table 5-3 Results of mixed model ANOVA for the Effect of Condition, Timing and Order on PVT Performance.

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
PVT Response Speed [a d]	Condition	1, 45	1.42	.2396
	Timing	1, 45	3.05	.0877
	Order	1, 45	3.26	.7302
Fastest 10% of Responses [a d]	Condition	1, 45	0.07	.7990
	Timing	1, 45	1.03	.3153
	Order	1, 45	0.96	.3321
Slowest 10% of Responses [b c d]	Condition	1, 43.9	3.09	.0858
	Timing	1, 43.9	0.52	.4755
	Order	1, 43.9	0.48	.4936

[a] Number of observations used: 64/64; [b] Number of observations used: 63/63; [c] one outlier removed; [d] the interaction CONDITION x TIMING was not significant, therefore was removed from the final model.

5.4.2 Results

PVT response speed, fastest 10% of responses, and slowest 10% of responses did not differ significantly between the pre and post simulated flight in either the non-rested or rested condition. A trend was observed where the LS-mean estimate for each PVT variable was slower following each simulated flight however this effect was not statistically significant. In addition, there was no effect of simulated flight order on PVT response speed, fastest 10% of responses or slowest 10% of responses.

Figure 5-2 Estimated PVT Response Speed by Condition and Timing

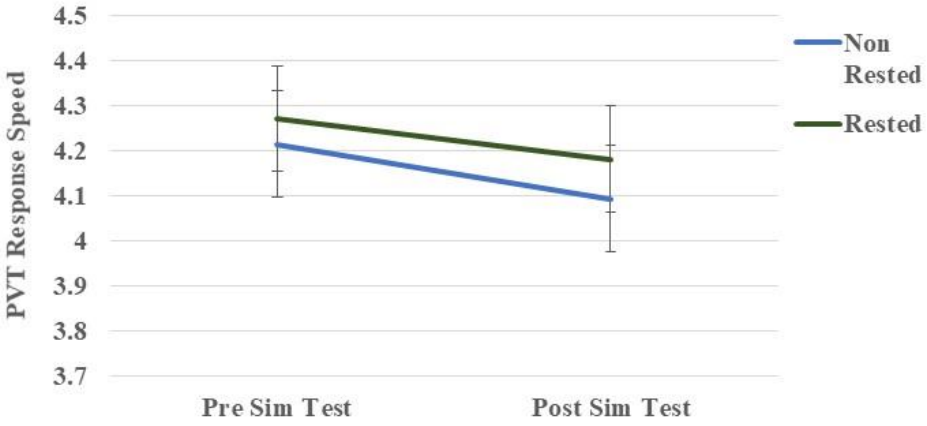


Figure 5-3 Estimated Mean Fastest 10% of Responses by Condition and Timing

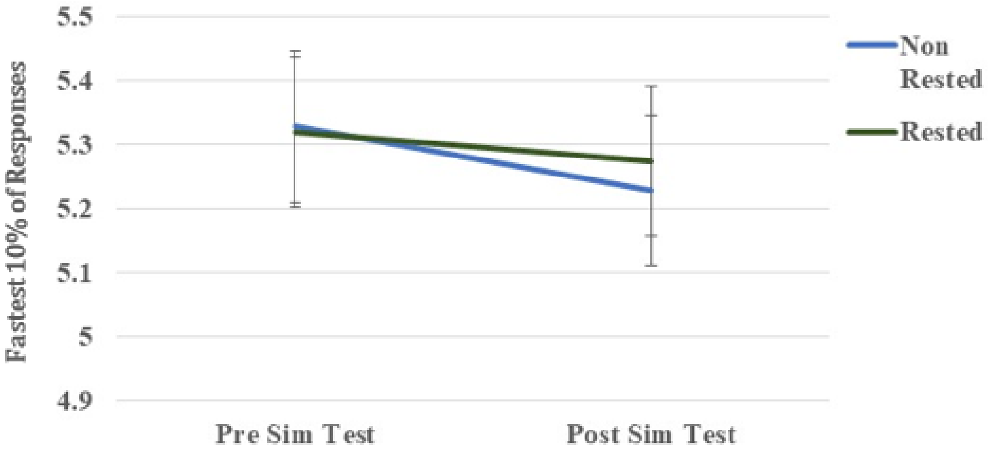
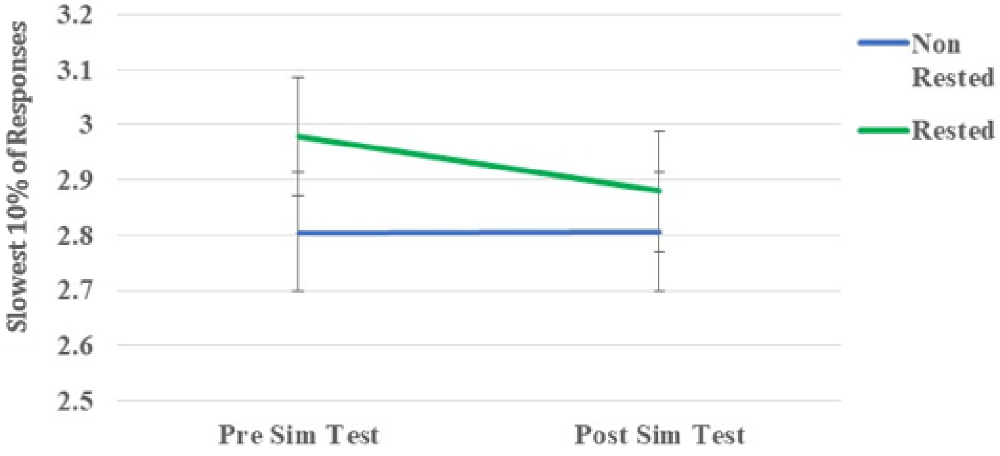


Figure 5-4 Estimated Mean Slowest 10% of Responses by Condition and Timing



5.5 The Effect of Sleep Related Variables, Fatigue and Sleepiness on Psychomotor Vigilance Task Performance

This section includes analyses and results for the following research questions:

Q4. Is PVT performance associated with sleep related variables?

Q5. Is PVT performance associated with subjective ratings of fatigue and sleepiness?

5.5.1 Analysis

Table 5-4, Table 5-5 and Table 5-6 summarise linear mixed model results for the effect of sleep related variables and ratings of fatigue and sleepiness on PVT variables. Table 5-7 shows the direction of association between dependent and independent variables.

Table 5-4 Results of Mixed Model ANOVA for the Effect of Sleep Related Variables and Subjective Ratings of Fatigue and Sleepiness on PVT Response Speed

Dependent Variable	Independent Variable	DF	F-value	P(F)
Pre-Simulator PVT Response Speed [a]	Cumulative Sleep Debt	1, 26.7	0.13	.7230
	Time Since Sleep	1, 24	0.24	.6298
	Total Sleep in 24hrs	1, 26.8	0.82	.3743
	Pre Simulated Flight Fatigue	1, 26.4	0.24	.6314
Pre-Simulator PVT Response Speed [a]	Cumulative Sleep Debt	1, 26.9	0.57	.4557
	Time Since Sleep	1, 21.6	0.08	.7838
	Total Sleep in 24hrs	1, 26.8	2.08	.1611
	Pre Simulated Flight Sleepiness	1, 20.1	0.10	.7508
Pre-Simulator PVT Response Speed [a]	Cumulative Sleep Debt	1, 24.1	0.00	.9967
	Time Since Sleep	1, 20.7	0.33	.5700
	Total Sleep in 48hrs	1, 26.2	8.98	**.0059**
	Pre Simulated Flight Fatigue	1, 25.2	0.38	.5444
Pre-Simulator PVT Response Speed [a]	Cumulative Sleep Debt	1, 25.2	0.06	.8015
	Time Since Sleep	1, 20.7	0.25	.6230
	Total Sleep in 48hrs	1, 24.2	10.95	**.0029**
	Pre Simulated Flight Sleepiness	1, 24.5	0.01	.9082
Post-Simulator PVT Response Speed [b]	Cumulative Sleep Debt	1, 24.4	0.09	.7707
	Time Since Sleep	1, 15.7	2.52	.1322
	Total Sleep in 24hrs	1, 22.9	0.45	.5087
	Post Simulated Flight Fatigue	1, 22.8	7.12	**.0138**
Post-Simulator PVT Response Speed [b]	Cumulative Sleep Debt	1, 25	0.06	.8109
	Time Since Sleep	1, 15	1.08	.3159
	Total Sleep in 24hrs	1, 21.1	0.90	.3530
	Post Simulated Flight Sleepiness	1, 18.8	4.70	**.0431**
Post-Simulator PVT Response Speed [b]	Cumulative Sleep Debt	1, 24.4	0.39	.5374
	Time Since Sleep	1, 16.7	0.84	.3734
	Total Sleep in 48hrs	1, 24.7	1.13	.2974
	Post Simulated Flight Fatigue	1, 22.4	3.82	.0632
Post-Simulator PVT Response Speed [b]	Cumulative Sleep Debt	1, 25	0.39	.5392
	Time Since Sleep	1, 15.1	0.05	.8310
	Total Sleep in 48hrs	1, 24.8	1.55	.2248
	Post Simulated Flight Sleepiness	1, 19.5	1.84	.1905

[a] Number of observations used: 32/32; [b] Number of observations used: 30/32.

Table 5-5 Results of mixed model ANOVA for the effect of sleep related variables and subjective ratings of fatigue and sleepiness on Fastest 10% of PVT Responses

Dependent Variable	Independent Variable	DF	F-value	P(F)
Pre-Simulator Fastest 10% of Responses [a]	Cumulative Sleep Debt	1, 25.1	0.01	.9249
	Time Since Sleep	1, 25.6	0.01	.9406
	Total Sleep in 24hrs	1, 25.1	2.74	.1101
	Pre Simulated Flight Fatigue	1, 26.9	0.10	.7499
Pre-Simulator Fastest 10% of Responses [a]	Cumulative Sleep Debt	1, 26.7	0.05	.8257
	Time Since Sleep	1, 23.5	0.01	.9101
	Total Sleep in 24hrs	1, 26.9	3.79	.0620
	Pre Simulated Flight Sleepiness	1, 23.4	0.41	.5298
Pre-Simulator Fastest 10% of Responses [a]	Cumulative Sleep Debt	1, 22.9	0.04	.8493
	Time Since Sleep	1, 22.5	0.09	.7718
	Total Sleep in 48hrs	1, 25.7	18.00	**.0003**
	Pre Simulated Flight Fatigue	1, 26.6	0.18	.6781
Pre-Simulator Fastest 10% of Responses [a]	Cumulative Sleep Debt	1, 24.4	0.06	.8129
	Time Since Sleep	1, 22.1	0.14	.7155
	Total Sleep in 48hrs	1, 24	19.28	**.0002**
	Pre Simulated Flight Sleepiness	1, 26.1	0.14	.7066
Post-Simulator Fastest 10% of Responses [b c]	Cumulative Sleep Debt	1, 24.6	0.04	.8494
	Time Since Sleep	1, 16.2	1.96	.1800
	Total Sleep in 24hrs	1, 23.1	0.13	.7222
	Post Simulated Flight Fatigue	1, 22.9	3.47	.0755
Post-Simulator Fastest 10% of Responses [b d]	Cumulative Sleep Debt	1, 24.8	0.32	.5739
	Time Since Sleep	1, 14.5	0.96	.3429
	Total Sleep in 24hrs	1, 20.8	0.59	.4512
	Post Simulated Flight Sleepiness	1, 18.4	4.93	**.0392**
Post-Simulator Fastest 10% of Responses [b c]	Cumulative Sleep Debt	1, 24.7	0.23	.6391
	Time Since Sleep	1, 16.5	0.73	.4037
	Total Sleep in 48hrs	1, 24.9	1.14	.2953
	Post Simulated Flight Fatigue	1, 21.7	1.56	.2255
Post-Simulator Fastest 10% of Responses [a b]	Cumulative Sleep Debt	1, 24.9	0.74	.3985
	Time Since Sleep	1, 12.3	0.09	.7656
	Total Sleep in 48hrs	1, 25	1.04	.3170
	Post Simulated Flight Sleepiness	1, 16.2	1.99	.1777

[a] Number of observations used: 32/32; [b] Number of observations used: 30/32; [c] REFL SQRT transformation applied to normalise distribution; [d] SQRT transformation applied to normalise distribution.

Table 5-6 Results of Mixed Model ANOVA for the Effect of Sleep Related Variables and Subjective Ratings of Fatigue and Sleepiness on the Slowest 10% of PVT Responses

Dependent Variable	Independent Variable	DF	F-value	P(F)
Pre-Simulator Slowest 10% of Responses [a]	Cumulative Sleep Debt	1, 23.6	0.01	.9159
	Time Since Sleep	1, 26.8	0.02	.8950
	Total Sleep in 24hrs	1, 23.4	0.83	.3708
	Pre Simulated Flight Fatigue	1, 25.9	2.15	.1550
Pre-Simulator Slowest 10% of Responses [b c]	Cumulative Sleep Debt	1, 24.8	0.31	.5832
	Time Since Sleep	1, 24.9	0.19	.6658
	Total Sleep in 24hrs	1, 25.2	4.65	**.0409**
	Pre Simulated Flight Sleepiness	1, 25.5	0.03	.8571
Pre-Simulator Slowest 10% of Responses [a]	Cumulative Sleep Debt	1, 20.9	0.06	.8110
	Time Since Sleep	1, 25.3	0.01	.9403
	Total Sleep in 48hrs	1, 24.3	6.83	**.0152**
	Pre Simulated Flight Fatigue	1, 26.6	2.56	.1214
Pre-Simulator Slowest 10% of Responses [a]	Cumulative Sleep Debt	1, 22.4	0.31	.5844
	Time Since Sleep	1, 25.1	0.09	.7663
	Total Sleep in 48hrs	1, 23.5	10.48	**.0036**
	Pre Simulated Flight Sleepiness	1, 26.7	0.52	.4766
Post-Simulator Slowest 10% of Responses [d]	Cumulative Sleep Debt	1, 23.9	0.00	.9923
	Time Since Sleep	1, 16.3	0.04	.8390
	Total Sleep in 24hrs	1, 23.2	0.07	.7996
	Post Simulated Flight Fatigue	1, 23.2	2.34	.1396
Post-Simulator Slowest 10% of Responses [d]	Cumulative Sleep Debt	1, 24.8	0.01	.9295
	Time Since Sleep	1, 15.4	0.05	.8254
	Total Sleep in 24hrs	1, 21.3	0.13	.7229
	Post Simulated Flight Sleepiness	1, 18.9	1.10	.3081
Post-Simulator Slowest 10% of Responses [d]	Cumulative Sleep Debt	1, 24.1	0.03	.8733
	Time Since Sleep	1, 17.3	0.08	.7773
	Total Sleep in 48hrs	1, 24.3	1.01	.3246
	Post Simulated Flight Fatigue	1, 23.3	0.97	.3340
Post-Simulator Slowest 10% of Responses [d]	Cumulative Sleep Debt	1, 24.8	0.00	.9553
	Time Since Sleep	1, 16.2	0.65	.4334
	Total Sleep in 48hrs	1, 24.4	1.49	.2344
	Post Simulated Flight Sleepiness	1, 21.4	0.21	.6552

[a] Number of observations used: 32/32; [b] Number of observations used: 31/32; [c] one outlier removed; [d] Number of observations used: 30/32.

Table 5-7 Direction of Association between PVT Variables, Sleep Related Variables and Subjective Ratings of Fatigue and Sleepiness

Dependent Variable	Independent Variable					
	Cumulative Sleep Debt	**Time Since Sleep**	**Total Sleep in 24hrs**	**Total Sleep in 48hrs**	**Fatigue**	**Sleepiness**
Pre-Simulator PVT Response Speed	▼	▼	▲	⬛	▼	⬛
Pre-Simulator PVT Response Speed	▼	▼	▲	⬛	⬛	▲
Pre-Simulator PVT Response Speed	▼	▼	⬛	🟦▲	▼	⬛
Pre-Simulator PVT Response Speed	▼	▼	⬛	🟦▲	⬛	▼
Pre-Simulator Fastest 10% of Responses	▼	▼	▲	⬛	▲	⬛
Pre-Simulator Fastest 10% of Responses	▼	▼	▲	⬛	⬛	▲
Pre-Simulator Fastest 10% of Responses	▲	▼	⬛	🟦▲	▲	⬛
Pre-Simulator Fastest 10% of Responses	▲	▼	⬛	🟦▲	⬛	▲
Pre-Simulator Slowest 10% of Responses	▼	▼	▲	⬛	▼	⬛
Pre-Simulator Slowest 10% of Responses	▼	▲	🟦▲	⬛	⬛	▼
Pre-Simulator Slowest 10% of Responses	▼	▲	⬛	🟦▲	▼	⬛
Pre-Simulator Slowest 10% of Responses	▼	▲	⬛	🟦▲	⬛	▼
Post-Simulator PVT Response Speed	▲	▼	▼	⬛	🟦▼	⬛
Post-Simulator PVT Response Speed	▲	▼	▼	⬛	⬛	🟦▼
Post-Simulator PVT Response Speed	▲	▼	⬛	▲	▼	⬛
Post-Simulator PVT Response Speed	▲	▼	⬛	▲	⬛	▼
Post-Simulator Fastest 10% of Responses	▲	▼	▼	⬛	▼	⬛
Post-Simulator Fastest 10% of Responses	▲	▼	▼	⬛	⬛	🟦▼
Post-Simulator Fastest 10% of Responses	▲	▼	⬛	▲	▼	⬛
Post-Simulator Fastest 10% of Responses	▲	▼	⬛	▲	⬛	▼
Post-Simulator Slowest 10% of Responses	▼	▼	▼	⬛	▼	⬛
Post-Simulator Slowest 10% of Responses	▼	▲	▼	⬛	⬛	▼
Post-Simulator Slowest 10% of Responses	▲	▲	⬛	▲	▼	⬛
Post-Simulator Slowest 10% of Responses	▲	▲	⬛	▲	⬛	▼

▲	Increase in IV = Increase in DV
▼	Increase in IV = Decrease in DV
🟦	Significant Association
⬜	Non-significant Association
⬛	Independent variable not included within the model

5.5.2 Results

Cumulative Sleep Debt and PVT Performance

Cumulative sleep debt was not significantly associated with any of the PVT variables in tests before and following simulated flights. In 10 of 12 models which examined the relationship between pre-simulator PVT performance and cumulative sleep debt, a non-significant trend was observed for PVT performance to decline with greater sleep debt. The opposite (non-significant) pattern was observed for post-simulator PVT performance, which in 10 of 12 models appeared to increase as cumulative sleep debt increased.

Time Since Sleep and PVT Performance

Time since sleep was not significantly associated with any PVT variables in tests before and following simulated flights. In 9 of 12 models which examined the relationship between pre and post simulator PVT performance and time since sleep, a non-significant trend was observed for PVT performance to decline with an increase in time since sleep.

Total Sleep in 24hrs and PVT Performance

Total sleep in 24hrs was significantly associated with the slowest 10% of responses before each simulated flight in the model which accounted for sleepiness, but not in the model which accounted for fatigue. With each additional hour of sleep in the previous 24hrs hour, the slowest 10% of responses increased by 0.1788 responses per second. Aside from this result, total sleep in 24hrs was not significantly associated with other PVT variables. A non-significant trend was identified in models that examined the relationship between pre-simulator PVT performance and total sleep in 24hrs where PVT performance increased with an increase in total sleep in 24hrs. The opposite (non-significant) pattern was observed for post-simulator PVT performance which appeared to increase as total sleep time decreased.

Total Sleep in the Previous 48 hour Period and PVT Performance

There was a significant association between sleep in the previous 48 hours and PVT performance at the start of the simulator flight. With every additional hour of sleep in the previous 48 hours, PVT response speed increased by 0.1126 responses per second in the model which accounted for subjective fatigue, and by 0.1197 responses per second in the model which accounted for sleepiness. Similar increases were found for the fastest and slowest 10% of responses.

Table 5-8 Model Estimates for PVT Variables in Models that have a Significant Association between PVT Performance and Total Sleep in 48hrs

Dependent Variable	Model Estimate	Model which includes:
Pre-Simulator PVT Response Speed	0.1126	Fatigue
Pre-Simulator PVT Response Speed	0.1197	Sleepiness
Pre-Simulator Fastest 10% of Responses	0.1157	Fatigue
Pre-Simulator Fastest 10% of Responses	0.1519	Sleepiness
Pre-Simulator Slowest 10% of Responses	0.0939	Fatigue
Pre-Simulator Slowest 10% of Responses	0.1122	Sleepiness

There was no significant association with PVT performance at the end of the simulated flight, however in all 6 models, a non-significant trend was observed for better PVT performance with more sleep obtained in the previous 48 hours.

Ratings of Fatigue and PVT Performance

Post simulated flight fatigue was significantly associated with PVT response speed in the model which accounted for total sleep in 24hrs (but not in the model that included total sleep in 48hrs). For each one unit increase in fatigue, PVT response speed decreased by 0.1756 responses per second. For the five non-significant post-simulator models, a trend (non-significant) was observed for reduced PVT performance with an increase in fatigue.

Ratings of Sleepiness and PVT Performance

Post simulated flight sleepiness was significantly associated with both PVT response speed and the fastest 10% of responses following simulated flights in the model which accounted for total sleep in the previous 24 hours (but not in the model that included total sleep in the last 48 hours). For each one unit increase in sleepiness, PVT response speed decreased by 0.0937 responses per second and the fastest 10% of responses decreased by 0.087 responses per second. Aside from this result, ratings of sleepiness were not significantly associated with any other PVT variable. A trend (non-significant) was observed where an increase in subjective sleepiness results in a decrease in PVT performance in the four non-significant post-simulator models.

5.6 Summary

The effect of condition, timing and order on PVT performance

PVT performance was not significantly different between the non-rested or rested condition. It did not change significantly across simulated flights, and it was not significantly influenced by the order in which the simulated flights were flown. A non-significant trend was observed where PVT performance was slower in the non-rested condition and following simulated flights.

The effect of sleep related variables on PVT performance

Cumulative sleep debt and time since sleep were not associated with PVT performance whereas, at the start of the simulated flights, more sleep in the previous 24 and 48 hour period was associated with faster PVT performance. At the start of the simulated flights, the slowest 10% of responses were faster when more sleep was obtained in the previous 24 hours (after accounting for sleepiness) and performance for all PVT variables was faster when more sleep was obtained in the previous 48 hours. Although non-significant, the following trends were observed:

- PVT performance at the start of simulated flights appeared to decline as cumulative sleep debt accrued, whereas post-simulator PVT performance appeared to improve.
- PVT response speed and the fastest 10% of responses, appeared to slow as time since sleep increased whereas the slowest 10% of responses appeared to improve.
- PVT performance at the start of simulated flights appeared to be faster when more sleep was obtained in the previous 24 hour period, whereas post-simulator PVT performance was slower with increased sleep.
- PVT performance at the end of simulated flights appeared to be faster when more sleep was obtained in the previous 48 hour period.

The effect of Fatigue and Sleepiness on PVT performance

At the end of simulated flights, PVT response speed was faster when ratings of fatigue and sleepiness were lower (after accounting for total sleep in the previous 24 hours) and the fastest 10% of responses were faster when ratings of sleepiness were lower (after accounting for total sleep in the previous 24 hours). Although not significant, PVT performance at the end of simulated flights appears to be faster when ratings of fatigue and sleepiness are lower.

CHAPTER 6 RESULTS: SIMULATED FLIGHT DATA MEASURES

6.1 Overview

This chapter presents findings from the analysis of flight data collected during simulated flights flown by participants. It focuses on the influence of sleep related variables and subjective workload on flight crew performance during initial climb and go around, when using the autopilot and completing the go around checklist. In addition, the influence of condition (non-rested or rested), flight order (first flight or second flight) and flight location (Christchurch – Wellington or Wellington – Christchurch) was considered. Analyses and results associated are grouped by research question.

6.2 Research Questions

The following research questions are addressed.

Simulated Flight Protocol

Question 1: Does the flown simulated flight protocol reflect the planned simulated flight protocol?

Pilot Task performance

Question 2: Do simulated flight data measures differ between the non-rested and rested condition?

Question 3: Do simulated flight data measures differ between the first and second simulated flight?

Question 4: Do simulated fight data analysis measures differ between the Christchurch – Wellington and the Wellington – Christchurch simulated flight?

Question 5: Are simulated flight data measures associated with cumulative sleep debt, time since sleep and total sleep time?

Question 6: Are simulated flight data measures associated with subjective ratings of workload, fatigue or sleepiness?

6.3 Method

6.3.1 Measures

Dependent Variables

The following dependent variables were utilised:

Initial Climb and Go Around

The following variables are measured in 50ft altitude bins between 300ft and 750ft during both initial climb and go around.

Airspeed in Climb: The standard deviation of the absolute difference between airspeed and commanded airspeed.

Pitch in Climb: The standard deviation of the absolute difference between pitch and flight director pitch order.

Roll in Climb: The standard deviation of the absolute difference between roll and flight director roll order.

Airspeed go around: The standard deviation of the absolute difference between airspeed and commanded airspeed.

Pitch go around: The standard deviation of the absolute difference between pitch and flight director pitch order.

Roll go around: The standard deviation of the absolute difference between roll and flight director roll order.

Autopilot usage status

Autopilot engagement altitude following take off: The lowest altitude where the autopilot was engaged following take off.

Autopilot engagement altitude following go around: The lowest altitude where the autopilot was engaged following go around.

Autopilot disengagement before landing: The lowest altitude where the autopilot was disengaged prior to landing.

The time taken to re-engage the autopilot: Time taken to re-engage the autopilot following an un-commanded autopilot disconnection.

The percentage of each flight where the autopilot is engaged[79].

Go around checklist

Time taken to complete the go around/missed approach procedure.

Time taken to initiate go around: The time taken for pilots to initiate the go around.

Independent Variables

The following variables were included in linear mixed models, which are described in further detail below.

Flight Duty Protocol Related Variables

Non-rested or rested condition: This variable identifies if dependent variable values are from the non-rested or rested condition.

Location: This variable identifies if dependent variable values are from the Christchurch – Wellington or Wellington – Christchurch simulated flight.

Flight order: This variable identifies if dependent variable values are from the first or second simulated flight.

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[79] Each flight starts when the aircraft leaves the ground and stops once it lands (first instance of runway contact).

50ft altitude bin: This variable identifies if dependent variable values are from bin 1 (300ft – 349ft), bin 2 (350ft – 399ft), bin 3 (400ft – 449ft), bin 4 (450ft – 499ft), bin 5 (500ft – 549ft), bin 6 (550ft – 599ft), bin 7 (600ft – 649ft), bin 8 (650ft – 699ft) or bin 9 (700ft – 749ft).

Sleep Related Variables

Cumulative Sleep Debt: the amount of sleep debt (in minutes) accrued by the end of day 4, which is the final 24 hour period prior to the non-rested (18:00) or rested simulated flight (20:00 – 22:00).

Time Since Sleep: the duration of time since sleep at the start of the simulated flight.

Total sleep in 24hrs: Total sleep in the 24 hour period before the non-rested (18:00 – 18:00) or rested simulated flight (20:00 – 20:00).

Total sleep in 48hrs: Total sleep in the 48 hour period before the non-rested (18:00 – 18:00) or rested simulated flight (20:00 – 20:00).

Samn Perelli fatigue rating: pre simulated flight fatigue rating.

Karolinska Sleepiness Scale rating: pre simulated flight sleepiness rating.

Workload

Overall workload rating on the raw NASA Task Load Index following each simulated flight.

6.3.2 Statistical Analyses

Descriptive statistics (mean, standard deviation, median, and range) are provided for each dependent variable. Linear mixed models were used to investigate the association between dependent and independent variables.

Collinearity

For linear mixed models that included continuous independent variables (sleep related variables, ratings of workload and pre simulated flight ratings of fatigue and sleepiness), collinearity between variables was checked. Total sleep in 24hrs and 48hrs were found to be colinear as were pre simulated flight fatigue and sleepiness ratings, and were therefore, not included within the same model. Further collinearity tests indicated no redundancy between remaining variables. For simulated flight data measures, four separate models were run which included the following variables:

- Cumulative sleep debt, time since sleep, total sleep in 24hrs, workload and pre simulated flight fatigue.
- Cumulative sleep debt, time since sleep, total sleep in 48hrs, workload and pre simulated flight fatigue.
- Cumulative sleep debt, time since sleep, total sleep in 24hrs, workload and pre simulated flight sleepiness.
- Cumulative sleep debt, time since sleep, total sleep in 48hrs, workload and pre simulated flight sleepiness.

Transformations

Details on dependent variable transformation are included as a footnote in the applicable model results table. Where transformations were undertaken, differences in parameter estimates from the transformed model were not reported, however relative relationships were.

6.3.3 Test Details

A total of 16 simulated flights were flown with eight flights flown during the non-rested condition and eight flights flown during the rested condition. Simulated flight data and brief/ debrief video files were available from all simulated flights. Table 6-1 includes descriptive statistics for times associated with the start of recording, taxi, liftoff, initial climb, go around, go around checklist, autopilot usage, touchdown, engine shutdown, as well as flight duration and recording duration. Table 6-2 includes descriptive statistics for the duration between liftoff and initial climb, go around and autopilot usage. The dataset which included values relating to the time taken to re-engage the autopilot included 15 autopilot re-engagements from 16 flights[80] and the autopilot engagement altitude following go around dataset included 14 autopilot re-engagements from 16 flights[81]. Outliers were checked and retained in the dataset if the observation was operationally feasible. To help determine operational feasibility, it was necessary to determine if the outlier was in keeping with the intent of the simulated flight data measure.

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[80] One flight crew did not re-engage the autopilot following the un-commanded autopilot disconnection scenario. The autopilot was re-engaged after the go around but before landing.

[81] One flight crew conducted a go around above 1000ft. This go around was excluded from the go around dataset.

Table 6-1 Mean, Standard Deviation, Median and Range of Recording and Flight Duration, and Times Associated with Key Points during Simulated Flights

Variable	Non-rested					Rested				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Recording Duration (hours)	1.32	0.06	1.33	1.13 – 1.38	16	1.35	0.06	1.36	1.23 – 1.46	16
Flight Duration (hours)	0.96	0.01	0.98	0.9 – 1.01 c	16	0.98	0.01	0.98	0.95 – 1.0	16
Start of Recording	18:12	0:19	18:06	17:55 – 18:55 [a]	16	19:48	0:47	20:04	17:57 – 20:15 [b]	16
Off Blocks	18:27	0:15	18:22	18:13 – 19:00 [a]	16	20:05	0:47	20:18	18:14 – 20:34 [b]	16
Start of Initial Climb	18:31	0:15	18:26	18:16 – 19:04 [a]	16	20:09	0:48	20:24	18:17 – 20:40 [b]	16
Autopilot Engagement Altitude Following Take off	18:32	0:14	18:27	18:18 – 19:05 [a]	16	20:11	0:48	20:24	18:18 – 20:41 [b]	16
Time Taken to Reengage the Autopilot	19:08	0:15	19:03	18:53 – 19:41 [a]	16	20:46	2:21	20:59	18:55 – 21:17 [b]	14
Go Around	19:14	0:15	19:09	18:59 – 19:48 [a]	14	20:52	0:48	21:07	19:00 – 21:25 [b]	16
Autopilot Engagement Altitude Following Go around	19:15	0:15	19:10	19:00 – 19:50 [a]	14	20:54	0:48	21:08	19:01 – 21:26 [b]	14
Autopilot Disengagement before Landing	19:29	0:15	19:25	19:14 – 20:02 [a]	16	21:08	0:48	21:22	19:16 – 21:40 [b]	16
Touchdown	19:30	0:15	19:26	19:14 – 20:03 [a]	16	21:08	0:48	21:23	19:17 – 21:41 [b]	16
On Blocks	19:31	0:15	19:27	19:16 – 20:04 [a]	16	21:10	0:47	21:24	19:19 – 21:42 [b]	16

[a] Includes 2 outliers[82]; [b] Includes 2 extreme outliers[83]; [c] Includes 2 outliers[84].

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[82] These outliers relate to a flight crew that did not start their flight until 18:55 as the simulator was reset.

[83] These outliers relate to a flight crew who had their rested simulated flight rescheduled because of simulator unserviceability. Their rested simulated flight occurred between 18:00 and 20:00 rather than 20:00 and 22:00.

[84] The two outliers relate to a crew who completed their flight in 55 minutes (liftoff until touchdown).

Table 6-2 Mean, Standard Deviation, Median and Range of the duration between Lift-off and Key Points during Simulated Flights

Time interval between liftoff and the following Key Points (minutes):	**Non-rested**					**Rested**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Start of Initial Climb	0.00	0.00	0.00	0.00 – 0.00	16	0.00	0.00	0.00	0.00 – 0.00	16
Autopilot Engagement Altitude Following Take off	1.00	0.00	0.00	0.00 – 2.00	16	1.00	0.00	1.00	0.00 – 3.00	16
Time Taken to Reengage the Autopilot	36.00	0.00	37.00	36.00 – 37.00	16	36.00	0.00	37.00	34.00 – 38.00	14
Go Around	43.00	0.00	43.00	42.00 – 44.00 [a]	14	43.00	0.00	42.00	41.00 – 45.00	16
Autopilot Engagement Altitude Following Go around	44.00	1.00	44.00	42.00 – 46.00	14	44.00	0.00	44.00	44.00 – 46.00	14
Autopilot Disengagement before Landing	57.00	1.00	58.00	54.00 – 1.00	16	58.00	0.00	59.00	57.00 – 60.00	16

[a] Includes 4 outliers[85].

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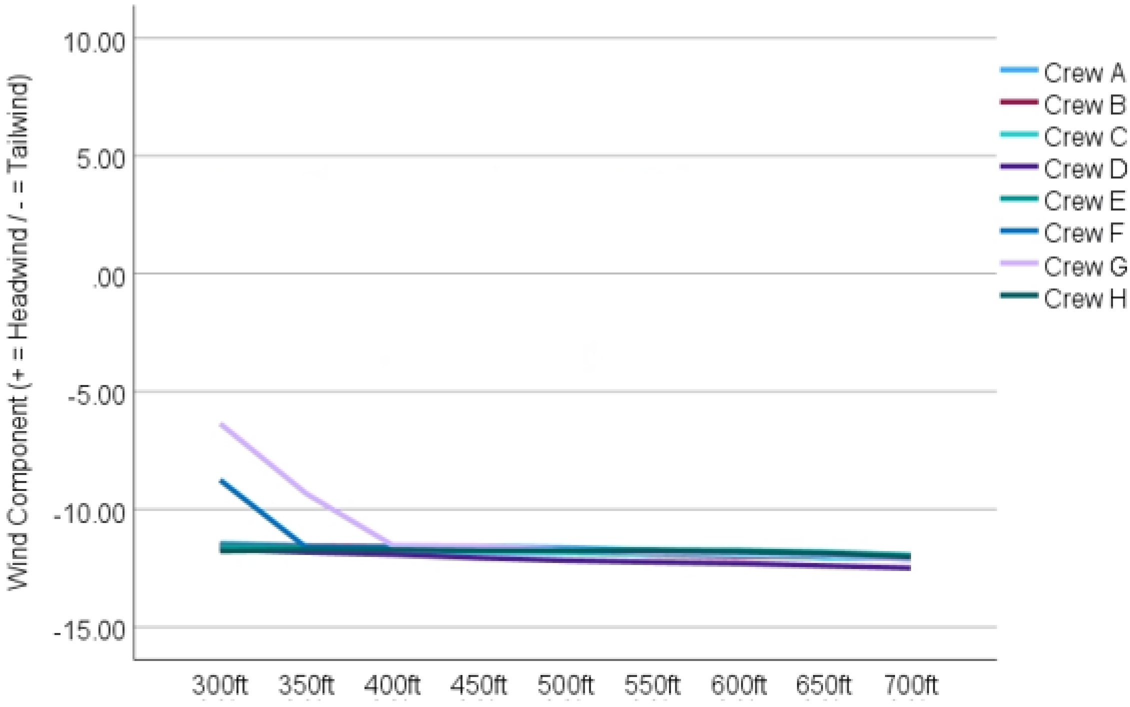
[85] These four outliers represent two flights, one where the flight crew initiated the go around at 42 minutes following liftoff and the other at 44 minutes following liftoff.

6.3.3.1 Initial Climb

Performance measures were collected during the initial climb between 300ft and 750ft. The initial climb dataset started at 300ft to allow comparison with the go around dataset which also started at 300ft. Figure 6-1 and Figure 6-2 illustrate that the wind component during initial climb differed by departure location with an 11kt tailwind recorded in Christchurch and a 9kt headwind recorded in Wellington, as planned. Location was therefore included as an independent variable in statistical analyses to determine if variation in initial climb measures was attributable to differences in tailwind. Descriptive statistics for dependent variables are outlined in Table 6-3 and box plots[86] for airspeed (see Figure 6-3), pitch (see Figure 6-4) and roll during climb (see Figure 6-5) show variation in these measures.

Figure 6-1 Wind Component between 300ft and 750ft departing Christchurch



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[86] A constant y-axis scale is used for the three box plots to illustrate the magnitude of variation between measures.

Figure 6-2 Wind Component between 300ft and 750ft departing Wellington

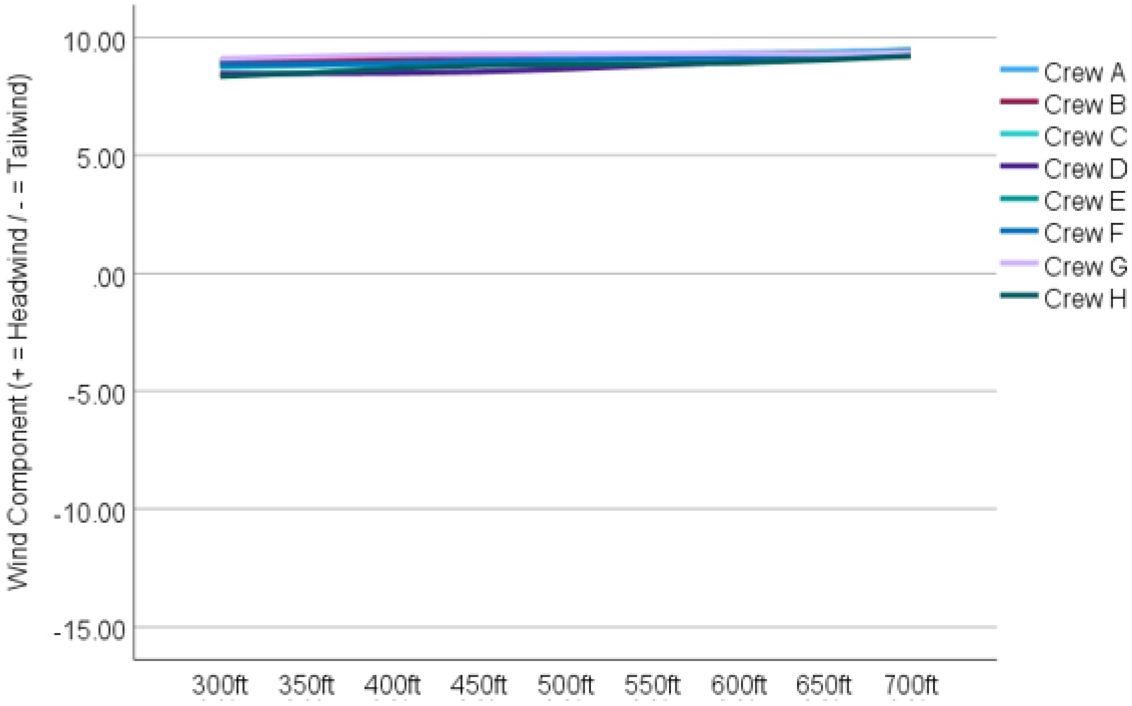


Figure 6-3 Box plot of Airspeed in Climb grouped by Condition and 50ft Altitude Bin

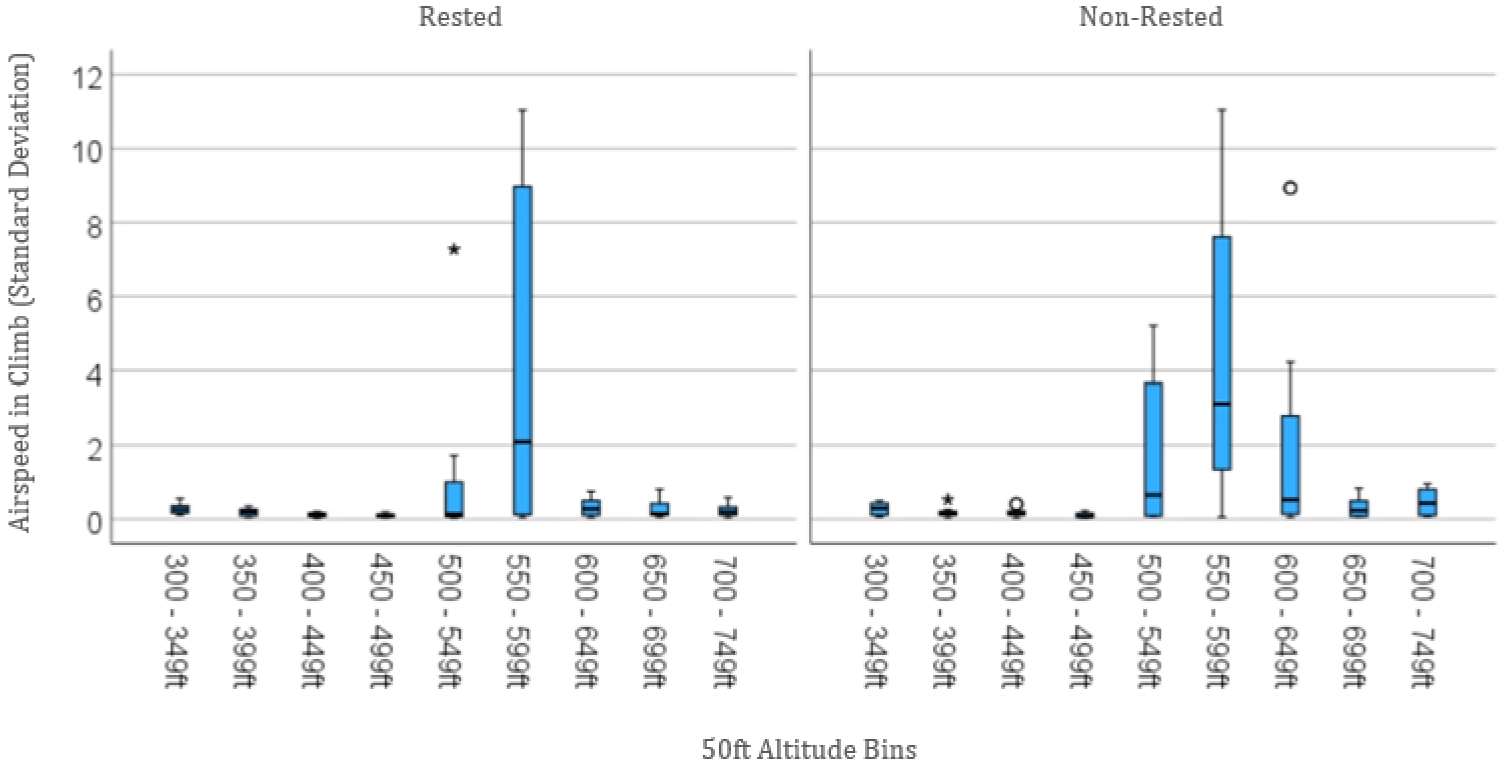


Figure 6-4 Box plot of Pitch in Climb grouped by Condition and 50ft Altitude Bin

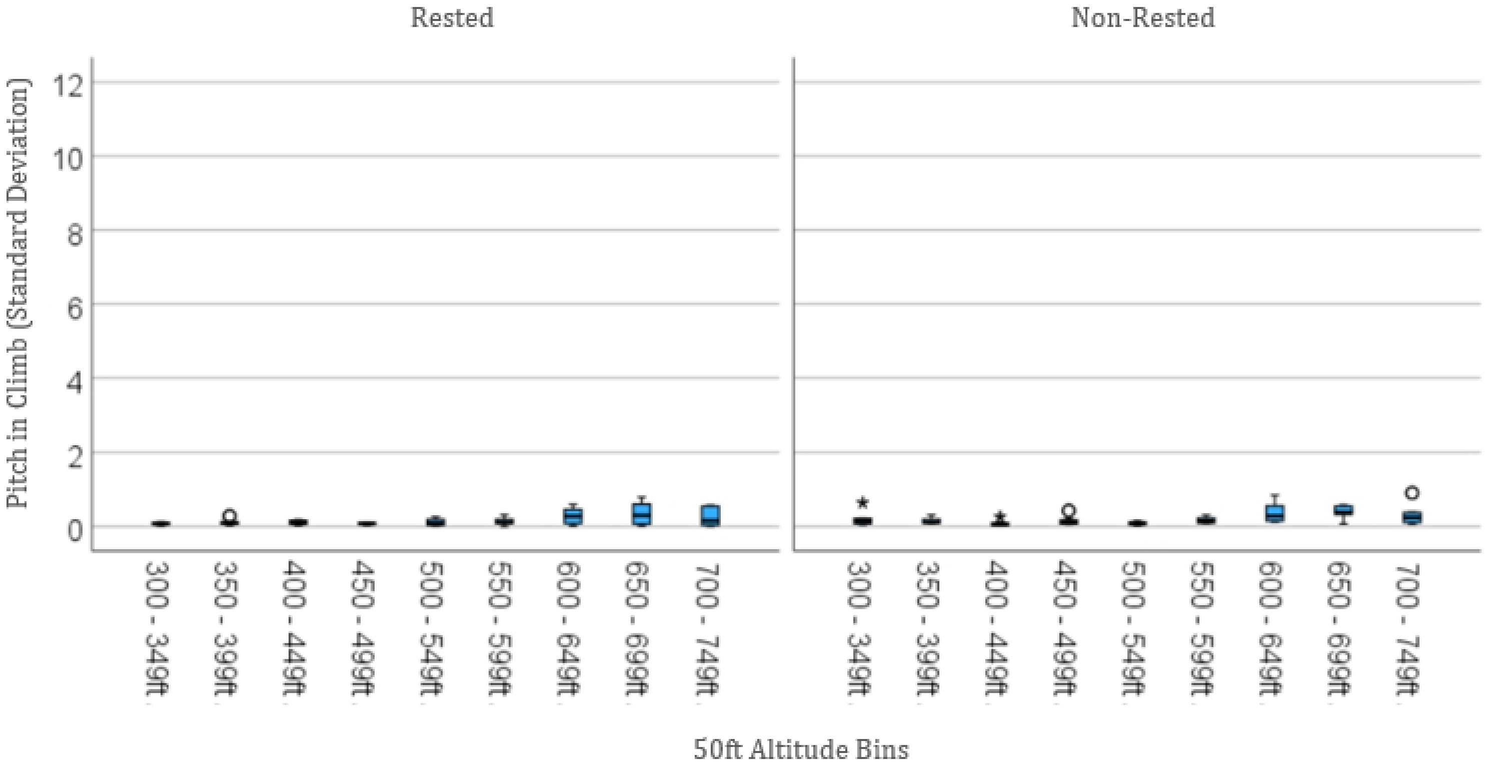


Figure 6-5 Box plot of Roll in Climb grouped by Condition and 50ft Altitude Bin

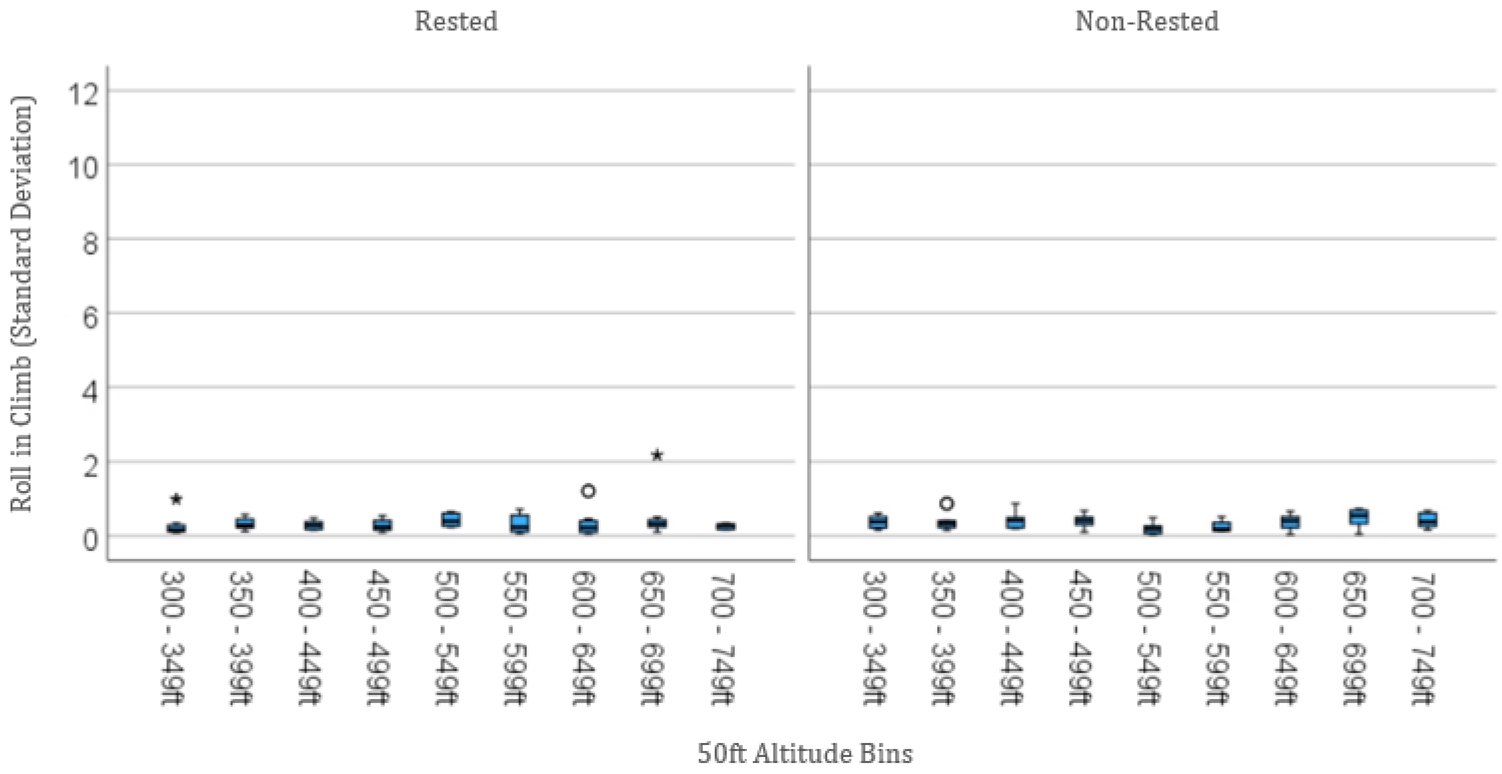


Table 6-3 Mean, Standard Deviation, Median, and Range for Dependent Variables collected during Initial Climb

		Non-rested condition					**Rested condition**				
Variable	50ft Altitude Bin	Mean [c]	SD	Median	Range	N	Mean [c]	SD	Median	Range	N
Airspeed in Climb: Standard deviation of the absolute difference between airspeed and target airspeed, measured in kts.	300ft – 349ft	0.2801	0.1641	0.2917	0.0606 - 0.4972	16	0.2817	0.1456	0.2618	0.1124 - 0.5645	16
	350ft – 399ft	0.1867	0.1457	0.1405	0.0362 - 0.5274 [a]	16	0.1884	0.1054	0.1919	0.0513 - 0.3474	16
	400ft – 449ft	0.1745	0.1077	0.1339	0.0350 - 0.4080 [b]	16	0.1187	0.0605	0.1221	0.0242 - 0.2022	16
	450ft – 499ft	0.1060	0.0646	0.0791	0.0403 - 0.2249	16	0.1034	0.0462	0.1017	0.0449 - 0.1898	16
	500ft – 550ft	1.759	2.112	0.6515	0.0664 – 5.205	16	1.217	2.424	0.1357	0.0390 – 7.230 [a]	16
	550ft – 600ft	4.401	3.915	3.106	0.0588 – 11.04	16	4.182	4.674	2.093	0.0480 – 11.031	16
	600ft – 649ft	1.985	3.023	0.5255	0.0483 – 8.929 [b]	16	0.3204	0.2410	0.2769	0.0455 - 0.7527	16
	650ft – 699ft	0.3140	0.2671	0.2361	0.0609 - 0.8352	16	0.2787	0.2541	0.1422	0.0564 - 0.8101	16
	700ft – 749ft	0.4774	0.3201	0.4328	0.0741 - 0.9592	14	0.2389	0.1723	0.2013	0.0460 - 0.5848	14
Pitch in Climb: Standard deviation of the absolute difference between pitch and pitch order, measured in deg.	300ft – 349ft	0.1928	0.1863	0.1365	0.0460 - 0.6419 [a]	16	0.0776	0.0331	0.0759	0.0164 - 0.1309	16
	350ft – 399ft	0.1524	0.0756	0.1186	0.0839 - 0.3136	16	0.1106	0.0763	0.0955	0.0246 - 0.2833 [b]	16
	400ft – 449ft	0.0829	0.0741	0.0589	0.0242 - 0.2959 [a]	16	0.1049	0.0594	0.0926	0.0250 - 0.1842	16
	450ft – 499ft	0.1544	0.1171	0.1261	0.0557 - 0.4271 [b]	16	0.0782	0.0241	0.0805	0.0352 - 0.1133	16
	500ft – 550ft	0.0874	0.0451	0.0792	0.0193 - 0.1570	16	0.1144	0.0907	0.0898	0.0123 - 0.2568	16
	550ft – 600ft	0.1655	0.0830	0.1412	0.0875 - 0.3093	16	0.1401	0.0915	0.1208	0.0033 - 0.3206	16

		Non-rested condition					Rested condition				
Variable	50ft Altitude Bin	Mean [c]	SD	Median	Range	N	Mean [c]	SD	Median	Range	N
	600ft – 649ft	0.3721	0.2068	0.4010	0.0365 - 0.6631	16	0.3370	0.3675	0.2195	0.0494 – 1.208 [b]	16
	650ft – 699ft	0.3954	0.1616	0.3816	0.0693 - 0.5793	16	0.3423	0.2950	0.3015	0.0119 - 0.7886	16
	700ft – 749ft	0.3975	0.1838	0.3804	0.1598 - 0.6764	14	0.2572	0.0726	0.2739	0.1586 - 0.3364	14
Roll in Climb: Standard deviation of the absolute difference between roll and roll order, measured in deg.	300ft – 349ft	0.3749	0.1705	0.3812	0.1567 - 0.6085	16	0.2739	0.2906	0.1594	0.0893 - 0.9890 [a]	16
	350ft – 399ft	0.3664	0.2149	0.3233	0.1458 - 0.8698 [b]	16	0.3233	0.1466	0.2854	0.1201 - 0.5714	16
	400ft – 449ft	0.4147	0.2145	0.4132	0.1941 - 0.8709	16	0.2889	0.1190	0.2842	0.1541 - 0.4828	16
	450ft – 499ft	0.3986	0.1702	0.4115	0.0990 - 0.6749	16	0.2846	0.1578	0.2467	0.0914 - 0.5458	16
	500ft – 550ft	0.1904	0.1467	0.1766	0.0401 - 0.4862	16	0.4273	0.1679	0.3983	0.2410 - 0.6473	16
	550ft – 600ft	0.2504	0.1420	0.1812	0.1228 - 0.5181	16	0.3220	0.2611	0.2323	0.0596 - 0.7218	16
	600ft – 649ft	0.3721	0.2068	0.4010	0.0365 - 0.6631	16	0.3370	0.3675	0.2195	0.0494 – 1.208 [b]	16
	650ft – 699ft	0.4905	0.2308	0.5495	0.0479 - 0.7310	16	0.5322	0.6523	0.3173	0.1027 – 2.178 [a]	16
	700ft – 749ft	0.3975	0.1838	0.3804	0.1598 - 0.6764	14	0.2572	0.0726	0.2739	0.1586 - 0.3364	14

a Includes two extreme outliers; b Includes two outliers; c This value represents the MEAN of the standard deviation of the difference between the actual and the commanded/ordered value within each 50ft altitude bin.

6.3.3.2 Go Around

Performance measures were collected during go around between 300ft and 750ft. Descriptive statistics for each dependent variable are outlined in Table 6-4. Box plots show variation in airspeed go around (Figure 6-6), pitch go around (Figure 6-7) and roll go around (Figure 6-8) during the go around procedure. Acceleration altitude during go around occurs at an altitude which is higher than the 700ft – 749ft altitude bin.

Figure 6-6 Box plot of Airspeed Go Around grouped by Condition and 50ft Altitude Bin

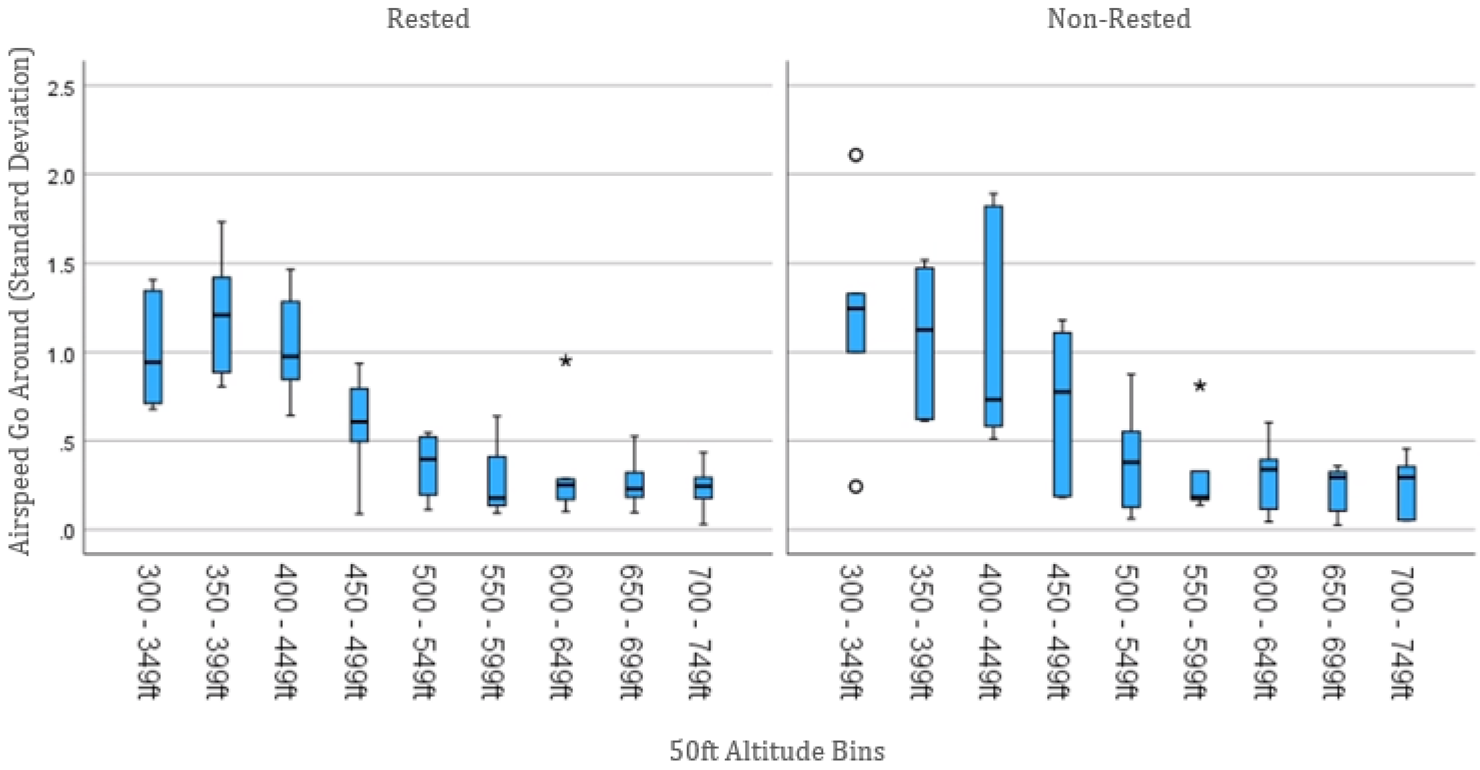


Figure 6-7 Box plot of Pitch Go Around grouped by Condition and 50ft Altitude Bin

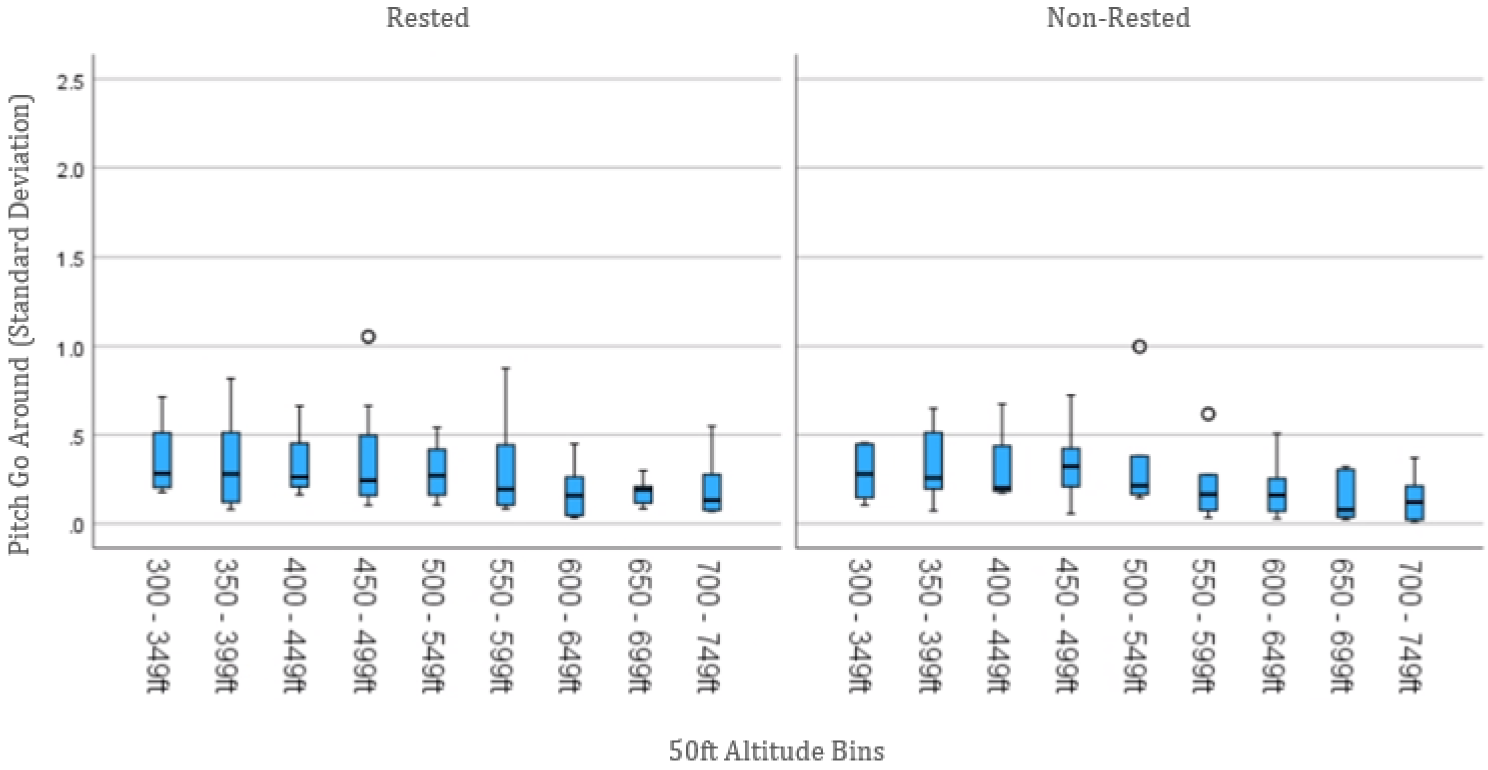


Figure 6-8 Box plot of Roll Go Around grouped by Condition and 50ft Altitude Bin

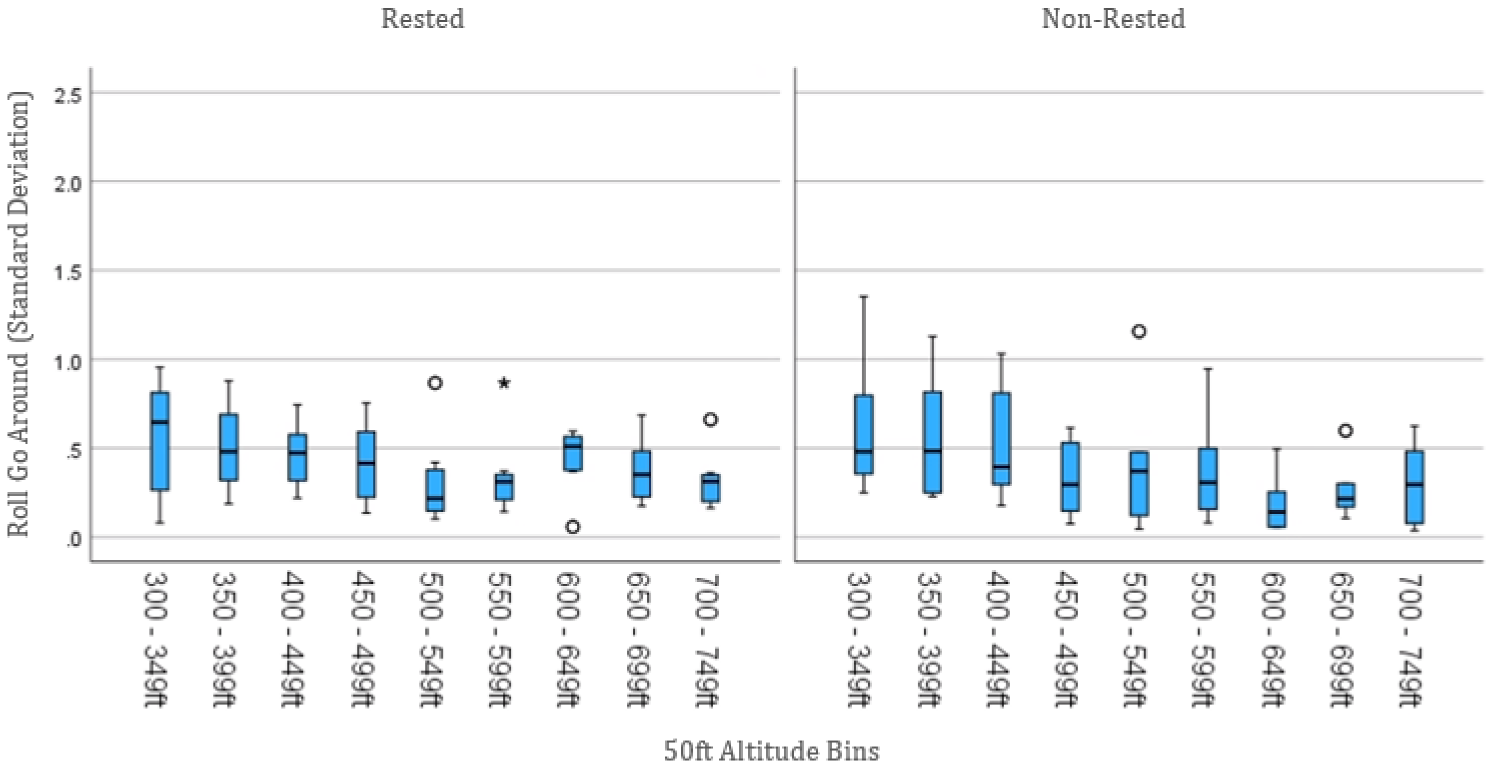


Table 6-4 Mean, Standard Deviation, Median, and Range for Dependent Variables collected during Go Around

		Non-rested condition					**Rested condition**				
Variable	50ft Altitude Bin	Mean [D]	SD	Median	Range	N	Mean [D]	SD	Median	Range	N
Airspeed Go Around Standard deviation of the absolute difference between airspeed and target airspeed, measured in kts.	300ft – 349ft	1.208	0.5275	0.1246	0.2429 – 2.107 [c]	14	1.01	0.3052	0.9430	0.6780 – 1.407	16
	350ft – 399ft	1.092	0.3891	1.125	0.6129 – 1.515	14	1.196	0.3295	1.209	0.8062 – 1.733	16
	400ft – 449ft	1.060	0.5730	0.7321	0.5125 – 1.892	14	1.040	0.2709	0.9753	0.6434 – 1.465	16
	450ft – 499ft	0.7105	0.4209	0.7755	0.1811 – 1.179	14	0.6021	0.2553	0.6069	0.0889 - 0.9352	16
	500ft – 550ft	0.2232	0.2763	0.3789	0.0614 - 0.8740	14	0.3609	0.1708	0.3966	0.1115 - 0.5469	16
	550ft – 600ft	0.3000	0.2271	0.1843	0.1387 - 0.8118 [a]	14	0.2725	0.1978	0.1777	0.0924 – 0.6384	16
	600ft – 649ft	0.3003	0.1821	0.3385	0.0449 – 0.8408	14	0.3081	0.2606	0.2510	0.1019 - 0.9519 [a]	16
	650ft – 699ft	0.2360	0.1182	0.2940	0.0262 - 0.3585	14	0.2617	0.1263	0.2298	0.0974 - 0.5265	16
	700ft – 749ft	0.2572	0.1454	0.2939	0.0519 - 0.4552	14	0.2369	0.1169	0.2450	0.0295 - 0.4355	16
Pitch Go Around Standard deviation of the absolute difference between pitch and pitch order, measured in deg.	300ft – 349ft	0.2919	0.1465	0.2793	0.1038 - 0.4545	14	0.3605	0.1918	0.2820	0.1761 - 0.7131	16
	350ft – 399ft	0.3299	0.1941	0.2581	0.0732 - 0.6496	14	0.3405	0.2596	0.2790	0.0808 - 0.8174	16
	400ft – 449ft	0.3015	0.1814	0.2003	0.1724 - 0.6749	14	0.3340	0.1675	0.2624	0.1624 - 0.6629	16
	450ft – 499ft	0.3410	0.1985	0.3221	0.0562 - 0.7238	14	0.3692	0.3160	0.2432	0.1025 – 1.053 [b]	16
	500ft – 550ft	0.3347	0.2905	0.2144	0.1445 - 0.9971 [b]	14	0.2932	0.1525	0.2700	0.1063 - 0.5414	16
	550ft – 600ft	0.2258	0.1873	0.1657	0.0334 - 0.6179 [b]	14	0.3055	0.2661	0.1945	0.0829 - 0.8748	16

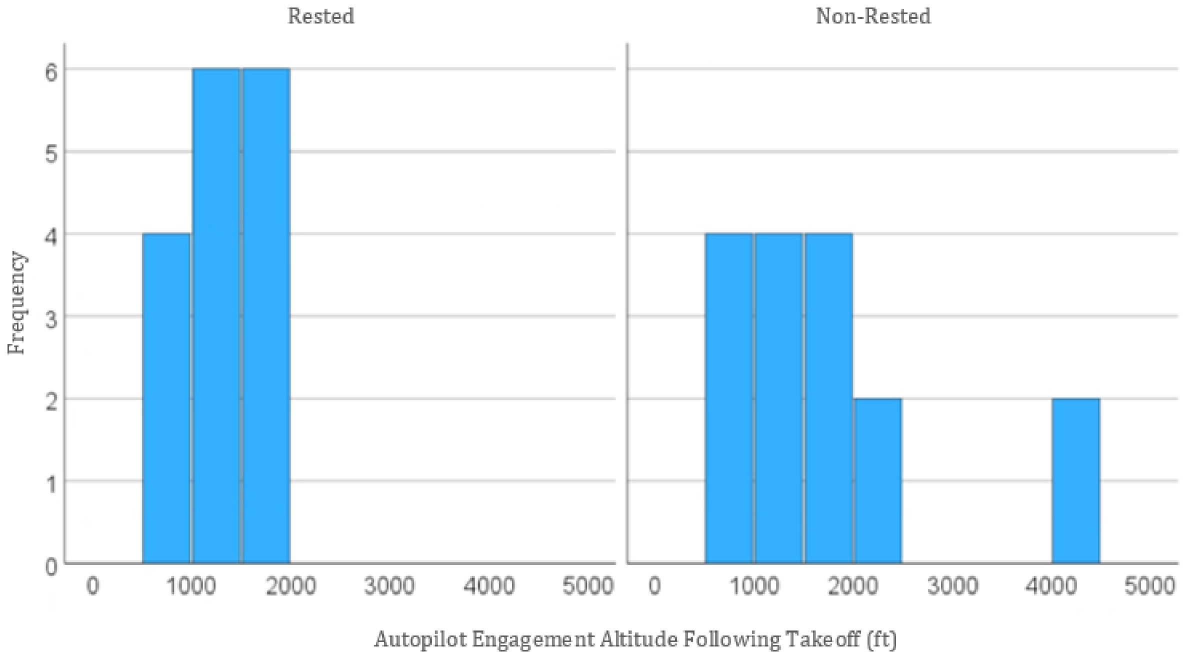
		Non-rested condition					Rested condition				
Variable	50ft Altitude Bin	Mean [D]	SD	Median	Range	N	Mean [D]	SD	Median	Range	N
	600ft – 649ft	0.1835	0.1543	0.1606	0.0278 - 0.5076	14	0.1771	0.1393	0.1574	0.0340 - 0.4494	16
	650ft – 699ft	0.1281	0.1226	0.0777	0.0238 - .3205	14	0.1770	0.0667	0.1901	0.0845 - 0.2986	16
	700ft – 749ft	0.1390	0.1185	0.1208	0.0112 - 0.3707	14	0.1989	0.1671	0.1323	0.0707 - 0.5493	16
Roll Go Around Standard deviation of the absolute difference between roll and roll order, measured in deg.	300ft – 349ft	0.6196	0.3600	0.4807	0.2500 – 1.353	14	0.5594	0.3140	0.6448	0.0808 - 0.9542	16
	350ft – 399ft	0.5681	0.3053	0.4832	0.2282 – 1.127	14	0.5057	0.2336	0.4803	0.1883 - 0.8785	16
	400ft – 449ft	0.5020	0.2931	0.3938	0.1779 – 1.031	14	0.4621	0.1659	0.4735	0.2201 - 0.7433	16
	450ft – 499ft	0.3349	0.1896	0.2951	0.0756 - 0.6146	14	0.4190	0.2118	0.4151	0.1362 - 0.7534	16
	500ft – 550ft	0.4081	0.3491	0.3700	0.0464 – 1.156 [b]	14	0.3066	0.2424	0.2176	0.1020 - 0.8664 [b]	16
	550ft – 600ft	0.3748	0.2741	0.3069	0.0806 - 0.9452	14	0.3440	0.2195	0.3102	0.1418 - 0.8660 [a]	16
	600ft – 649ft	0.1851	0.1495	0.1412	0.0539 - 0.4953	14	0.4440	0.1725	0.5094	0.0580 - 0.5958 [a]	16
	650ft – 699ft	0.2691	0.1527	0.2157	0.1072 - 0.5982 [b]	14	0.3726	0.1699	0.3516	0.1747 - 0.6856	16
	700ft – 749ft	0.2975	0.2121	0.2953	0.0367 - 0.6244	14	0.3183	0.1517	0.3115	0.1629 - 0.6609 [a]	16

a Includes two extreme outliers; b Includes two outliers; c Includes four outliers; D This value represents the MEAN of the standard deviation of the difference between the actual and the commanded/ordered value within each 50ft altitude bin.

6.3.3.3 Autopilot Status

Descriptive statistics for autopilot status measures are outlined in Table 6-5. Histograms show the distribution of values for autopilot engagement altitude following take off (see Figure 6-9), autopilot engagement altitude following go around (see Figure 6-10), autopilot disengagement before landing (see Figure 6-11), time taken to re-engage the autopilot (see Figure 6-12) and autopilot usage during flight (see Figure 6-13). Two values were excluded from datasets that included either time taken to re-engage the autopilot[87], or autopilot engagement altitude following go around[88].

Figure 6-9 Distribution of Autopilot Engagement Altitude Following Take off



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[87] A value of 885.4 seconds was excluded. This crew did not immediately re-engage the autopilot following the un-commanded autopilot disconnection.

[88] A value of 2892ft was excluded as this represents the altitude that the autopilot was re-engaged (885.4 seconds following the un-commanded autopilot disconnection) while the aircraft was flying downwind prior to its second approach.

Figure 6-10 Distribution of Autopilot Engagement Altitude Following Go around

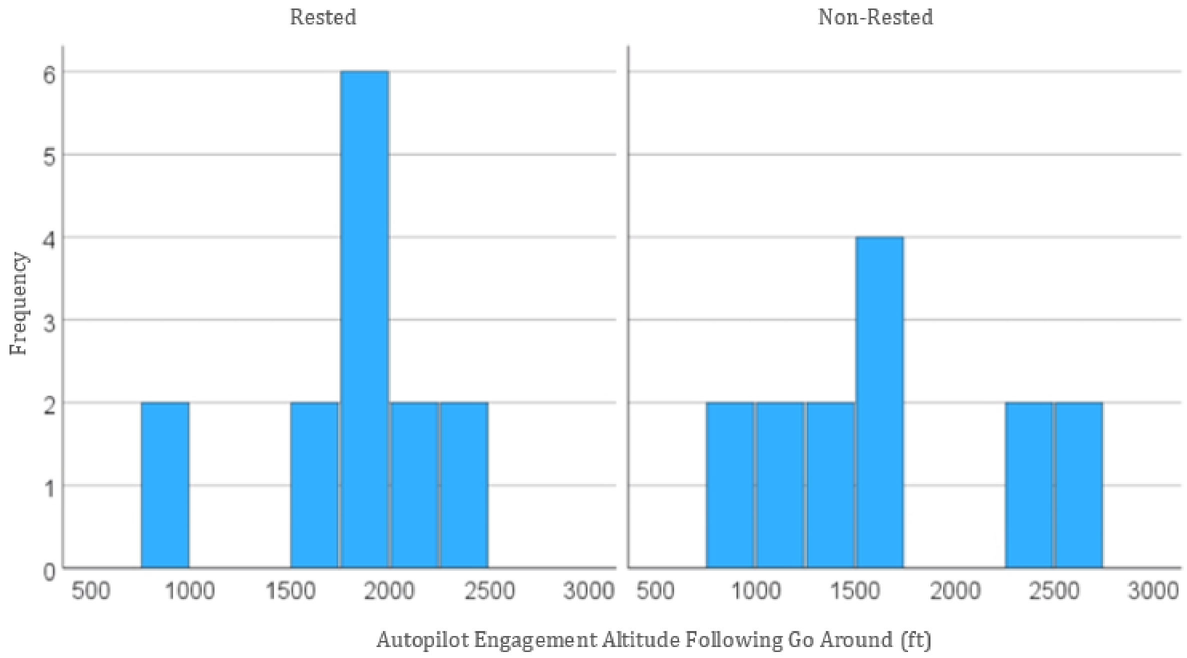

Figure 6-11 Distribution of Autopilot Disengagement before Landing

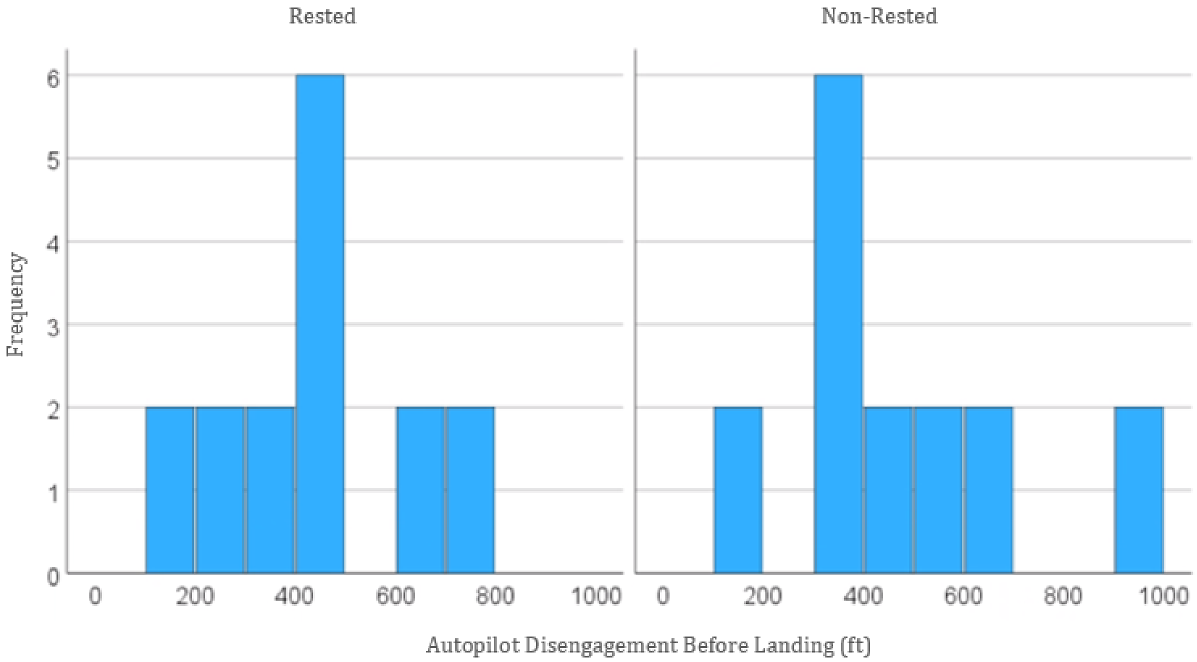

Figure 6-12 Distribution of Time Taken to Re-engage the Autopilot

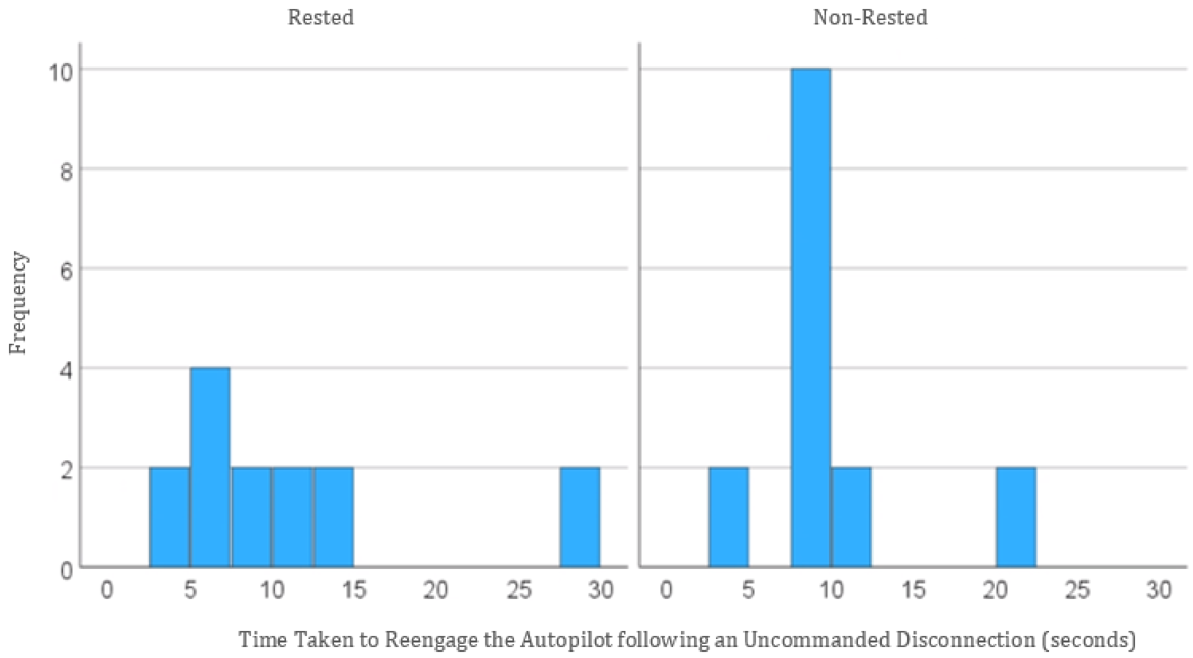

Figure 6-13 Distribution of Autopilot Usage During Flight

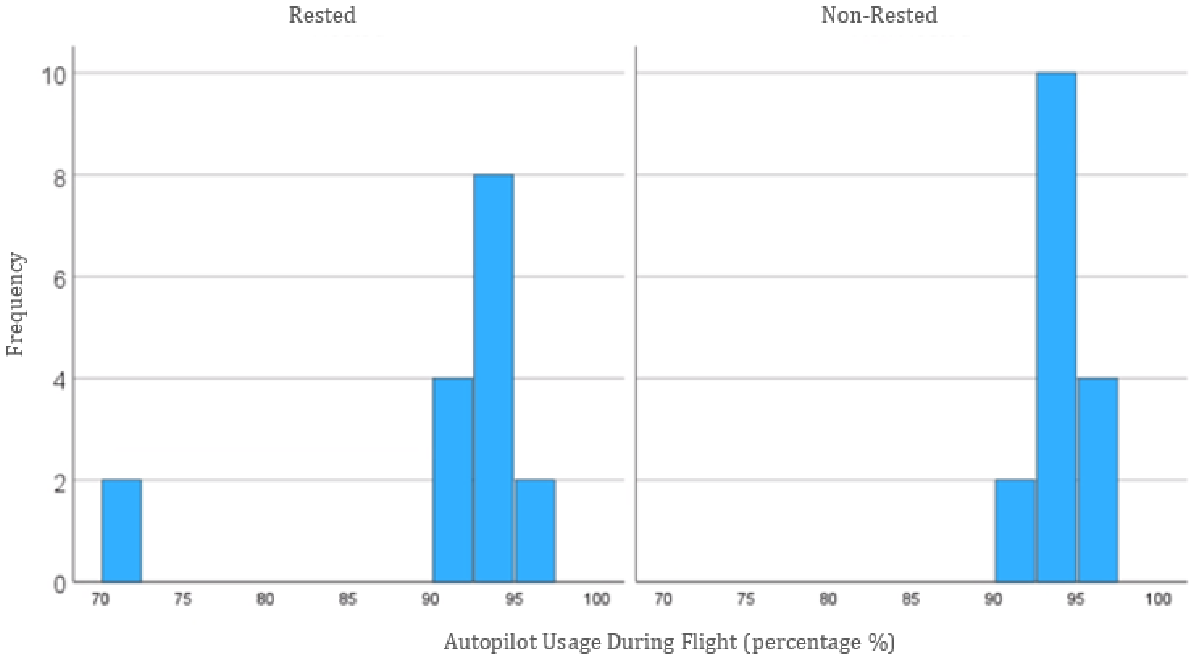

Table 6-5 Mean, Standard Deviation, Median, and Range for Performance Measures associated with Autopilot status

Variable	**Non-rested**					**Rested**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Autopilot Engagement Altitude Following Take off (ft)	1786.2	1208	1364	798 – 4357 [a]	16	1324.7	322.3	1327.5	922 - 1840	16
Autopilot Engagement Altitude Following Go around (ft)	1632.8	622	1666.8	752 – 2542	16	1792.7	496.7	1831.4	831 - 2454	14
Autopilot Disengagement before Landing (ft)	510	203.6	400.35	313 – 922	16	466.4	178.8	452.7	154 - 713	16
Time Taken to Reengage the Autopilot (seconds)	9.80	5.42	8.80	3 – 22 [a, b]	14	11.24	7.76	8.50	4 – 29 [a]	14
Autopilot Usage During Flight (%)	93.68	1.93	93.57	90.17 – 97.18 [a]	16	90.75	7.51	92.95	71.74 – 95.82 [b]	16

[a] Includes two outliers; [b] Includes two extreme outliers; [c] Includes four outliers.

6.3.3.4 Go Around Checklist

Descriptive statistics for each go around measure are outlined in Table 6-6 and histograms show the distribution of values for time taken to complete the go around/missed approach procedure (see Figure 6-14) and the time taken to initiate the go around (see Figure 6-15).

Figure 6-14 Distribution for Time Taken to Complete the Go around/Missed Approach Procedure

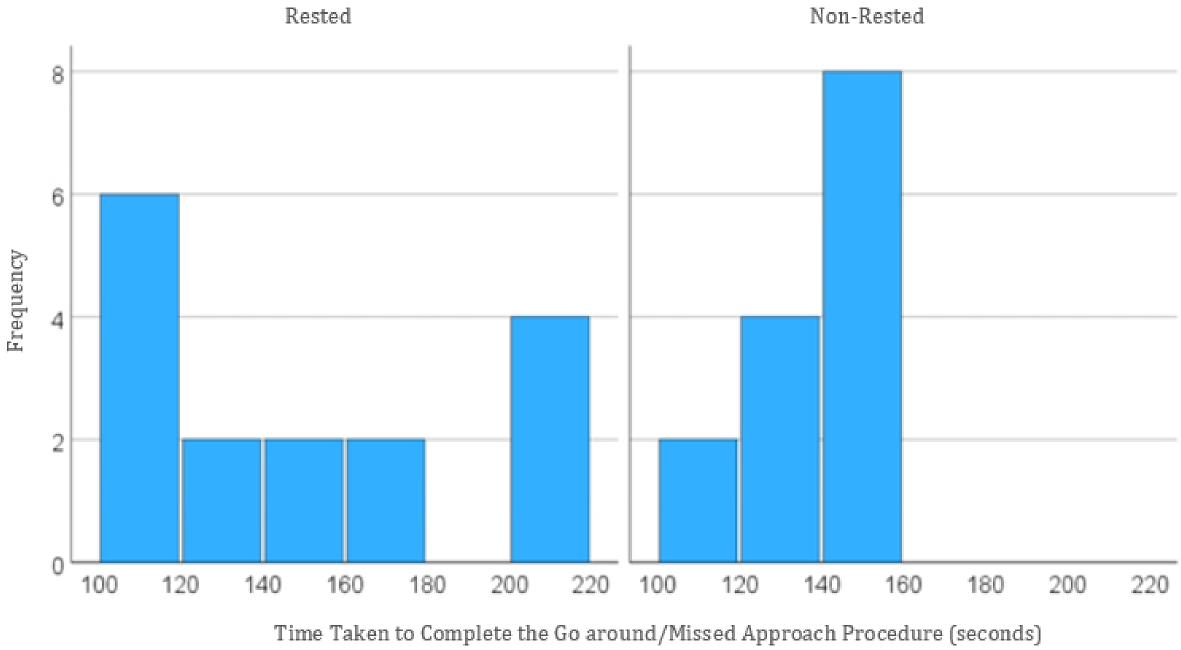

Figure 6-15 Distribution for the Time Taken to Initiate Go around

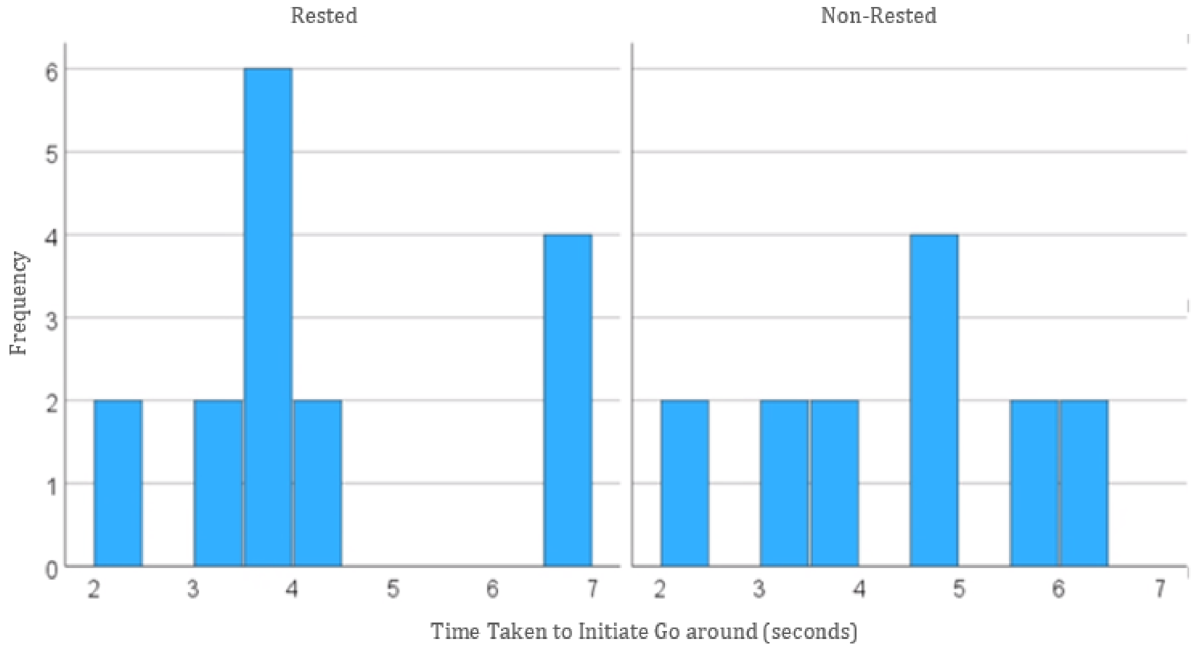

Table 6-6 Mean, Standard Deviation, Median, and Range for Performance Measures associated with the Go Around Checklist

Variable	**Non-rested**					**Rested**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Time Taken to Complete the Go around/Missed Approach Procedure (sec)	135.8	15.91	140.2	101.9 – 151.7 [a]	14	149.6	43.7	140.2	106.8 – 217.8	16
Time Taken to Initiate Go Around (sec)	4.45	1.31	4.8	2.3 – 6.4	14	4.21	1.71	3.59	2 – 6.9	16

a Includes two outliers.

6.4 Simulated Flight Protocol Compliance

This section includes analyses and results for the following research question:

Q1. Does the flown simulated flight protocol reflect the planned simulated flight protocol?

Values from customised events were reviewed to determine if simulated flights complied with flight characteristics and scenarios as outlined in the final simulated flight protocol (see section 3.8). Customised events associated with flight characteristics are outlined in Table 6-7 and scenarios in Table 6-8. An event cannot be used to determine levels of turbulence, cloud base height or coverage, precipitation rates and visibility.

Table 6-7 Customised Events for Flight Characteristics

Customised Events
Weight at recording start
Centre of gravity
Weather condition at start of take off (magnetic wind direction)
Weather condition at start of take off (wind speed)
Weather condition at start of take off (outside air temperature)
Weather condition at start of take off (QNH – pressure correction)
Wind direction at 2000ft during climb
Wind speed at 2000ft during climb
Wind direction at start of cruise
Wind speed at start of cruise
Wind direction at 2000ft during descent
Wind speed at 2000ft during descent
Weather condition at end of landing (magnetic wind direction)
Weather condition at end of landing (wind speed)
Weather condition at end of landing (outside air temperature)

Customised Events
Weather Condition at end of landing (QNH – pressure correction)

Table 6-8 Customised Events for Simulated Flight Protocol Scenarios

Customised event	Scenario
Altitude when wind direction is 240M and wind velocity is >= 15kts ex CHC	Tailwind during initial climb
Altitude when wind direction is 240M ex CHC	Tailwind during initial climb
Altitude when wind velocity >= 15kts ex CHC	Tailwind during initial climb
Wind component at 500ft ex CHC	Tailwind during initial climb
Wind component at 2000ft ex CHC	Tailwind during initial climb
The point when the aircraft reaches the constraint altitude ex CHC	Tailwind during initial climb
Altitude when wind direction is 300M and wind velocity >= 15kts ex WLG	Tailwind during climb
Altitude when wind direction is 300M ex WLG	Tailwind during climb
Altitude when wind velocity >= 15kts ex WLG	Tailwind during climb
Wind component at 2500ft ex WLG	Tailwind during climb
Wind component at 4000ft ex WLG	Tailwind during climb
The point when the aircraft reaches the constraint altitude ex WLG	Tailwind during climb
The altitude when total air temperature is less than 7 deg C	Ice accretion during climb
Icing condition duration during climb	Ice accretion during climb
Amber icing condition duration during climb	Ice accretion during climb
The altitude when total air temperature is greater than 7 deg C	Ice accretion during descent
Icing condition duration during descent	Ice accretion during descent
Amber icing condition duration during descent	Ice accretion during descent
The altitude at the point when the un-commanded auto pilot disconnection occurs	Un-commanded AP disconnect
The airspeed at 5DME on approach	Speed Restriction

Customised event	Scenario
The altitude at 5DME on approach	Speed restriction
Altitude when airspeed is stable during approach	Speed restriction
The glideslope deviation at 8DME on approach	Height restriction
The altitude at 8DME on approach	Height restriction
Altitude when re capturing the glide slope while approaching CHC	Height restriction
Altitude when go around is initiated	Go around

6.4.1 Results: Simulated Flight Protocol Compliance

Focus is placed on identifying where flown simulated flights deviated from the planned simulated flight protocol. Deviations would likely be caused by the simulator instructor deviating from the planned simulated flight protocol or because the researcher did not account for other possible sub scenarios.

6.4.1.1 Flight Characteristics

Descriptive statistics for flight characteristic variables are grouped by location and are detailed in Table 6-9 and Table 6-10. The difference between the requested flight characteristic variable value and the average recorded value was calculated for variables associated with flight characteristics. Differences that varied by more than one unit of measurement include:

- weight at start (CHC-WLG: +20kg, WLG-CHC: +15kg)
- wind direction during take off (WLG-CHC: -1 deg C)
- wind direction at 2000ft during climb (WLG-CHC: +21 deg C)
- wind speed at 2000ft during climb (CHC-WLG: +4.61knots, WLG-CHC: +6.96knots)
- wind direction and speed during cruise (CHC-WLG: +1 degree / +2.72knots, WGL-CHC: -2 degrees / +2knots)
- wind direction at 2000ft during descent (CHC-WLG: +1 deg C, WLG-CHC: -1 deg C)

- wind speed during landing (CHC-WLG: +1.1knots, WLG-CHC: 1.1knots)

Values for the following six flight characteristic variables were not constant across flights.

For CHC-WLG flights:

- Temperature at the start of take off (Range = 21.75 deg C – 21.99 deg C).
- Wind speed at 2000ft during climb (Range = 19.61kts – 19.63kts).

For WLG-CHC flights:

- Weight at start (Range = 22400kg – 22420kg).
- Temperature at the start of take off (Range = 19.97 deg C – 20.08 deg C[89]).
- Wind direction at 2000ft during climb (Range = 214 deg M – 233 deg M).
- Wind speed at 2000ft during climb (Range = 15.24kts – 19.85kts).

Figure 6-16 and Figure 6-17 illustrate that, for some flights, when passing 2000ft, the wind direction was already veering to the northwest and that wind velocity was greater than that requested at 2000ft (e.g. 200 degrees at 10knots).

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[89] During one flight, a temperature of 20.08 deg C was recorded in Wellington prior to departure. It was identified as an outlier in Table 6-10 (Mean = 19.98 deg C, Range = 19.97 deg C – 20.08 deg C).

Figure 6-16 Wind Direction at 2000ft During Climb (WLG – CHC) [90]

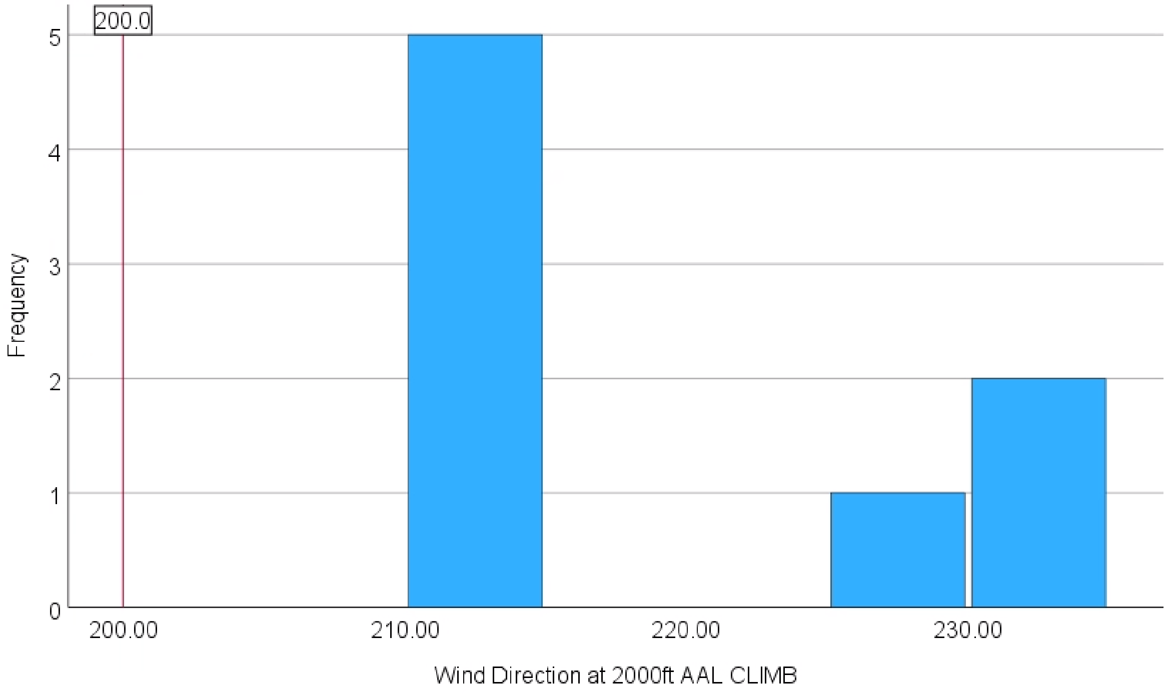
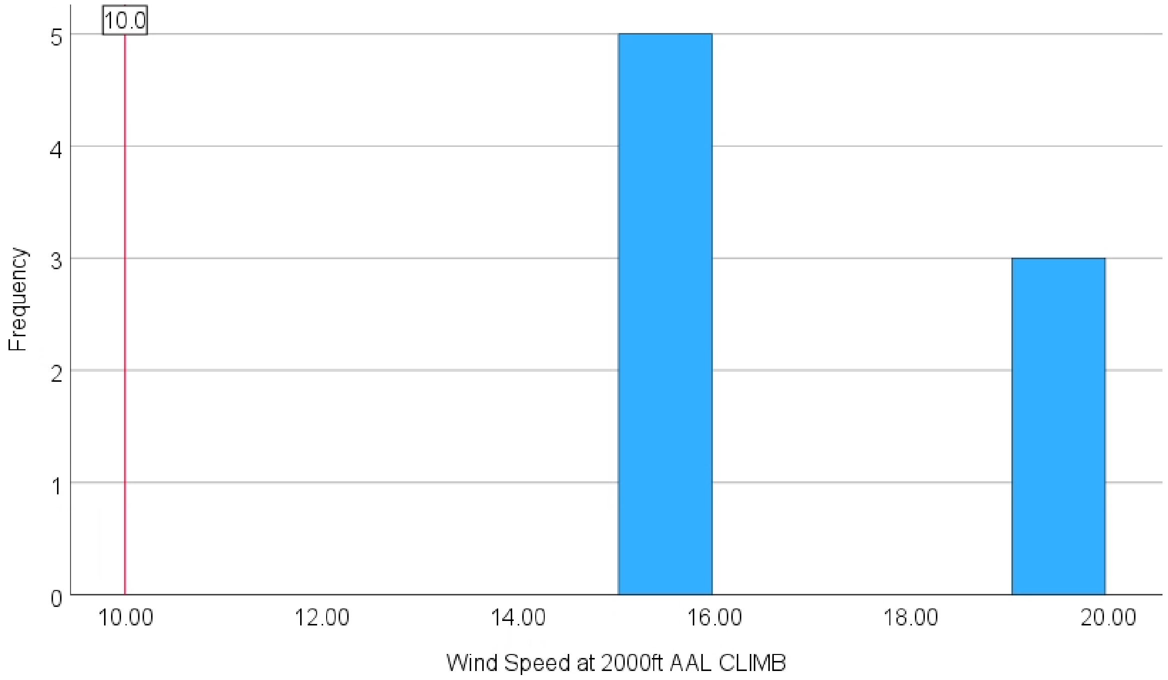


Figure 6-17 Wind Speed at 2000ft During Climb (WLG – CHC) [91]



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[90] The x axis represents wind direction, measured in degrees as the aircraft passes 2000ft during climb. The requested wind direction was 200 degrees.

[91] The requested wind speed was 10 knots.

Table 6-9 Mean, Standard Deviation, Median and Range for Flight Characteristics during the Christchurch Wellington Simulated Flight

Flight characteristics variables	**Christchurch – Wellington Flight**					**Comparison**		
	Mean	SD	Median	Range	N	Requested Value	Delta	Delta (%)
Weight at the start of take off (kg)	22520	0.000	22520	22520 – 22520	8	22500	20	0.08
Centre of gravity at the start of take off (%mean aerodynamic chord)	0.28	0.000	0.28	0.28 – 0.28	8	0.28	0	0.00
Weather condition at start of take off (magnetic wind direction)	340	0.000	340	340 – 340	8	340	0	0.00
Weather condition at start of take off (wind speed, kts)	10.54	0.000	10.54	10.54 – 10.54	8	10	0.54	5.12
Weather condition at start of take off (outside air temperature) (deg C)	21.93	0.10	21.98	21.75 – 21.99	8	22	-0.07	0.31
Weather Condition at start of Take off (QNH – pressure correction)	1006	0.000	1006	1006 – 1006	8	1006	0	0.00
Wind direction at 2000ft during climb (deg M)	240	0.000	240	240 – 240	8	240	0	0.00
Wind speed at 2000ft during climb (kts)	19.61	0.007	19.62	19.61 – 19.63	8	15	4.61	23.50
Wind direction at the start of cruise (deg M)	241	0.000	241	241 – 241	8	240	1	0.27
Wind speed at the start of cruise (kts)	47.2	0.000	47.2	47.2 – 47.2	8	45	2.72	5.76
Wind direction at 2000ft during descent (deg M)	301	0.000	301	301 – 301	8	300	1	0.27
Wind speed at 2000ft during descent (kts)	24.3	0.000	24.3	24.3 – 24.3	8	25	0.7	2.8

Flight Characteristics variables	**Christchurch – Wellington Flight**					**Comparison**		
	Mean	SD	Median	Range	N	Requested Value	Delta	Delta (%)
Weather condition at the end of landing (wind direction)	310	0.000	310	310 – 310	8	310	0	0
Weather condition at end of landing (wind speed, kts)	21.1	0.000	21.1	21.1 – 21.1	8	20	1.1	5.21
Weather condition at end of landing (outside air temperature) (deg C)	19.15	0.000	19.15	19.15 – 19.15	8	19	0.15	0.78
Weather condition at end of landing (QNH – pressure correction)	1002	0.000	1002	1002 – 1002	8	1002	0	0

Table 6-10 Mean, Standard Deviation, Median and Range for Flight Characteristics during the Wellington - Christchurch Simulated Flight

Flight characteristics variables	**Christchurch – Wellington Flight**					**Comparison**		
	Mean	SD	Median	Range	N	Requested Value	Delta	Delta (%)
Weight at the start of take off (kg)	22415	9.31	22420	22400 – 22420	8	22400	15	0.06
Centre of gravity at the start of take off (%mean aerodynamic chord)	0.28	0.000	0.28	0.28 – 0.28	8	0.28	0	0.00
Weather condition at the start of take off (magnetic wind direction)	199	0.000	199	199 – 199	8	200	-1	0.27
Weather condition at the start of take off (wind speed, kts)	10.54	0.000	10.54	10.5 – 10.5	8	10	0.54	5.40
Weather condition at start of take off (outside air temperature) (deg C)	19.98	0.036	19.97	19.97 – 20.08 [a]	8	20	-0.02	0.00
Weather Condition at the start of Take off (QNH – pressure correction)	1002	0.000	1002	1002 – 1002	8	1002	0	0.00
Wind direction at 2000ft during climb (deg M)	221	8.92	214	214 – 233	8	200	21	5.83
Wind speed at 2000ft during climb (kts)	16.96	2.38	15.24	15.24 – 19.85	8	10	6.96	69.6
Wind direction at the start of cruise (deg M)	318	0.000	318	318 – 318	8	320	-2	0.55
Wind speed at the start of cruise (kts)	47	0.000	47	47 – 47	8	45	2	4.4
Wind direction at 2000ft during descent (deg M)	241	0.000	241	241 – 241	8	240	1	0.27
Wind speed at 2000ft during descent (kts)	24.4	0.000	24.4	24.4 – 24.4	8	25	-0.6	2.4

Flight Characteristics variables	**Christchurch – Wellington Flight**					**Comparison**		
	Mean	SD	Median	Range	N	Requested Value	Delta	Delta (%)
Weather condition at the end of landing (wind direction)	230	0.000	230	230 – 230	8	230	0	0.00
Weather condition at the end of landing (wind speed, kts)	21.1	0.000	21.1	21.1 – 21.1	8	20	+1.1	5.5
Weather condition at the end of landing (outside air temperature) (deg C)	14.8	0.000	14.8	14.8 – 14.8	8	15	-0.2	1.3
Weather condition at the end of landing (QNH – pressure correction)	1002	0.000	1002	1002 – 1002	8	1002	0	0.00

a Includes one extreme outlier.

6.4.1.2 Flown Simulated Flight Protocol Scenarios

The role of the simulator instructor was to configure the simulated flight (flight characteristics) and to initiate scenarios at the correct time and this role is therefore key to ensuring that the flown simulated flight reflected the planned simulated flight. Although sub scenarios were included within the planned simulated flight protocol, these were not required during any of the simulated flights. Where applicable, each customised event includes a footnote which indicates if the simulator instructor or the flight crew were responsible for ensuring that the flown simulated flight reflected the planned simulated flight protocol.

Scenario: Tailwind During Climb

Descriptive statistics are detailed in Table 6-11 and Table 6-12. Each customised event within these tables includes a footnote which indicates if the simulator instructor or the flight crew were responsible for ensuring that the flown simulated flight reflected the planned simulated flight protocol. During departure from Christchurch, the aircraft was required to pass NUBKA at or above 2000ft and during departure from Wellington, the aircraft was required to pass TAXUP at or above 4000ft. In Christchurch, a 7kt headwind was requested at surface level and in Wellington, a 7kt headwind was requested at 2000ft. Intervention by the simulator instructor was required to ensure that a 11kt tailwind was present at 500ft in Christchurch and at 2500ft in Wellington. In both locations, the required change in wind direction was 100 degrees and the change in wind velocity was 5kts. Time available for this change was in the vicinity of 23 seconds in Christchurch and 19.7 seconds in Wellington. For flights that departed from Christchurch, the requested wind velocity and direction at 500ft was achieved (see Figure 6-18). The average tailwind component was 11.8 knots at 500ft (see Figure 6-20) and 13.6 knots at 2000ft (see Figure 6-22). For flights that departed Wellington, three flights did not have the requested wind direction at 2500ft (see Figure 6-19) and one flight did not have the requested tailwind component at 2500ft (see Figure 6-21), however, this was achieved by 2750ft. At 4000ft, all flights had the requested tailwind component (see Figure 6-23). For departures from both Christchurch and Wellington, although wind direction was constant once the requested value was achieved, wind speed (and subsequently, tailwind component) continued to increase, see Figure 6-24 (Christchurch) and Figure 6-25 (Wellington). The increase in wind speed was consistent for all flights. Four of eight flights achieved the constraint altitude at Christchurch and all flights achieved the constraint altitude at Wellington.

Table 6-11 Tailwind during Initial Climb during departure from Christchurch

Customised event	**Christchurch – Wellington Flight**					**Comparison**	
	Mean	SD	Median	Range	N	Requested Value	Number of flights which meet Criteria
The altitude when the wind direction is 240M and wind velocity >- 15kts ex CHC (ft) [a]	264	64.88	244.50	204 – 387	8	240 deg M/15kts by 500ft	8
Altitude when the wind direction is 240M ex CHC (ft) [a]	264	64.88	244.50	201 – 387	8	240 deg M by 500ft	8
The altitude where wind velocity >= 15kts ex CHC (ft) [a]	46	4.5	45	43 – 57 [c]	8	15kts by 500ft	8
The wind component at 500ft ex CHC (kts) [a]	-11.79	0.164	-11.75	-12.17 - -11.62 [d]	8	-11.6kts by 500ft	8
The wind component at 2000ft ex CHC (kts) [a]	-13.62	0.475	-13.58	-14.38 - -13.12	8	-11.6kts by 2000ft	8
The point when the aircraft reaches the constraint altitude ex CHC (ft) [b]	1938	214	1895	1728 – 2219	8	2000ft	4

[a] Simulator instructor responsibility, [b] Flight crew responsibility, [c] Includes 1 extreme outlier; [d] Includes 1 extreme outlier.

Table 6-12 Tailwind During Climb during departure from Wellington

Customised event	**Wellington – Christchurch Flight**					**Comparison**	
	Mean	SD	Median	Range	N	Requested Value	Number of flights which meet criteria
The altitude when the wind direction is 300M and wind velocity >= 15kts ex WLG (ft) [a]	2440	178	2443	2256 – 2793	8	300/15 by 2500ft	5
Altitude where the wind direction is 300M ex WLG (ft) [a]	2440	178	2443	2256 – 2793	8	300 by 2500ft	5
Altitude where wind velocity >= 15kts ex WLG (ft) [a]	1901	2.12	1900.5	1899 – 1904	8	15 by 2500ft	8
Wind component at 2500ft ex WLG (kts) [a]	-13.03	8.27	-16.25	-16.54 – 7.37 [c]	8	-11.6 by 2500ft	7
Wind component at 4000ft ex WLG (kts) [a]	-19.63	.456	-19.50	-20.76 - -19.40 [d]	8	-11.6 by 4000ft	0
The point when the aircraft reaches the constraint altitude ex WLG (ft) [b]	4467	261	4427	4080 – 4987 [e]	8	4000ft	8

a Simulator Instructor responsibility, b Flight crew responsibility, c Includes 1 extreme outlier; d Includes 1 extreme outlier; e Includes one outlier .

Figure 6-18 Altitude where Wind Velocity and Direction is 240M/15kts departing Christchurch

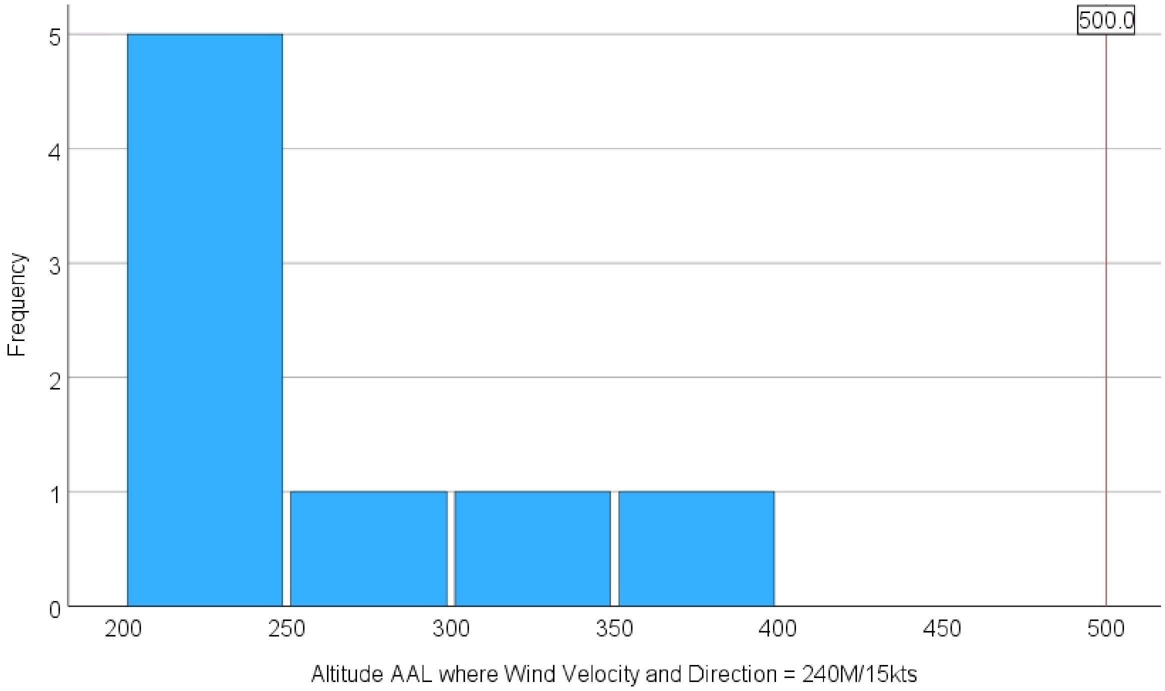


Figure 6-19 Altitude where Wind Velocity and Direction is 300M/15kts departing Wellington

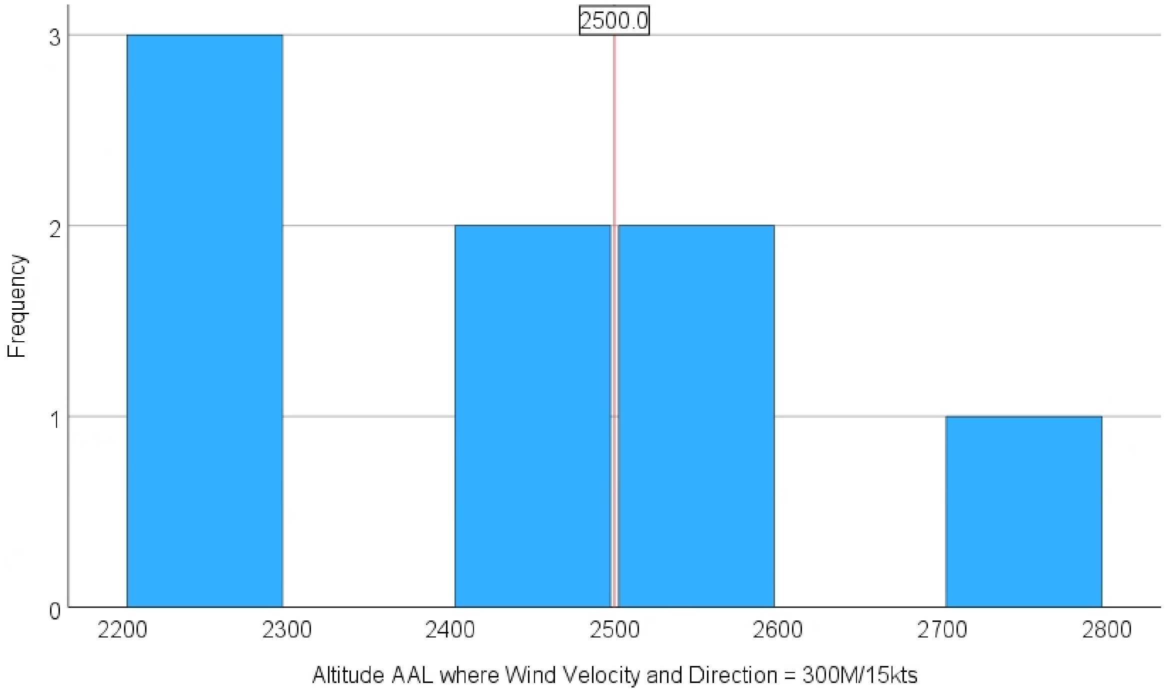


Figure 6-20 Wind Component at 500ft departing Christchurch

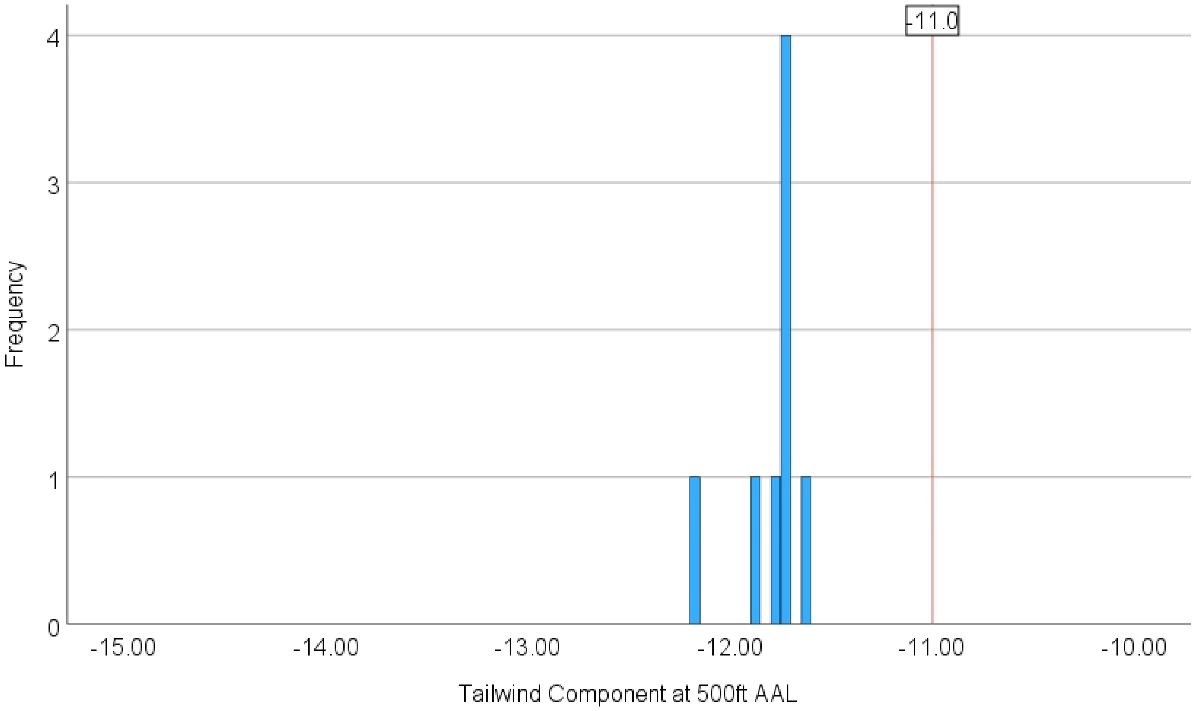


Figure 6-21 Wind Component at 2500ft departing Wellington

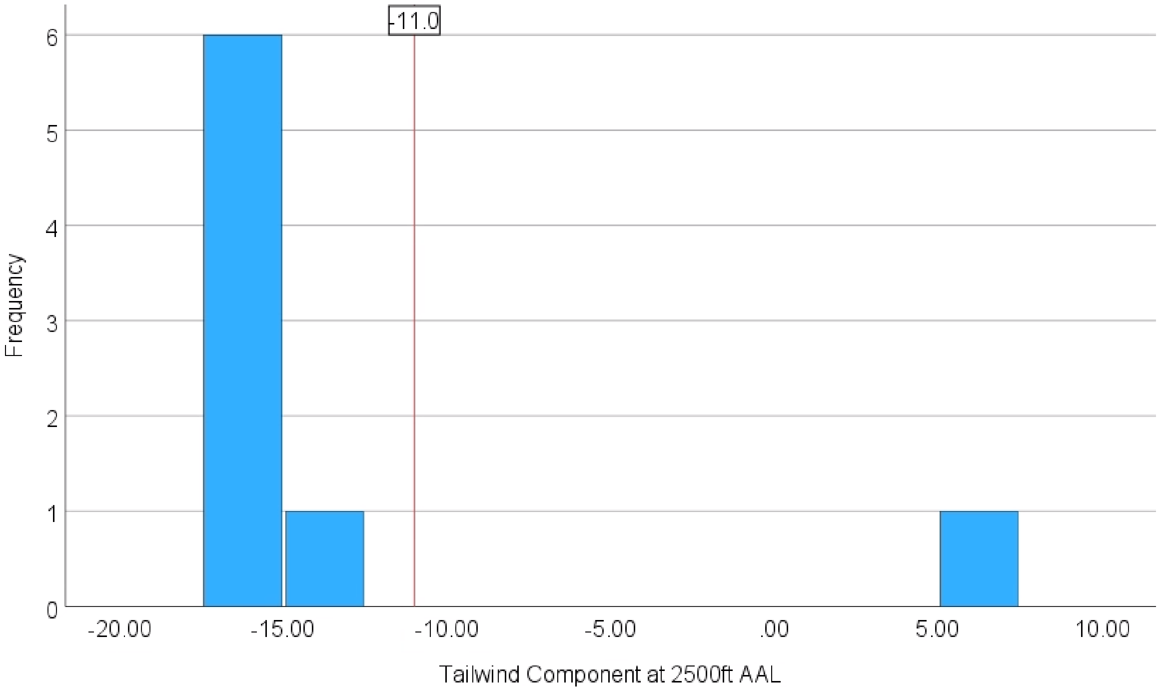


Figure 6-22 Wind Component at 2000ft departing Christchurch

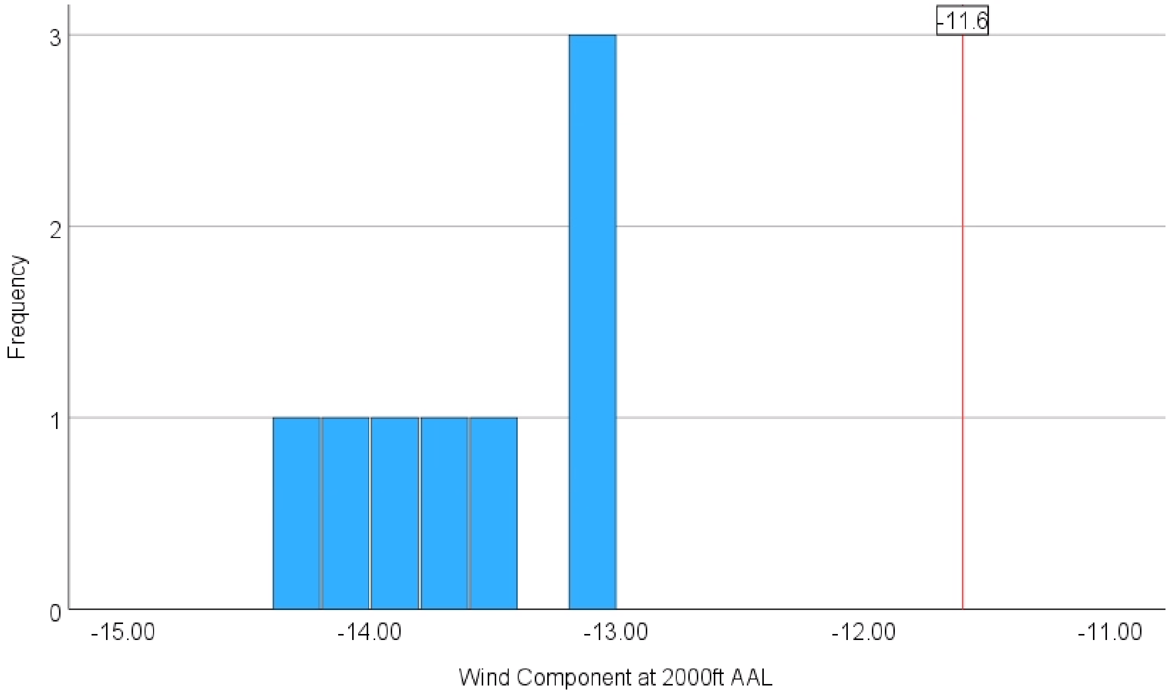


Figure 6-23 Wind Component at 4000ft departing Wellington

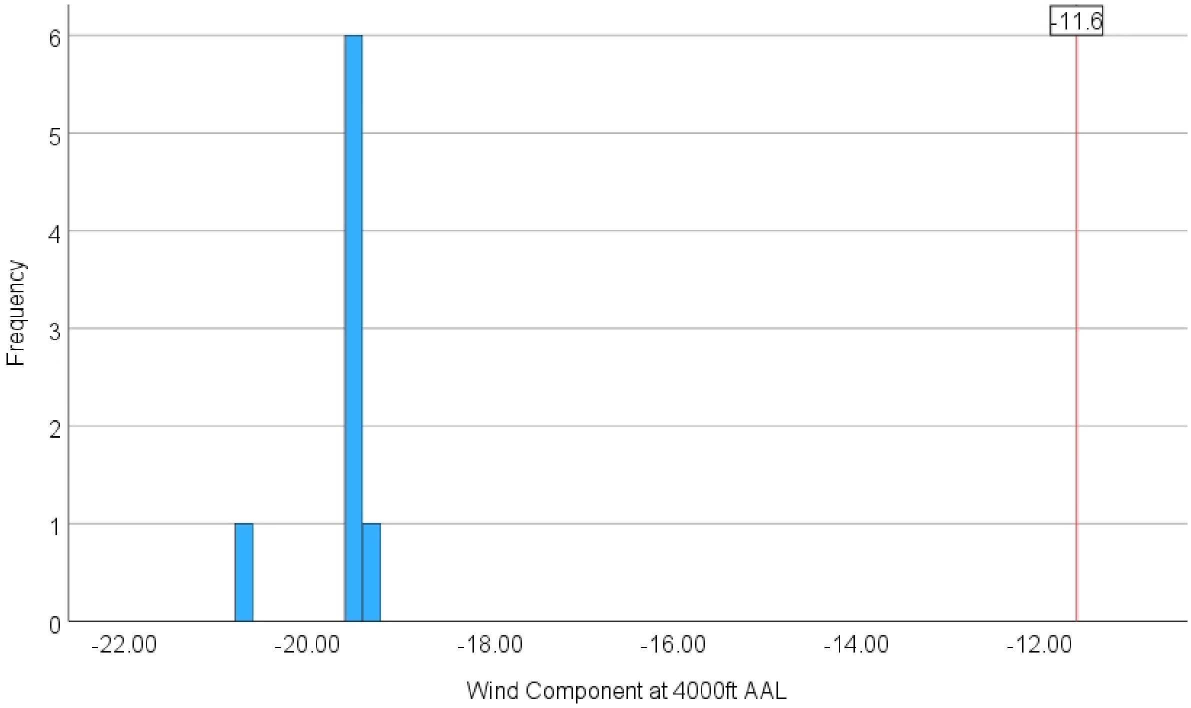


Figure 6-24 Wind Component between 500ft and 2000ft for Flights that Departed from Christchurch

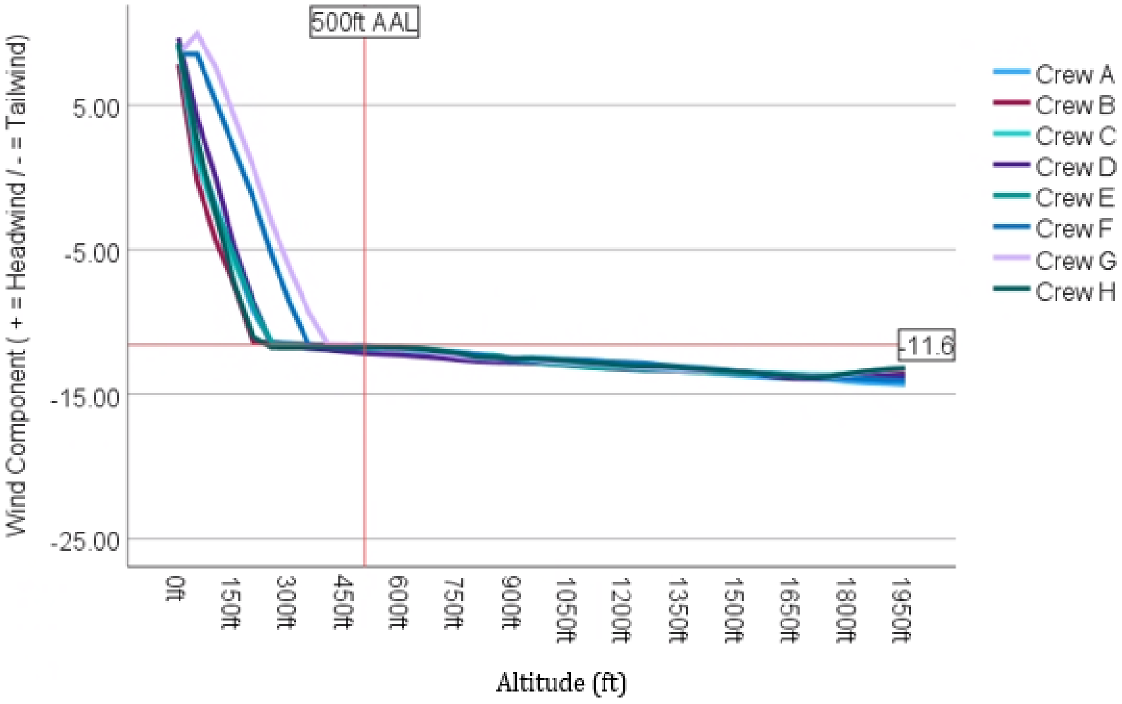
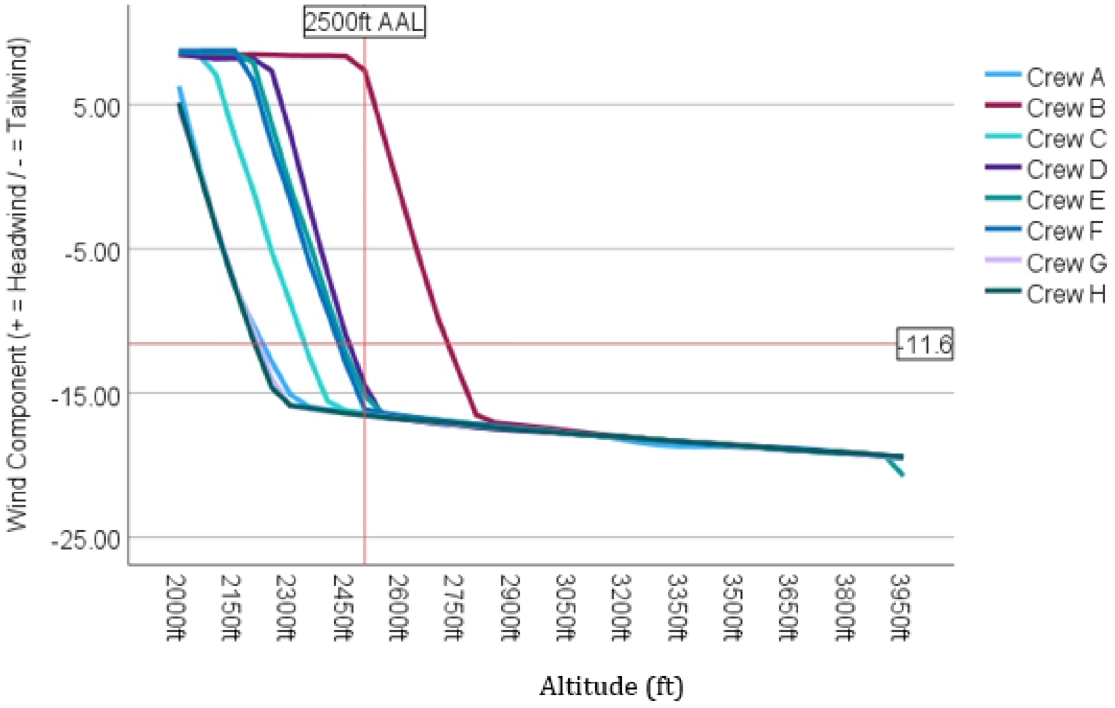


Figure 6-25 Wind component between 2500ft and 4000ft for Flights that Departed from Wellington



Scenario: Ice Accretion

The purpose of the ice accretion scenario was to facilitate the collection and analysis of measures that relate to the completion of checklists associated with flight in icing conditions and ice accretion. In icing conditions or during ice accretion, checklists are required to be completed at the following times:

- Entering icing conditions
- At first visual indication of ice accretion, and as long as atmospheric icing conditions exist
- When leaving icing conditions
- When the aircraft is visually verified clear of ice

The simulator instructor was responsible for ensuring that environmental conditions during the simulated flights reflected those outlined within the planned simulated flight protocol. Flight crews were responsible for initiating the appropriate checklist at the correct time, which they did. Customised events which relate to scenario compliance (as opposed to checklist compliance) are outlined in Table 6-8 and Table 6-13 and include descriptive statistics for those definitions. Differences in the duration of flight in icing conditions and ice accretion are illustrated in Figure 6-26, Figure 6-27, Figure 6-28 and Figure 6-29. All crew during all flights completed the required icing checklists.

Figure 6-26 Ice Accretion Duration during Climb

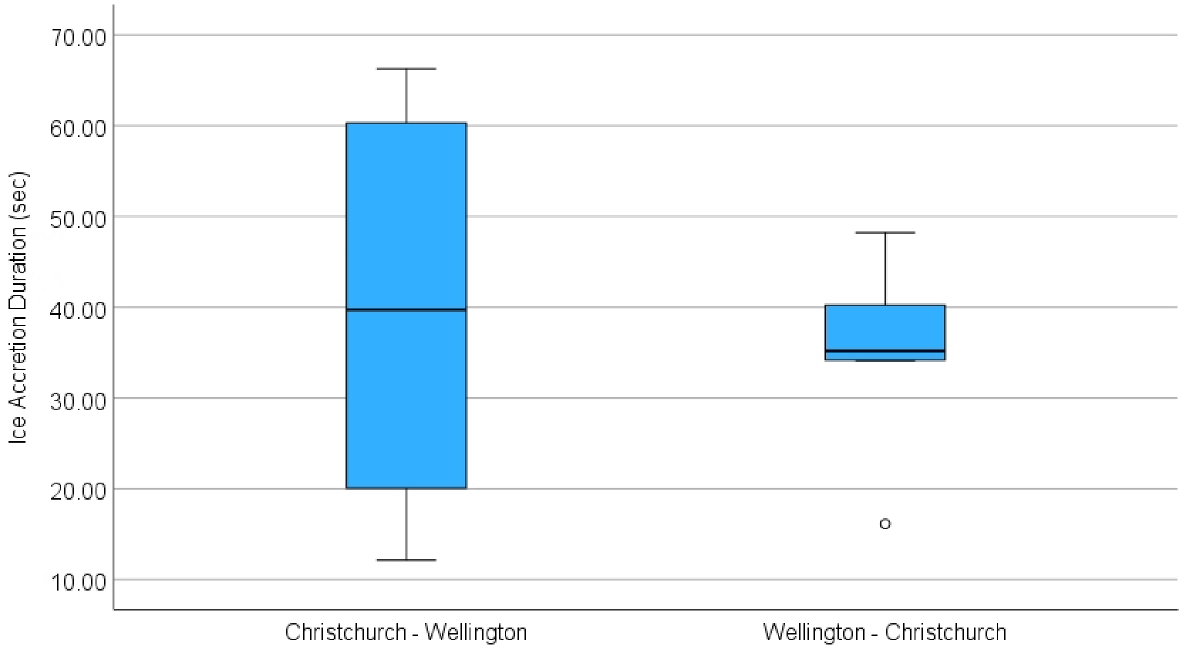


Figure 6-27 Ice Accretion during Descent

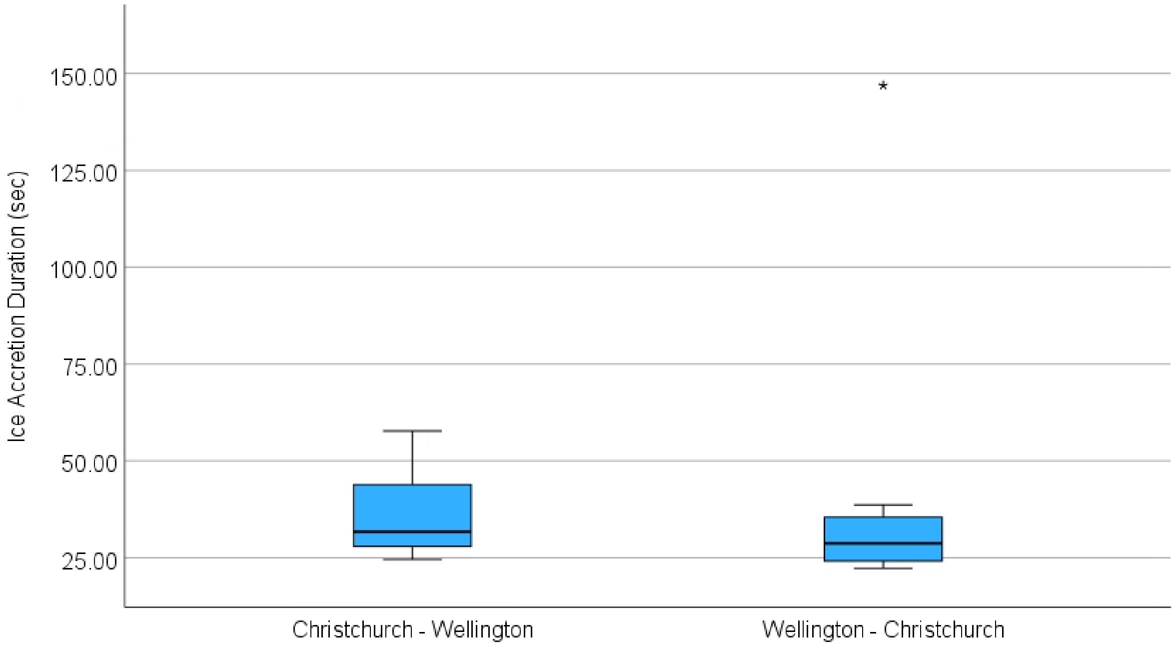


Figure 6-28 Duration of Atmospheric Icing Conditions During Climb

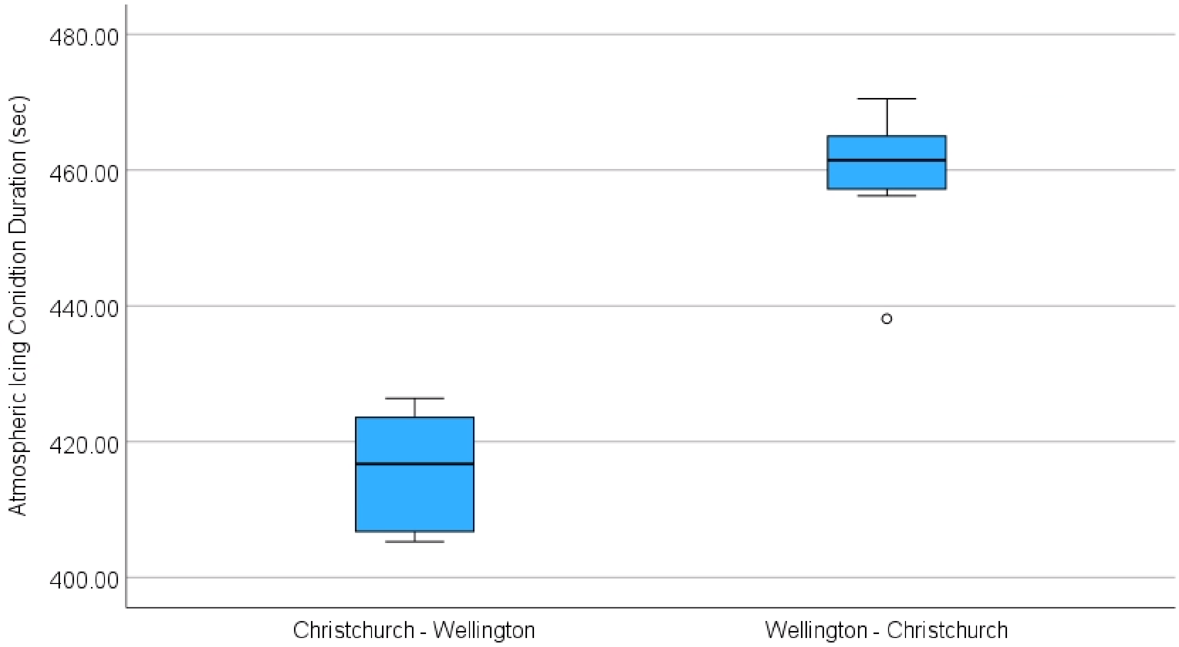


Figure 6-29 Duration of Atmospheric Icing Condition During Descent

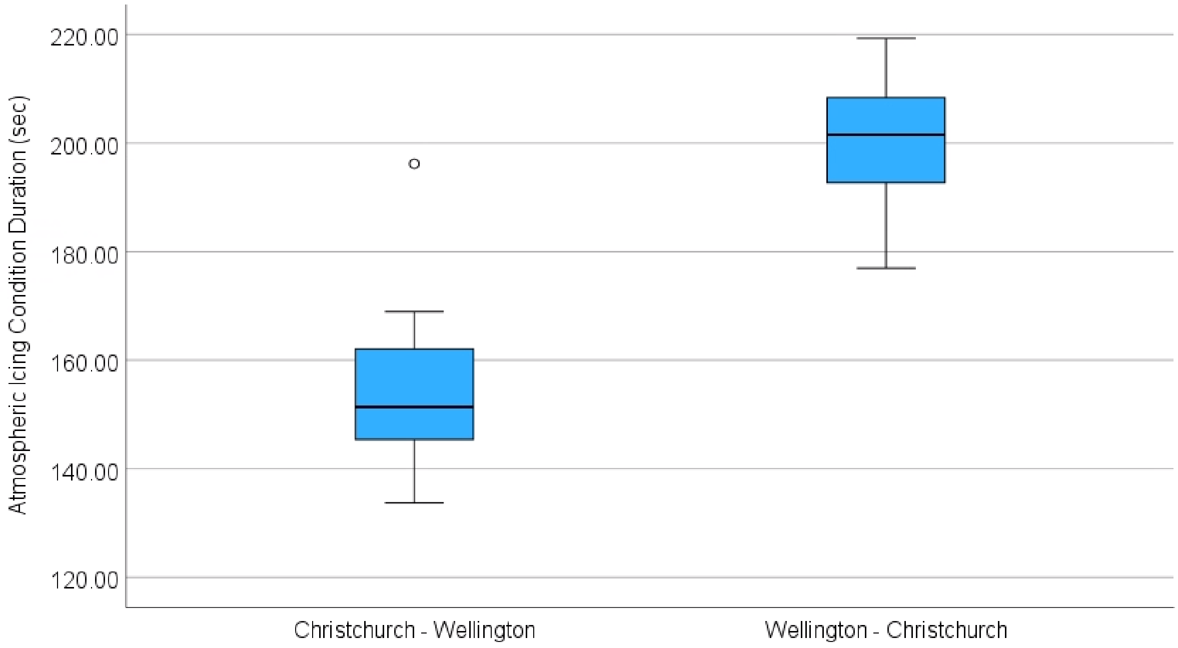


Table 6-13 Ice Accretion

Variable	**Christchurch - Wellington**					**Wellington – Christchurch**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
The altitude when the total air temperature is less than 7 deg C during climb (ft) [a]	7848	137	7781	7684 – 8100	8	6655	259	6544	6498 – 7270 [b]	8
Icing condition duration during climb (secs) [a]	415	8.6	416	405 – 426	8	459	9.84	461	438 – 470 [d]	8
Amber icing condition duration during climb (secs) [a]	39.82	21	39.73	12 – 66	8	35.44	9.15	35.18	16.12 – 48.24 [f]	8
The altitude when the total air temperature is greater than 7 deg C during descent (ft) [a]	9727	387	9826	8927 – 10181 [c]	8	8927	202	8902	8704 – 9322	8
Icing condition duration during descent (secs) [a]	155	19	151	133 – 196 [e]	8	200	13	201	176 – 219	8
Amber icing condition duration during descent (secs) [a]	36.13	11.50	31.67	24.52 – 57.75	8	43.21	42.24	28.68	22 – 146 [g]	8

a Simulator instructor responsibility, b Includes 1 outlier, c Includes 1 outlier, d Includes 1 outlier, e Includes 1 outlier, f Includes 1 outlier, g Includes 1 outlier.

Scenario: Un-commanded Autopilot Disconnect

All flights included an un-commanded autopilot disconnect. Descriptive statistics relating to the altitude at the start of the scenario are detailed in Table 6-14. The simulator instructor was responsible for ensuring that the un-commanded autopilot disconnect occurred at the correct point during flight. Although no outliers were identified, one crew re-engaged the autopilot only for it to immediately disengage. The duration between the initial disengagement and first re-engagement attempt is included within analysis. Following the second disengagement, crew re-engaged the autopilot after 16 seconds. Figure 6-30 illustrates that autopilot disengagement occurred over a greater range of altitudes during the Wellington – Christchurch flight (Range = 2730ft) compared with the Christchurch - Wellington flight (Range = 300ft). This is not because flights crossed the waypoint CH409 at varying altitudes, rather because autopilot disengagement occurred at varying distances prior to the aircraft crossing CH409 (see Figure 6-32) compared with JONAH (see Figure 6-31). The variation in altitude associated with the un-commanded autopilot disconnect had no impact on the validity of individual values within the scenario.

Figure 6-30 Altitude when the Un-commanded Autopilot Disconnection Occurs

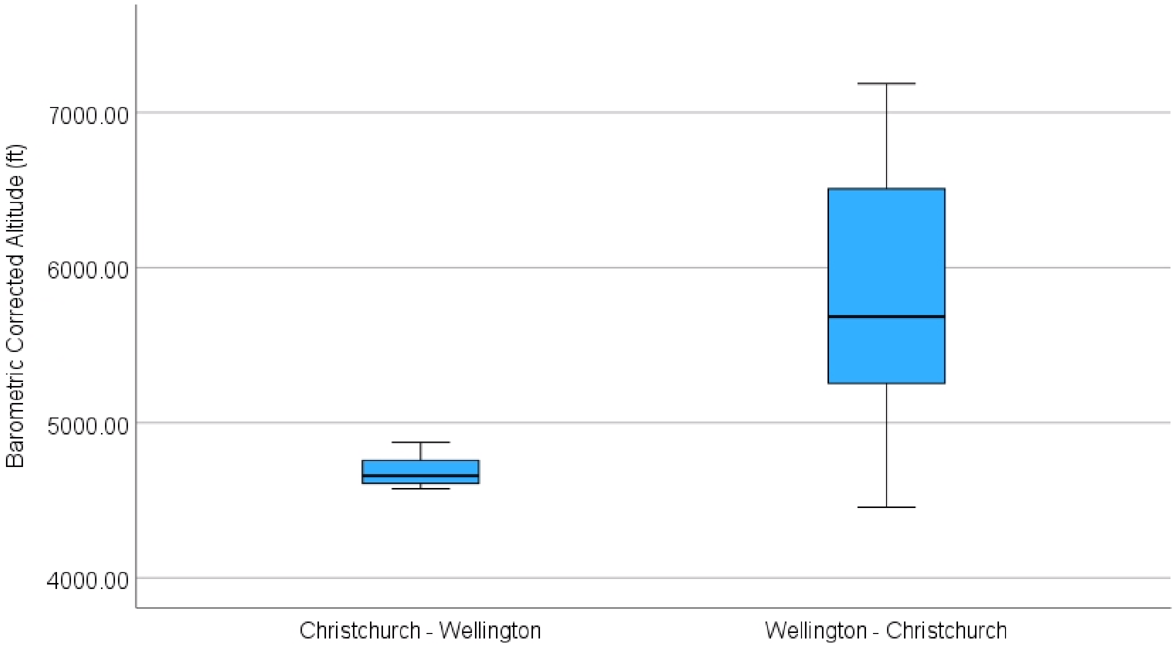
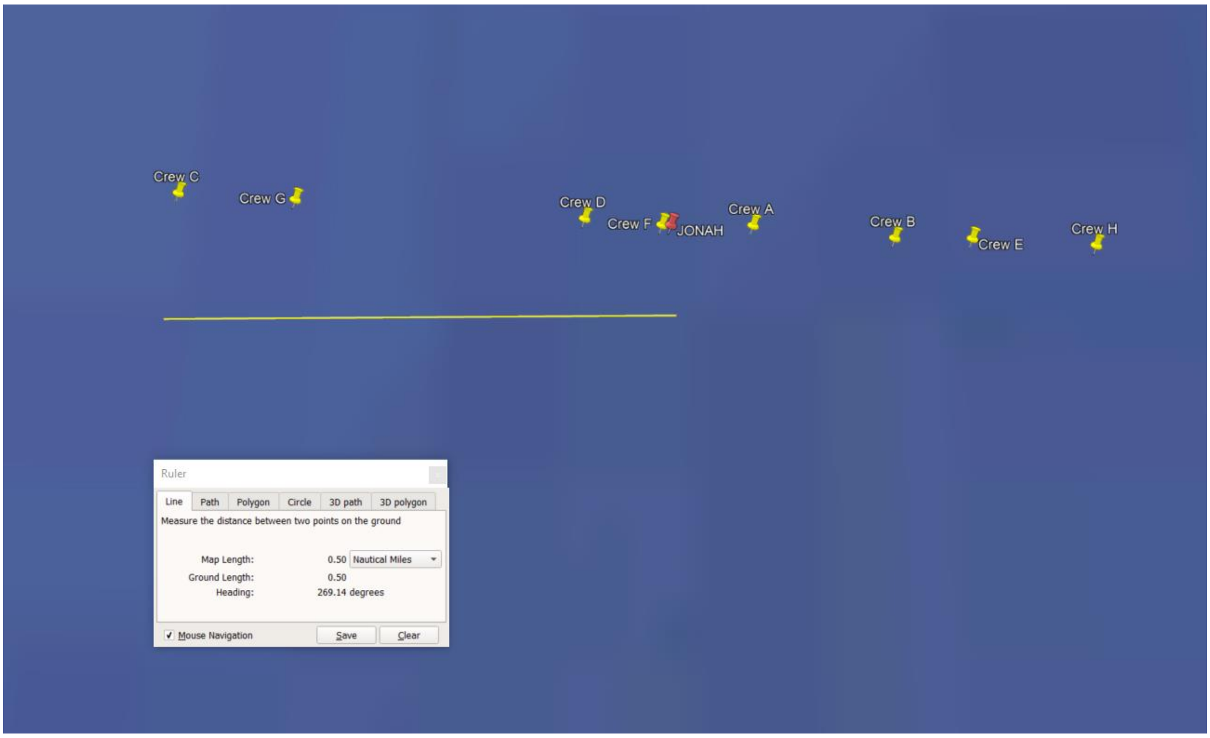


Table 6-14 Un-commanded Autopilot Disconnection

Variable	**Christchurch - Wellington**					**Wellington – Christchurch**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
The altitude at the point when the un-commanded auto pilot disconnection occurs (ft) [a]	4686	110	4657	4572 – 4873	8	5815	924	5682	4453 – 7184	8

a Simulator instructor responsibility.

Figure 6-31 Location of Un-commanded Autopilot Disconnection (CHC – WLG)



Measure the distance between two points on the ground

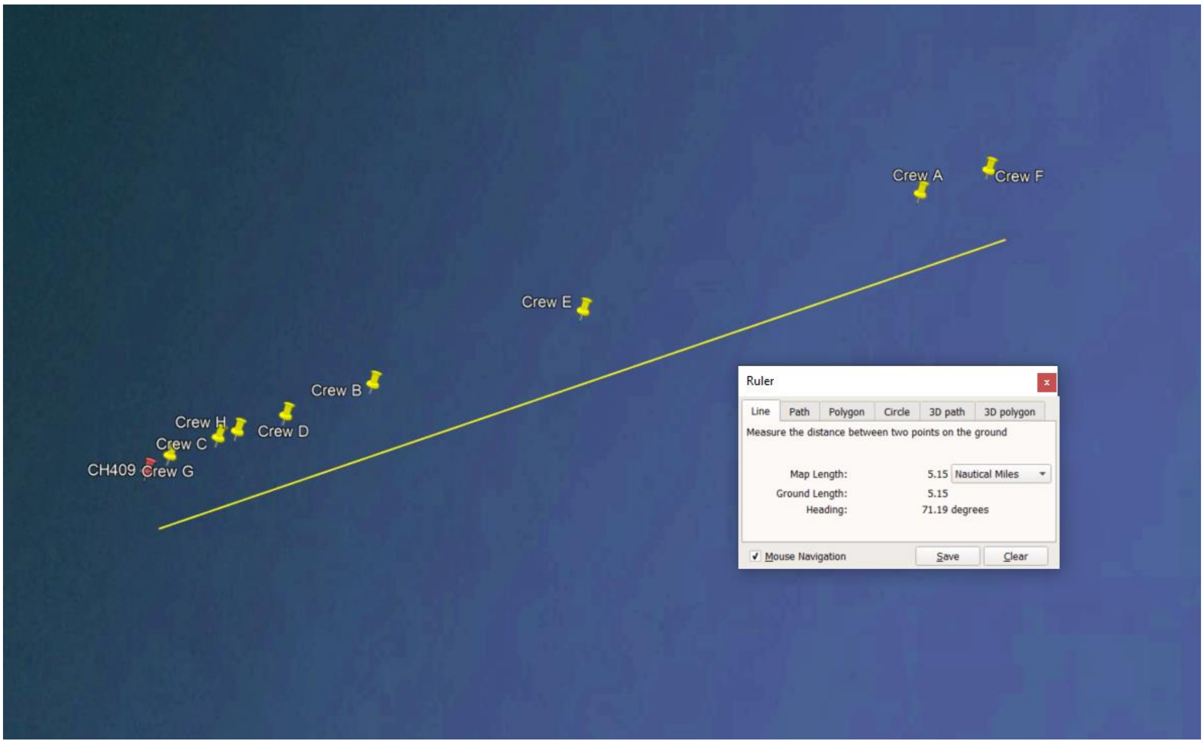
Map Length: 0.50 Nautical Miles

Ground Length: 0.50

Heading: 269.14 degrees

☑ Mouse Navigation

Figure 6-32 Location of Un-commanded Autopilot Disconnection (WLG – CHC)



Measure the distance between two points on the ground

Map Length: 5.15 Nautical Miles

Ground Length: 5.15

Heading: 71.19 degrees

☑ Mouse Navigation

Scenario: Excess Energy During Approach above 1000ft

The purpose of the excess energy during approach scenario was to facilitate the analysis of measures that relate to approach stability. The simulator instructor was responsible for ensuring that crew did not descend below 3000ft prior to reaching 8nm from the airfield (8DME) at Christchurch and that the crew maintained 160kts until 5DME at Wellington. Flight crews were responsible for complying with these requests. Descriptive statistics associated with this customised are detailed in Table 6-15 and Table 6-16.

Height Restriction

At 8nm from the airfield, the aircraft should be at 3000ft. At this point, the aircraft is above profile and requires the flight crew to promptly descend the aircraft to meet stable approach criteria at 1000ft above aerodrome level. The average glide slope deviation[92] at 8DME was 1.16dots high (Range = 0.97dot – 1.27dot) and the average height where stable approach criteria was met was 1649ft (Range = 1274ft – 2272ft). One crew initiated a missed approach from 3000ft. For this crew, the aircraft remained at 3000ft until 7.4DME where it was then 1.72dots high [93]. A descent was initiated, however shortly thereafter, the flight crew initiated a missed approach and climbed to 4000ft.

Speed Restriction

No flights maintained 160kts until 5DME.

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[92] The vertical glideslope scale on a typical instrument landing system (ILS) indicator provides an indication of the position of the glideslope relative to the aircraft (Wagtendonk et al., 2000a). The scale is measured in dots and consists of a central dot and five dots above and below the central dot. Full scale deflection (five dots above, or five dots below the central dot) suggests the aircraft is 0.7 deg above or below the glide slope. One dot represents 14ft per nm. For example, if one dot high, the aircraft is 14ft above the glideslope at 1nm and 112ft above the glideslope at 8nm.

[93] At 8DME, the aircraft was at 157kts (Mean = 150kts, Range = 126kts – 166kts) with no flap extended.

Table 6-15 Excess Energy During Approach above 1000ft: Wellington

Customised event	**Wellington**					**Comparison**	
	Mean	SD	Median	Range	N	Requested Value	Number of flights which meet criteria
The airspeed at 5DME on approach (kts) [a]	133.9	8.72	129.83	125.9 – 152.9 [b]	8	160 at 5DME	0
The altitude at 5DME (ft)	1631	53	1607	1598 – 1756 [b]	8	--	--
The point when the aircraft meets stable gate criteria during approach (ft)	1577	183	1619	1192 – 1766 [b]	8	--	--

a Flight Crew Responsibility, b Includes one outlier.

Table 6-16 Excess Energy During Approach above 1000ft: Christchurch

Customised event	**Christchurch**					**Comparison**	
	Mean	SD	Median	Range	N	Requested Value	Number of flights which meet criteria
The glideslope deviation at 8DME on approach (dots)	1.16	0.11	1.20	0.97 – 1.27	8	--	--
The airspeed at 8DME on approach (kts)	150	14.3	151	126.1 – 166.8	8	--	--
The altitude at 8DME on approach (ft) [a b]	2985	27	2998	2935 – 3004 [c]	8	3000ft at 8DME	8
The point when the aircraft meets stable gate criteria during approach (ft)	1649	359	1559	1274 – 2272	8	--	--

[a] Simulator instructor responsibility, [b] Start represents 8DME, [c] Includes one outlier.

Scenario: Go Around

The simulator instructor was responsible for ensuring crew received a go around instruction at 300ft during their first approach and flight crew were responsible for complying with the go around instruction. Descriptive statistics associated with customised events are detailed in Table 6-17. Fifteen flight crew conducted a go around that complied with the go around scenario. One flight crew conducted a go around above 2000ft, this go around was excluded from analysis. Figure 6-33 illustrates that all go arounds that complied with the go around scenario, were initiated below 300ft.

Figure 6-33 Lowest Altitude Above Aerodrome Level During Go Around

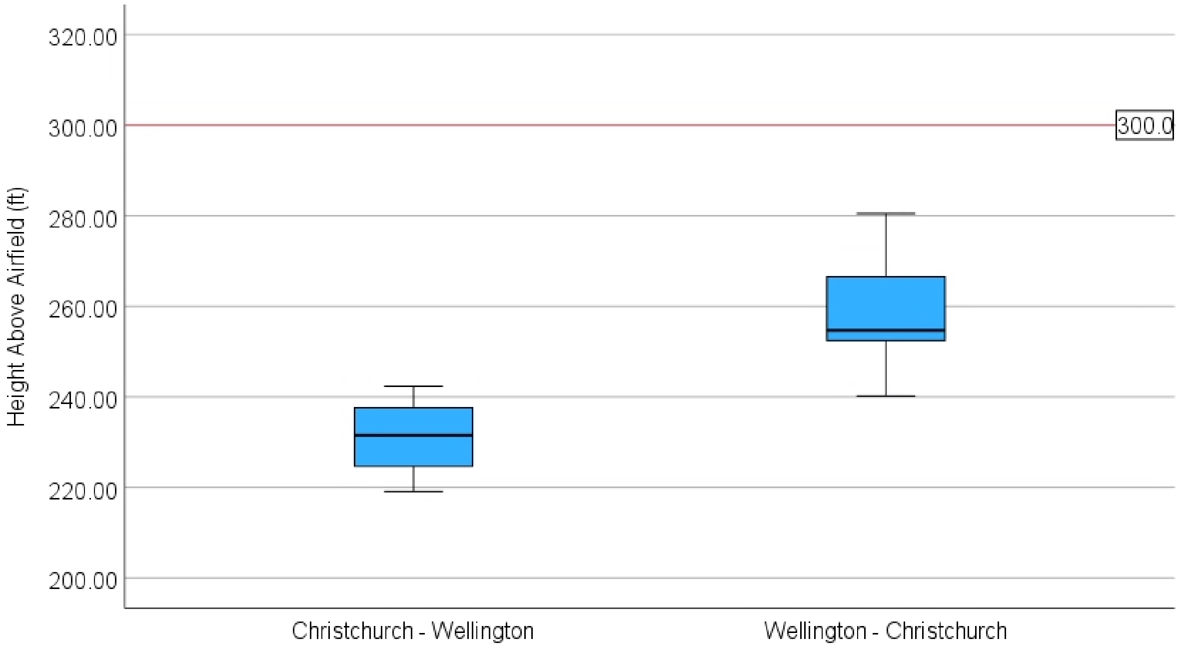


Table 6-17 Go Around

Variable	**Christchurch - Wellington**					**Wellington – Christchurch**				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
The point when the aircraft stops descending before go around (ft)	231	8.06	231	219 – 242	8	259	14.1	254	240 – 280	7

6.5 The Effect of Condition, Order and Location on Simulated Flight Data Measures

This section includes analyses and results for the following research questions:

Q2. Do flight data measures differ between the non-rested and rested condition?

Q3. Do flight data measures differ between the first and second simulated flight?

Q4. Do flight data measures differ between the Christchurch – Wellington and the Wellington – Christchurch simulated flight?

6.5.1 Analysis

A series of linear mixed models evaluated the influence of condition (non-rested or rested), flight order (first flight or second flight), flight location (Christchurch – Wellington or Wellington – Christchurch) on simulated flight data measures.

Models for the dependent variables “initial climb” and “go around” included the independent variable “50ft altitude bin” (see Chapter 2, section 2.11.3.2). Flight order was not considered to be a factor that would contribute to variability in autopilot engagement altitude following take off, autopilot disengagement before landing, and the percentage of each flight where the autopilot is engaged. It was excluded from models which included these auto pilot status measures. Location was only included in the models which evaluated flight data measures during initial climb and for autopilot engagement altitude following take off because departures from Christchurch included a tailwind during initial climb scenario below 2000ft whereas departures from Wellington did not. It was necessary to determine if the tailwind scenario in Christchurch contributed to variation in the applicable dependent variables.

The simulated flight data measures (dependent variables) are grouped by initial climb (Table 6-18), go around (Table 6-19), autopilot status (Table 6-20), and go around checklist (Table 6-21).

Table 6-18 Results of mixed model ANOVAs for the Effect of Condition, Order and Location on Simulated Flight Data Measures: Initial Climb

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Airspeed in Climb [a, b, c]	50ft Altitude Bin	8, 207	20.38	<**.0001**
	Condition	1, 64.7	12.20	**.0009**
	50ft Altitude Bin x Condition	8, 207	3.26	**.0016**
	Order	1, 67.8	0.46	.5002
	Location	1, 64.6	5.26	**.0251**
	50ft Altitude Bin x Location	8, 207	4.15	**.0001**
Pitch in Climb [b, d, e]	50ft Altitude Bin	8, 203	23.09	<**.0001**
	Condition	1, 63.3	11.54	**.0012**
	50ft Altitude Bin x Condition	8, 203	2.90	**.0044**
	Order	1, 64.2	0.93	.3396
	Location [h]	1, 63.4	6.58	.0127
	50ft Altitude Bin x Location	8, 203	16.29	<**.0001**
Roll in Climb [f, g, i]	50ft Altitude Bin	8, 187	1.68	.1055
	Condition	1, 27.3	5.60	**.0253**
	50ft Altitude Bin x Condition	8, 187	5.90	<**.0001**
	Order	1, 27.4	2.61	.1176
	Location	1, 27.4	0.02	.8879

[a] Number of observations used: 278/282, excludes 6 outliers; [b] Autoregressive covariance structure; [c] LOG transformation applied to normalise distribution; [d] Number of observations used: 272/276, excludes 12 outliers, includes 6 outliers; [e] SQRT transformation applied to normalise distribution; [f] Number of observations used: 278/282, excludes 6 outliers, includes 4 outliers; [g] Autoregressive covariance structure with random variance components; [h] Levene's test was significant, a more conservative alpha level of 0.01 was used; [i] the non-significant (NS) interaction Location x 50ft Altitude bin was removed from the final model;

Table 6-19 Results of mixed model ANOVAs for the Effect of Condition, Order and Location on Simulated Flight Data Measures: Go Around

Dependent Variable	Independent Variable	DF	F-value	P(F)
Airspeed Go Around [b, h, k, l]	50ft Altitude Bin	8, 208	38.97	**<.0001**
	Condition	1, 53.4	0.26	.6104
	Order	1, 53.3	0.38	.5389
Pitch Go Around [b, i, k, l]	50ft Altitude Bin	8, 215	5.67	**<.0001**
	Condition	1, 65.6	2.97	.0896
	Order	1, 65.6	0.02	.8760
Roll Go Around [b, e, j, k]	50ft Altitude Bin	8, 210	5.51	**<.0001**
	Condition	1, 64.7	2.57	.1138
	Order	1, 64.4	9.09	**.0037**

[b] Autoregressive covariance structure; [e] SQRT transformation applied to normalise distribution; [h] Number of observations used: 258/276, excludes 12 outliers; [i] Number of observations used: 270/288, includes 2 outliers; [j] Number of observations used: 266/284, excludes 4 outliers; [k] the non-significant (NS) interaction Condition x 50ft Altitude bin was removed from the final model.

Table 6-20 Results of mixed model ANOVAs for the Effect of Condition, Order and Location on Simulated Flight Data Measures: Autopilot Status

Dependent Variable	Independent Variable	DF	F-value	P(F)
Autopilot Engagement Altitude Following Take off [k]	Condition	1, 13.9	0.01	.9320
	Location	1, 13.9	0.09	.7726
Autopilot Engagement Altitude Following Go around [l]	Condition	1, 11.1	3.63	.0828
	Order	1, 11	20.88	**.0008**
Autopilot Disengagement before Landing [e, m]	Condition	1, 15	0.40	.5361
Time Taken to Reengage the Autopilot [n]	Condition	1, 4.04	2.07	.2232
	Order	1, 3.9	23.50	**.0089**
Autopilot Usage During Flight [o]	Condition	1, 14.2	0.36	.5587

[e] SQRT transformation applied to normalise distribution; [k] Number of observations used: 30/30, excludes 2 outliers; [l] Number of observations used: 28/32; [m] Number of observations used: 32/32; [n] Number of observations used: 24/26, 6 outliers excluded.

Table 6-21 Results of mixed model ANOVAs for the Effect of Condition, Order and Location on Simulated Flight Data Measures: Go Around Checklist

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Time Taken to Complete the Go around/Missed Approach Procedure [p]	Condition	1, 27	1.09	.3057
	Order	1, 27	8.23	**.0079**
Time Taken to Initiate Go Around [p, q]	Condition	1, 13.6	0.58	.4588
	Order	1, 13.6	0.15	.7040

[p] Number of observations used: 30/32; [q] LOG transformation applied to normalise distribution.

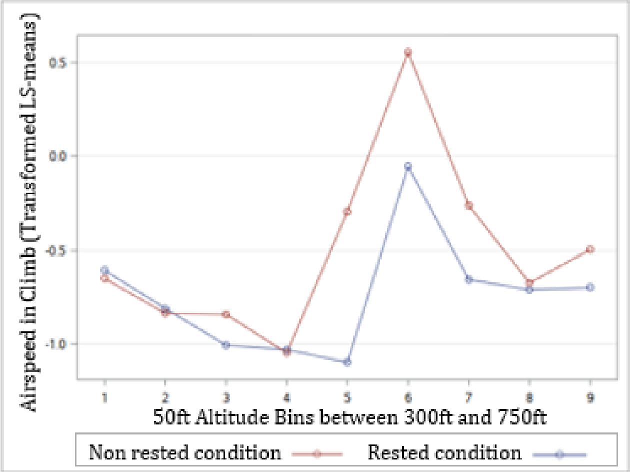
6.5.2 Results: Condition

6.5.2.1 Initial Climb

Airspeed in Climb

The interaction between condition and the 50ft altitude bins was significant (see Table 6-18). Simple effect tests showed that airspeed during climb was significantly higher in the non-rested condition in bin 5 (p = <.0001), 6 (p = .0003) and 7 (p = .0138), see Figure 6-34. Untransformed model estimates were significantly higher, in the non-rested condition, in bin 5 (1.75 kts versus -0.17 kts), 6 (5.37 kts versus 4.18 kts) and 7 (1.98 kts degrees versus 0.32 kts). Differences in estimates of standard deviation were not significantly different between levels of condition during bin 1 (p = .9978), 2 (p = .9975), 3 (p = .9205), 4 (p = .9963), 8 (p = .9496) and 9 (p = .6489).

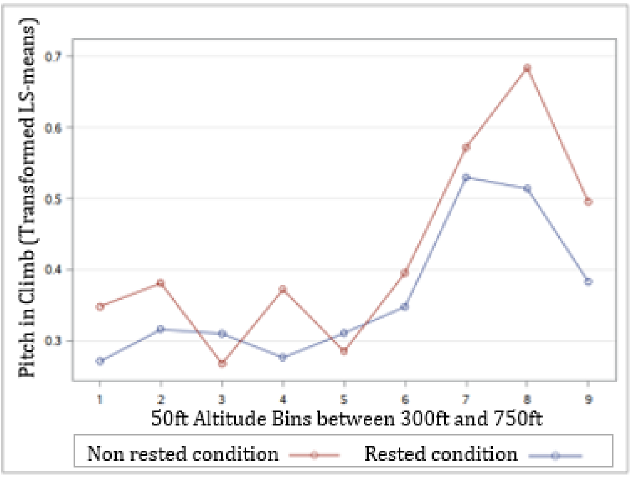
Figure 6-34 Transformed LS-means Estimates of Airspeed in Climb for the Interaction: 50ft Altitude Bin x Condition



Pitch in Climb

The interaction between condition and the 50ft altitude bins was significant (see Table 6-18). Pitch in climb was significantly higher in the non-rested condition in bin 4 (p = .0342), 8 (p = .0008) and 9 (p = .0248), see Figure 6-35. Compared with the rested condition, untransformed model estimates were significantly higher in the non-rested condition in bin 4 (0.15 degrees versus 0.07 degrees), 8 (0.46 degrees versus 0.34 degrees) and 9 (0.25 degrees versus 0.19 degrees). Model estimates did not differ significantly between levels of condition in bin 1 (p = .0714), 2 (p = .1158), 3 (p = .3048), 5 (p = .5331), 6 (p = .2484) or 7 (p = .3216).

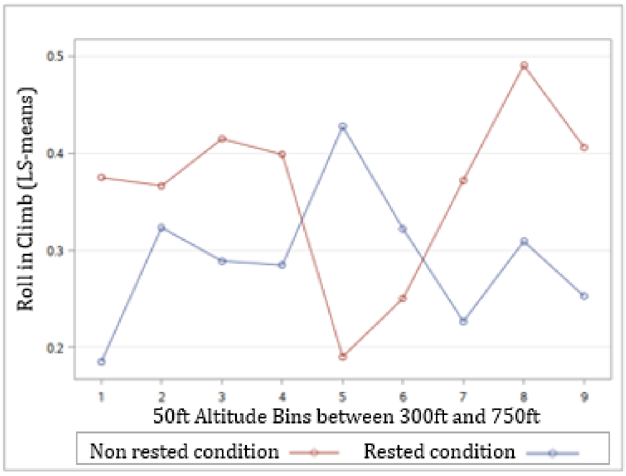
Figure 6-35 Transformed LS-means Estimates of Pitch in Climb for the Interaction: 50ft Altitude Bin x Condition



Roll in Climb

The interaction between condition and the 50ft altitude bins was significant (see Table 6-18). Roll during climb was significantly higher in the non-rested condition during bin 1 (p = .0029), 3 (p = .0407), 7 (p = .0221), 8 (p = .0045) and 9 (p = .0193). However, model estimates were significantly higher in the rested condition in bin 5 (p = .0001). Compared with the rested condition, model estimates were significantly higher in the non-rested condition in bin 1 (0.37 degrees versus 0.18 degrees), 3 (0.41 degrees versus 0.28 degrees), 7 (0.37 degrees versus 0.22 degrees), 8 (0.49 degrees versus 0.30 degrees) and 9 (0.40 degrees versus 0.25 degrees). As mentioned above, in bin 5, the model estimate was significantly higher in the rested condition (0.42 degrees versus 0.19 degrees). Differences between the non-rested and rested condition were not significant in bins 2 (p = .4816), 4 (p = .0634) and 6 (p = .2422).

Figure 6-36 LS-means Estimates of Roll in Climb for the Interaction: 50ft Altitude Bin x Condition



6.5.2.2 Go Around

The interaction between condition and the 50ft altitude bins was not significant. In reduced models, go around measures did not differ significantly between the non-rested and rested condition (see Table 6-19).

6.5.2.3 Autopilot Status

Auto pilot status measures did not differ significantly between the non-rested and rested condition (see Table 6-20).

6.5.2.4 Go Around Checklist

Time taken to complete the go around/missed approach procedure and initiate go around did not differ significantly between the non-rested and rested condition (see Table 6-21).

6.5.3 Results: Order

6.5.3.1 Initial Climb

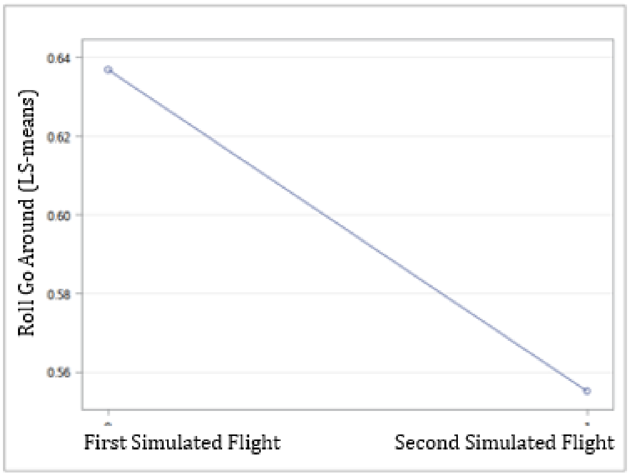
Initial climb measures did not differ significantly between the first and second simulated flight (see Table 6-18).

6.5.3.2 Go Around

Roll Go Around

There was a significant effect of order on roll during go around. The standard deviation of the absolute difference between roll and flight director roll order during go around was larger (more variable) during the first simulated flight compared to the second simulated flight (see Table 6-19 and Figure 6-37). Untransformed estimates of roll during climb were significantly higher during the first simulated flight compared with the second simulated flight (0.44 versus 0.34). Airspeed and pitch during go around were not significantly associated with order.

Figure 6-37 LS-means Estimates for Roll Go Around during the First and Second Simulated Flight



6.5.3.3 Autopilot Status

Autopilot Engagement altitude following go around

Time taken to re-engage the autopilot following an un-commanded autopilot disconnection

Autopilot engagement altitude following go around and time taken to re-engage the autopilot differed significantly between the first and second simulated flights (see Table 6-20). Following go around, the autopilot was engaged at a lower altitude during the first simulated flight (1490ft versus 1864ft, see Figure 6-38). Following the un-commanded autopilot disconnection, a significantly longer period of time was taken to re-engage the autopilot during the first simulated flight when compared with the second simulated flight (10.16sec versus 7.35sec, see Figure 6-39). For Figure 6-38 and Figure 6-39, 0 = First Flight and 1 = Second Flight.

Figure 6-38 LS-means Estimates for Autopilot Engagement Altitude Following Go around during the First and Second Simulated Flight

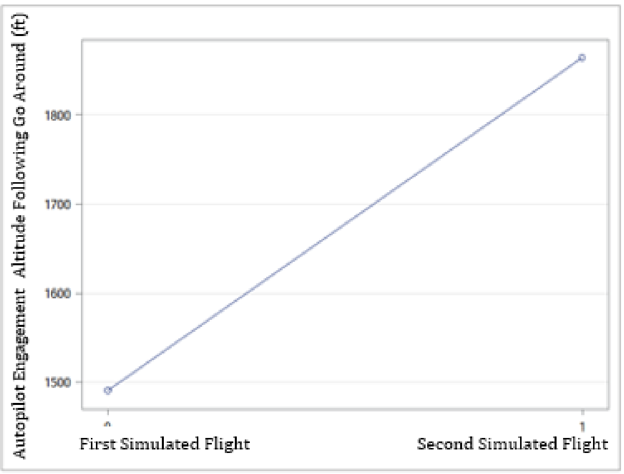
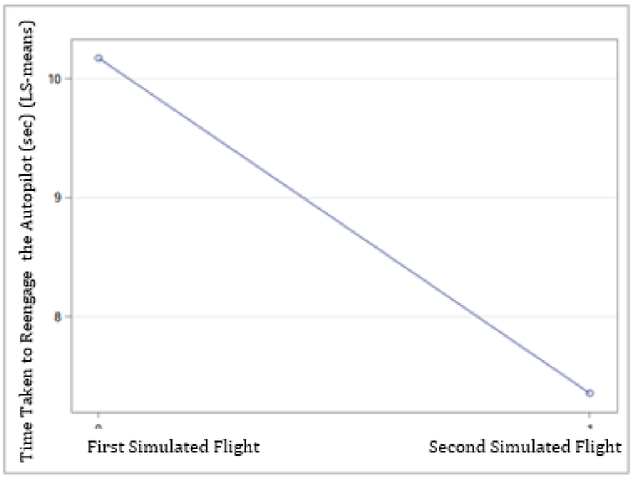


Figure 6-39 LS-means Estimates for Time Taken to Reengage the Autopilot during the First and Second Simulated Flight

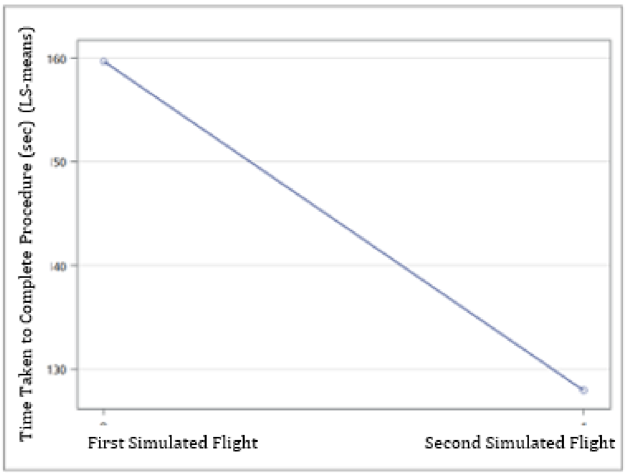


6.5.3.4 Go Around Checklist

Time taken to complete the go around/missed approach procedure

Flight crew took significantly longer to complete the go around/missed approach procedure checklist during the first simulated flight when compared with the second simulated flight (159.7sec versus 127.9sec, see Table 6-21 and Figure 6-40).

Figure 6-40 LS-means Estimates for the Time Taken to Complete the Go around/Missed Approach Procedure during the First and Second Simulated Flight



The time taken to initiate go around was not significantly associated with order (see Table 6-21).

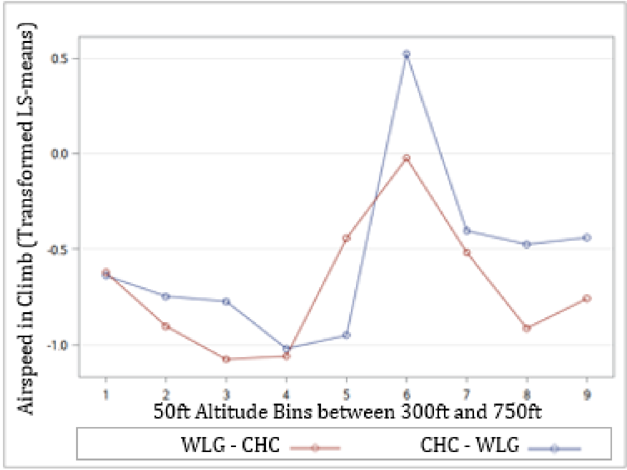
6.5.4 Results: Location

6.5.4.1 Initial Climb

Airspeed in Climb

The interaction between 50ft altitude bin and departure location was significant (see Table 6-18). Simple effects tests showed that airspeed during climb differed by location in bin 5 (p = .0036), 6 (p = .0010) and bin 8 (p = .0062), see Figure 6-41. When compared with departures from Christchurch, untransformed model estimates were significantly higher during departures from Wellington in bin 5 (1.62 kts versus -0.04 kts). However, estimates were significantly lower in bin 6 (3.15 kts versus 6.40 kts) and bin 8 (0.17 kts versus 0.41 kts). Differences in model estimates did not differ significantly by departure location in bin 1 (p = .9183), 2 (p = .3275), 3 (p = .0570), 4 (p = .8010), 7 (p = .4788) and 9 (p = .0638).

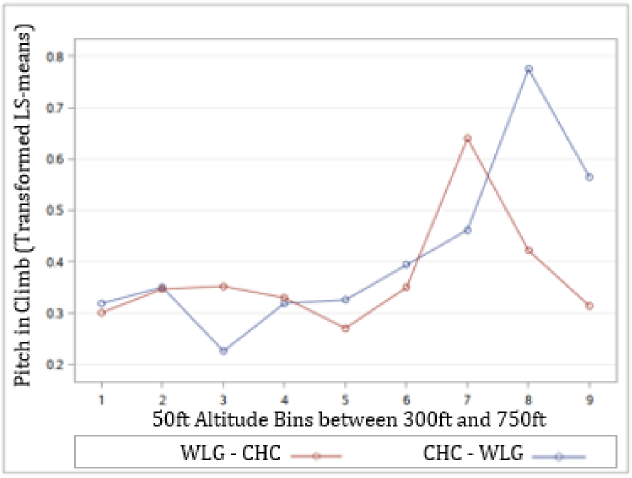
Figure 6-41 LS-means Estimates of Airspeed in Climb for the Interaction: 50ft Altitude Bin x Location



Pitch in Climb

Simple effect tests showed that pitch in climb differed by location in bin 3 (p = .0025), 7 (p = <.0001), 8 (p = <.0001) and 9 (p = <.0001), see Figure 6-42. When compared with departures from Christchurch, untransformed model estimates were significantly higher for departures from Wellington in bin 3 (0.13 degrees versus 0.05 degrees) and bin 7 (0.47 degrees versus 0.22 degrees). However, estimates were significantly lower in bin 8 (0.21 degrees versus 0.59 degrees) and bin 9 (0.11 degrees versus 0.32 degrees). Differences in model estimates did not differ significantly by departure location in bin 1 (p = .6697), 2 (p = .9381), 4 (p = .7965), 5 (p = .1840) or 6 (p = .2879).

Figure 6-42 LS-means Estimates of Pitch in Climb for the Interaction: 50ft Altitude Bin x Location



As shown in Table 6-18, location did not contribute to a significant difference in roll during climb.

6.5.4.2 Autopilot Status

As shown in Table 6-20, autopilot engagement altitude following take off did not differ significantly by departure location.

6.6 The Effect of Sleep Related Variables, Workload, Fatigue and Sleepiness on Simulated Flight Data Measures

This section includes analyses and results for the following research questions:

Q5. Are flight data measures associated with cumulative sleep debt, time since sleep and total sleep time?

Q6. Are flight data measures associated with subjective ratings of workload, fatigue or sleepiness?

6.6.1 Analysis

This section describes the results of a series of linear mixed models which evaluated the influence of sleep related variables, pre simulated flight subjective ratings of fatigue and sleepiness and ratings of workload on simulated flight data measures. The influence of order and location was also considered. Flight order was not considered to be a factor that would contribute to variability in autopilot engagement altitude following take off, disengagement before landing, and the percentage of each flight where the autopilot is engaged. It was excluded from models which included these auto pilot status measures. Location was only included in the models which evaluated flight data measures during initial climb and for autopilot engagement altitude following take off because departures from Christchurch included a tailwind during initial climb scenario below 1000ft whereas departures from Wellington did not. It was necessary to determine if the tailwind scenario in Christchurch contributed to variation in the applicable dependent variables.

Total sleep in 24hrs and 48hrs prior to the simulator session were found to be colinear as were pre-simulator flight ratings of fatigue and sleepiness and, were therefore, not included in the same model. Further collinearity tests indicated no redundancy between the remaining variables. The simulated flight data measures (dependent variables) are grouped by initial climb (Table 6-22), go around (Table 6-23), autopilot status (Table

6-24), and go around checklist (Table 6-25). The direction of association between simulated flight data measures, sleep related variables and ratings of workload, fatigue and sleepiness are outlined in Table 6-26.

Table 6-22 Results of mixed model ANOVAs for the Effect of Sleep Related Variables and Subjective Ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures: Initial Climb

Dependent Variable	Independent Variable	DF	F-value	P(F)
Airspeed in Climb [a, b, c]	50ft Altitude Bin	8, 214	19.18	**<.0001**
	Cumulative Sleep Debt	1, 64.3	0.04	.8473
	Time Since Sleep	1, 64.3	8.62	**.0046**
	Total Sleep in 24hrs	1, 64.6	2.46	.1217
	Workload	1, 64.6	0.28	.5973
	Pre Simulated Flight Fatigue	1, 66.1	0.05	.8294
	Order	1, 64.5	0.04	.8427
	Location	1, 62	3.54	.0645
	50ft Altitude Bin*Location	8, 214	2.74	**.0068**
Airspeed in Climb [b, c, d]	50ft Altitude Bin	8, 215	21.42	**<.0001**
	Cumulative Sleep Debt	1, 67	1.81	.1831
	Time Since Sleep	1, 67.6	8.89	**.0040**
	Total Sleep in 24hrs	1, 66.9	0.30	.5832
	Workload	1, 67	1.94	.1686
	Pre Simulated Flight Sleepiness	1, 67.8	11.15	**.0014**
	Order	1, 67.4	0.15	.6988
	Location	1, 65.2	7.01	**.0102**
	50ft Altitude Bin*Location	8, 215	3.58	**.0006**
Airspeed in Climb [b, c, e]	50ft Altitude Bin	8, 217	18.33	**<.0001**
	Cumulative Sleep Debt	1, 64.8	0.00	.9842
	Time Since Sleep	1, 65.4	6.76	**.0115**
	Total Sleep in 48hrs	1, 64.1	0.82	.3693
	Workload	1, 65	0.30	.5833
	Pre Simulated Flight Fatigue	1.65.4	0.10	.7472
	Order	1, 64.6	0.00	.9867
	Location	1, 62.3	2.50	.1189

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
	50ft Altitude Bin*Location	8, 217	3.07	**.0027**
Airspeed in Climb [b, c, f]	50ft Altitude Bin	8, 215	20.19	<**.0001**
	Cumulative Sleep Debt	1, 68.9	2.48	.1199
	Time Since Sleep	1, 68.9	10.77	**.0016**
	Total Sleep in 48hrs	1, 68	0.38	.5413
	Workload	1, 68.9	1.72	.1944
	Pre Simulated Flight Sleepiness	1,69.9	13.13	**.0005**
	Order	1, 68.8	0.36	.5497
	Location	1, 67.2	6.89	**.0107**
	50ft Altitude Bin*Location	8, 215	2.94	**.0039**
Pitch in Climb [b, g, h]	50ft Altitude Bin	8, 216	10.42	<**.0001**
	Cumulative Sleep Debt	1, 51.8	0.32	.5726
	Time Since Sleep	1, 51.7	6.30	**.0152**
	Total Sleep in 48hrs	1, 51.6	1.94	.1700
	Workload	1, 51.8	1.54	.2202
	Pre Simulated Flight Fatigue	1,51.9	0.24	.6239
	Order	1, 51.8	0.24	.6294
	Location	1, 48.8	2.53	.1178
	50ft Altitude Bin*Location	8, 216	7.91	<**.0001**
Pitch in Climb [b, h, I]	50ft Altitude Bin	8, 215	10.87	<**.0001**
	Cumulative Sleep Debt	1, 53.1	0.14	.7142
	Time Since Sleep	1, 53.1	9.03	**.0041**
	Total Sleep in 24hrs	1, 53	1.18	.2822
	Workload	1, 53	1.47	.2314
	Pre Simulated Flight Fatigue	1,53.1	4.25	**.0442**
	Order	1, 53.1	0.58	.4512
	Location	1, 50.2	2.93	.0933
	50ft Altitude Bin*Location	8, 215	7.91	<**.0001**

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Pitch in Climb [b, h, j]	50ft Altitude Bin	8, 206	21.83	<**.0001**
	Cumulative Sleep Debt	1, 61.7	0.06	.8121
	Time Since Sleep	1, 61.7	5.26	**.0253**
	Total Sleep in 48hrs	1, 62.5	2.56	.1144
	Workload	1, 61.7	0.47	.4967
	Pre Simulated Flight Fatigue	1,61.8	5.68	**.0203**
	Order	1, 62	0.20	.6532
	Location	1, 61.7	3.94	.0516
	50ft Altitude Bin*Location	8, 206	14.16	<**.0001**
Pitch in Climb [b, h, k]	50ft Altitude Bin	8, 215	10.80	<**.0001**
	Cumulative Sleep Debt	1, 52.4	0.34	.5597
	Time Since Sleep	1, 52.4	8.29	**.0058**
	Total Sleep in 48hrs	1, 52.4	0.59	.4442
	Workload	1, 52.3	1.17	.2851
	Pre Simulated Flight Sleepiness	1,52.4	5.95	**.0182**
	Order	1, 52.3	0.70	.4080
	Location	1, 49.5	2.19	.1454
	50ft Altitude Bin*Location	8, 215	7.90	<**.0001**
Roll in Climb [h, l, n, p]	50ft Altitude Bin [m]	8, 199	2.27	.0241
	Cumulative Sleep Debt	1, 23.9	0.87	.3608
	Time Since Sleep	1, 23.7	0.12	.7280
	Total Sleep in 24hrs	1, 23.7	0.15	.7035
	Workload	1, 23.9	3.09	.0917
	Pre Simulated Flight Fatigue	1,24	4.38	**.0470**
	Order	1, 23.9	4.19	.0517
	Location	1, 23.9	0.44	.5145
Roll in Climb [h, l, n, p]	50ft Altitude Bin [m]	8, 200	2.27	.0242
	Cumulative Sleep Debt	1, 24.2	0.05	.8234

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
	Time Since Sleep	1, 24	0.54	.4677
	Total Sleep in 24hrs	1, 24	1.90	.1811
	Workload	1, 24	1.59	.2194
	Pre Simulated Flight Sleepiness	1,24.1	0.02	.8940
	Order	1, 24.1	3.72	.0656
	Location	1, 24.1	0.45	.5095
Roll in Climb [b, h, o, p]	50ft Altitude Bin [m]	8, 228	2.24	.0253
	Cumulative Sleep Debt	1, 68.8	1.21	.2752
	Time Since Sleep	1, 68.8	0.37	.5444
	Total Sleep in 48hrs	1, 68.7	0.80	.3741
	Workload	1, 68.8	5.10	**.0270**
	Pre Simulated Flight Fatigue	1,68.9	7.26	**.0088**
	Order	1, 68.8	6.12	**.0158**
	Location	1, 68.9	0.99	.3237
Roll in Climb [h, l, n, p]	50ft Altitude Bin [m]	8, 200	2.27	.0243
	Cumulative Sleep Debt	1, 24.2	0.20	.6602
	Time Since Sleep	1, 24.2	0.45	.5108
	Total Sleep in 48hrs	1, 24.1	1.99	.1712
	Workload	1, 24	1.39	.2499
	Pre Simulated Flight Sleepiness	1,24.1	1.39	.6736
	Order	1, 24.1	3.30	.0816
	Location	1, 24.2	1.03	.3202

[a] Number of observations used: 278/282, excludes 6 outliers, includes 4 outliers; [b] Autoregressive covariance structure; [c] LOG transformation applied to normalise distribution; [d] Number of observations used: 278/282, excludes 6 outliers, includes 2 outliers; [e] Number of observations used: 279/283, excludes 5 outliers, includes 6 outliers; [f] Number of observations used: 279/283, excludes 5 outliers, includes 3 outliers; [g] Number of observations used: 284/288, includes 13 outliers; [h] SQRT transformation applied to normalise distribution; [i] Number of observations used: 284/288, includes 10 outliers; [j] Number of observations used: 273/277, excludes 11 outliers, includes 2 outliers; [k] Number of observations used: 284/288, includes 15 outliers; [l] Autoregressive covariance structure with random variance components; [m] Levene's test was significant, a more conservative alpha level of 0.01 was used; [n] Number of observations used: 284/288, includes 2 outliers; [o] Number of observations used: 284/288, includes 3 outliers; [p] the non-significant (NS) interaction Location x 50ft Altitude Bin was removed from the final model;

Table 6-23 Results of mixed model ANOVAs for the Effect of Sleep Related Variables and Subjective Ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures: Go Around

Dependent Variable	Independent Variable	DF	F-value	P(F)
Airspeed Go Around [a, b]	50ft Altitude Bin	8, 214	29.11	<**.0001**
	Cumulative Sleep Debt	1, 44.8	0.36	.5516
	Time Since Sleep	1, 44.8	0.21	.6465
	Total Sleep in 24hrs	1, 44.8	0.05	.8236
	Workload	1, 44.8	0.27	.6088
	Pre Simulated Flight Fatigue	1, 44.8	0.08	.7804
	Order	1, 44.8	0.70	.4060
Airspeed Go Around [a, b]	50ft Altitude Bin	8, 215	29.11	<**.0001**
	Cumulative Sleep Debt	1, 44.8	0.04	.8435
	Time Since Sleep	1, 44.8	0.25	.6195
	Total Sleep in 24hrs	1, 44.8	0.33	.5676
	Workload	1, 44.8	0.27	.6031
	Pre Simulated Flight Sleepiness	1, 44.8	0.21	.6527
	Order	1, 44.8	0.62	.4357
Airspeed Go Around [b, c]	50ft Altitude Bin	8, 214	29.58	<**.0001**
	Cumulative Sleep Debt	1, 44.9	0.25	.6228
	Time Since Sleep	1, 44.9	0.59	.4469
	Total Sleep in 48hrs	1, 44.9	0.95	.3362
	Workload	1, 44.9	0.33	.5703
	Pre Simulated Flight Fatigue	1, 44.9	0.00	.9568
	Order	1, 44.9	0.77	.3864
Airspeed Go Around [a, b]	50ft Altitude Bin	8, 214	29.58	<**.0001**
	Cumulative Sleep Debt	1, 45.1	0.05	.8288
	Time Since Sleep	1, 45.1	0.41	.5262
	Total Sleep in 48hrs	1, 45.1	1.28	.2639
	Workload	1, 45.1	0.33	.5674

Dependent Variable	Independent Variable	DF	F-value	P(F)
	Pre Simulated Flight Sleepiness	1, 45.1	0.18	.6702
	Order	1, 45.1	0.69	.4112
Pitch Go Around [b, d, e]	50ft Altitude Bin	8, 213	5.47	<**.0001**
	Cumulative Sleep Debt	1, 60.6	0.01	.9072
	Time Since Sleep	1, 60.6	0.09	.7708
	Total Sleep in 24hrs	1, 60.6	1.96	.1664
	Workload	1, 60.6	1.22	.2743
	Pre Simulated Flight Fatigue	1, 60.6	0.95	.3338
	Order	1, 60.6	0.01	.9071
Pitch Go Around [b, e, f]	50ft Altitude Bin	8, 213	5.45	<**.0001**
	Cumulative Sleep Debt	1, 60.3	0.44	.5106
	Time Since Sleep	1, 60.3	0.02	.9003
	Total Sleep in 24hrs	1, 60.3	0.58	.4508
	Workload	1, 60.3	1.03	.3149
	Pre Simulated Flight Sleepiness	1, 60.3	0.25	.6177
	Order	1, 60.3	0.04	.8469
Pitch Go Around [b, d, e]	50ft Altitude Bin	8, 213	5.43	<**.0001**
	Cumulative Sleep Debt	1, 60	0.47	.4943
	Time Since Sleep	1, 60	0.92	.3415
	Total Sleep in 48hrs	1, 60	0.80	.3754
	Workload	1, 60	2.10	.1525
	Pre Simulated Flight Fatigue	1, 60	0.00	.9451
	Order	1, 60	0.00	.9475
Pitch Go Around [d, e, b]	50ft Altitude Bin	8, 213	5.51	<**.0001**
	Cumulative Sleep Debt	1, 60.5	1.30	.2586
	Time Since Sleep	1, 60.5	0.45	.5061
	Total Sleep in 48hrs	1, 60.5	1.24	.2690
	Workload	1, 60.5	2.33	.1317

Dependent Variable	Independent Variable	DF	F-value	P(F)
	Pre Simulated Flight Sleepiness	1, 60.5	1.13	.2923
	Order	1, 60.5	0.03	.8748
Roll Go Around [b, g, h]	50ft Altitude Bin	8, 213	4.22	**.0001**
	Cumulative Sleep Debt	1, 63.3	0.00	.9498
	Time Since Sleep	1, 63.3	0.38	.5390
	Total Sleep in 24hrs	1, 63.3	2.13	.1494
	Workload	1, 63.3	0.05	.8176
	Pre Simulated Flight Fatigue	1, 63.3	0.56	.4575
	Order	1, 63.3	4.13	**.0462**
Roll Go Around [b, h, i]	50ft Altitude Bin	8, 208	5.22	<**.0001**
	Cumulative Sleep Debt	1, 63.7	0.05	.8240
	Time Since Sleep	1, 63.8	0.85	.3602
	Total Sleep in 24hrs	1, 63.3	2.59	.1126
	Workload	1, 63.5	0.43	.5128
	Pre Simulated Flight Sleepiness	1, 63.7	0.96	.3304
	Order	1, 63.8	5.51	**.0220**
Roll Go Around [b, h, j]	50ft Altitude Bin	8, 208	5.28	<**.0001**
	Cumulative Sleep Debt	1, 64.7	0.01	.9093
	Time Since Sleep	1, 64.7	1.03	.3135
	Total Sleep in 48hrs	1, 63.9	4.35	**.0410**
	Workload	1, 64.1	0.06	.8016
	Pre Simulated Flight Fatigue	1, 64	0.85	.3604
	Order	1, 64.4	5.99	**.0172**
Roll Go Around [b, h, j]	50ft Altitude Bin	8, 208	5.26	<**.0001**
	Cumulative Sleep Debt	1, 64.5	0.00	.9833
	Time Since Sleep	1, 64.4	1.40	.2418
	Total Sleep in 48hrs	1, 64.1	3.87	.0535
	Workload	1, 64.2	0.24	.6247

Dependent Variable	Independent Variable	DF	F-value	P(F)
	Pre Simulated Flight Sleepiness	1, 64.4	0.49	.4846
	Order	1, 64.4	5.77	**.0192**

[a] Number of observations used: 270/288, includes 8 outliers; [b] Autoregressive covariance structure; [c] Number of observations used: 270/288, includes 9 outliers; [d] Number of observations used: 270/288, includes 1 outlier; [e] LOG transformation applied to normalise distribution; [f] Number of observations used: 270/288, includes 2 outliers; [g] Number of observations used: 270/288, includes 3 outliers; [h] SQRT transformation applied to normalise distribution; [i] Number of observations used: 268/286, excludes 2 outliers, includes 1 outlier; [j] Number of observations used: 268/286, excludes 2 outliers, includes 2 outliers.

Table 6-24 Results of mixed model ANOVAs for the Effect of Sleep Related Variables and Subjective Ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures: Autopilot Status

Dependent Variable	Independent Variable	DF	F-value	P(F)
Autopilot Engagement Altitude Following Take off [a]	Cumulative Sleep Debt	1, 22.4	0.85	.3659
	Time Since Sleep	1, 22.6	1.42	.2460
	Total Sleep in 24hrs	1, 21.9	0.80	.3799
	Workload	1, 23	0.05	.8291
	Pre Simulated Flight Fatigue	1, 22.8	0.34	.5642
	Location	1, 13.2	2.28	.1549
Autopilot Engagement Altitude Following Take off [a]	Cumulative Sleep Debt	1, 22.7	2.53	.1252
	Time Since Sleep	1, 21.8	1.32	.2630
	Total Sleep in 24hrs	1, 22.3	3.19	.0879
	Workload	1, 23	0.00	.9732
	Pre Simulated Flight Sleepiness	1, 22.7	1.00	.3273
	Location	1, 13.5	1.99	.1812
Autopilot Engagement Altitude Following Take off [a]	Cumulative Sleep Debt	1, 20.9	0.88	.3585
	Time Since Sleep	1, 22.6	1.80	.1932
	Total Sleep in 48hrs	1, 21.9	2.73	.1129
	Workload	1, 22.4	0.41	.5304
	Pre Simulated Flight Fatigue	1, 22.6	0.61	.4435
	Location	1, 13.7	1.70	.2139
Autopilot Engagement Altitude Following Take off [a]	Cumulative Sleep Debt	1, 20.2	2.38	.1386
	Time Since Sleep	1, 22.8	1.96	.1747
	Total Sleep in 48hrs	1, 20.1	5.06	**.0359**
	Workload	1, 21.4	0.30	.5906
	Pre Simulated Flight Sleepiness	20.8	0.67	.4208
	Location	1, 14.4	1.04	.3237

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Autopilot Engagement Altitude Following Go around [b, c]	Cumulative Sleep Debt	1, 12	3.17	.1006
	Time Since Sleep	1, 8.3	4.69	.0610
	Total Sleep in 24hrs	1, 11.3	0.00	.9516
	Workload	1, 7.83	3.64	.0936
	Pre Simulated Flight Fatigue	1, 11.1	3.19	.1013
	Order	1, 6.28	43.86	**.0005**
Autopilot Engagement Altitude Following Go around [b, c]	Cumulative Sleep Debt	1, 19.2	0.08	.7748
	Time Since Sleep	1, 7.53	3.49	.1012
	Total Sleep in 24hrs	1, 15.2	0.38	.5450
	Workload	1, 7.48	1.43	.2677
	Pre Simulated Flight Sleepiness	1, 19.6	0.00	.9495
	Order	1, 4.71	21.56	**.0065**
Autopilot Engagement Altitude Following Go around [b, c]	Cumulative Sleep Debt	1, 19.1	1.17	.2932
	Time Since Sleep	1, 8.01	9.40	**.0154**
	Total Sleep in 48hrs	1, 18	3.12	.0943
	Workload	1, 6.99	9.36	**.0184**
	Pre Simulated Flight Fatigue	1, 14.1	6.94	**.0195**
	Order	1, 6.23	86.01	<**.0001**
Autopilot Engagement Altitude Following Go around [b, c]	Cumulative Sleep Debt	1, 17.3	0.74	.4008
	Time Since Sleep	1, 9.95	8.98	**.0135**
	Total Sleep in 48hrs	1, 15	4.15	.0597
	Workload	1, 5.83	12.94	**.0120**
	Pre Simulated Flight Sleepiness	1, 13.3	3.60	.0796
	Order	1, 5.87	78.84	**.0001**

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Autopilot Disengagement before Landing [c, d]	Cumulative Sleep Debt	1, 24.5	0.36	.5560
	Time Since Sleep	1, 19.9	0.06	.8040
	Total Sleep in 24hrs	1, 23.7	0.05	.8319
	Workload	1, 19.5	0.29	.5970
	Pre Simulated Flight Fatigue	1, 19.9	3.71	.0685
Autopilot Disengagement before Landing [d]	Cumulative Sleep Debt	1, 25.4	0.93	.3449
	Time Since Sleep	1, 24	0.59	.4512
	Total Sleep in 24hrs	1, 25.8	0.15	.6984
	Workload	1, 25.6	1.14	.2958
	Pre Simulated Flight Sleepiness	1, 26	6.83	**.0147**
Autopilot Disengagement before Landing [c, d]	Cumulative Sleep Debt	1, 24.1	0.18	.6752
	Time Since Sleep	1, 16.4	0.42	.5272
	Total Sleep in 48hrs	1, 25.1	0.16	.6938
	Workload	1, 19.5	0.29	.5939
	Pre Simulated Flight Fatigue	1, 21	6.37	**.0197**
Autopilot Disengagement before Landing [d]	Cumulative Sleep Debt	1, 23	0.74	.3977
	Time Since Sleep	1, 22.4	0.17	.6848
	Total Sleep in 48hrs	1, 23.6	0.65	.4282
	Workload	1, 25.5	1.49	.2338
	Pre Simulated Flight Sleepiness	1, 26	9.55	**.0047**
Time Taken to Reengage the Autopilot [e]	Cumulative Sleep Debt	1, 16.4	0.22	.6466
	Time Since Sleep	1, 14	4.79	**.0461**
	Total Sleep in 24hrs	1, 18	14.40	**.0013**
	Workload	1, 18	1.38	.2559
	Pre Simulated Flight Fatigue	1, 13.7	0.58	.4600

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
	Order	1, 9.09	25.52	**.0007**
Time Taken to Reengage the Autopilot [f]	Cumulative Sleep Debt	1, 17.2	1.00	.3312
	Time Since Sleep	1, 10.5	0.26	.6227
	Total Sleep in 24hrs	1, 18.3	4.89	**.0399**
	Workload	1, 16.9	0.19	.6711
	Pre Simulated Flight Sleepiness	1, 17.9	0.73	.4042
	Order	1, 8.21	7.42	**.0255**
Time Taken to Reengage the Autopilot [g]	Cumulative Sleep Debt	1, 19	0.01	.9295
	Time Since Sleep	1, 16.5	1.22	.2845
	Total Sleep in 48hrs	1, 18.2	5.98	**.0248**
	Workload	1, 16.9	0.02	.8932
	Pre Simulated Flight Fatigue	1, 10.7	0.10	.7557
	Order	1, 8.46	10.24	**.0117**
Time Taken to Reengage the Autopilot [g]	Cumulative Sleep Debt	1, 18.5	0.00	.9984
	Time Since Sleep	1, 13.7	1.37	.2623
	Total Sleep in 48hrs	1, 16.3	6.66	**.0199**
	Workload	1, 17	0.04	.8526
	Pre Simulated Flight Sleepiness	1, 17.2	0.09	.7682
	Order	1, 8.72	10.79	**.0099**
Autopilot Usage During Flight [h]	Cumulative Sleep Debt	1, 21.2	0.00	.9694
	Time Since Sleep	1, 22	3.68	.0675
	Total Sleep in 24hrs	1, 19.2	1.78	.1977
	Workload	1, 22.5	4.45	**.0462**
	Pre Simulated Flight Fatigue	1, 21.2	1.63	.2157
Autopilot Usage During Flight [h]	Cumulative Sleep Debt	1, 19.5	1.13	.3014
	Time Since Sleep	1, 22.9	1.64	.2135

Dependent Variable	Independent Variable	DF	F-value	P(F)
	Total Sleep in 24hrs	1, 20	3.29	.0849
	Workload	1, 22.3	6.59	**.0175**
	Pre Simulated Flight Sleepiness	1, 16.9	6.93	**.0176**
Autopilot Usage During Flight [I, j]	Cumulative Sleep Debt	1, 23	0.00	.9989
	Time Since Sleep	1, 23	6.14	**.0210**
	Total Sleep in 48hrs	1, 23	3.09	.0919
	Workload	1, 23	6.46	**.0183**
	Pre Simulated Flight Fatigue	1, 23	1.93	.1783
Autopilot Usage During Flight [k]	Cumulative Sleep Debt	1, 18.1	0.61	.4442
	Time Since Sleep	1, 22.3	1.35	.2584
	Total Sleep in 48hrs	1, 19.9	3.76	.0669
	Workload	1, 22.5	6.15	**.0211**
	Pre Simulated Flight Sleepiness	1, 18.8	5.50	**.0301**

[a] Number of observations used: 30/30, excludes 2 outliers; [b] Number of observations used: 28/32; [c] LOG transformation applied to normalise distribution; [d] Number of observations used: 32/32; [e] Number of observations used: 25/27, excludes 5 outliers; [f] Number of observations used: 26/28, excludes 4 outliers, includes 1 outlier; [g] Number of observations used: 26/28, excludes 4 outliers; [h] Number of observations used: 29/29, excludes 3 outliers; [i] Number of observations used: 29/29, excludes 3 outliers, includes 3 outliers; [j] REFL SQRT transformation applied to normalise distribution; [k] Number of observations used: 29/29, excludes 3 outliers, includes 1 outlier;

Table 6-25 Results of mixed model ANOVAs for the Effect of Sleep Related Variables and Subjective Ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures: Go Around Checklist

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
Time Taken to Complete the Go around/Missed Approach Procedure [a, b]	Cumulative Sleep Debt	1, 23	0.05	.8334
	Time Since Sleep	1, 23	7.65	**.0110**
	Total Sleep in 24hrs	1, 23	1.73	.0947
	Workload	1, 23	9.66	**.0049**
	Pre Simulated Flight Fatigue	1, 23	0.08	.7785
	Order	1, 23	7.48	**.0118**
Time Taken to Complete the Go around/Missed Approach Procedure [b, c]	Cumulative Sleep Debt	1, 22	0.00	.9488
	Time Since Sleep	1, 22	16.47	**.0005**
	Total Sleep in 24hrs	1, 22	4.02	.0947
	Workload	1, 22	17.01	**.0004**
	Pre Simulated Flight Sleepiness	1, 22	1.00	.3271
	Order	1, 22	5.04	**.0352**
Time Taken to Complete the Go around/Missed Approach Procedure [d]	Cumulative Sleep Debt	1, 23	0.01	.9296
	Time Since Sleep	1, 23	7.25	**.0130**
	Total Sleep in 48hrs	1, 23	3.50	.0742
	Workload	1, 23	13.95	**.0011**
	Pre Simulated Flight Fatigue	1, 23	0.05	.8295
	Order	1, 23	9.72	**.0048**
Time Taken to Complete the Go around/Missed Approach Procedure [b, e]	Cumulative Sleep Debt	1, 23	0.07	.7983
	Time Since Sleep	1, 23	11.36	**.0026**
	Total Sleep in 48hrs	1, 23	4.32	**.0490**
	Workload	1, 23	10.52	**.0036**

Dependent Variable	**Independent Variable**	**DF**	**F-value**	**P(F)**
	Pre Simulated Flight Sleepiness	1, 23	1.13	.2985
	Order	1, 23	7.80	**.0104**
Time Taken to Initiate Go Around ^{d}	Cumulative Sleep Debt	1, 19.4	1.00	.3292
	Time Since Sleep	1, 22.5	0.24	.6265
	Total Sleep in 24hrs	1, 19.6	0.27	.6116
	Workload	1, 22.2	2.39	.1365
	Pre Simulated Flight Fatigue	1, 21.8	0.29	.5943
	Order	1, 12.5	0.29	.6025
Time Taken to Initiate Go Around ^{d}	Cumulative Sleep Debt	1, 19.6	1.51	.2330
	Time Since Sleep	1, 21.8	0.13	.7205
	Total Sleep in 24hrs	1, 21.1	1.02	.3240
	Workload	1, 22.5	2.33	.1405
	Pre Simulated Flight Sleepiness	1, 20.1	0.09	.7694
	Order	1, 13.2	0.38	.5506
Time Taken to Initiate Go Around ^{d}	Cumulative Sleep Debt	1, 19.1	1.16	.2950
	Time Since Sleep	1, 20.6	0.50	.4869
	Total Sleep in 48hrs	1, 21.4	0.66	.4270
	Workload	1, 22.7	2.36	.1385
	Pre Simulated Flight Fatigue	1, 22.9	0.43	.5194
	Order	1, 12.5	0.25	.6249
Time Taken to Initiate Go Around ^{d}	Cumulative Sleep Debt	1, 17.6	1.42	.2494
	Time Since Sleep	1, 21.5	0.46	.5050
	Total Sleep in 48hrs	1, 20.5	1.27	.2721
	Workload	1, 22.9	2.01	.1698
	Pre Simulated Flight Sleepiness	1, 19.6	0.01	.9210

Dependent Variable	Independent Variable	DF	F-value	P(F)
	Order	1, 12.9	0.30	.5907

[a] Number of observations used: 30/32; includes 1 outlier; [b] REFL SQRT transformation applied to normalise distribution; [c] Number of observations used: 29/31; excludes 1 outlier; [d] Number of observations used: 30/32; [e] Number of observations used: 30/32, includes 2 outliers.

Table 6-26 Direction of Association between Simulated Flight Data Measures, Sleep Related Variables and Subjective Ratings of Workload, Fatigue and Sleepiness

DEPENDENT VARIABLE	INDEPENDENT VARIABLE						
	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs	Workload	Pre Simulated Flight Fatigue	Pre Simulated Flight Sleepiness
Airspeed in Climb	▲	▼	▼	■	▼	▼	■
Airspeed in Climb	▼	▼	▼	■	▼	■	▲
Airspeed in Climb	▲	▼	■	▼	▼	▲	■
Airspeed in Climb	▼	▼	■	▼	▼	■	▲
Airspeed Go Around	▼	▼	▼	■	▼	▲	■
Airspeed Go Around	▼	▼	▼	■	▼	■	▼
Airspeed Go Around	▼	▼	■	▼	▼	▲	■
Airspeed Go Around	▼	▼	■	▼	▼	■	▼
Pitch in Climb	▲	▼	▼	■	▼	▲	■
Pitch in Climb	▼	▼	▼	■	▼	■	▲
Pitch in Climb	▲	▼	■	▲	▼	▲	■
Pitch in Climb	▼	▼	■	▼	▼	■	▲

DEPENDENT VARIABLE	INDEPENDENT VARIABLE						
	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs	Workload	Pre Simulated Flight Fatigue	Pre Simulated Flight Sleepiness
Pitch Go Around	▼	▼	▼	⬛	▲	▼	⬛
Pitch Go Around	▼	▼	▼	⬛	▲	⬛	▲
Pitch Go Around	▼	▲	⬛	▲	▲	▲	⬛
Pitch Go Around	▼	▲	⬛	▲	▲	⬛	▲
Roll in Climb	▼	▼	▼	⬛	▼	🟦 ▲	⬛
Roll in Climb	▼	▼	▼	⬛	▼	⬛	▲
Roll in Climb	▼	▼	⬛	▼	🟦 ▼	🟦 ▲	⬛
Roll in Climb	▼	▼	⬛	▼	▼	⬛	▲
Roll Go Around	▲	▲	▼	⬛	▼	▼	⬛
Roll Go Around	▲	▲	▼	⬛	▼	⬛	▼
Roll Go Around	▼	▲	⬛	🟦 ▼	▼	▼	⬛
Roll Go Around	▲	▲	⬛	▼	▼	⬛	▼
Autopilot Disengagement before Landing	▼	▲	▼	⬛	▲	▲	⬛
Autopilot Disengagement before Landing	▼	▼	▼	⬛	▲	⬛	🟦 ▲

DEPENDENT VARIABLE	INDEPENDENT VARIABLE						
	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs	Workload	Pre Simulated Flight Fatigue	Pre Simulated Flight Sleepiness
Autopilot Disengagement before Landing	▼	▲	■	▲	▲	🟦▲	■
Autopilot Disengagement before Landing	▼	▼	■	▲	▲	■	🟦▲
Time Taken to Reengage the Autopilot	▼	🟦▲	🟦▲	■	▲	▲	■
Time Taken to Reengage the Autopilot	▼	▲	🟦▲	■	▼	■	▲
Time Taken to Reengage the Autopilot	▼	▲	■	🟦▲	▼	▼	■
Time Taken to Reengage the Autopilot	▲	▲	■	🟦▲	▼	■	▼
Autopilot Engagement Altitude Following Go around	▲	▲	▼	■	▼	▼	■
Autopilot Engagement Altitude Following Go around	▲	▲	▲	■	▼	■	▲
Autopilot Engagement Altitude Following Go around	▲	🟦▲	■	▼	🟦▼	🟦▼	■
Autopilot Engagement Altitude Following Go around	▲	🟦▲	■	▼	🟦▼	■	▼
Autopilot Engagement Altitude Following Take off	▲	▲	▼	■	▼	▲	■
Autopilot Engagement Altitude Following Take off	▲	▲	▼	■	▼	■	▼
Autopilot Engagement Altitude Following Take off	▲	▲	■	▼	▼	▲	■
Autopilot Engagement Altitude Following Take off	▲	▲	■	🟦▼	▼	■	▼

DEPENDENT VARIABLE	INDEPENDENT VARIABLE						
	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs	Workload	Pre Simulated Flight Fatigue	Pre Simulated Flight Sleepiness
Autopilot Usage During Flight	▲	▼	▼	■	🟦 ▼	▼	■
Autopilot Usage During Flight	▲	▼	▼	■	🟦 ▼	■	🟦 ▼
Autopilot Usage During Flight	▲	🟦 ▼	■	▼	🟦 ▼	▼	■
Autopilot Usage During Flight	▲	▼	■	▼	🟦 ▼	■	🟦 ▼
Time Taken to complete the Go around/Missed approach Procedure	▼	🟦 ▲	▲	■	🟦 ▲	▼	■
Time Taken to Complete the Go around/Missed approach procedure	▼	🟦 ▲	▲	■	🟦 ▲	■	▼
Time Taken to Complete the Go around/Missed approach procedure	▼	🟦 ▲	■	▲	🟦 ▲	▼	■
Time Taken to Complete the Go around/Missed approach procedure	▲	🟦 ▲	■	🟦 ▲	🟦 ▲	■	▼
Time Taken to Initiate Go around	▲	▲	▼	■	▼	▲	■
Time Taken to Initiate Go around	▲	▲	▼	■	▼	■	▼
Time Taken to Initiate Go around	▲	▲	■	▼	▼	▲	■
Time Taken to Initiate Go around	▲	▲	■	▼	▼	■	▼

DEPENDENT VARIABLE	INDEPENDENT VARIABLE						
	Cumulative Sleep Debt	Time Since Sleep	Total Sleep in 24hrs	Total Sleep in 48hrs	Workload	Pre Simulated Flight Fatigue	Pre Simulated Flight Sleepiness

▲	Increase in IV = Increase in DV
▼	Increase in IV = Decrease in DV
🟦	Significant Association
⬜	Non-significant Association
⬛	Independent variable not included within the model

6.6.2 Results: Sleep Related Variables

Cumulative Sleep Debt

Cumulative sleep debt was not significantly associated with simulated flight data measures during the initial climb (see Table 6-22) and go around (see Table 6-23), nor was it associated with autopilot usage status (see Table 6-24) or time taken to complete the go around checklist (see Table 6-25).

Time Since Sleep

During initial climb, time since sleep was significantly associated with airspeed and pitch during climb, but not with roll during climb (see Table 6-22). In the model that included total sleep in 24hrs and ratings of fatigue, untransformed model estimates show that each 1 hour increase in time since sleep, variation in airspeed during climb decreased by 0.23 kts. Model estimates also show that variation in pitch during climb decreased by 0.03 degrees for each 1 hour increase in time since sleep.

Table 6-27 Model Estimates for Airspeed in Climb and Pitch in Climb in Models that have a Significant Association with Time Since Sleep

Dependent Variable	Model Estimate	Model which includes:
Airspeed in Climb [a]	-0.23 kts	Total Sleep in 24hrs, Pre Simulated Flight Fatigue
Airspeed in Climb [a]	-0.14 kts	Total Sleep in 24hrs, Pre Simulated Flight Sleepiness
Airspeed in Climb [a]	-0.19 kts	Total Sleep in 48hrs, Pre Simulated Flight Fatigue
Airspeed in Climb [a]	-0.10 kts	Total Sleep in 48hrs, Pre Simulated Flight Sleepiness
Pitch in Climb [a]	-0.03 degrees	Total Sleep in 24hrs, Pre Simulated Flight Fatigue
Pitch in Climb [a]	-0.02 degrees	Total Sleep in 24hrs, Pre Simulated Flight Sleepiness
Pitch in Climb [a]	-0.01 degrees	Total Sleep in 48hrs, Pre Simulated Flight Fatigue
Pitch in Climb [a]	-0.02 degrees	Total Sleep in 48hrs, Pre Simulated Flight Sleepiness

[a] Estimates represent untransformed values

Similar associations were found for models which included total sleep time in the previous 48 hour period and those with either ratings of fatigue or sleepiness (see Table 6-27). Time since sleep was not associated with any go around measures (see Table 6-23). Among the autopilot status measures, time since sleep was significantly associated with the autopilot engagement altitude following go around, but only in the model which included total sleep in 48hrs, see Table 6-24. For each one hour increase in time since sleep, the untransformed model estimate shows that the lowest altitude where the autopilot was re-engaged following go around, increased by 72ft in the model which included ratings of fatigue and increased by 81ft in the model which included ratings of sleepiness. An increase in time since sleep was significantly associated with an increase in time taken to re-engage the autopilot following an un-commanded autopilot disconnection in the model which included total sleep in 24hrs and ratings of fatigue. However, the association was not significant in the model which included sleepiness or total sleep in the previous 48 hour period. A one hour increase in time since sleep was associated with a reduction in autopilot usage during the entire flight of 18 seconds in the model which included total sleep in 48hrs and fatigue. However, the association was not significant in the model which included sleepiness or total sleep in 24hrs. All other autopilot status measures were not associated with time since sleep.

Time since sleep was significantly associated with time taken to complete the go around/missed approach procedure (see Table 6-25). For each one hour increase in time since sleep, the untransformed estimate of the time taken to complete the procedure increased by 9.93 seconds in the model which included total sleep in 24hrs and ratings of fatigue. Similar associations were found for the models which included either total sleep in 24hrs or 48hrs and ratings of fatigue or sleepiness, as summarised in Table 6-28.

Table 6-28 Model Estimates for Time Taken to Complete the Go around/Missed approach procedure in Models that have a Significant Association with Time Since Sleep

Dependent Variable	Model Estimate	Model which includes:
Time Taken to Complete the Go around/Missed approach procedure [a]	0.16 seconds	Total Sleep in 24hrs, Pre Simulated Flight Fatigue
Time Taken to Complete the Go around/Missed Approach Procedure [a]	0.24 seconds	Total Sleep in 24hrs, Pre Simulated Flight Sleepiness
Time Taken to Complete the Go around/Missed Approach Procedure	0.17 seconds	Total Sleep in 48hrs, Pre Simulated Flight Fatigue
Time Taken to Complete the Go around/Missed approach Procedure [a]	0.18 seconds	Total Sleep in 48hrs, Pre Simulated Flight Sleepiness

[a] Estimates represent untransformed values.

Time since sleep was not associated with the time taken to initiate go around.

Total Sleep in 24hrs before Simulated Flights

Total sleep in the previous 24 hour period was significantly associated with the time taken to re-engage the autopilot following an un-commanded autopilot disconnection (see Table 6-24). For each one hour increase in total sleep in 24hrs, untransformed model estimates show that time taken to re-engage the autopilot increased. In the model which included fatigue ratings, it increased by 1.63 seconds and in the model which included sleepiness, it increased by 1.13 seconds. No other significant associations between simulated flight data measures and total sleep in 24hrs were identified. A non-significant trend was identified where an increase in total sleep in 24hrs resulted in a decrease in time taken to complete the go around/missed approach procedure. Although the associations were non-significant, the direction was constant, and p-values neared significance in the model which included fatigue ratings, p=.0947 and in the model which included sleepiness, p=.0947.

Total Sleep in 48hrs before Simulated Flights

Aside from roll during go around, total sleep in the previous 48 hour period was not significantly associated with either initial climb or go around measures, see Table 6-23. An increase in total sleep in the previous 48 hour period was significantly associated with a reduction in roll during go around in the model which included ratings of fatigue. However, the association was not significant in the model which included sleepiness or in models which included total sleep in 24hrs. Total sleep in 48hrs was significantly associated with some auto pilot status and go around checklist measures. For each additional hour of sleep during the previous 48 hour period, in models which included either fatigue or sleepiness, time taken to re-engage the autopilot following an un-commanded autopilot disconnection increased by 0.6 seconds. A one hour increase in total sleep in the 48 hour period before each simulated flight was associated with a decrease in autopilot engagement altitude of 94ft following take off in the model which included sleepiness. However, the association was not significant in the model which included fatigue or total sleep in 24hrs. An increase in total sleep in 48hrs was significantly associated with an increase in time taken to complete the go around/missed approach procedure in the model which included sleepiness. However, the association was not significant in the model which included fatigue or in models which included total sleep in 24hrs.

A non-significant trend was identified between total sleep in 48hrs, and time taken to complete the go around/missed approach procedure in the model that included fatigue. Although the association was not significant, the direction was consistent with the model that included sleepiness and in models which included total sleep in 24hrs. In addition, the p-value neared significance, p=.0742.

6.6.3 Results: Workload

Workload was significantly associated with roll during climb (see Table 6-22), autopilot engagement altitude following go around, autopilot usage during flight (see Table 6-24) and time taken to complete the go around/missed approach procedure (see Table 6-25). In the model which included total sleep in 28hrs and ratings of fatigue, an increase in workload was significantly associated with a decrease in roll variability during climb. However, the association was not significant in the model which included sleepiness or in models which included total sleep in 24hrs. Autopilot engagement altitude following go around was significantly associated with workload in the models which included total sleep in 48hrs and either ratings of fatigue or sleepiness. Untransformed model estimates show that a 10 point increase in workload was associated with a 65ft reduction in the altitude where the autopilot was re-engaged following go around. In the model which included total sleep in 24hrs and ratings of fatigue, a 10 point increase in workload was associated with an overall reduction of 0.42% in autopilot usage during flight. When considering mean flight duration, this model estimate represents 14.8 seconds. Similar associations were found for the models which included either total sleep in 24hrs or 48hrs and ratings of fatigue or sleepiness, as summarised in Table 6-29.

Table 6-29 Model Estimates for Autopilot Usage During Flight in Models that have a Significant Association with Workload

Dependent Variable	Model Estimate	Model which includes:
Autopilot Usage During Flight	-0.42%	Total Sleep in 24hrs, Pre Simulated Flight Fatigue
Autopilot Usage During Flight	-0.44%	Total Sleep in 24hrs, Pre Simulated Flight Sleepiness
Autopilot Usage During Flight [a]	-0.42%	Total Sleep in 48hrs, Pre Simulated Flight Fatigue
Autopilot Usage During Flight	-0.42%	Total Sleep in 48hrs, Pre Simulated Flight Sleepiness

a Estimates represent untransformed values.

For each 10 point increase in workload, the untransformed model estimate of the time taken to complete the go around/missed approach procedure increased. In the model which included total sleep in 24hrs and pre simulated flight fatigue, the estimate increased by 12.9 seconds. Similar associations were found for the models which included either total sleep in 24hrs or 48hrs and fatigue or sleepiness (see Table 6-30).

Table 6-30 Model Estimates for Time Taken to Complete the Go around/Missed approach Procedure in Models that have a Significant Association with Workload

Dependent Variable	Model Estimate	Model which includes:
Time Taken to Complete the Go around/Missed approach Procedure [a]	12.9 seconds	Total Sleep in 24hrs, Pre Simulated Flight Fatigue
Time Taken to Complete the Go around/Missed approach Procedure [a]	15.9 seconds	Total Sleep in 24hrs, Pre Simulated Flight Sleepiness
Time Taken to Complete the Go around/Missed approach Procedure	8 seconds	Total Sleep in 48hrs, Pre Simulated Flight Fatigue
Time Taken to Complete the Go around/Missed approach Procedure [a]	12.5 seconds	Total Sleep in 48hrs, Pre Simulated Flight Sleepiness

[a] Estimates represent untransformed values

Workload was not significantly associated with airspeed or pitch during climb (see Table 6-22) or go around measures (see Table 6-23). In addition, workload was not significantly associated with autopilot status measures aside from autopilot engagement altitude following go around, autopilot usage during flight (see Table 6-24) or time taken to initiate go around (see Table 6-25).

6.6.4 Results: Fatigue

For each one unit increase in fatigue, in the model that included total sleep in 48hrs, untransformed model estimates of pitch in climb increased by 0.02 degrees. In models that included either total sleep 24hrs or 48hrs, untransformed model estimates show that a one unit increase in fatigue was also associated with an increase in variation of roll during climb of 0.05 degrees. In models which included total sleep in 48hrs, untransformed model estimates show that a one unit increase in fatigue resulted in the autopilot being disengaged at a higher altitude (+87ft) prior to landing. In addition, following go around, the autopilot was engaged at a lower altitude (-141ft).

6.6.5 Results: Sleepiness

Sleepiness was significantly associated with airspeed and pitch during climb. For each one unit increase in sleepiness, untransformed model estimates of airspeed during climb increased by 0.15 kts in the model which included sleep in 24hrs and 0.10 kts in the model which included sleep in 48hrs. Untransformed model estimates of pitch during climb increased by 0.01 degrees in models which included either sleep in 24hrs or 48hrs. When considering autopilot status measures, model estimates show that prior to landing, a one unit increase in sleepiness resulted in the autopilot being disengaged at a higher altitude. In the model which included total sleep in 24hrs, it was disengaged 74ft higher and in the model which included total sleep 48hrs, it was disengaged 81ft higher. Sleepiness ratings were also significantly associated with a decrease in autopilot usage during flight. For each one unit increase in sleepiness, model estimates show that autopilot usage decreased. In the model which included total sleep in 24hrs, usage decreased by 0.59% (20 seconds when considering mean flight duration). Similar results were found in the model which included sleep total sleep in 48hrs.

6.7 Go Around/Missed Approach Procedure Checklist Item Sequence

This section provides results on the sequence of checklist items completed by flight crew during the go around procedure. The go around/missed approach procedure checklist includes items that must be competed in chronological order. The checklist groups items in sections which include initiating go around, positive rate of climb, flaps 15 indicated, gear retracted, acceleration altitude, VmLB 0, flap 0 indicated and > 1000ft. Each section may have multiple groups of actions (e.g., initiating go around includes two groups) and each group may have one or more actions (e.g., group 1). A correct group sequence means that all checklist items within a phase were completed before checklist items in the next phase were started and, a correct action sequence means that all action items within a phase were completed in the correct order.

6.7.1 Analysis

The following variables are described by condition and flight order but were not analysed further due to the limited variability within each variable. Results are reported by flight crew, rather than by individual participants as associations with individuals' sleep timing and duration, and ratings of fatigue, sleepiness, and workload were not evaluated.

Checklist sequence variables

- Number of correct group sequences: The count of correct group sequences during the go around/missed approach procedure.
- Number of incorrect group sequences: The count of incorrect group sequences during the go around/missed approach procedure.
- Percentage of correct group sequences: The percentage of correct group sequences during the go around/missed approach procedure.
- Percentage of incorrect group sequences: The percentage of incorrect group sequences during the go around/missed approach procedure.
- Number of correct action sequences: The count of correct action sequences during the go around/missed approach procedure.
- Number of incorrect action sequences: The count of incorrect action sequences during the go around/missed approach procedure.
- Percentage of correct action sequences: The percentage of correct action sequences during the go around/missed approach procedure.
- Percentage of incorrect action sequences: The percentage of incorrect action sequences during the go around/missed approach procedure.

6.7.2 Results

Group sequences

Ten flights flown by seven flight crew were completed with no incorrect group sequences, however five flights included one incorrect group sequence. Three flight crew had one incorrect group sequence each during one of the two flights flown, whereas one flight crew had one incorrect group sequence during both flights. All incorrect group sequences relate to items in Group 2 being initiated before items in Group 1 had been completed (see Table 6-31). Table 6-32 lists descriptives for checklist sequence variables grouped by condition, and Table 6-33 lists these variables by flight order.

Table 6-31 Go Around Checklist Group Order

Phase	Group Order	Action
Initiating Go around	1	Power Lever Go Around BUTTON…………………………PRESS PITCH……….ROTATING TO PITCH ATTITUDE ON FLIGHT DIRECTOR[94] PL 1+2……………………………………….RAMP
	2	Go Around…………………………………….DISPLAYED FLAPS………………………………SELECT F15

A total of five incorrect group sequences were included in the descriptive analysis, rather than six, as during one flight, flight crew selected Flap 15 prior to the power lever go around push button being pushed and prior to the aircraft being rotated to the flight director pitch order. Although this group sequence included multiple actions that were completed out of sequence, in combination, it still represents one incorrect group sequence. To provide perspective, in all five incorrect group sequences, actions in group two were started between 4.2 seconds and 2.2 seconds before actions in group one were

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[94] For this action to be met, pitch attitude must equal FD Pitch Order or be greater than 5 degrees.

completed. In two incorrect group sequences, Flap 15 was selected prior to the power lever go around push button being pushed. The implication is that go around would not have been annunciated on the pilot's primary flight display and flight director pitch order would not reflect the required go around pitch attitude. In four incorrect group sequences, Flap 15 was selected prior to the aircraft being rotated to the flight director pitch order. Figure 6-43 illustrates that three flights had one incorrect group sequence in the non-rested condition and two flights had one incorrect group sequence in the rested condition. Figure 6-44 illustrates that two flights had one incorrect group sequence during the first simulated flight and three flights had one incorrect group sequence during the second simulated flight.

Figure 6-43 Number of Incorrect Group Sequences by Non-Rested or Rested Condition

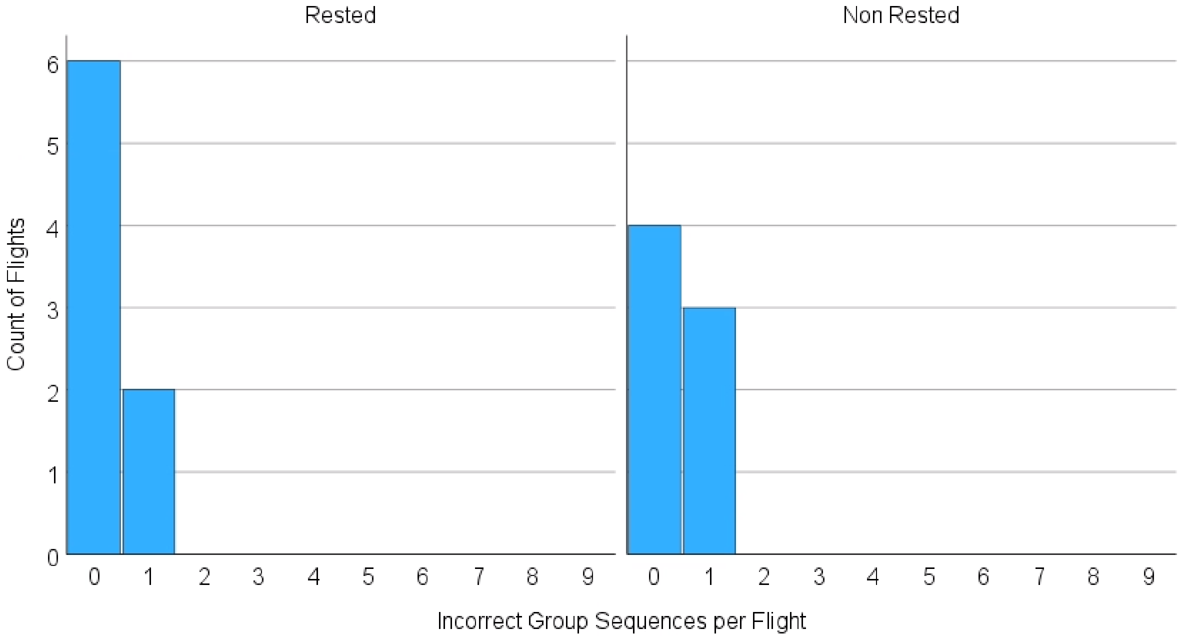

Figure 6-44 Number of Incorrect Group Sequences by First Simulated Flight or Second Simulated Flight Order

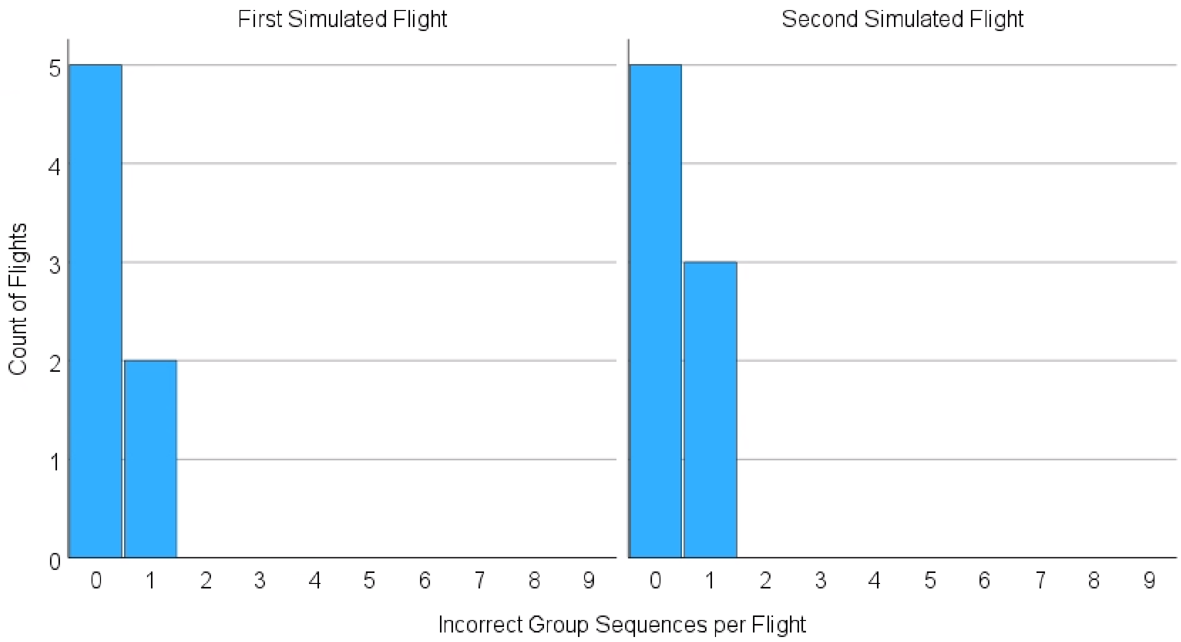

Table 6-32 Descriptives for Go Around Checklist Group Sequence by Condition

Variable	Non-rested					Rested				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Number of correct group sequences	8.57	0.53	9	8 – 9	7	8.75	0.46	9	8 – 9	8
Number of incorrect group sequences	0.25	0.46	0	0 – 1	7	0.43	0.53	0	0 – 1	8
Percentage of correct group sequences	95.23	5.93	100	88.89 – 100	7	97.2	5.14	100	88.89 – 100	8
Percentage of incorrect group sequences	4.76	5.93	0	0 – 11.1	7	2.7	5.14	0	0 – 11.1	8

Table 6-33 Descriptives for Go Around Checklist Group Sequence by Flight Order

Variable	First simulated flight					Second simulated flight				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Number of correct group sequences	8.71	0.48	9	8 – 9	7	8.63	0.51	9	8 – 9	8
Number of incorrect group sequences	0.29	0.48	0	0 – 1	7	0.38	0.51	0	0 – 1	8
Percentage of correct group sequences	96.82	5.42	100	88.89 – 100	7	95.8	5.75	100	88.89 – 100	8
Percentage of incorrect group sequences	3.17	5.42	0	0 – 11.1	7	4.16	5.75	0	0 – 11.1	8

Action Sequences

Incorrect action sequences (see Table 6-34) relate to either the initiating go around phase (Group Order 2) or the acceleration altitude phase (Group Order 7). Eight flights flown by six flight crew were flown with no incorrect action sequences, however seven flights flown by six flight crew included nine incorrect action sequences. Five flights flown by five flight crew included one incorrect action sequence and two flights flown by one flight crew, included two incorrect action sequences per flight. Two flights operated by the same flight crew included an incorrect action sequence in group order 2 and seven flights operated by six flight crew included an incorrect action sequence in group order 7. Table 6-35 lists descriptives for checklist sequence variables grouped by condition, and Table 6-36 lists these variables by flight order.

Table 6-34 Go around Checklist Action Order

Phase	Group Order	Action Order	Action
Initiating Go around	2	1 2	Go Around……………………………DISPLAYED FLAPS………………………………SELECT F15
Acceleration Altitude	7	1 2 3 4 5	PL 1 + 2…………………………………NOTCH PWR MGT………………………………….CLB BLEEDS……………………………………….ON TAXI & T.O LIGHT…………………………OFF IAS TARGET BUG…………..170kts MAGENTA

In action sequences associated with group order 2, there were two instances where Flap 15 was selected between 1 second and 2.2 seconds before go around was displayed on the pilot's primary flight display. In action sequences associated with group order 7, there were seven instances where the IAS TARGET BUG indicated 170kts MAGENTA between 0.9 seconds and 5.5 seconds before the TAXI & T.O. LIGHT was selected off. Figure 6-45 illustrates that five incorrect action sequences occurred during rested flights and four occurred during non-rested flights. Figure 6-46 illustrates that three incorrect action sequences occurred during the first flight and six incorrect action sequences occurred during the second flight.

Figure 6-45 Number of Incorrect Action Sequences by Non-Rested or Rested condition

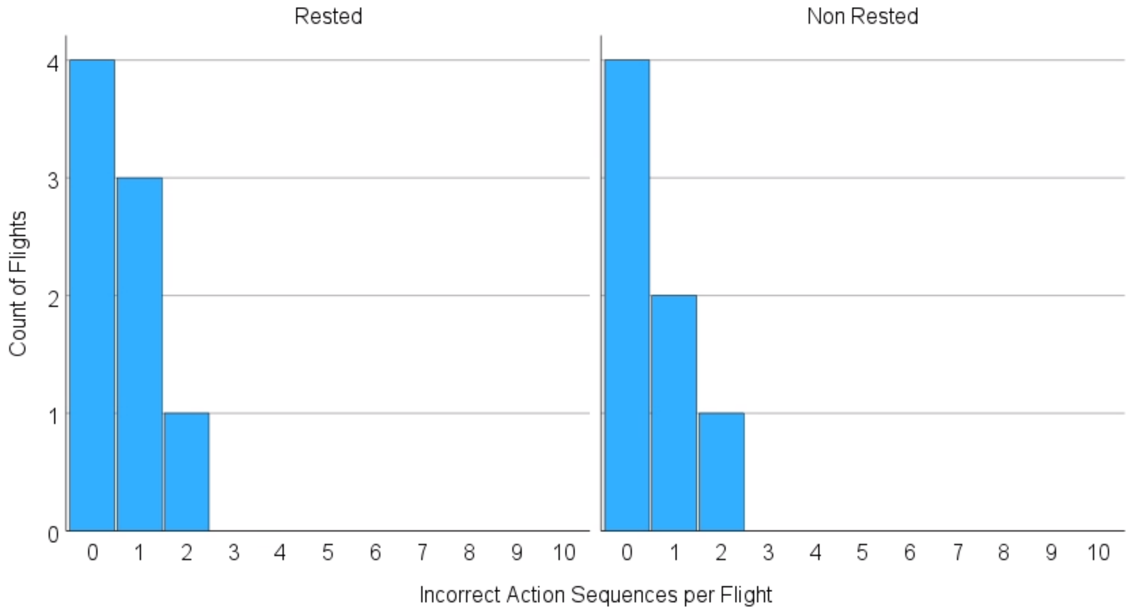

Figure 6-46 Number of Incorrect Action Sequences by First Simulated Flight or Second Simulated Flight

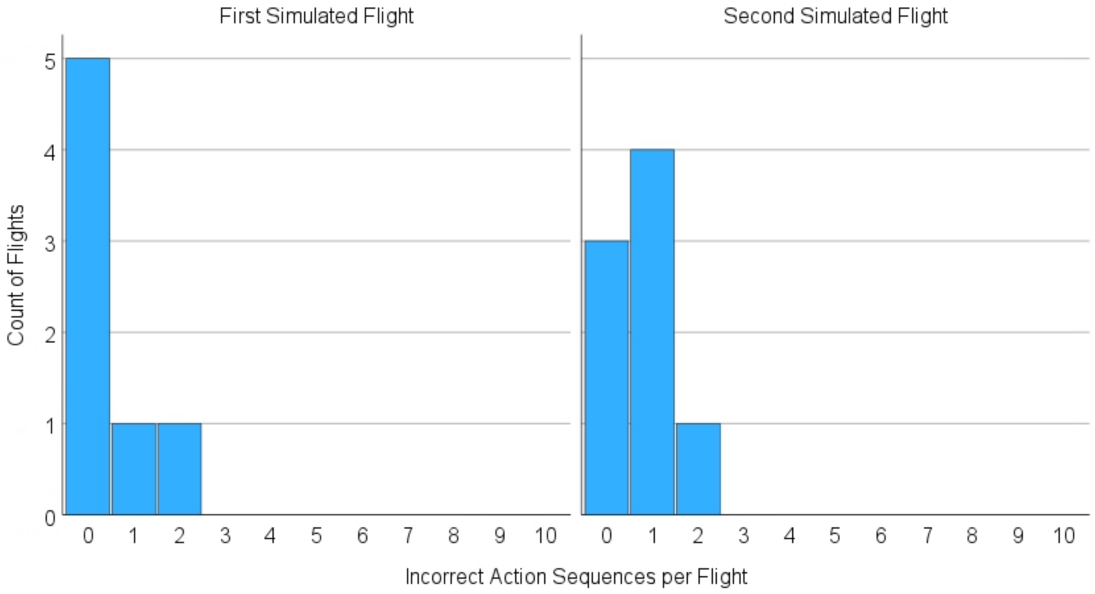

Table 6-35 Descriptives for Go Around Checklist Action Sequence by Condition

Variable	Non-rested					Rested				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Number of correct action sequences	9.43	0.78	10	8 – 10	7	9.38	0.74	9.5	8 – 10	8
Number of incorrect action sequences	0.57	0.61	0	0 – 2	7	.63	0.74	0.50	0 – 2	8
Percentage of correct action sequences	94.29	7.86	100	80 – 100	7	93.75	7.4	95	80 – 100	8
Percentage of incorrect action sequences	5.71	7.86	0	0 – 20	7	6.25	7.44	5	0 – 20	8

Table 6-36 Descriptives for Go Around Checklist Action Sequence by Flight Order

Variable	First simulated flight					Second simulated flight				
	Mean	SD	Median	Range	N	Mean	SD	Median	Range	N
Number of correct action sequences	9.57	.78	10	2 (8 – 10)	7	9.25	.70	9	2 (8 – 10)	8
Number of incorrect action sequences	.43	.78	0	2 (0 – 2)	7	.75	.70	1	2 (0 – 2)	8
Percentage of correct action sequences	95.71	7.86	100	20 (80 – 100)	7	92.5	7.07	90	20 (80 – 100)	8
Percentage of incorrect action sequences	4.29	7.86	0	20 (0 – 20)	7	7.5	7.07	10	20 (0 – 20)	8

6.8 Summary

Simulated Flight Protocol Compliance

For the tailwind during climb, ice accretion and the excess energy during approach scenarios, performance measures were not developed, and no statistical analysis was undertaken. The tailwind during climb scenarios were not considered sufficiently comparable while the ice accretion scenario was excluded due to time constraints. Analysis of the excess energy during approach scenario was not possible as no flight crew complied with the need to maintain 160kts to 5DME at Wellington. For the un-commanded autopilot disconnect and go around scenarios, performance measures were developed, and statistical analysis was undertaken.

The effect of Condition, Order and Location on Simulated Flight Data Measures

There was no main effect of condition in any of the analyses, however the interaction between 50ft altitude bin and condition was significant for initial climb measures including airspeed, pitch and roll. In several of the altitude bins, predominantly those at a higher altitude, variation in performance was greater during the non-rested condition. The interaction between bin and condition was also significant for roll during the go around, where, in one bin, variation was greater in the rested condition.

Flight order contributed to differences in some simulated flight data measures. During the first simulated flight, variation in the roll measure during go around was greater and more time was taken to re-engage the autopilot following an un-commanded autopilot disconnection. In addition, the autopilot was re-engaged at a lower altitude following go around and the go around/missed approach procedure checklist took longer to complete. Initial climb measures, airspeed go around, pitch go around and time taken to initiate the go around procedure did not differ significantly between the first and second simulated flight. Order was also included in models that included sleep related variables and ratings of workload, fatigue and sleepiness. Results were consistent with other models, aside from the model which included roll during climb, total sleep in 48hrs and ratings of fatigue. In this model, variation in roll during climb was greater during the second flight.

The interaction between 50ft altitude bin and location was significant for airspeed and pitch measures during climb. In several of the 50ft altitude bins, predominantly those at a higher altitude, variation was greater during departure from Christchurch. Roll during climb and autopilot engagement altitude following take off did not differ significantly by location. Location was also included in models that included sleep related variables and ratings of workload, fatigue and sleepiness. Results were consistent with other models.

The Effect of Sleep Related Variables and Subjective ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures

Cumulative sleep debt was not significantly associated with any simulated flight data measures. Time since sleep was significantly associated with some simulated flight data measures. An increase in time since sleep contributed to a reduction in airspeed and pitch in climb variability, later autopilot engagement following go around and an increase in time taken to both re-engage the autopilot following an un-commanded disconnection. In addition, it contributed to an increase in time taken to complete the go around/missed approach procedure and an overall reduction in autopilot usage during flight. Time since sleep was not significantly associated with any go around measures, all other autopilot usage status measures or with time taken to initiate go around. Total sleep in 24hrs and 48hrs was significantly associated with some simulated flight data measures. An increase in the total sleep in 24hrs contributed to an increase in time taken to re-engage the autopilot following an un-commanded autopilot disconnection. For total sleep in 48hrs, an increase in sleep contributed to a reduction in variation of roll during go around and earlier autopilot engagement following take off. An increase in total sleep in 24hrs and 48hrs contributed to an increase in time taken to both re-engage the autopilot following an un-commanded autopilot disconnection and to complete the go/around missed approach procedure (in the model which included total sleep in 48hrs and sleepiness). All other simulated flight data measures were not significantly associated with total sleep in 24hrs or 48hrs however a non-significant trend was identified where an increase in sleep contributed to an increase in time taken to complete the go around/missed approach procedure.

The Effect of Subjective Ratings of Workload, Fatigue and Sleepiness on Simulated Flight Data Measures

An increase in workload contributed to reduced variability in roll during climb, earlier autopilot engagement during go around, a reduction in autopilot usage during flight and an increase in time taken to complete the go around/missed approach procedure. Ratings of workload were not significantly associated with airspeed or pitch during climb, all go around measures, all other autopilot status measures and time taken to initiate the go around procedure.

An increase in fatigue was associated with increased variation in pitch and roll during climb, an increase in autopilot disconnection altitude prior to landing and a decrease in autopilot engagement altitude following go around. Fatigue was not significantly associated with roll during climb, all go around measures, all other autopilot status measures, time taken to initiate go around or time taken to complete the go around/missed approach procedure.

An increase in sleepiness was associated with increased variability in airspeed and pitch during climb, an increase in autopilot disconnection altitude prior to landing and a decrease in autopilot usage during flight. Sleepiness was not significantly associated with roll during climb, all go around measures, all other autopilot status measures, time taken to initiate go around or time taken to complete the go around/missed approach procedure.

Go Around/Missed Approach Procedure Checklist

Fifteen flight crew conducted a go around from 300ft as instructed by the simulator instructor. Descriptive analysis of the go around/missed approach procedure checklist focused on incorrect group sequences and incorrect action sequences. Three incorrect group sequences occurred during the non-rested condition and two occurred during the rested condition. In addition, two incorrect group sequences occurred during the first simulated flight and three occurred during the second simulated flight. Five incorrect action sequences occurred during the non-rested flight and four occurred during the rested flight. In addition, three incorrect action sequences occurred during the first flight and six occurred during the second flight. Although incorrect group or action sequences were identified, all checklist items were completed promptly meaning that these errors would likely be operationally irrelevant.

CHAPTER 7 DISCUSSION

7.1 Overview

This chapter discusses the logistics, practical considerations and challenges associated with conducting a simulator study in a field setting. The research design is discussed, including consideration of both the flight duty period protocol and simulated flight protocol. Key findings from chapters 3, 4, 5 and 6 are presented and interpreted within the broader context of literature. A particular focus is placed on the identification of changes in performance because of either the non-rested and rested condition or changes in sleep related variables. Strengths and limitations are outlined and considerations for future research are discussed. Finally, several recommendations are proposed.

7.2 Key Findings

Although logistically challenging, the present study has demonstrated the feasibility of conducting a simulator study in a field setting including the use of a flight duty period protocol that incorporated a non-rested and rested condition. The study also demonstrated that it is possible to record simulated flight data measures from a suitably configured SOQA programme. The flight duty period protocol was partially successful. In the non-rested condition participants initially experienced cumulative sleep debt and ratings of fatigue and sleepiness were significantly higher both before and following each simulated flight. However, following the last sleep opportunity before each simulated flight, there were no differences between the rested and non-rested flight duty period protocol in any sleep related variables aside from cumulative sleep debt and time since sleep. This was not the original intention of the protocol. Some changes in simulator performance were identified, with greater variability observed in a number of initial climb measures during the non-rested condition. Findings were mixed with an increase in time since sleep associated with reduced variability in some initial climb measures. Time taken to complete the go around/missed approach procedure checklist increased with greater time since sleep and with a greater amount of sleep in the 48 hour period preceding the simulated flight. Time taken to re-engage the autopilot following an un-commanded autopilot disconnection increased with greater time since sleep and with an increase in total sleep in 24hrs and 48hrs. Increases in fatigue and sleepiness were associated with increased variability in some initial climb measures. When considering errors associated with completion of the go around/missed approach procedure, all checklist items were completed promptly meaning that these errors would likely be operationally insignificant.

7.3 Simulator Study Implementation

7.3.1 Administration

Unlike most previous simulator based studies (see section 1.7), this study was conducted in a field setting with line pilots who operated revenue flights. The successful completion of this study demonstrates the importance of the collaboration between Massey University, each Pilot Union and the Operator. Without the support of any one group, the study would not have been possible. Key features that contributed to the success of this study include a project reference group to ensure that Massey University, each Pilot Union and the Operator were informed of the study’s conduct and progress. This also provided an opportunity for key individuals to comment on information and documents relating to data collection, the flight duty period protocol and simulated flight protocol.

Operator Support

The study did not receive any external funding and therefore, relied on the goodwill of the Operator who absorbed all costs. Without the support of the Operator, the study would not have been possible. It is acknowledged that costs associated with the study would have been considerable and the absorption of these costs by the operator is an illustration of its commitment to operational safety.

When it became apparent that the flight duty period protocol would have an impact on the published roster, endorsement was required from the Operator's Chief Flight Operations and Safety Officer and Chief Operations Officer. The Operator's Flight Operations Manager, Training Manager and Deputy Training Manager were invaluable from a practical perspective. For example, they facilitated meetings between the researcher, the Crew Planning Manager Airlines and the Senior Crew Planner Airline Training to book simulator sessions, to identify when participants could complete data collection without interrupting their training or other admin requirements. This ensured that participants were paired together, thereby ensuring that, as a flight crew, they could operate together during the entire flight duty period protocol. In addition, the Operator's Flight Operations Manager, Training Manager and Deputy Training Manager ensured that the flight duty period protocol was incorporated within the published roster and complied with during the live roster. Considering that all pilots completed the protocol, this is evidence of collaboration between the various departments and individuals. The Operator's Training Manager and Deputy Training Manager also had a significant input into the design of the simulated flight protocol. In addition, the Operator's Deputy Training

Manager was instrumental in helping the researcher set up and configure the SOQA software including facilitation of discussion to resolve issues with the Operator's Simulator Engineers and Engineers employed by the simulator's manufacturer.

Pilot Union Support

Pilot Union endorsement of the study was necessary to facilitate recruitment and data collection. When the project was being planned, no agreement existed between the operator, each Pilot Union and the researcher to enable the researcher access to SOQA data. An agreement to access SOQA data was signed in 2017 and expired following the completion of data collection in 2019.

Ethics Approval

Ethics approval for the simulator study was granted in November 2016. The committee was supportive of the research and was flexible when various challenges were presented (over the Christmas period) in the lead up to data collection in January 2019.

7.3.2 The Flight Duty Period Protocol

The flight duty period protocol was constructed to facilitate comparisons between two operationally realistic conditions, one where more fatiguing work conditions were scheduled (non-rested condition) and another where participants were free from duty (rested condition). To account for individual sleep behaviour within these different conditions, analyses also investigated the influence of sleep timing and duration variables on performance (either PVT or simulated flight data measures) while controlling for potential confounding factors, such as the order of simulated flights, timing of tests and the departure location of each simulated flight. Control of possible confounds was also achieved through the use of a flight simulator to reduce real-world variance and ensuring that scenarios were as similar to each other as practicable. The within-subjects research design enabled the protocol to account for individual factors (e.g. age, performance and sensitivity to sleep loss) although a potential disadvantage is the introduction of systematic bias due to practice or boredom effects (Field & Miles, 2010). These biases can contribute to variation in performance that is not attributable to different levels of condition. By systematically varying the order and location of simulated flights through the process of counterbalancing, it was possible to identify if systematic bias contributed to variation in simulated flight data measures by including order and location as independent variables within statistical models.

The flight duty period protocol included well validated and widely used measures of psychomotor performance, sleep and subject ratings of fatigue, sleepiness, sleep quality and workload. The PVT was selected as a measure of simple cognitive performance as it has been validated and is sensitive to sleep loss, sleep restriction and extended wakefulness (Balkin et al., 2004; Basner & Dinges, 2011; Van Dongen et al., 2022). Actigraphy was selected to monitor sleep in participants as it is currently the most practical and reliable way to monitor sleep in pilots during multiday flight duty periods. The Samn-Perelli Crew Status Check, the Karolinska Sleepiness Scale and the NASA Task Load Index were selected as they are easy to use and are widely used in commercial aviation (Liu & Lee, 2003; Vejvoda et al., 2014).

7.3.2.1 Flight Duty Period Characteristics

The Crew Planner – Rostering was provided with guidance to ensure that study flight duty periods within the non-rested condition of the flight duty period protocol included fatiguing characteristics. When comparing non-rested study flight duty periods to those flight duty periods completed during the same roster period by line pilots on that fleet, the non-rested study periods started earlier, were longer and included more sectors which indicates that the flight duty period protocol was successful in ensuring that study flight duty periods included fatiguing characteristics. Although achieved flight duty period characteristics in the non-rested condition were significantly different from those planned, this has no impact on the operational relevance of study findings. Flight duty periods met all legal requirements and were not atypical of flight duty periods that could be rostered during routine regional aircraft flight operations.

When compared with duties flown by American short haul pilots during three and four day flight duty periods (Gander et al., 1994), study flight duty periods started one hour earlier, were two hours shorter, participants operated two fewer flights and finished two hours 30 minutes earlier. Differences are likely attributable to different network structures, flight and duty time limitations, crew utilisation and aircraft types.

In the non-rested condition, the flight duty period protocol provided participants with an unrestricted sleep opportunity between 22:00 and 08:00 the night before the non-rested simulated flight.

Multiple factors contributed to this unintended consequence. The predominant factor was the timing of the simulated flight in combination with the operator’s 11 hour flight duty period limitation. On the day of the non-rested simulated flight, the operator’s maximum duty limit of 11 hours resulted in an average sign on time of 10:46 (range = 09:55 – 12:04) with four flight crew (eight participants) overnighting at a hotel which would have increased the likelihood of those participants having an opportunity to extend sleep without influence of social pressure or family commitments (Beersma & Gordijn, 2007; Drake et al., 2022). If an earlier simulator slot were to have been available (e.g. 14:00 – 18:00), sign on time prior to the non-rested simulated flight could have been as early as 05:00. Although the 14:00 – 18:00 slot was requested, this was not available.

Although not related to the non-rested condition, another challenge associated with participant rosters relates to the violation of the rested flight duty period protocol (see section 7.3.2.3). The rested simulated flight protocol required that participants have two days free from work and two nights unrestricted sleep before their rested simulated flight. This was to ensure that participants were well rested prior to their rested simulated flight, and importantly, to provide an opportunity to determine participant baseline sleep and therefore, the calculation of cumulative sleep debt in participants. Although three participants did work before their rested simulated flight, the impact of this was mitigated by using the definition of baseline sleep, defined in section 2.13.2, to identify if baseline sleep was achieved during other parts of the flight duty period protocol.

The latter two paragraphs clearly illustrate the operational challenges associated with meeting flight duty period protocol requirements. Compromises, because of these challenges, in part contributed to the failure of the flight duty period protocol to produce significant differences in PVT performance and total sleep in 24hrs and 48hrs prior to simulated flights.

7.3.2.2 Possible Implications of an Unrestricted Sleep Opportunity before the Non-rested Simulated Flight

As discussed above, the non-rested flight duty period protocol included an unrestricted sleep opportunity before the non-rested simulated flight. It is possible that the unrestricted sleep opportunity before the non-rested simulated flight provided an opportunity for participants to recover from any sleep loss accumulated during the first part of the non-rested flight duty period protocol. Recovery from sleep restriction is dependent on the extent of sleep restriction, the duration of the recovery period (i.e. single or multiple sleep episodes) and the amount of sleep obtained during the recovery period (Banks et al., 2022). The present study protocol resulted in mild to moderate sleep restriction[95], and it is currently not clear if recovery could be achieved in a single night. Prior research demonstrates that a single night is not sufficient to recover from more severe or prolonged sleep restriction (Banks et al., 2010; Belenky et al., 2003; Dinges et al., 1997). However, 7.4 hours total sleep time is considered to be sufficient to restore the bulk of performance capacity following a period of chronic sleep restriction (Belenky et al., 2003; Van Dongen et al., 2006). Participants in this study achieved, on average 8.39 hours total sleep time before the non-rested simulated flight. In addition, it has been demonstrated that recovery from 24hrs of total sleep deprivation is possible within one nine hour sleep opportunity (Jay et al., 2007).

Although total sleep in 24hrs and 48hrs before simulated flights did not differ by condition, ratings of fatigue were significantly higher in the non-rested condition following simulated flights. This could suggest that participants had not fully recovered from the effects of sleep loss during the initial part of the non-rested flight duty period protocol. Even if this were to be the case, any remaining fatigue related performance decrement between the non-rested and rested condition was not pronounced enough to be detected by PVT, either before or following simulated flights. This likely affirms the assumption that the fight duty period protocol did not

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[95] Belenky et al. (2003) refers to seven hours' time-in-bed over a seven day period as mild sleep restriction and five hours' time-in-bed over a seven day period as moderate sleep restriction.

produce a significant difference in PVT performance because the final rest period before the non-rested simulated flight offered an opportunity for participants to recover from sleep loss.

7.3.2.3 Flight Duty Period Protocol Compliance

Once the roster had been published, and flown, compliance with the rostered flight duty periods was remarkably good. A likely contributing factor to this was that Operations Control were instructed to “protect” participants by not changing their roster or requesting that they operate duties they were not rostered to operate. Despite this, non-compliance did occur; one participant did not complete their second flight duty period in the non-rested condition, meaning that they only completed two consecutive flight duty periods prior to their non-rested simulated flight. During the rested condition, three flight duty periods were operated during day 2 and two flight duty periods were operated during day 3 by three participants. These participants were not rostered to operate these duties however it is likely that if they had declined, this would have resulted in operational disruption. Although one flight duty period [96] encroached the local night, the start time of that participants next flight duty period would not likely have contributed to sleep restriction given that the duty started at 12:30.

The flight duty period protocol was also designed to ensure participants flew together prior to their first simulated flight and that they flew together during the non-rested condition to account for improvements in performance associated with flight crew familiarity (Foushee et al., 1986). One flight crew did not operate together before their first simulated flight, however, all flight crew operated

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[96] Five flight duty periods were operated during days 2 and 3 of the rested condition, see Table 4-5.

together before their non-rested simulated flight. A mitigating factor associated with this violation, is that the operators training programme would likely minimise differences in flight crew performance. Flight crew would be very familiar with the way other crew operate the aircraft, due to the standardised, and procedural nature of the flight operation.

Despite a small amount of non-conformance with the flight duty period protocol (as discussed above), this was considered minor and data collected from all participants was included within analysis.

7.3.2.4 Baseline and Non-baseline Sleep Periods

Baseline sleep was defined as the average amount of sleep achieved in a 24 hour period from midday to midday on days free from work, excluding the 24 hour period after a flight duty period and the 24 hour period preceding a flight duty period starting before 08:00. This approach acknowledges that the amount of sleep participants achieve varies and makes a best guess at an individual's ideal sleep duration. During baseline sleep periods, despite participants staying in bed longer and going to bed and waking at a more favourable time, the difference in total sleep over a 24 hour period was non-significant between baseline and non-baseline sleep periods.

This suggests that, on average, study flight duty periods did not contribute to a significant difference in participants' total sleep time when compared with their ideal sleep duration. However, during baseline sleep periods, participants reported lower levels of subjective fatigue, both at the start and end of sleep. This could be due to the absence of early starts and busy flight duty periods which were a feature of non-baseline sleep periods.

Although the flight duty period protocol did not include planned baseline sleep days, the protocol required, during the rested condition, that participants were rostered two days free from duty before operating their rested simulated flight. This provided participants with an opportunity for two nights of unrestricted sleep. An unforeseen challenge with this approach was that if participants were not able to achieve two days free of duty, this could jeopardise the calculation of cumulative sleep debt for these participants. To account for this, the method outlined in section 2.13.2 was adopted to determine baseline sleep duration and allow the identification of additional baseline days over the entire flight duty period protocol. Although it is not known if this method used was reflective of a participant's true baseline sleep need, the definition does require that, prior to a baseline sleep, the participant has been free of duty for 24hrs. This would likely ensure that the previous night's sleep was unrestricted offering an opportunity for recovery sleep prior to the baseline sleep period. It is acknowledged that it is not possible to determine if baseline sleep included recovery sleep. Although similar studies that included simulated flights and operational levels of fatigue did not calculate cumulative sleep debt (Foushee et al., 1986; Thomas et al., 2006), the study undertaken by Gander et al. (1994), which investigated the psychophysiological effects of short haul flight duty periods on pilots, did include between one and two days of baseline sleep to allow for the calculation of cumulative sleep debt. During baseline sleep periods, participants in the present study achieved 40mins more sleep than American short haul pilots in the Gander et al. (1994) study.

To reduce the likelihood of confounding subsequent calculations of cumulative sleep debt, consideration was given to excluding 19 abnormal baseline sleep periods[97]. Baseline sleep periods less than seven hours or greater than 10 hours, were not excluded as this would have resulted in an inability to calculate cumulative sleep debt for three participants. It is acknowledged that by including abnormal baseline sleep periods, there is a possibility that cumulative sleep debt was underestimated for participants with baseline sleep periods less than seven hours and overestimated for participants with baseline sleep periods greater than 10hrs[98].

7.3.3 The Simulated Flight Protocol

The simulated flight protocol provided guidance for the conduct of the simulated flight. It included detailed instructions to allow the simulator instructor to ensure that flight characteristics (for example, aircraft take off weight) were correct and that each simulated flight included scenarios (interventions) that would allow for specific simulated flight data measures to be captured and recorded.

7.3.3.1 Simulated Flight Protocol Development

The development of the simulated flight protocol and the selection of scenarios for the simulated flight protocol was challenging as there were many different tasks to choose from, and within each task, many factors (aside from fatigue) could contribute to variation in task performance. For example, pilots who responded to a survey which asked which flight phase was most affected when performance is affected by fatigue found that 40% of respondents identified the enroute phase, 30% landing, 19% descent, 7% take off and 4% taxi (Co et al., 1999). This suggests that different pilots likely find different phases of flight fatiguing, e.g. a fatiguing task for one pilot may not be fatiguing for another pilot. In addition, the requirement that

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[97] Abnormal baseline sleep periods are defined as baseline sleep durations which are less than 7hrs or greater than 10hrs (Gander et al., 1994).

[98] Of the 47 baseline sleep periods identified, 15 were less than seven hours and four were greater than 10hrs.

scenarios must be monitored by flight data analysis restricted the types of tasks that could be focused on and literature that could be referred to, to support decisions. In hindsight, it would have been practical to focus on one paired scenario that occurred multiple times during a flight, rather than multiple paired scenarios which occurred once, during different parts of a flight. Multiple scenarios increased time associated with the discussion, planning and validation of each paired scenario, time taken to prepare datasets and time required for configuration of the SOQA software. However, it is acknowledged that because it was not clear which tasks would be sensitive to fatigue, it was necessary to look at a broad range of tasks.

Considerable effort was applied to develop scenarios. The researcher worked with the operator’s Training Manager and Deputy Training Manager, the simulator instructor, and consulted with several academics who had researched pilot performance within a simulated environment. In addition to the scenario itself, consideration was given to the likelihood that participants may deviate away from the intended scenario. Sub scenarios were developed to allow the simulator instructor to keep the flight crew on track. Again, this required discussion with key individuals, as sub scenarios were required to be realistic and not appear contrived or artificial. As it turned out, no sub scenarios were required. The interview which followed the second trial simulated flight illustrated just how different some of the scenarios (within a paired scenario) were. A concerted effort was therefore undertaken following the second trial to ensure that scenarios were as similar as practical, but also subtly different. However, it became apparent that this was also not feasible as there were still too many differences between each paired scenario. For example, comparing the influence of a tailwind on climb performance (Paired Scenario: Tailwind During Climb) was not possible as the difference in aircraft configuration made comparison of results inappropriate. Another example was the influence of excess energy during approach (Paired Scenario: Excess Energy During Approach) which sought to compare time taken to stabilise the aircraft following either excess speed or excess height. In this scenario, analysis was not possible as the speed restriction during the Wellington ILS/DME RW34 scenario was not complied with by participants. The excess height scenario also resulted in the loss of one dataset as the flight crew elected to conduct a missed approach at 3000ft. This likely illustrates the conservative nature of pilot actions, e.g. electing to go around at 3000ft rather than attempt to regain approach stability prior to meeting the 1000ft stable gate. It only became apparent following data collection that extensive differences existed between the tailwind during climb scenario and the excess energy during approach scenario. As a result, analysis of these paired scenarios was not undertaken. And although the ice accretion scenario was successful, a pragmatic decision was made not to analyse this scenario due to time constraints. Ultimately, only the un-commanded autopilot disconnection and go around paired scenarios were incorporated within the results section. The final decision to focus on a relatively small proportion of the flight for the thesis was difficult, given all the effort and work that went into preparing the entire protocol, but this was entirely necessary to contain the size of the thesis. An alternate approach to account for systematic bias (e.g. the effect practice has on performance) would have been to provide pilots with a training opportunity to familiarise themselves with the scenario and to provide them with enough practice to reach asymptotic performance. However, this approach would have increased the number of simulator slots required, which was not an option.

Scenarios that were excluded from analysis, were either excluded because they were incomplete (i.e. excess energy during approach), incompatible (i.e. tailwind during climb) or because other scenarios were prioritised due to time constraints (i.e. ice accretion). See section 3.8 for additional information.

7.3.3.2 Anticipated Fatigue Related Changes in Flight Crew Performance during Simulated Flights

The simulated flight data measures within this thesis research are representative of fundamental tasks associated with aircraft operation such as aircraft manual handling, the order and timing of checklist items, time taken to initiate go around, time taken to complete the go around/missed approach procedure and autopilot utilization. Flight crew performance in these tasks likely rely on a combination of simple cognitive functions including attention and vigilance as well as more complex cognitive functions including working memory, cognitive control, convergent and divergent thinking, risk taking and decision making.

Alertness and vigilance is likely to remain relatively stable during the first 16 hours of wakefulness (Goel et al., 2009), and given that alertness and vigilance peaks during the early evening (Skeiky et al., 2022), it could be assumed that simple reaction time performance of participants in the present study is unlikely to be severely affected. In addition, pilots have the ability to maintain a reasonable level of flying precision following extended periods of wakefulness exceeding 20hrs (Collins, 1976; McIntosh et al., 1952; Previc et al., 2009) including the ability to fly instrument approaches (Hartman, 1965). Although sleep loss prior to the non-rested simulated flight was not excessive, it was operationally relevant (see section 7.3.2.2).

Sleep loss can impair alertness, attention and psychomotor vigilance by contributing to slower and inconsistent responses (see section 1.6.1). It also impairs complex cognitive functions by affecting accuracy and response time during tasks that require working memory, the ability to switch efficiently between tasks and slower and less efficient performance on tasks that require cognitive thinking (see section 1.6.2).

Therefore, decrements in multi-tasking, working memory and degraded flight crew coordination because of fatigue related changes in mood, frustration, tolerance, emotional control or inhibitory control could be expected to influence simulated flight data measures in the present study.

An awareness of fatigue in participants could contribute to the incorporation of strategies that reduce fatigue or protect their performance (Cabon et al., 2012). For example, Thomas et al. (2006) identified that an increase in fatigue contributed to flight crew placing a greater emphasis on monitoring their performance and that they incorporated specific adaptive strategies to reduce the likelihood of error. In the present study, although participants were not asked if they applied additional compensatory effort, it is assumed that they would “try their best” given the presence of the simulator instructor. This could potentially have the effect of protecting performance.

Results from Chapters Five and Six show that unlike some simulated flight data measures, PVT performance did not differ significantly between the two conditions. The different results from the two performance measures reflects the different nature of what they measure. As discussed above and within section 1.6, the PVT test likely represents simple cognitive performance relating to vigilance and attention whereas simulated flight data measures likely represent complex cognitive performance. Although complex cognitive tasks require simple cognitive functions such as alertness or vigilance, they also require executive functions that are not reflected within PVT performance

7.3.3.3 Simulated Flight Data Measures

Performance in the initial climb and go around was measured using a variability metric (standard deviation) rather than average, maximum or minimum performance values. Similar studies have also used standard deviation to identify increases in variability as a result of sleep loss (Hartman, 1965; Neville et al., 1994). Although standard deviation was used as a measure of variability in this thesis research, other studies have used root mean square error (RMSE) (Caldwell et al., 2004); Caldwell and Roberts (2000); (Previc et al., 2009). Consideration does need to be given to the nature of the scenario when determining if standard deviation or root mean standard error is the most appropriate function. For scenarios where a broad range of values will meet standard operating procedure requirements, standard deviation will likely be more appropriate given that “more” outliers are likely to be present. For example, Neville et al. (1994, p. 343) used standard deviation as a measure of pilot performance because “many factors could have affected whether or not pilots adhered to recommended flight parameters”. RMSE would have been chosen by Caldwell et al. (2004), Caldwell and Roberts (2000) and Previc et al. (2009) given that their protocols included practice sessions and that the various scenarios (manoeuvres) were clearly defined. Depending on the nature of the scenario, consideration should be given to which metric is best suited as a measure of pilot performance in future research. For some initial climb and go around measures, the influence of height on performance variability was important to consider. For example, changes in weather condition had been requested to start at 500ft which could have impacted performance after this height but not prior. The value of accounting for the influence of height (the 50ft altitude bins) within analyses was that it was it was possible to identify if differences in either condition or location were consistent as the aircraft climbed. Although this makes analyses more complex, similar variables (i.e. height, time or distance) should be considered when investigating the variability of (simulated) flight data measures which capture parameter values continuously between two points.

Aside from initial climb and go around measures, all other measures were limited to one value per flight. For go around/missed approach procedure item sequence measures, this likely contributed to limited variability (go around/missed approach procedure item sequence measures). For autopilot status measures, in addition to the small number of values available, the operator did not define when the autopilot should be engaged or disengaged[99]. The implication of this was that variation in autopilot status measures was observed given that pilots will use automation at their discretion. These datasets would benefit from a much larger number of flights (e.g. a dataset associated with a FOQA programme) in combination with a fatigue or sleepiness rating, roster metric (Cabon et al., 2012) or biomathematical model prediction (European Aviation Safety Agency, 2019) to understand if fatigue or sleep loss contributes to changes in checklist efficacy or autopilot usage during flight. In addition, given that go arounds occur infrequently, consideration of another checklists is also recommended.

When considering what factors contribute to variation in pilot performance, simulated flight data cannot explain why a flight crew made a particular decision. For example, following an un-commanded autopilot disconnection, rather than assuming that delayed re-engagement is due to reduced vigilance (i.e. unintentional), delayed re-engagement could be associated with increased vigilance as the flight crew may intentionally prioritise other tasks. An implication of this is

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[99] The Operator suggests that automation must be used to enhance safety, passenger comfort, schedule, and economy and that its use will allow other matters requiring pilot attention to be attended to more effectively (Operator Documentation, 2018),

that it is not possible to know why flight crew operated the aircraft in a certain way or why they made particular decisions. Given that an aim of this thesis research was to identify if it was possible to detect changes in simulator flight deck performance, consideration of the operational significance of those changes, and what contributed to those changes was considered out of scope.

The simulated flight protocol offered an opportunity to account for numerous factors that are likely to reduce measurement sensitivity. Although not exhaustive, these include weather, air traffic control and workload. For example, to maximise measure sensitivity associated with aircraft handing, numerous studies have eliminated non-pilot related deviations by removing wind and turbulence during simulated flight (Caldwell et al., 2004; Caldwell et al., 1997; Caldwell et al., 1995). The implication is that when investigating the same measures in-flight, with the presence of wind and turbulence, measurement sensitivity was reduced (Caldwell & Roberts, 2000). Other studies have also identified that measurement sensitivity is greater within the simulator compared to actual flights (Billings et al., 1975).

Another factor that may influence measurement sensitivity is individual differences. The use of a within-subjects research design allows for variation associated with individual differences to be accounted for. The contribution of individual differences to variation within a measure can be substantial. For example Van Dongen et al. (2006) identified that after baseline correction, systematic individual differences in impairment levels accounted for around 50% of the variation observed in pilot simulator performance.

The simulator in combination with a within-subjects research design therefore offers an opportunity to determine if changes in pilot performance can be reliably predicted. In normal flight operations, the influence of fatigue may not be identifiable due to the presence of confounds and thus its importance overlooked.

7.3.3.4 Simulated Flight Protocol Compliance

Compliance with the simulated flight protocol was, for the most part, remarkable. This was primarily attributed to the extensive effort the simulator instructor undertook to ensure that simulated flights followed the protocol. This involved configuring the simulated flight (e.g. ensuring that flight characteristics were as requested) and making changes at specific points during the flight to ensure conditions or actions associated with a scenario occurred at the required time. For example, the protocol required that for flights that departed from Christchurch, the wind direction and velocity would be 240 degrees magnetic at 15 knots by 500ft above aerodrome level. The largest deviations in flight characteristics included +20kg for take off weight, +20 deg C for wind direction and +7kts for wind speed, however these differences are unlikely to have had any impact on the scenarios.

As for the scenarios, from a compliance perspective, no concerns were identified for tailwind during climb, ice accretion or go around. These scenarios occurred at the correct time, with correct conditions and flight characteristics. For the un-commanded autopilot disconnection, there was some variation in altitude and distance from the localiser where the autopilot disconnection occurred for arrivals into Christchurch. The excess energy during approach scenario was successful for arrivals into Christchurch. It was conducted as planned with all flights experiencing the intervention. However, for arrivals into Wellington, this scenario was not successful as no flights experienced the intervention. It is not known why this occurred. It is likely that pilots received the speed instruction at the correct time but omitted the constraint.

7.3.3.5 Order and Location

Order and location are important as they represent a potential source of systematic bias. The order (first flight or second flight) and location (Christchurch – Wellington or Wellington – Christchurch) of flights was counterbalanced to allow these potential effects to be accounted for independent of the non-rested and rested condition.

Order

Although practice effects contaminate most cognitive performance tasks (Skeiky et al., 2022), results from this study illustrate that order was not associated with changes in PVT performance. In addition, order was not found to be associated with ratings of fatigue and sleepiness, time since sleep and workload.

The order of simulated flights did contribute to significant differences in some simulated flight data measures. For initial climb and go around measures, only roll during go around was influenced by order, which was reflected in a reduction in roll variability during the second flight. This suggests that completing a go around recently might contribute to improved tracking consistency in the roll axis during a subsequent go around. Although a go around is a normal flight phase, it is a relatively rare manoeuvre where, on average, a short haul pilot will conduct a go around once or twice a year (Tzvetomir & Curtis, 2017). However, the order effect is likely operationally insignificant as the difference in standard deviation between first and second simulated flight was 0.10 degrees.

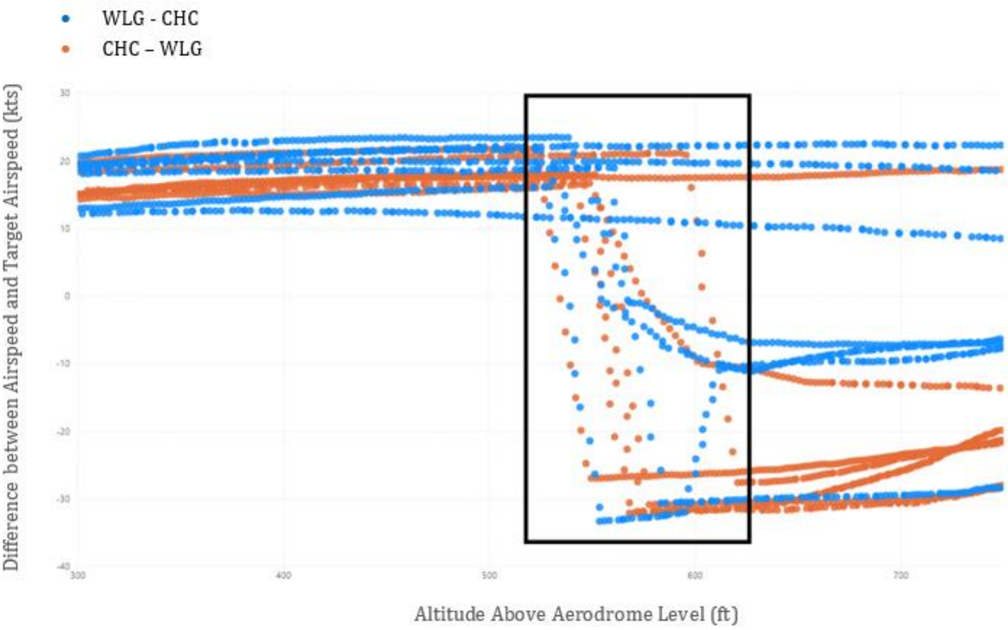
During the first simulated flight, flight crew engaged the autopilot at a lower altitude following go around, took longer to re-engage the autopilot following an un-commanded autopilot disconnect and took longer to complete the go around checklist. The difference in autopilot engagement altitude following go around differed by 350ft between the first and second simulated flight which equates to roughly 14 seconds. This could represent a strategy to reduce workload given the unexpected nature of the go around. For both autopilot re-engagement following an un-commanded autopilot disconnection and time taken to complete the go around checklist, the reduced duration during the second simulated flight could represent a learning effect. For example, perhaps improved task familiarity (and knowledge of the previous outcome) may have contributed to less time being taken to decide on an action.

Order was also included in models which included sleep related variables and ratings of workload, fatigue and sleepiness. Results were relatively consistent with other models, aside from the model which included roll during climb, total sleep in 48hrs and ratings of fatigue.

Location

The likely reason for differences in some simulated flight data measures by location was the inclusion of a tail wind during initial climb during departure from Christchurch, which was not present during the departure from Wellington. Therefore, location was only expected to influence climb related variables, autopilot engagement altitude following take off, and ratings of workload. Location did not contribute to significant differences in roll during climb, autopilot engagement following take off or ratings of workload. For airspeed during climb, differences in location were seen in the same bins where changes to the commanded airspeed occurred. At the acceleration altitude there is a change in commanded airspeed (see Figure 7-1). In the current study, there was an abrupt change in the difference between airspeed and the commanded airspeed which contributed to a momentary large standard deviation. Differences because of location for airspeed in climb were not consistent. Variation was greater in bin 5 (500ft – 549ft) during departures from Wellington, however variation was greater in bins 6 (550ft – 599ft) and 8 (650ft – 699ft) during departures from Christchurch. In all other bins, estimates did not differ by location. This would suggest that changes in commanded airspeed, rather than location contributed to these significant differences and that those changes, due to the initiation of actions associated with acceleration altitude, occurred at a slightly higher altitude in Christchurch. These results are not considered relevant to the present study.

Figure 7-1 Changes in the difference between Airspeed and Commanded Airspeed due to Pilots setting Climb Power on reaching Acceleration Altitude[100]



When considering pitch in climb, differences were found in location across four 50ft altitude bins, however, the extent of variation was likely not operationally

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[100] This chart depicts the difference in airspeed and commanded airspeed in relation to altitude during climb. Orange traces represent flights departing Christchurch and blue traces represent flights departing Wellington. Some flight crew did not set climb power below 750ft (straight lines at the top of the chart) which means that commanded airspeed did not change.

significant as differences between untransformed estimates, because of location were less than 0.4 degrees. Departures from Wellington exhibited greater variation at lower altitudes whereas departures from Christchurch exhibited greater variation at higher altitudes which was likely due to actions associated with acceleration altitude being initiated at a slightly higher altitude in Christchurch.

Location was also included in models which included sleep related variables and ratings of workload, fatigue and sleepiness. Results were consistent with other models.

7.4 The Non-rested and Rested Condition

To the author’s knowledge, there have been no prior studies that have investigated the influence of sleep loss on the simulated performance (within a zero flight time simulator) of commercial airline pilots using a within-subjects research design. Foushee (1986) conducted a protocol where flight crew operated a simulated flight either before or following a three day flight duty period pairing and Thomas et al. (2006) undertook a protocol where flight crew operated a simulated flight after at least four consecutive days free from duty, or immediately following a long-haul international flight. In both cases, only one simulated flight was undertaken by each flight crew. Numerous studies involving military pilots operating a full flight time simulator have adopted a within-subjects design however sleep loss was controlled within a laboratory setting (Caldwell et al., 2004; Caldwell et al., 1997; Caldwell et al., 1995; Leino et al., 2007; Previc et al., 2009).

7.4.1 Sleep Related Variables, Fatigue, Sleepiness and Sleep Quality during the Flight Duty Period Protocol

During the four-day period prior to each simulated flight, the influence of the non-rested and rested condition on ratings of fatigue, sleepiness and sleep quality, and the timing and duration of sleep was investigated. Sleep related variables (aside from time since sleep) were found to be reliably associated with ratings of fatigue and sleepiness suggesting that participants have some perception of the impact of their prior sleep behaviour. At the beginning of a sleep period, ratings of fatigue and sleepiness did not differ between the non-rested and rested condition, aside from ratings of fatigue being greater in the non-rested condition on day 4. Following sleep, fatigue ratings were greater in the non-rested condition independent of day and sleepiness ratings were greater in the non-rested condition during day 2 and 3. Ratings of sleep quality did not differ between the non-rested and rested condition however ratings were significantly better following sleep on day 4 compared with days 1, 2 and 3.

As mentioned in Chapter 2, fatigue ratings of five or more suggest that flight is permissible, although not recommended (Samn & Perelli, 1982) and sleepiness ratings of seven or more have been associated with short periods of involuntary sleep (Akerstedt & Gillberg, 1990). Although LS-means estimates for fatigue were 5.43 in the non-rested condition prior to the main sleep period during day 4, all other model estimates for both fatigue and sleepiness did not exceed ratings of five or seven respectively. Aside from the start of sleep during day 4 in the non-rested condition, this could suggest that participants were not excessively fatigued or sleepy at the start of sleep.

In the non-rested condition, the amount of sleep obtained in each 24 hour period was shorter during the first two days of the protocol, likely due to earlier rise times associated with early flight duty periods. During day 4, sleep obtained over the 24 hour period was greater than that during the first three days, however, it did not differ between the non-rested and rested condition. In addition, sleep obtained in the previous 48 hours did not differ between the non-rested and rested condition on day 4. Total sleep in the previous 24 hour period prior to simulated flights, in both conditions, exceeded sleep during baseline days by 38 minutes in the non-rested condition and 25 minutes in the rested condition. When compared with average baseline sleep duration from a study that investigated sleep loss in pilots associated with short-haul flight duties (Gander et al., 1994), participants slept for an additional one hour and 20 minutes in the non-rested condition and one hour seven minutes in the rested condition. This longer sleep period is possibly due to pilots attempting to recover from any existing fatigue prior to both simulated flights.

In the non-rested condition during days 2 and 3, participants accumulated an average of 60-70 minutes of cumulative sleep debt per night. By day 4, 43% of pilots had accumulated between zero and two hours of cumulative sleep debt and 25% had accumulated between two and four hours. In addition, 6% had accumulated between four and six hours, 20% had accumulated between six and eight hours and 6% included cumulative sleep debt greater than eight hours. During the first three days in the non-rested condition, total sleep in the previous 24 hour period was on average one hour less than baseline sleep which suggests that participants probably accumulated a sleep debt. The average accumulation of sleep loss per night and variation in levels of cumulative sleep debt between participants were consistent with that reported by Gander et al. (1994) in their study of 74 short haul pilots during three and four day flight duty period pairings, which included early sign-on and long duty days during daytime and evening operations. However, when comparing average sleep duration, participants in the present study achieved 30minutes more sleep during flight duty period days and 40 minutes more sleep during baseline days compared with American short-haul pilots in the Gander et al. (1994) study.

Time awake at the start of the simulated flight was significantly shorter for participants in the non-rested condition. This was because wake times following day 4 did not differ between conditions and the non-rested simulated flight and PVT tests started earlier. In both conditions, the length of time awake prior to the simulator session would not be expected to result in detectable PVT performance decrements as, after 12 hours of wakefulness, PVT responses are likely to be maintained at a fast and consistent level with no evidence of false starts (errors of commission) or occasional lapses in attention (Doran et al., 2001). Results from PVT tests showed that PVT response speed for pre and post simulated flight, independent of condition exceeded four responses per second, a speed which is unusually fast and comparable with response speeds of participants in laboratory settings who achieved between seven to eight hours' time in bed at night (Gander et al., 2015). In addition, the timing of simulated flights likely coincided with the circadian peak in performance and the likely peak in PVT performance which occurs between 16:00 and 20:00 (Skeiky et al., 2022). It is likely that any possible performance impairment as a result of increasing sleep pressure associated with increasing time awake was minimised by the circadian process which partially protects performance during the late afternoon and early evening and is most pronounced several hours before habitual bedtime (Mollicone et al., 2010). In addition, it is unknown if participants would have applied compensatory effort to protect performance.

Overall, results illustrate that in both the non-rested and rested condition, participants undertook simulated flights and PVT tests following an unrestricted night's sleep. No significant differences in total sleep in the previous 24 and 48 hour period were identified between levels of condition. Simulated flights were undertaken at a time of day where performance impairment was reduced and when attention and vigilance likely peaks.

Due to minimal differences in fatigue causing factors between the non-rested and rested condition, the researcher also investigated the association between sleep related variables, independent of condition on PVT performance and Simulated Flight Data measures. Results are discussed in section 7.4.5.

7.4.2 Fatigue and Sleepiness during Simulated Flights

Results showed that in the non-rested condition, following simulated flights, subjective fatigue and sleepiness was significantly higher compared to the rested condition. To place these results in context, comparisons are made with results from Spencer and Robertson (2000) and Powell et al. (2007).

Spencer and Robertson (2000) undertook a diary study of aircrew operating short-haul multi-sector flight operations to investigate the effect of flight duty period characteristics on ratings of fatigue and workload. Three hundred diaries were provided to pilots who recorded information on their sleep, and how they felt at various times during flight duty periods. At the end of the flight duty period, they entered ratings of fatigue and workload. Results were based on 159 diaries that were returned. Over one third of flight duty periods started before 07:00, and flight duty periods typically included between two and five sectors and flight duty period pairings were between two and six days. Spencer and Robertson (2007) identified that later start times improved the quality and duration of the sleep period that preceded a flight duty period, and that for each one hour advance in report time before 09:00, there was a reduction in sleep duration of 30 minutes. Each additional sector following two sectors, contributed to an increase in fatigue equivalent to an increase in duty length of one hour 20 minutes and duties on consecutive days contributed to an increase in fatigue equivalent to an increase in duty length of 20 minutes per day.

Powell et al. (2007) also investigated the effect of flight duty period characteristics on ratings of fatigue recorded by short-haul pilots during multi-sector flight duty periods. Over a period of three months, at top of descent on the last sector, pilots recorded the duty start time, current time and number of sectors flown during that duty period. From a possible 2034 duties, responses were received from 1466 pilots. Almost half of the flight duty periods started before 07:00, the average duty period was 7.2 hours and most flights had four sectors. Powell et al. (2007) found that fatigue increases with an increase in duty length and the number of sectors flow. Although time of day had a weaker influence, fatigue was found to be lower at midday and higher later in the day.

In the present study, duties that included the non-rested simulated flight finished on average at 19:57, the duty length was 9.1 hours and 3.25 sectors were flown. The average subjective rating of fatigue was 5.34 which equates to “moderately tired, let down. By comparison, Spencer and Robertson (2000) identified that average subjective ratings of fatigue at 20:00 was 3.12, whereas following 3.25 sectors it was 3.5 and following a nine hour duty, it was 3.9. Powell et al. (2007) identified that subjective ratings of fatigue following 3.25 sectors was 3.9 and when accounting for both duty length and time of day, it was 3.9. This would suggest that in the present study, fatigue following the non-rested simulated flight was elevated when compared with similar studies. A likely reason for this is the inclusion of the simulated flight within the flight duty period.

An increase in cumulative sleep debt was associated with an increase in ratings of fatigue and sleepiness. In the non-rested condition, it is possible that higher levels of cumulative sleep debt contributed to higher ratings of fatigue and sleepiness. In addition, pre simulated flight ratings of fatigue and sleepiness and post simulated flight ratings of sleepiness were consistently associated with cumulative sleep debt.

7.4.3 Workload during Simulated Flights

Workload did not differ between levels of condition, although variability was observed in both conditions. It is unknown if workload was excessive during simulated flights, given there is no accepted cut-off associated with NASA-RTLX (Hart, 2006).

7.4.4 Psychomotor Vigilance Task Performance prior to and Following Simulated Flights

PVT response speed for pre and post simulated flight PVT tests in both the non-rested and rested condition exceeded four responses per second. This is considered unusually fast and is comparable with response speeds of participants in laboratory settings who achieved between seven to eight hours' time in bed at night (Gander et al., 2015). Although, participants' PVT response speeds were comparable to response speeds reported in other studies involving pilots (Gander et al., 2015; Lopez et al., 2012).

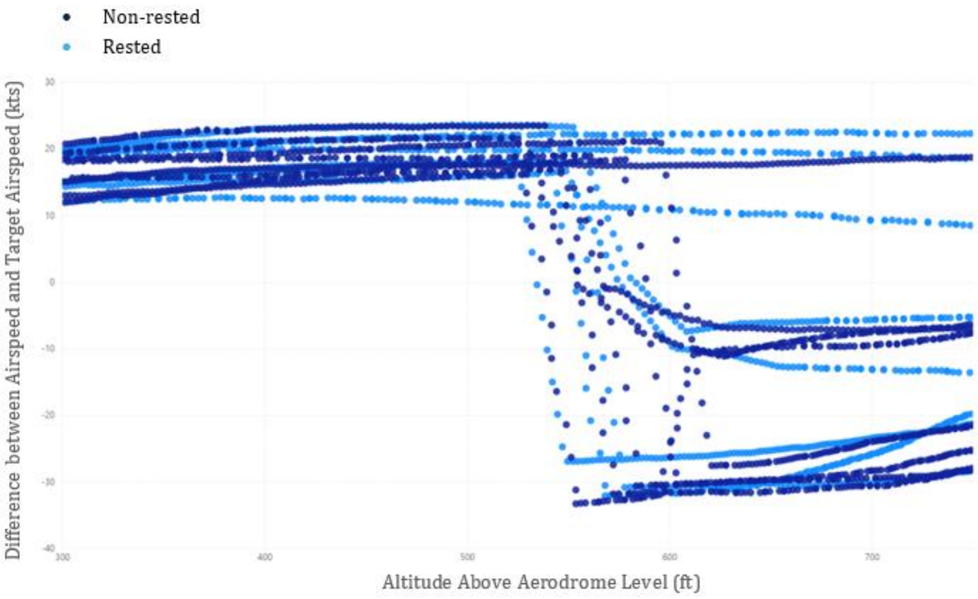
Despite higher levels of cumulative sleep debt and higher ratings of fatigue and sleepiness in the non-rested condition, none of the PVT measures differed between the non-rested and rested condition or before or following simulated flights. These results illustrate that condition, time of day and the simulated flight itself did not contribute to significant differences in PVT performance. Given that the PVT test was designed to be sensitive to sleep deprivation induced by chronic partial sleep restriction (Dorrian et al., 2005) and the PVT response speed of participants' was considered unusually fast, this could suggest that fatigue levels were modest in both conditions. However, it could also suggest that the PVT is not a reliable measure of fatigue related impairment in pilots (Gander et al., 2015).

However, these results are not unexpected given that little variation in performance is expected during the waking portion of a normal day (Lim & Dinges, 2010) and that PVT performance is likely to peak between 16:00 and 20:00 (Skeiky et al., 2022). It is also possible that participants applied compensatory effort to protect PVT performance (Wilkinson, 1991).

7.4.5 Simulated Flight Data Measures

Airspeed during climb was significantly higher in the non-rested condition in bin 5 (500ft – 549ft), 6 (550ft – 599ft) and 7 (600ft – 649ft). As discussed previously, these results are likely due to pilots initiating actions associated with acceleration altitude (see Figure 7-2). No significant differences in model estimates between the non-rested and rested condition were identified in bins that did not include a rapid change in commanded speed. Similar results were found during go around. Given that acceleration altitude occurred above 750ft during all go around's, no 50ft altitude bins which included airspeed during the go around included a rapid change in commanded airspeed. This likely contributed to an absence of significant differences in estimates of standard deviation of differences in airspeed and commanded airspeed during go around between levels of condition.

Figure 7-2 Changes in Airspeed in Climb between 300ft and 750ft during Initial Climb [101]



Pitch variability in the climb was higher in the non-rested condition in bin 4 (450ft – 499ft), 8 (650ft – 699ft) and 9 (700ft – 749ft). Figure 7-3 illustrates that changes in aircraft pitch in relation to pitch order occur in the vicinity of 600ft along with flight crew initiating actions associated with acceleration altitude. The difference between estimates in bins 4, 8 and 9 were very small (less than 0.15deg) and are likely operationally insignificant.

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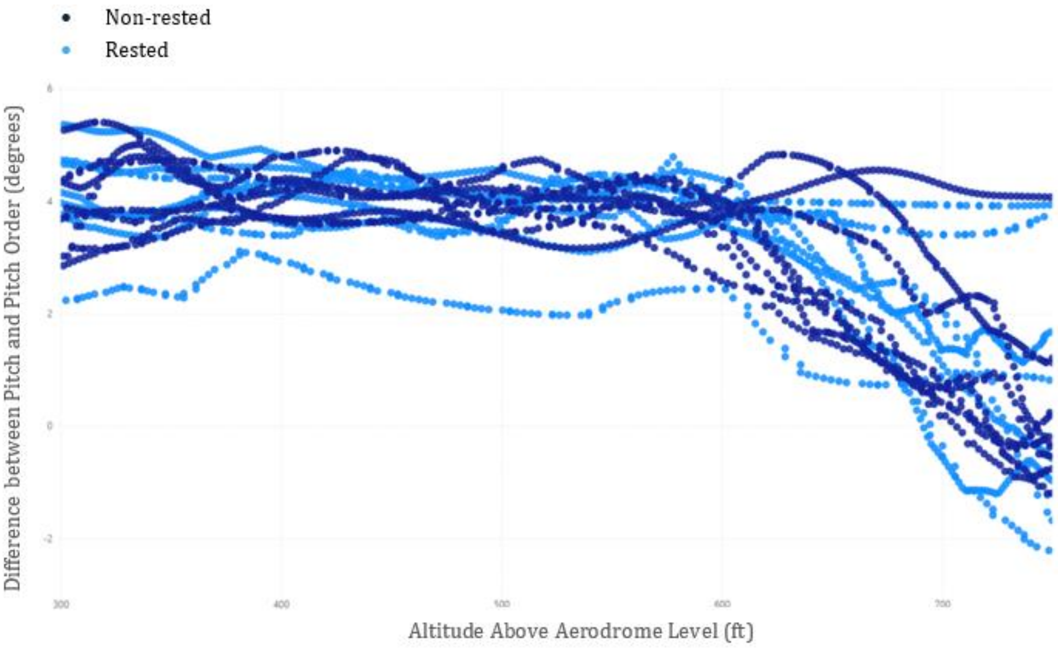
[101] This chart depicts the difference between airspeed and commanded airspeed. A positive value means the aircraft is travelling faster than the commanded airspeed.

Figure 7-3 Changes in Pitch in Climb between 300ft and 750ft during Initial Climb[102]



Variation in roll during climb was greater in the non-rested condition in bin 1 (300ft – 349ft), 3 (400ft – 449ft), 7 (600ft – 649ft), 8 (650ft – 699ft) and 9 (700ft – 749ft). Unlike airspeed and pitch during climb, where all estimates were significantly higher in the non-rested condition, for roll during climb, in bin 5 (500ft – 549ft), estimates were higher in the rested condition. Figure 7-4 illustrates that changes in aircraft roll are somewhat aperiodic and would likely represent pilot response to changes in wind speed and direction and turbulence. It does appear that a greater amount of variation in the difference between roll and roll order is undertaken by pilots in the non-rested condition in five of the nine 50ft altitude bins which could suggest that greater control movements are being made. In helicopter pilots, the amplitude of control movements increased with an increase in fatigue (Billings et al., 1968). As with pitch in climb, the difference in model estimates between the non-

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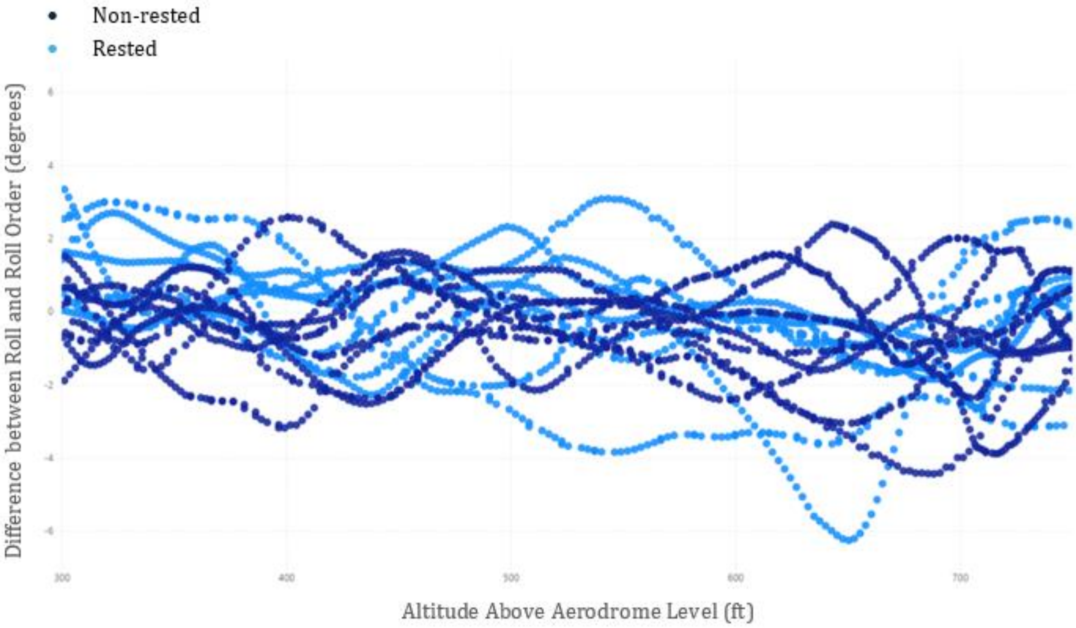
[102] This chart depicts the difference between pitch attitude and flight director pitch order. A positive value means that the aircraft pitch attitude is less than the flight director pitch order (the aircraft nose is lower than commanded).

rested and rested condition in bins 1, 3, 5, 7, 8 and 9 are very small (less than 0.23 degrees) and therefore likely to be operationally insignificant. Variation in initial climb measures was significantly higher in the non-rested condition. These results are consistent with previous research that found increases in fatigue contributed to aperiodic increases in variability in flight data measures (Hartman, 1965).

Figure 7-4 Changes in Roll in Climb between 300ft and 750ft during Initial Climb[103]



The implication of these results is that a performance decrement (i.e. increased variation) could be present during duties that meet legal requirements. However, as discussed above, the observed increase in variation is likely operationally insignificant. If participant fatigue and sleep loss within this study was similar to that of participants in simulator studies reviewed in section 1.7.3, i.e. Caldwell et al. (2004), it is likely that greater variation would be observed. Although, even then,

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[103] This chart depicts the difference between roll attitude and flight director roll order. A positive value means that the aircraft needs to roll to the right.

satisfactory performance in relation to aircraft manual handling may be retained (see section 7.3.3.2).

Simulated flight data measures during initial climb and go around were collected and analysed using identical methods. Differences in pitch and roll during climb, but not in go around measures could be a result of differences in environmental conditions or increased compensatory effort which allowed pilots to protect performance. It could also be due to differences in arousal, whereby impairment caused by the non-rested condition may have been overcome by a possible increase in arousal due to the go around procedure. Although workload did not differ significantly between levels of condition, it is possible that an increase in workload during go around in both conditions may have contributed to a reduction in measure sensitivity.

No significant differences were found between levels of condition and either auto pilot usage status measures or go around checklist measures. It is difficult to place these results in context as the studies reviewed in section 1.7 did not include these types of measures. As discussed in 7.3.3.3, to identify if checklist efficacy or autopilot usage measures are sensitive to fatigue and sleep loss, these datasets would benefit from a much larger number of flights.

As discussed above, cumulative sleep debt and post simulated flight fatigue ratings in the non-rested condition were the only sleep-related factors to suggest that the non-rested condition was more fatiguing than the rested condition. For this reason, statistical analysis was also undertaken to investigate possible associations between prior sleep timing and duration (sleep history) and simulated flight data measures.

7.5 Sleep Related Variables

This section discusses results from the analysis of sleep related variables (cumulative sleep debt, time since sleep, total sleep in 24hrs and 48hrs) independent of the non-rested and rested condition. In the non-rested condition, the minimum time away from work between duty periods was 13 hours 29 minutes. Despite this, in both conditions, some participants only achieved 6 hours 24 minutes total sleep in the 24 hour period before their simulated flight. This clearly illustrates that other factors aside from work, such as social pressure or personal choice can influence sleep related variables.

7.5.1 Fatigue and Sleepiness

Results showed that fatigue and sleepiness ratings increase with increases in cumulative sleep debt (excluding post simulated flight fatigue ratings) and that they increase with a reduction in total sleep in the previous 24 and 48 hour period. Results also showed that an increase in time since sleep were associated with a significant decrease in fatigue and sleepiness ratings. This is not consistent with studies that investigated the influence of duty time on pilot fatigue ratings (Powell et al., 2007; Spencer & Robertson, 2000) where fatigue ratings increase as duty length increases. It is possible that the time of day may have influenced ratings however this is unlikely as Ferguson et al. (2012) found that circadian time is significantly associated with pre and post sleep ratings of fatigue, and that fatigue ratings gradually increase between 12:00 and 00:00.

7.5.2 Workload

Ratings of workload were not associated with prior sleep/wake history. Workload has been significantly, but weakly correlated with sleep duration in short-haul pilots

(Arsintescu et al., 2020). It is therefore likely that the lack of association between sleep related variables and workload is due to the absence of excessive sleep loss associated with the flight duty period protocol.

7.5.3 The Effect of Fatigue and Sleepiness on Psychomotor Vigilance Task Performance

Statistical analysis was undertaken to identify if changes in ratings of fatigue and sleepiness were associated with significant changes in psychomotor vigilance task (PVT) performance. To place results in context, Van Dongen et al. (2003) found that during sleep deprivation, a decrease in PVT performance was associated with increases in sleepiness. They also found that during chronic sleep restriction, despite a decline in PVT performance, ratings of sleepiness initially increased, then stabilised with participants reporting that they felt only slightly sleepy. This suggests that during chronic sleep restriction, individuals may underestimate the impact of sleep loss on performance. A possible explanation for this is that:

> Subjects either cannot reliably introspect with regard to their actual sleepiness levels, or as long as they are receiving at least approximately 4 h of sleep nightly they do not experience a sense of sleepiness anywhere near the levels found for total sleep deprivation (Van Dongen et al., 2003, p. 124).

Results of the present study show that an increase in ratings of fatigue and sleepiness following simulated flight was associated with slower post simulated flight PVT performance. This is consistent with an observation that a general slowing of PVT response speed occurs as a result of sleep loss and increase in task duration (Basner & Dinges, 2011). Pre simulated flight fatigue and sleepiness ratings were not significantly associated with pre simulated flight PVT performance and post simulated flight ratings of fatigue and sleepiness were not significantly associated with the slowest 10% of responses. Overall, these results suggest that, in this study, there was some relationship between ratings of fatigue, sleepiness and performance (excluding the slowest 10% of responses). Given this relationship is not present before the simulated flights, it is not entirely clear why a post simulated flight association exists.

7.5.4 Psychomotor Vigilance Task Performance

Cumulative sleep debt and time since sleep were not consistently associated with PVT performance. Total sleep in 24hrs before each simulated flight, for the most part, was also not associated with PVT performance. It was associated with the slowest 10% of responses during tests before simulated flights. Results showed that an increase in total sleep in 24hrs before each simulated flight contributed to faster response speeds in the slowest 10% of responses. All other associations between total sleep in 24hrs before each simulated flight and PVT performance were not significant. As noted above, it could also reflect the possibility that PVT performance might not be a discriminating measure of fatigue related impairment in pilots (Gander et al., 2015).

For pre simulated flight PVT tests, total sleep in 48hrs was significantly associated with all PVT measures. Results suggest that an increase in sleep loss contributes to a general slowing of PVT responses which is consistent with findings from studies reviewed by Basner and Dinges (2011). As discussed previously, independent of condition, total sleep in 24hrs during day 3 was significantly lower when compared with day 4. Therefore, greater sleep loss during day 3 and the absence of sleep loss during day 4 likely contributed to an increase in sensitivity of PVT measures to total sleep in the previous 48 hour period. Although total sleep loss in the 48 hour period likely reflects sleep loss during the flight duty period protocol when sleep was restricted, we don’t know why no association was identified between cumulative sleep debt and PVT measures. As discussed above, it is possible that an unrestricted sleep during day 4 likely facilitated a full or partial recovery from sleep restriction which was not reflected within the cumulative sleep debt measure.

Despite significant associations between pre simulated flight PVT performance and total sleep in the previous 48 hour period, these associations were not significant during post simulated flight PVT tests. This is likely due to changes in post simulated flight PVT performance given that total sleep during the 48 hour period before each simulated flight was constant (no sleep occurred during simulated flights). Although statistical analysis identified no significant differences between pre and post simulated flight PVT performance, average values associated with PVT measures were all slower in tests that followed simulated flights. Understanding what may have contributed to changes in post simulated flight PVT performance is speculative. Possibilities include compensatory effort, circadian variation or that the simulated flight itself contributed to an increase in arousal.

7.5.5 The Effect of pre Simulated Flight Fatigue and Sleepiness on Simulated Flight Data Measures

To investigate if ratings of fatigue and sleepiness are reliable predictors of pilot simulator performance, statistical analysis was undertaken, see section 6.6. Although both pre and post simulated flight ratings were available, analysis was only undertaken with pre simulated flight ratings as it was unknown if arousal associated with simulated flights would influence ratings of fatigue and sleepiness.

An association between subjective fatigue and pilot performance has been previously reported (French et al., 1993; Neville et al., 1994; Perelli, 1980). For example, in C-141 air crew during flight duty periods that included extended wakefulness, Neville et al. (1994) found that, although non-significant (p = .07), an increase in subjective fatigue was associated with an increase in the variability of the airspeed flight data measure, and to a lesser extent, the heading flight data measure.

In comparable simulator studies, although changes in performance were accompanied by changes in ratings of fatigue, sleepiness and measures of mood disturbance (Caldwell et al., 2004; Foushee et al., 1986; Previc et al., 2009), it was not clear if these studies undertook analyses to investigate if ratings of fatigue or sleepiness were predictors of pilot simulator performance.

Although not directly comparable to this thesis research as the measures of performance did not reflect aircraft manual handling, nor were they derived from simulated flight data, Thomas et al. (2006) did include ratings of fatigue as an independent variable in models which assessed long-haul flight crew performance. They found that fatigue was not significantly associated with changes in flight crew threat detection, threat response and outcome, error rate, error detection or error outcome. However, they did find that an increase in fatigue contributed to increases in time taken to finalise decisions (decreased performance) and increases in cross checking (improved performance). Again, although not reflective of either performance measures or measures of fatigue and sleepiness used within this thesis research, Thomas and Ferguson (2010) investigated the influence of fatigue on short-haul pilots during normal flight operations. They found that a reduction in subjective estimates of total sleep in the previous 24 and 48 hour period was significantly associated with changes in flight crew threat and error management performance.

Although there are no directly comparable analyses to compare results from this thesis research with, findings from Thomas and Ferguson (2010) and Neville et al. (1994) show that during aircraft operation, fatigue is associated with pilot performance.

Findings from the present study show that less total sleep in 24hrs and 48hrs prior to the simulated flight, and greater cumulative sleep debt were associated with increased fatigue and sleepiness before simulated flights. As expected, less sleep contributes to higher ratings of fatigue and sleepiness. Findings also show that there is some association between how participants feel and how they function. For example, increased fatigue was associated with increased variation in pitch and roll during climb and increased sleepiness was associated with increased variation in airspeed and pitch during climb. Although the direction of these associations is meaningful, i.e. an increase in fatigue or sleepiness contributes to increased variability in performance. The relevance of the finding is questionable because the estimated change in performance because of a one unit change in fatigue or sleepiness, is very small. In addition, associations are not consistent in that fatigue or sleepiness are not associated with all initial climb measures.

An increase in ratings of fatigue and sleepiness was associated with earlier autopilot engagement following go around, earlier autopilot disengagement prior to landing and an overall reduction of autopilot usage during flight. Given that a one unit increase in either fatigue or sleepiness contributes to a change of less than 100ft in autopilot engagement or disengagement altitudes and a reduction in autopilot usage of less than 20 seconds per flight, the relevance of these findings is questionable.

7.5.6 Simulated Flight Data Measures

Time since sleep was significantly associated with airspeed and pitch in climb, but the association between time since sleep and airspeed during climb should be treated with caution given the influence of early initiation of acceleration altitude, see section 7.4.5. An increase in time since sleep was also associated with a decrease in airspeed and pitch during climb. As discussed elsewhere, time since sleep is confounded with performance during the evening wake maintenance zone. In addition, sleep deprivation studies show that aircraft manual handling performance reaches a lull in the early morning following 24 hour of extended wakefulness before improving slightly as the second day progresses (Caldwell et al., 2004; Caldwell et al., 2003). Increases in performance, despite no are a result of circadian variations in performance. Caldwell and Roberts (2000) undertook a similar simulator study where aircraft manual handling performance of UH-60 pilots was assessed during the final 23 hours of 40 hours of extended wakefulness. They found that the 01:00 flight on the second day was not considered to be influenced by fatigue caused by extended wakefulness or time of day which suggests that aircraft manual handling performance could potentially be maintained up until 01:00 before performance begins to be influenced by fatigue due to sleep loss and extended wakefulness. In a similar study, Caldwell et al. (2004) undertook a simulator study where they monitored aircraft manual handling performance of F-117 pilots during 5 flights across 37 hours of extended wakefulness (flights occurred at 23:00, 04:00, 09:00. 14:00 and 19:00). They found that when compared with baseline performance, aircraft handling performance deteriorated during flights between 23:00 to 09:00, performance then remained poor during flights between 09:00 to 14:00 then recovered slightly at 19:00 (although not to baseline). Thus, aircraft manual handling performance improved at 19:00 despite near 37 hours of extended wakefulness. Stolze (1971) also identified that pilot performance was almost constantly high during the late afternoon.

This suggests that flights at this time of day (19:00) are likely associated with improved levels of aircraft manual handling performance. When considering changes in performance as a result of time of day and time since sleep, in their sleep deprivation study Previc et al. (2009) identified that a 25% decrement in aircraft handling performance occurred from baseline performance. Between 12:30 and 21:30 performance increased by 10%, between 21:30 and 09:30 the following day, performance decreased by 25%, then between 09:30 and 12:30, despite extended wakefulness, performance increased by 15%. This also illustrates that within a three hour period, relative to baseline, changes of up to 20% can occur and that between 18:30 and 21:30, performance, relative to baseline, increased by 6%. The implication of this is that, in the present study, pilot performance during the session at 20:00 could potentially be better than performance during the session at 18:00 due to circadian variations in performance.

Results showed that for each one hour increase in time since sleep, estimates of airspeed and pitch in climb was in the vicinity of 0.2kts and 0.030 deg. It would be interesting to know if these estimates would be greater if the simulated flights were conducted at a different time of day or following greater amounts of sleep loss. When considering autopilot status measures, a one hour increase in time since sleep was associated with an increase in autopilot engagement altitude of 72ft following go around. To put autopilot status results in context, there were 16 take off’s, 15 go arounds and 16 participants. In addition, there was only one datapoint for each autopilot status measure as opposed to between 10 and 30 values per 50ft altitude bin for initial climb and go around measures. Given that autopilot status measures have no target associated with autopilot engagement or disengagement, variation in these measures reflects pilot discretion. Because of this, autopilot status measures would benefit from a much larger dataset (see section 7.3.3.3).

An increase in total sleep in 24hrs and 48hrs before each simulated flight was associated with an increase in time taken to re-engage the autopilot following an un-commanded autopilot disconnection. It is unusual for the autopilot to automatically disengage and when it does, it is normally indicative of a non-normal situation. At face value, the measure appears to represent real-world vigilance where the assumption is that pilots would re-engage the autopilot as soon as practical. The average time to re-engage the autopilot was 10.4 seconds (min = 3.2 seconds, max = 28.5 seconds) which suggests that pilots were likely considering if it was appropriate to re-engage the autopilot. This illustrates that other factors (aside from alertness) will likely also influence the speed in which the autopilot is re-engaged. However, it is also possible that with greater sleep loss, pilots will re-engage the autopilot sooner to free up cognitive resources, i.e., to reduce workload sooner. In addition, these events will not occur during every flight and may occur during any flight phase. As discussed above, the autopilot re-engagement measure following an un-commanded autopilot disconnection would likely benefit from a much larger dataset to further investigate this association.

An increase in time since sleep (which coincides with increasing alertness associated with the evening wake maintenance zone) was associated with an increase in time taken to complete the go around/missed approach procedure (of between 16 and 24 seconds). It is unknown if these associations are operationally significant. As discussed elsewhere, further analysis of this measure would benefit from a much larger dataset. In addition, focus should be placed on a checklist that occurs during every flight (e.g. the approach checklist) rather than the go around checklist which may only occur during one in 340 flights (Tzvetomir & Curtis, 2017) or once or twice per year from a pilot's perspective.

Results show that an increase in time since sleep likely contributed to an increase in performance which reduced variability in some initial climb measures. This is consistent with findings reported in similar studies (Previc et al., 2009).

7.6 Factors that Contribute to Fatigue

Neither sleep related variables nor the condition, location or order of simulated flights were associated with workload. It is unknown if fatigue and sleepiness are associated with workload, or if workload is associated with PVT performance, as these analyses were not undertaken within this thesis research. However, workload reported by participants during flight duty periods was consistent with workload reported at top of descent by short-haul pilots in a study by Arsintescu et al. (2020). However, workload during simulated flights (estimate = 40) was significantly higher than workload during flight duty periods (estimate = 33). A factor which likely contributed to this was that each simulated flight included a go around which is a recognised time of high workload for pilots (Tzvetomir & Curtis, 2017). In the second trial simulated flight, one of the participants said that "the first 75% of it was just a normal flight I guess, you know, just the standard thing the ATC or um TCAS if you, if you got one but yeah, the last 25% was defiantly um heavy workload" (Small group discussion 4). Given this participant's recollection, it would be interesting to know what influence the go around had on workload ratings at the end of the flight, it is not possible to determine this. Another factor that could contribute to higher workload during simulated flight is compensatory effort to protect performance.

For a number of reasons, pilots are likely to place considerable emphasis on performance during simulated flights given that activities within the simulator often involve assessment. The lack of a clear cut-off for the NASA-RTLX means that it is unknown if participants felt that workload, at times, was too high during each simulated flight.

When considering the scenarios (see section 3.8), and their likely contribution to overall workload, aside from the go around, the only other scenario that could have potentially contributed to an increase in workload over and above that expected during routine flights, was the scenario excess energy during approach. However, this is unlikely because this scenario was incomplete[104]. Given that only the Wellington – Christchurch simulated flight included an excess energy during approach scenario, and that workload was not significantly different between the Christchurch – Wellington or Wellington – Christchurch simulated flight, this would suggest that either the scenario did not contribute to differences in workload between the two flights or that the single workload measure during each flight did not reflect increased workload associated with this scenario.

In comparable simulator studies, only Foushee et al. (1986) included a subjective measure of workload and it was not clear if they undertook analyses to investigate if ratings of workload were associated with pilot simulator performance. Therefore, there are no analyses to compare results from this thesis research with. However, results from this study show that during go around, increased workload was associated with a reduction in roll variation, a lower auto pilot engagement altitude and an increase in time taken to complete the go around/missed approach

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[104] Although the height restriction during approaches into Christchurch was complied with, the speed restriction during approaches into Wellington was not complied with (see section 6.4.1.2).

procedure. In addition, autopilot utilization over the entire flight reduced. The extent of these differences does need to be considered. For example, a 10 unit increase in workload would result in the autopilot being engaged two or three seconds earlier and overall auto pilot usage during the flight would decrease by 15 seconds. These results suggest that workload is unlikely to contribute to operationally significant performance decrements in these simulated flight data measures. This is inconsistent with what is known about workload and its effect on pilot performance. For example, "safety depends upon reducing human error. Human error depends upon both the amount and stability of workload. Since the jet aircraft presents variable amounts of workload at variable times, there is ample opportunity for pilot error" (Kantowitz & Casper, 1988, p. 125).

It acknowledged that workload varies during flight (Gander et al., 1994), therefore it is unknown if a single post flight workload measure can be applied to simulated flight data measures that occur at different points during flight during different levels of workload. This represents a limitation of this research. Future research should focus on capturing workload associated with each scenario as opposed to each flight to remove the effect that other scenarios may have on levels of workload.

7.7 Limitations

Findings must be treated as preliminary and interpreted with caution as formal power calculations were not undertaken (Lancaster et al., 2004) and therefore the null findings may be due to insufficient statistical power. To minimise the effect of insufficient statistical power, the number of participants recruited was consistent with the number of participants recruited in similar studies. For example, Caldwell and Caldwell (1997) recruited 12 UH-60 pilots, Leino et al. (2007) recruited 13 Bae

Hawk Mk 51 pilots and Previc et al. (2009) recruited 10 T-6 pilots. In addition, a within-subjects research design was employed and systemic bias was considered by counter balancing and the inclusion of order and location within statistical models.

Participants self-selected to participate in this study; a potential limitation with self-selection (as opposed to random selection) is that a participant's motivation to participate may influence the generalisability of findings. Flight duty periods were also not experimentally controlled, so a range of factors would have contributed to variations in key sleep, fatigue and sleep quality variables from one flight duty period to the next.

Data loss is not likely to be a limitation as all datasets were complete, aside from a small number of missing responses within the sleep/duty diary and a small amount of data loss associated with simulated flight protocol scenarios. Findings showed that workload during simulated flights was higher than workload during flights. Although it is likely that the inclusion of a go around during each simulated flight contributed to this finding, it is possible that other factors contributed to higher workload during simulated flights It is not clear if it is appropriate to use a rating of workload which covers an entire flight, as a measure of workload during a scenario that occur during a specific part of the flight.

There are both weaknesses and strengths associated with using actigraphy to record sleep. A key limitation is the ability of the actigraph to distinguish between being asleep and being awake but not moving. To account for this, best practice methods were used to record this data. This included asking participants to press a button ("event marker") on the device when they started trying to sleep and when they stopped trying to sleep and scoring data in conjunction with information from their sleep/duty diary. A limitation associated with the calculation of cumulative sleep debt was that the flight duty period protocol did not include planned baseline sleep days. It is therefore not known if the methods used for determining baseline sleep days were reflective of a participant's true baseline sleep need or if baseline sleep included recovery sleep. In addition, by including abnormal baseline sleep periods for three participants, there is a possibility that cumulative sleep debt, for those participants could be under or overestimated.

Lapses were not included as a dependent variable on the basis that, after 12 hours of wakefulness, PVT responses are likely to be maintained at a relatively fast and consistent level with few false starts (errors of commission) or lapses in attention (Doran et al., 2001). However, it is not known if participants experienced lapses in attention during PVT tests.

Due to differences in regulations, standard operating procedures, training programmes and differences in organisational culture, findings may not be generalisable to different aircraft types, operators or aircraft operations in other geographic locations or in other settings (e.g. military aviation). It is also possible that pilots may fly the simulator differently from how they would fly the actual aircraft. Extrapolation of simulator data to actual flights must be approached with caution as proficiency in one, does not necessarily imply equal proficiency in the other (Billings et al., 1975).

Research into circadian effects on pilot manual handling measures has illustrated variations in pilot manual handling performance throughout the day (Caldwell et al., 2004) and that over a three hour period, at a similar time of day to the non-rested (18:00 – 20:00) and rested (20:00 – 22:00) simulated flight, Previc et al. (2009) identified an increase in performance, relative to baseline of 6%. The difference in timing between the non-rested and rested simulated flight of two hours could contribute to a slight improvement in performance during the rested simulated flight. In addition, findings may not be generalisable if applied to flights that occur at different times during the day.

The operational significance of findings in relation to initial climb and go around simulated flight data measures is not known as the mean, median and range of initial climb and go around measures was not reported on. When interpreting findings from the analysis of simulated flight data, without flight crew input, it will not be possible to discuss why flight crew made a particular decision.

Given that a higher degree of measurement sensitivity exists within the simulated environment (Caldwell & Roberts, 2000) it is uncertain if findings from this thesis research are generalisable to normal flight operations. The limitation is not as a result of the simulated flight protocol or the simulator. Rather, it is due to the presence of noise within normal flight operations which is likely to mask the influence of fatigue on pilot performance.

Due to collinearity, multiple statistical models were required for each dependent variable. In instances where only one of the models resulted in a significant finding, that model's results should be treated with caution.

7.8 Feasibility

This study has established processes and methods that will save considerable time in future research. A similar study could likely be completed within a shorter timeframe, if the operator can access flight data, is committed to prioritising the flight duty period protocol and that simulator slots can be reserved. A study such as this is feasible, however consideration should be given to factors that may contribute to the study becoming difficult to initiate or complete. These factors could potentially include work force management (planning and rostering) constraints, simulator availability, SOQA software configurability, discussion associated with the establishment of flight data agreements, participant recruitment, organisational / safety culture and the availability of key individuals (e.g., change of role or circumstance, redundancy, resignation). These factors represent a risk to study initiation and/or completion and should be subject to risk assessment (identification of risk controls) during regular risk reviews. In addition, a maturity assessment of factors before study initiation could help determine how robust each of these factors are (in isolation or combination) and if any additional effort is required before committing to a study timeline. Initiating and maintaining a project reference group is an important aspect of ensuring that there are no surprises and that the study can progress as planned.

7.9 Future Research

Further research could consider performance when simulated flights are undertaken at a different time of day and/or when sleep is restricted to a greater extent than that observed within this study. To achieve a greater extent of sleep loss in future studies, rather than relying on the selection of potentially fatiguing flight duty periods which might contribute to sleep restriction in an ad hoc way, flight duty periods in the non-rested condition should be controlled to a greater extent.

An alternative to controlling flight duty periods within the non-rested condition, although likely impractical due to workforce availability, would be to control the duration of sleep periods. The benefit of controlling the duration of a sleep period is that many extraneous variables that contribute to variation in the timing and duration of sleep can be removed within a laboratory environment. Further research could also consider incorporating simulated flight data measures from this study within a FOQA programme and/or a SOQA programme which monitors evidence based training simulator details. This would provide an opportunity to capture a far greater number of flights/simulated flights. However, a key consideration must involve identifying how measures of fatigue and sleep loss can be obtained from a far greater number of participants. One option could involve participants recording ratings of fatigue, sleepiness and workload[105] at specified points (e.g. start of duty, end of duty or at a particular point) during routine simulator sessions that are part of the operators training programme. In the operational environment, ratings of sleep related variables, fatigue, sleepiness and workload could be collected during duty using a sleep/duty or via a survey. If relying on participants to provide data, consideration would need to be given to the burden of data collection. Rather than relying on pilots to enter data, consideration should be given to extracting measures of fatigue or sleep loss data automatically from a bio mathematical model or a roster and scheduling database. Consideration will also need to be given to how measures of fatigue and sleep loss can be aggregated to represent fatigue levels of the crew rather than an individual pilot. The influence of other extraneous variables should also be considered and thought given to the ability to derive these variables (e.g. wind velocity and direction and turbulence level) from recorded flight data and include these within the analysis of performance data.

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[105] To reduce participant burden, the overall workload scale should be considered as it is simple, quick to complete, is validated (Vidulich & Tsang, 1987) and has been used in commercial aviation studies (van den Berg et al., 2023).

Given the association between simulated flight data measures and PVT performance was not investigated in the present study, it is unknown if PVT performance is associated with simulated flight data measures. Consideration should be given to investigating this association in future research given that PVT mean reciprocal reaction time has previously been identified as a reliable predictor of pilot simulator performance (Lopez et al., 2012).

Statistical analyses were not undertaken for checklist sequence measures due to limited variability. There could be merit in the investigation of checklist sequence and timing variation using a much larger dataset. For example, combining checklist sequence data sourced from a FOQA or SOQA programme with a measure of fatigue sourced from a sleep/duty diary or a survey, roster metric or bio mathematical model predictions as discussed above.

Future research should focus on capturing workload associated with each scenario as opposed to each flight to remove the effect that other scenarios may have on levels of workload.

7.10 Recommendations

Results from this research illustrate that the flight duty period protocol and the simulated flight protocol were achievable within a live operational environment and the accuracy of measurement associated with simulated flight data analysis is sufficient to warrant further investigation into the influence of fatigue and sleep loss on simulated flight data measures. The following recommendations highlight items that may guide and shape future research and, in some cases, represent lessons learnt during this thesis research.

Flight Duty Period Protocol

Focus must be placed on designing a flight duty period protocol that is likely to create systematic differences in levels of fatigue between the non-rested and rested condition. This can be achieved by carefully considering the nature of rest periods between duties in the non-rested condition to ensure that rest periods before the non-rested simulated flight do not offer participants an opportunity to recover from sleep loss. Given the focus of this thesis research was on regional airline pilots, conceivably this limits flight duty periods to a start time of no earlier than 05:00 and an end time of no later than 22:00. Given that duties with early start times (05:30) are associated with reduced sleep duration (6.8 hours) compared to duties with late start times (10:30 – 12:30) that have increased sleep duration (8.6 hours) (Rokicki et al., 1981), particular focus should be placed on the selection of flight duty periods with early start times. This is because flight duty periods flown by regional airline pilots often finish before 22:00 as opposed to short-haul jet operations where flight duty periods may finish later. The focus on duties with early start times is consistent with the causes of fatigue within regional airline pilots which includes restricted sleep due to short rest periods and early report times, multiple high workload periods during the flight duty period, multiple sectors and long duty days (Gander et al., 1994).

Different types of aircraft operation (i.e. back of the clock short-haul jet operations or long-haul operations) have different causes of fatigue (Gander, Gregory, Graeber, et al., 1998). The flight duty period protocol within this study could be easily adapted to focus on flight duty periods that occur at different times of the day (i.e. back of the clock), or that are considerably longer. If the intention is to assess operational levels of fatigue, consideration would need to be given to the legality of flight duty periods which include simulated flights in respect to flight and duty time limitations.

Flight duty periods should be controlled to ensure that the causes of fatigue within the flight duty period protocol are consistent between flight crews. This would remove ambiguity regarding flight crew that have different flight duty periods prior to a simulated flight. Consideration should be given to controlling the timing and duration of sleep opportunities if possible.

The circadian cycle contributes to variation in pilot performance. To account for this, the non-rested and rested simulated flights should start at the same time of day.

To ensure the accurate calculation of cumulative sleep debt, planned baseline sleep days should be incorporated within the flight duty period protocol. In addition, consideration should be given to excluding very short or very long baseline sleep periods to avoid abnormal baseline sleep durations which could contribute to inaccurate calculation of cumulative sleep debt (Gander et al., 1994). Consideration should be taken to capture additional days of recording before or following flight duty periods to ensure adequate baseline data for comparison.

Simulated Flight Protocol

Focus should be placed on recording and validating all required flight data variables (parameters) within the SOQA (or FOQA) programme. Parameter validation can be achieved by trialling the simulated flight protocol before the start of data collection. If using FOQA data, specific queries should be developed to identify instances that can validate parameters during routine flight operations or tests should be conducted to check parameter behaviour.

Focus should be placed on recording extraneous variables because multiple factors contribute to variation in pilot performance, e.g., cross wind, turbulence or runway location.

The simulated flight protocol should be trialled before data collection starts. This offers an opportunity to ensure that the simulated flight protocol checklist (e.g. see APPENDIX U) is fit for purpose and that the simulator instructor is familiar with protocol requirements.

To maximise measurement sensitivity, the simulated flight protocol should include scenarios that exclude non-pilot-related deviations(i.e. the exclusion of weather and environmental factors).

If multiple simulated flights are undertaken, considerable effort must be taken to ensure that the scenarios are as similar as practical, and that the simulator instructor(s) follows a specific set of instructions to improve consistency.

Consideration should be given to providing simulator training sessions to pilots for specific scenarios ahead of the non-rested or rested simulated flight to remove the likelihood of carryover effects.

<u>Data Handling and Analysis</u>

To understand how performance changes over time, consideration should be given to the simplicity of averaging data between two points (i.e. 300ft – 750ft) versus including multiple comparisons between those two points (i.e. 50ft altitude bins). Not all scenarios will require additional comparisons therefore careful consideration is required.

Consideration should be given to the function associated with each simulated flight data metric. In this study, the function associated with initial climb and go around measures was the standard deviation of the mean. For movement related measures, alternative functions should be considered. These could include root mean square error, mean, minimum or maximum values, the rate of change of values, the maximum value sustained for n seconds or the count of instances where a value exceeds an upper or lower threshold for n seconds. For (simulated) flight data measures, consideration should be given to calculating the standard deviation of a parameter in scenarios where increased variation is likely (i.e. variation in airspeed while flying an approach from 5000ft). Whereas the root mean square error should be calculated if scenarios are tightly defined (i.e. variation in roll while maintaining an altitude and turning the aircraft left through 270 degrees, at three degrees per second).

7.11 Conclusion

To support the use of simulator flight data in field settings, it was necessary to have an agreement with Pilot Unions regarding access to data. It was also necessary to have support from the operator to recruit participants, to implement the flight duty period protocol within both the published and live roster, to reserve simulator slots and to purchase and configure a SOQA programme. This activity was coordinated through the establishment of a project reference group consisting of Pilot Union representatives, Fleet Management, Flight Operations Management, Standards and Training Management and the researcher’s supervisory team at Massey University. Ultimately, collaboration between the Pilot Unions, the Operator and Massey University facilitated access to simulated flight data and the completion of this research illustrates that it is both feasible and possible to conduct a study like this within a field setting.

The influence of the flight duty period protocol on sleep related variables clearly illustrates that cumulative sleep debt can rapidly accumulate due to restricted sleep. It also illustrates that an unexpected extended rest period prior to the non-rested simulated flight likely resulted in the failure of the flight duty period protocol to produce systematic differences in fatigue levels between the non-rested and rested condition. In addition, the challenge associated with changing flight duty periods once published illustrates the inherent difficulty in manipulating pilot flight duty periods within an operational setting.

Key findings suggest that the non-rested condition contributed to a small increase in variability of pitch and roll measures during initial climb and that an increase in time since sleep during a period of increasing alertness contributed to reduced variation in pitch during climb. To determine if these findings are repeatable, a key recommendation is that this study is repeated, albeit with simulated flights timed at a time of greater circadian performance vulnerability in combination with a flight duty period protocol where flight duty periods are controlled.

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APPENDICES

APPENDIX A ETHICS APPROVAL LETTER

MASSEY
UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Date: 18 November 2016

Dear Cameron Dyer

Re: Ethics Notification - **SOA 16/64 - Evaluation of Simulated Flight Data Events as a Measure of Fatigue Risk in Operational Settings**

Thank you for the above application that was considered by the Massey University Human Ethics Committee: **Human Ethics Southern A Committee** at their meeting held on **Friday, 18 November,**

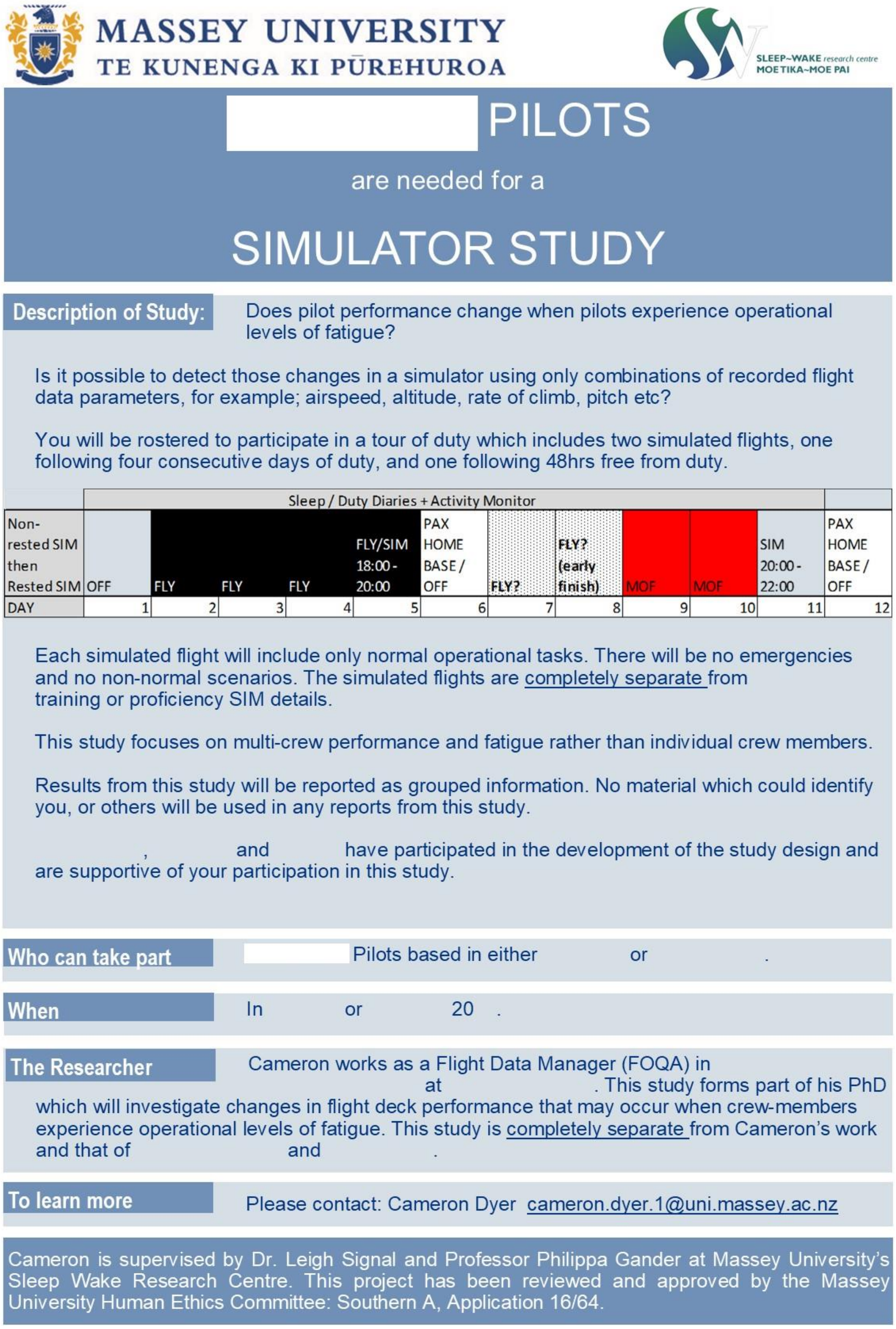
Approval is for three years. If this project has not been completed within three years from the date of this letter, reapproval must be requested.

If the nature, content, location, procedures or personnel of your approved application change, please advise the Secretary of the Committee.

Yours sincerely

Dr Brian Finch
Chair, Human Ethics Chairs' Committee and Director (Research Ethics)

APPENDIX B PARTICIPANT RECRUITMENT ADVERTISEMENT



MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

SLEEP~WAKE research centre
MOETIKA~MOE PAI

[redacted] PILOTS

are needed for a

SIMULATOR STUDY

Description of Study: Does pilot performance change when pilots experience operational levels of fatigue?

Is it possible to detect those changes in a simulator using only combinations of recorded flight data parameters, for example; airspeed, altitude, rate of climb, pitch etc?

You will be rostered to participate in a tour of duty which includes two simulated flights, one following four consecutive days of duty, and one following 48hrs free from duty.

	Sleep / Duty Diaries + Activity Monitor											
Non-rested SIM then Rested SIM	OFF	FLY	FLY	FLY	FLY/SIM 18:00 - 20:00	PAX HOME BASE / OFF	FLY?	FLY? (early finish)	MOF	MOF	SIM 20:00 - 22:00	PAX HOME BASE / OFF
DAY	1	2	3	4	5	6	7	8	9	10	11	12

Each simulated flight will include only normal operational tasks. There will be no emergencies and no non-normal scenarios. The simulated flights are completely separate from training or proficiency SIM details.

This study focuses on multi-crew performance and fatigue rather than individual crew members.

Results from this study will be reported as grouped information. No material which could identify you, or others will be used in any reports from this study.

, and have participated in the development of the study design and are supportive of your participation in this study.

Who can take part [redacted] Pilots based in either or .

When In or 20 .

The Researcher Cameron works as a Flight Data Manager (FOQA) in at . This study forms part of his PhD which will investigate changes in flight deck performance that may occur when crew-members experience operational levels of fatigue. This study is completely separate from Cameron's work and that of and .

To learn more Please contact: Cameron Dyer cameron.dyer.1@uni.massey.ac.nz

Cameron is supervised by Dr. Leigh Signal and Professor Philippa Gander at Massey University's Sleep Wake Research Centre. This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 16/64.

APPENDIX C INFORMATION SHEET

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

EVALUATION OF SIMULATED FLIGHT DATA EVENTS AS MEASURES OF FATIGUE RISK
INFORMATION SHEET

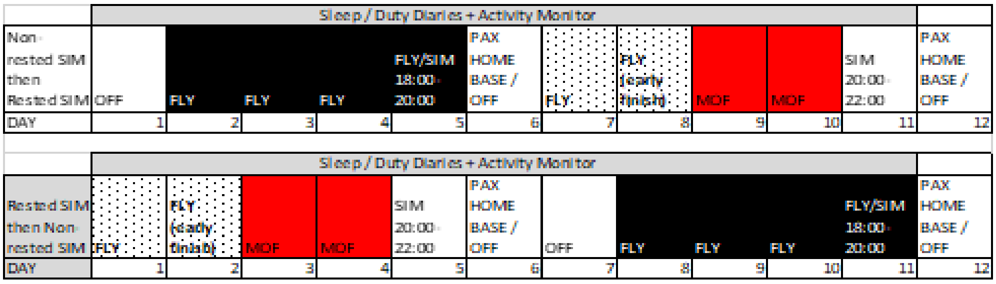
You are invited to take part in a simulator based study to investigate if fatigue related changes in flight deck performance can be detected during simulated flight. This study forms part of Cameron Dyer's doctoral research which will investigate changes in flight deck performance that may occur with fatigue. He is supervised by Associate Professor Leigh Signal and Professor Philippa Gander from Massey University's Sleep/Wake Research Centre (SWRC) in Wellington. Cameron is employed by and works in as Flight Data Manager FOQA. This study is both separate and independent from his role at .

ABOUT THE STUDY

Despite a relatively large body of knowledge on the relationship between fatigue and performance, currently little is known about how fatigue might impact complex, multi-crew performance. Its impact on flight crew performance has been measured in previous simulator based studies but to our knowledge this will be the first time that events derived from simulated flight data will be used to identify if fatigue related changes in flight deck performance are detectable in a simulated environment.

You will be rostered to participate in two simulated flights in an simulator in . The simulated flights are completely separate from training and proficiency details. Each simulated flight will involve a routine flight of 1hr duration. One simulated flight will occur immediately following duty on the last day of a flight duty pattern which includes four consecutive duty days (the non-rested SIM) and the other simulated flight will occur following two consecutive days free from duty (the rested SIM). You will operate either a rested or non-rested simulated flight first.

SIMULATOR STUDY PROTOCOL



	Sleep / Duty Diaries + Activity Monitor											
Non-rested SIM then Rested SIM	OFF	FLY	FLY	FLY	FLY/SIM 18:00-20:00	PAX HOME BASE / OFF	FLY	FLY (early finish)	MOF	MOF	SIM 20:00-22:00	PAX HOME BASE / OFF
DAY	1	2	3	4	5	6	7	8	9	10	11	12

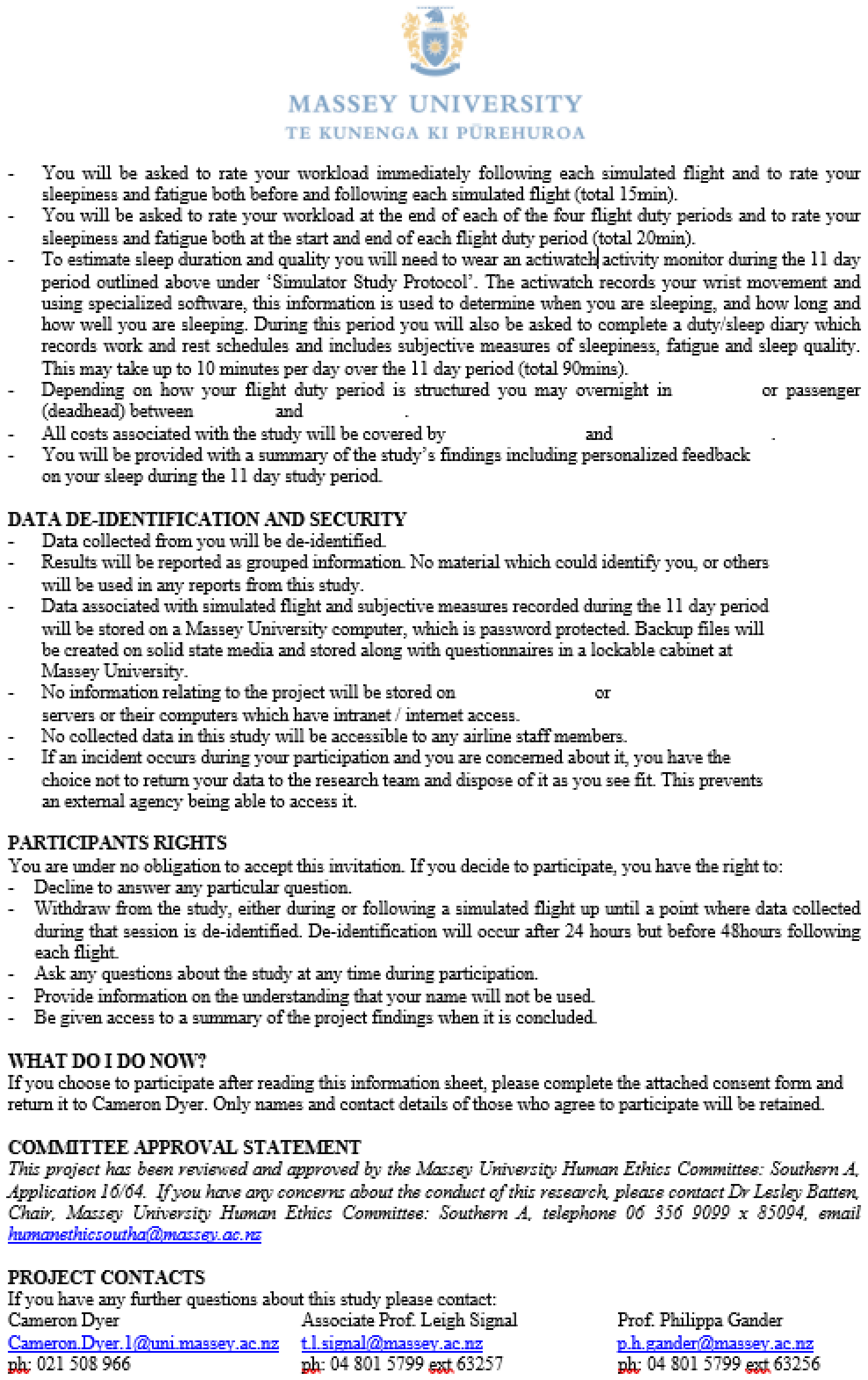
	Sleep / Duty Diaries + Activity Monitor											
Rested SIM then Non-rested SIM	FLY	FLY (early finish)	MOF	MOF	SIM 20:00-22:00	PAX HOME BASE / OFF	OFF	FLY	FLY	FLY	FLY/SIM 18:00-20:00	PAX HOME BASE / OFF
DAY	1	2	3	4	5	6	7	8	9	10	11	12

WHO CAN TAKE PART?

16 pilots will be invited to participate in the study. Once 8 Captains and 8 First Officers have agreed to participate, recruitment will stop.

WHAT CAN YOU EXPECT IF YOU TAKE PART?

- You will be asked to complete a short demographic questionnaire on sleep, age, gender, rank and work experience. (total 5min).
- You will be asked to complete a 5 minute reaction time test when picking up your study pack to familiarize yourself with the test, then once before each simulated flight (total 15min).
- Each simulated flight will occur in the simulator at Airport and will not exceed 1hr (total 2 hours).
- Simulated flight data parameters for each simulated flight will be retained for analysis purposes.
- The brief debrief station (BDS) file which includes a recording of aircraft instrumentation from each simulated flight will be retained for analysis purposes. All other recordings from the BDS file will be deleted.



MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

- You will be asked to rate your workload immediately following each simulated flight and to rate your sleepiness and fatigue both before and following each simulated flight (total 15min).
- You will be asked to rate your workload at the end of each of the four flight duty periods and to rate your sleepiness and fatigue both at the start and end of each flight duty period (total 20min).
- To estimate sleep duration and quality you will need to wear an actiwatch activity monitor during the 11 day period outlined above under 'Simulator Study Protocol'. The actiwatch records your wrist movement and using specialized software, this information is used to determine when you are sleeping, and how long and how well you are sleeping. During this period you will also be asked to complete a duty/sleep diary which records work and rest schedules and includes subjective measures of sleepiness, fatigue and sleep quality. This may take up to 10 minutes per day over the 11 day period (total 90mins).
- Depending on how your flight duty period is structured you may overnight in or passenger (deadhead) between and .
- All costs associated with the study will be covered by and .
- You will be provided with a summary of the study's findings including personalized feedback on your sleep during the 11 day study period.

DATA DE-IDENTIFICATION AND SECURITY

- Data collected from you will be de-identified.
- Results will be reported as grouped information. No material which could identify you, or others will be used in any reports from this study.
- Data associated with simulated flight and subjective measures recorded during the 11 day period will be stored on a Massey University computer, which is password protected. Backup files will be created on solid state media and stored along with questionnaires in a lockable cabinet at Massey University.
- No information relating to the project will be stored on or servers or their computers which have intranet / internet access.
- No collected data in this study will be accessible to any airline staff members.
- If an incident occurs during your participation and you are concerned about it, you have the choice not to return your data to the research team and dispose of it as you see fit. This prevents an external agency being able to access it.

PARTICIPANTS RIGHTS

You are under no obligation to accept this invitation. If you decide to participate, you have the right to:

- Decline to answer any particular question.
- Withdraw from the study, either during or following a simulated flight up until a point where data collected during that session is de-identified. De-identification will occur after 24 hours but before 48hours following each flight.
- Ask any questions about the study at any time during participation.
- Provide information on the understanding that your name will not be used.
- Be given access to a summary of the project findings when it is concluded.

WHAT DO I DO NOW?

If you choose to participate after reading this information sheet, please complete the attached consent form and return it to Cameron Dyer. Only names and contact details of those who agree to participate will be retained.

COMMITTEE APPROVAL STATEMENT

This project has been reviewed and approved by the Massey University Human Ethics Committee: Southern A, Application 16/64. If you have any concerns about the conduct of this research, please contact Dr Lesley Batten, Chair, Massey University Human Ethics Committee: Southern A, telephone 06 356 9099 x 85094, email humanethicsoutha@massey.ac.nz

PROJECT CONTACTS

If you have any further questions about this study please contact:

Cameron Dyer	Associate Prof. Leigh Signal	Prof. Philippa Gander
Cameron.Dyer.1@uni.massey.ac.nz	t.l.signal@massey.ac.nz	p.h.gander@massey.ac.nz
ph: 021 508 966	ph: 04 801 5799 ext 63257	ph: 04 801 5799 ext 63256

APPENDIX D CONSENT FORM

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

EVALUATION OF SIMULATED FLIGHT DATA EVENTS AS MEASURES OF FATIGUE RISK

CONSENT FORM

- I have read the Information Sheet and have had the details of the study explained to me. My questions have been answered to my satisfaction, and I understand that I may ask further questions at any time.
- I agree to participate in this study under the conditions set out in the Information Sheet.
- I agree to SOQA information being collected during both simulator sessions.
- I agree to participate on the basis that this agreement any my participation in the simulator session is subject to the terms of the Temporary Agreement Relating to Simulator Operational Quality Assurance System Agreement between , and Cameron Dyer [1st August 2017]

Signature: .... **Date:** ....

Full Name - printed ....

APPENDIX E CUSTOMISED EVENTS

Event name
The altitude when the wind direction is 240M and wind velocity >= 15kts ex CHC
Altitude when wind direction is 240M ex CHC
Altitude when wind velocity >= 15kts ex CHC
Wind component at 500ft ex CHC
Wind Component at 2000ft ex CHC
The altitude when the wind direction is 300M and wind velocity >= 15kts ex WLG
Altitude where wind direction is 300M ex WLG
Altitude where wind velocity >= 15kts ex WLG
Wind component at 2500ft ex WLG
Wind component at 4000ft ex WLG
Duration Airborne
Runway distance used at unstick during take off
Runway distance remaining at unstick during take off
Time at recording end
Time at recording start
Weather condition at end of landing
Weather condition at start of take off
Weight at recording start
Wind direction at 2000ft during climb
Wind direction at 2000ft during descent
Wind direction at start of cruise
Wind direction at end of cruise
Wind speed at 2000ft during climb

Event name
Wind speed at 2000ft during descent
Wind speed at start of cruise
Wind speed at end of cruise
Altitude when go around is initiated
Distance to centreline when go around is initiated
Go around start and end points
Distance to centreline at initial climb start
Distance to centreline at initial climb end
Distance to centreline at 10ft RALT prior to landing
Distance to centreline at landing start and end
Distance to centreline at 10ft RALT following take off
The point when the aircraft is on approach at 1000ft
The point when the aircraft is on approach at 500ft
The point when the aircraft unsticks from the runway during take off
The point when the aircraft contacts the runway during landing
The point when the aircraft is at 2000ft during go around
The point when either the auto pilot is engaged, or the aircraft reaches 2000ft during go around
The point when the auto pilot is engaged during go around
The point when the aircraft is at 1000ft during initial climb
The point when the after take off checklist is completed, following take off
The point when bleeds are on, following take off
The point when both power levers are in the notch, following take off
The point when PWR MGT CLB is selected, following take off
The point when SPEED is displayed on the primary flight display, following take off
The point when the auto pilot is disconnected before go around
The point when flap is retracted during go around

Event name
The point when the go around push button is pressed during go around
The first instance when pitch is greater than 5 degrees during go around
The point when gear is retracted during go around
The point when go around torque is set
The point when go around is no longer displayed on the primary flight display following go around
The point when heading hold is no longer displayed on the primary flight display following go around
The point when heading selected lo is displayed on the primary flight display following go around
The point when IAS is displayed on the primary flight display following go around
The point when LNAV is displayed on the primary flight display following go around
The point when the aircraft stops descending before go around
Vertical speed at the point when the aircraft stops descending before go around
At the point of go around initiation, what was the selected altitude
At the point of go around, what was the selected speed
At the point of go around, what was the target torques
At the point of go around, what was the white bug speed
When flap was retracted during go around, what was the airspeed
When flap was retracted during go around, what was the altitude
The point when the aircraft is 1000ft above decision altitude during approach
The point when the missed approach altitude is selected during approach
The point when landing flap is selected during approach
The point when landing flap is achieved during approach
The point when the aircraft is at 170knots during approach
The point when the aircraft is at 150knots during approach
The point when the landing gear is selected down during approach
The point when the landing gear is down during approach

Event name
The point when the aircraft meets stable gate criteria during approach
The point when the approach push button is pressed during approach
The point when GS* (glide slope capture) is displayed on the primary flight display during approach
The point when GS is displayed on the primary flight display during approach
The point when LOC* (localiser capture) is displayed on the primary flight display during approach
The point when LOC is displayed on the primary flight display during approach
Altitude when airspeed is stable during approach
The altitude when engine anti icing is selected off during descent
The point when airframe is selected off during descent
The altitude when engine anti icing is selected om during descent
The point when airframe is selected on during descent
The altitude when engine anti icing is selected off during climb
The point when airframe is selected off during climb
The altitude when engine anti icing is selected on during climb
The point when anti icing horns and props is selected off during descent
The point when anti icing horns and props is selected on during descent
The point when anti icing horns and props is selected off during climb
The point when anti icing horns and props is selected on during climb
Amber icing condition duration during descent
Amber icing condition duration during climb
Icing condition duration during descent
Icing condition duration during climb
The altitude when the total air temperature is less than 7 deg C during climb
The altitude when the total air temperature is greater than 7 deg C during descent
The point when the auto pilot is disengaged before go around

Event name
The point when the auto pilot is engaged following go around
Auto pilot disengagement altitude prior to landing
Auto pilot engagement altitude following take off
The airspeed at 5DME on approach
The altitude at 5DME on approach
The glideslope deviation at 8DME on approach
The airspeed at 8DME on approach
The altitude at 8DME on approach
Altitude when re capturing the glideslope while approaching CHC
The last instance where airspeed exceeds 160kts for 5 seconds
The total time between 2500ft and 50ft
The altitude when the auto pilot is disengaged prior to landing
The total time from when either gear or flap is selected until touch down (approach duration)
The total time the aircraft is unstable below 1000ft
The total time the aircraft is unstable below 1500ft
The total time the aircraft is unstable below 2000ft
The total time the aircraft is unstable below 2500ft
The point when the before landing checklist is completed
Landing flap position
The point when the aircraft reaches the constraint altitude ex CHC
The point when the aircraft reaches the constraint altitude ex WLG
Runway distance remaining at the point when the aircraft unsticks during take off
The altitude at the point when the un-commanded auto pilot disconnection occurs

APPENDIX F PARAMETERS INCLUDED IN INITIAL CLIMB AND GO AROUND DATASETS

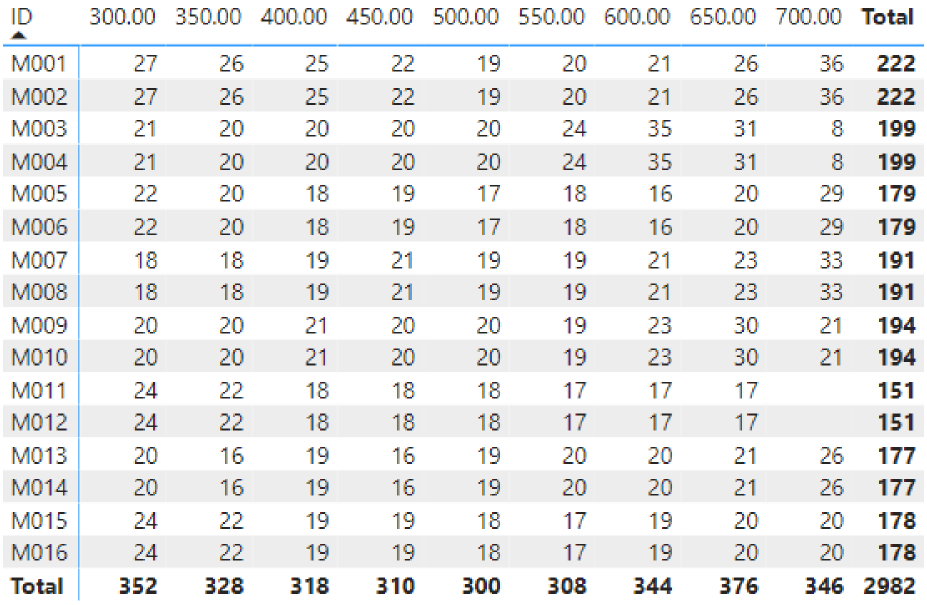
The following parameters were included in initial climb and go around datasets. Not all values were analysed due to time constraints.

Parameter Name
Participant ID
Condition
Order
Time (frame counter)
Barometric corrected altitude (ft)
Radio altitude (ft)
Height above airfield (ft)
Autopilot 1 engaged
Autopilot 2 engaged
Flap lever selection (deg)
Flap position (deg)
Active lateral mode (auto pilot mode)
Active vertical mode (auto pilot mode)
Roll angle (absolute) (deg)
Roll attitude (absolute) (deg)
Roll rate (deg/sec)
Roll rate (absolute) (deg/sec)
Flight director roll order from video (deg)
Flight director roll order from video (absolute) (deg)
Roll delta (= roll attitude – flight director roll order) (deg)
Roll delta (= roll attitude – flight director roll order) (absolute) (deg)

Parameter Name
Computed airspeed (kts)
Ground speed (kts)
Selected speed from video (kts)
Selected speed from video (10hz) (kts)
Airspeed delta (= computed airspeed – target airspeed) (kts)
Airspeed delta (= computed airspeed – target airspeed) (absolute) (kts)
Pitch angle (deg)
Pitch angle (absolute) (deg)
Pitch rate (deg/sec)
Pitch rate (absolute) (deg/sec)
Flight director pitch order from video (deg)
Flight director pitch order from video (10hz) (deg)
Pitch delta (= pitch – flight director pitch order) (deg)
Pitch delta (= pitch – flight director pitch order) (absolute) (deg)
Distance to centreline (ft)
Distance to centreline (absolute) (ft)
Distance from threshold (ft)
Distance from threshold (ft)
Distance to far end (ft)
Distance to far end (ft)
Lateral acceleration (g)
Longitudinal acceleration (g)
Normal acceleration (g)

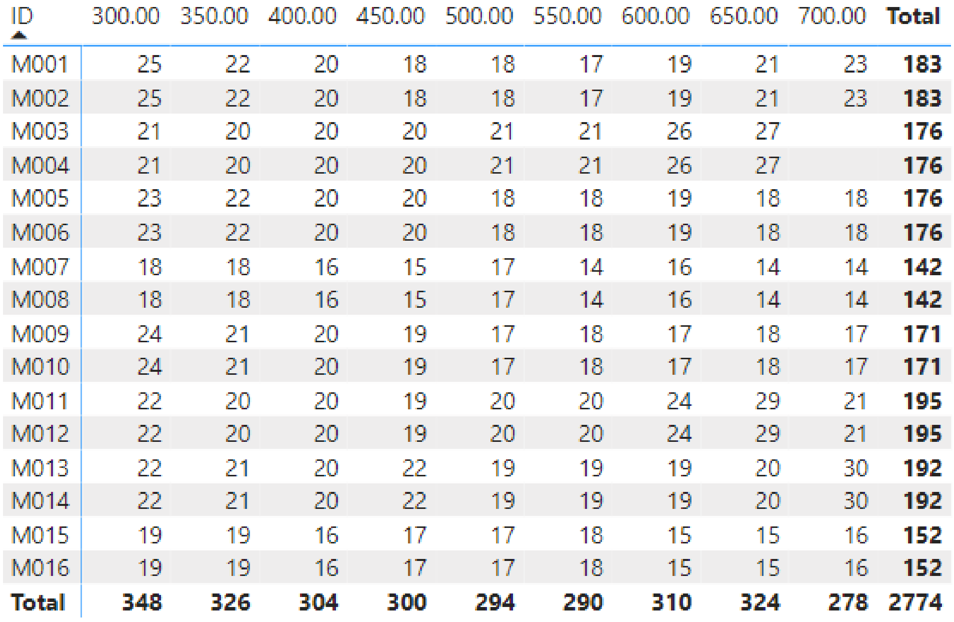
APPENDIX G COUNT OF VALUES WITHIN EACH 50FT ALTITUDE BIN

Initial Climb Non-Rested Condition[106]



ID	300.00	350.00	400.00	450.00	500.00	550.00	600.00	650.00	700.00	**Total**
M001	27	26	25	22	19	20	21	26	36	**222**
M002	27	26	25	22	19	20	21	26	36	**222**
M003	21	20	20	20	20	24	35	31	8	**199**
M004	21	20	20	20	20	24	35	31	8	**199**
M005	22	20	18	19	17	18	16	20	29	**179**
M006	22	20	18	19	17	18	16	20	29	**179**
M007	18	18	19	21	19	19	21	23	33	**191**
M008	18	18	19	21	19	19	21	23	33	**191**
M009	20	20	21	20	20	19	23	30	21	**194**
M010	20	20	21	20	20	19	23	30	21	**194**
M011	24	22	18	18	18	17	17	17		**151**
M012	24	22	18	18	18	17	17	17		**151**
M013	20	16	19	16	19	20	20	21	26	**177**
M014	20	16	19	16	19	20	20	21	26	**177**
M015	24	22	19	19	18	17	19	20	20	**178**
M016	24	22	19	19	18	17	19	20	20	**178**
Total	**352**	**328**	**318**	**310**	**300**	**308**	**344**	**376**	**346**	**2982**

Initial Climb Rested Condition



ID	300.00	350.00	400.00	450.00	500.00	550.00	600.00	650.00	700.00	**Total**
M001	25	22	20	18	18	17	19	21	23	**183**
M002	25	22	20	18	18	17	19	21	23	**183**
M003	21	20	20	20	21	21	26	27		**176**
M004	21	20	20	20	21	21	26	27		**176**
M005	23	22	20	20	18	18	19	18	18	**176**
M006	23	22	20	20	18	18	19	18	18	**176**
M007	18	18	16	15	17	14	16	14	14	**142**
M008	18	18	16	15	17	14	16	14	14	**142**
M009	24	21	20	19	17	18	17	18	17	**171**
M010	24	21	20	19	17	18	17	18	17	**171**
M011	22	20	20	19	20	20	24	29	21	**195**
M012	22	20	20	19	20	20	24	29	21	**195**
M013	22	21	20	22	19	19	19	20	30	**192**
M014	22	21	20	22	19	19	19	20	30	**192**
M015	19	19	16	17	17	18	15	15	16	**152**
M016	19	19	16	17	17	18	15	15	16	**152**
Total	**348**	**326**	**304**	**300**	**294**	**290**	**310**	**324**	**278**	**2774**

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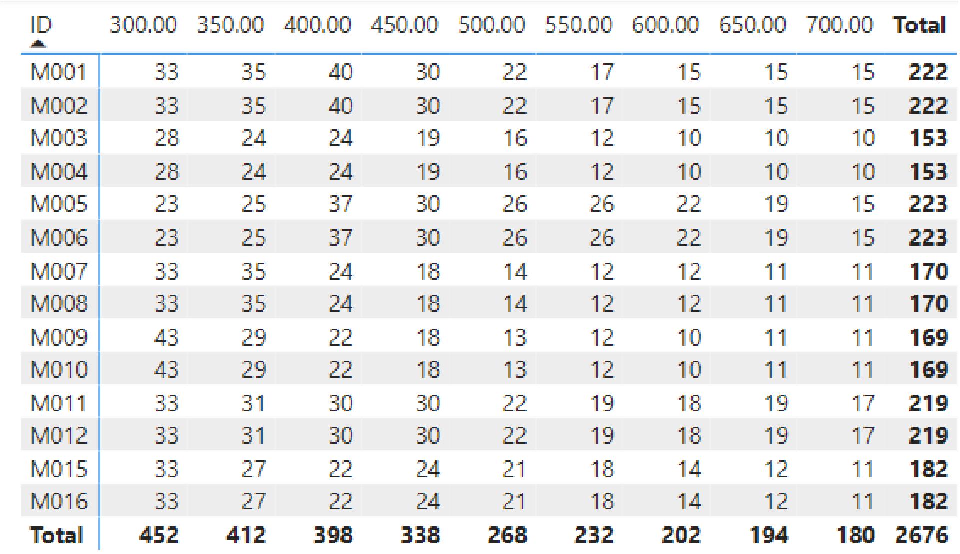
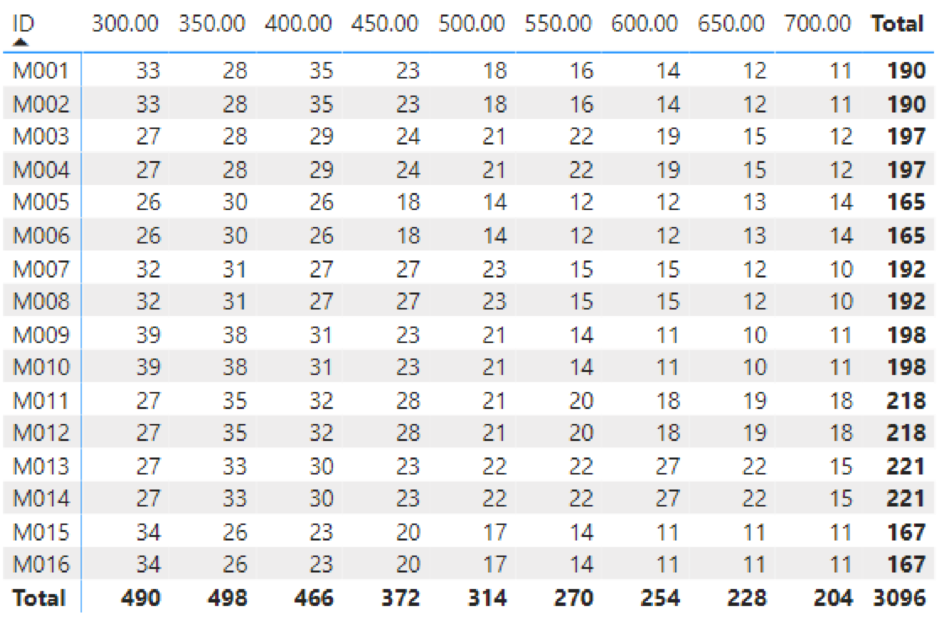
[106] Blank values represent instances where no values were recorded due to flap up selection having already occurred.

Go around non-rested condition



ID	300.00	350.00	400.00	450.00	500.00	550.00	600.00	650.00	700.00	**Total**
M001	33	35	40	30	22	17	15	15	15	**222**
M002	33	35	40	30	22	17	15	15	15	**222**
M003	28	24	24	19	16	12	10	10	10	**153**
M004	28	24	24	19	16	12	10	10	10	**153**
M005	23	25	37	30	26	26	22	19	15	**223**
M006	23	25	37	30	26	26	22	19	15	**223**
M007	33	35	24	18	14	12	12	11	11	**170**
M008	33	35	24	18	14	12	12	11	11	**170**
M009	43	29	22	18	13	12	10	11	11	**169**
M010	43	29	22	18	13	12	10	11	11	**169**
M011	33	31	30	30	22	19	18	19	17	**219**
M012	33	31	30	30	22	19	18	19	17	**219**
M015	33	27	22	24	21	18	14	12	11	**182**
M016	33	27	22	24	21	18	14	12	11	**182**
Total	**452**	**412**	**398**	**338**	**268**	**232**	**202**	**194**	**180**	**2676**

Go around rested condition



ID	300.00	350.00	400.00	450.00	500.00	550.00	600.00	650.00	700.00	**Total**
M001	33	28	35	23	18	16	14	12	11	**190**
M002	33	28	35	23	18	16	14	12	11	**190**
M003	27	28	29	24	21	22	19	15	12	**197**
M004	27	28	29	24	21	22	19	15	12	**197**
M005	26	30	26	18	14	12	12	13	14	**165**
M006	26	30	26	18	14	12	12	13	14	**165**
M007	32	31	27	27	23	15	15	12	10	**192**
M008	32	31	27	27	23	15	15	12	10	**192**
M009	39	38	31	23	21	14	11	10	11	**198**
M010	39	38	31	23	21	14	11	10	11	**198**
M011	27	35	32	28	21	20	18	19	18	**218**
M012	27	35	32	28	21	20	18	19	18	**218**
M013	27	33	30	23	22	22	27	22	15	**221**
M014	27	33	30	23	22	22	27	22	15	**221**
M015	34	26	23	20	17	14	11	11	11	**167**
M016	34	26	23	20	17	14	11	11	11	**167**
Total	**490**	**498**	**466**	**372**	**314**	**270**	**254**	**228**	**204**	**3096**

APPENDIX H GO AROUND/MISSED APPROACH PROCEDURE

Event	Pilot Flying	Pilot Monitoring
Initiating Go around	Announce “going around” Simultaneously: Push the Power Lever Go Around button Rotate to go around pitch attitude on the flight director Set both PLs to the RAMP Announce: “Flaps 15”	Check go around is displayed on the FMA Flaps……………..Select 15
Positive rate of climb	Verify positive rate of climb on VSI and altimeter. Announce: “Gear up, check power”.	Check positive rate of climb on VSI and altimeter. Announce: “Positive climb” Select gear up. Check go around power achieved. Announce “power set”
	Follow FD to climb at VGA	If LNAV is displayed on the FMA Announce “LNAV green” On the flight guidance and control panel select IAS On the FMA check IAS is displayed. Announce “IAS green” or If HDG HOLD is displayed on the FMA, select HDG on the flight guidance and control panel. On the FMA, check HDG SEL LO is displayed. Announce “heading select low green”

Event	Pilot Flying	Pilot Monitoring
	Select/Request LNAV as required.	On the flight guidance and control panel, select IAS On FMA check IAS is displayed Announce "IAS green" Check IAS target bug (magenta) matches VGA. Announce "VGA [xxx] magenta". Select LNAV as required.
	Check missed approach altitude set. Announce "[xxxx] checked"	Check missed approach altitude set. Announce "[xxxx] set ALT SEL Blue"
Flaps 15 indicated **Gear retracted**		Check Flaps 15 set. Announce: "Flaps 15" Check landing gear retracted. Announce: "Gear is up" Check target go around torque set. Announce: "Power Set"
		Broadcast "airline [xxx], going around".
Acceleration altitude	Retard PL 1 & 2 to the notch. Announce: "Power levers notch" Announce: "Climb procedure"	Announce: "Acceleration altitude" -verify PL 1 & 2 in the notch. -Set PWR MGT to CLB. -Check BLEEDS are on. -Select TAXI & T.O. light off.

Event	Pilot Flying	Pilot Monitoring
		Check IAS target bug (magenta) 170 knots. Announce: "Speed 170 magenta"
VmLB 0	Verify IAS for current flight conditions. Announce: "Flap Zero".	In normal conditions, announce: "White bug" at white bug. In icing conditions, announce: "Amber bug" at amber bug. Select ……… FLAPS ZERO
Flaps 0 indicated		Announce: "Flaps zero".
> 1000ft	Announce: "After Take off Checklist".	Perform the After Take off Checklist.

APPENDIX I GO AROUND/MISSED APPROACH PROCEDURE CHECKLIST GROUP AND ACTION ORDER

Event	Group order	Action order	Action	Group criteria	Item criteria	Mapping
Initiating Go around	1	NA	Power Lever Go Around BUTTON…………..PRESS PITCH……….ROTATING TO PITCH ATTITUDE ON FLIGHT DIRECTOR[107] PL 1+2……………………………………….RAMP	Actions completed in correct group order.	N/A	0 = Criteria not met 1 = Criteria met
	2	1 2	Go Around…………………………DISPLAYED FLAPS…………………………………SELECT F15	Actions completed in correct group order.	Actions completed in correct order	0 = Criteria not met 1 = Criteria met
Positive Rate of Climb	3	1 1 2 N/A	VSI………………….POSITIVE RATE OF CLIMB ALTITUDE…………………………INCREASING LDG GEAR…………………………SELECTED UP GO AROUND POWER……………….ACHEIVED	Actions completed in correct group order.	Actions completed in correct order	0 = Criteria not met 1 = Criteria met
	4 (4A)	N/A	PITCH…………FOLLOWING PITCH ATTITUDE ON FLIGHT DIRECTOR	Items completed	N/A	0 = Criteria not met

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[107] For this action to be met, pitch attitude must equal FD Pitch Order or be greater than 5 degrees.

Event	Group order	Action order	Action	Group criteria	Item criteria	Mapping
			LNAV……………………………..…DISPLAYED IAS……………………………..…...DISPLAYED IAS TARGET BUG……………………MAGENTA IAS TARGET BUG………..………………..VGA	in correct group order.		1 = Criteria met
	4 (4B)	N/A	PITCH…………FOLLOWING PITCH ATTITUDE ON FLIGHT DIRECTOR HDG SEL LO………………………...DISPLAYED IAS……………………………………DISPLAYED IAS TARGET BUG…………………..…MAGENTA IAS TARGET BUG………..………………..VGA			
	5	1 2	MISSED APPROACH ALTITUDE …………....SET ALT SEL BLUE…………………….....DISPLAYED	Items completed in correct group order.	Actions completed in correct order.	0 = Criteria not met 1 = Criteria met
Flaps 15 Indicated **Gear Retracted**	6	1 2 3	FLAPS …………………..…FLAP 15 INDICATED LDG GEAR...………………………RETRACTED TORQUE……….TARGET Go Around TORQUE SET	Items completed in correct group order	Actions completed in correct order.	0 = Criteria not met 1 = Criteria met
Acceleration Altitude	7	1 2 3 4 5	PL 1 + 2…………………………..……. NOTCH PWR MGT……………………………..….CLB BLEEDS…………………………………….ON TAXI & T.O LIGHT…………………………...OFF IAS TARGET BUG …………...170kts MAGENTA	Items completed in correct group order.	Actions completed in correct order.	0 = Criteria not met 1 = Criteria met

Event	Group order	Action order	Action	Group criteria	Item criteria	Mapping
VmLB 0	8	1 2	IAS…………………………………………WHITE BUG FLAPS……………………………SELECT FLAP 0	Items completed in correct group order.	Actions completed in correct order.	0 = Criteria not met 1 = Criteria met
Flaps 0 Indicated	9	N/A	FLAPS……………………………………FLAP 0	Items completed in correct group order.	N/A	0 = Criteria not met 1 = Criteria met
> 1000ft	10	N/A	PEFORM THE AFTER TAKE OFF CHECKLIST…………………………COMPLETE	Items completed in correct group order.	N/A	0 = Criteria not met 1 = Criteria met

APPENDIX J CUSTOMISED EVENTS ASSOCIATED WITH THE GO AROUND CHECKLIST

Event group	Customised event
Initiating go around	The point when the power lever go around push button is depressed
	The point when pitch = flight director pitch order
	The point when pitch > 5 deg
	The point when power lever 1+2 = ramp
	The point when flap 15 is selected
Positive rate of climb	The point when vertical speed > +500 foot per minute
	The point where the altitude has increased by 50ft
	The point where the gear is selected up
	The point where torque and propellor RPM = 100%
	The last point where HDG is displayed on the primary flight display
	The point where HDG SEL LO or LNAV is displayed on the primary flight display
	The last point where GA (go around) is displayed on the primary flight display
	The point where IAS is displayed on the primary flight display
	The point where target airspeed = velocity go around (VGA)
	The point where the miss approach altitude is set
	The point where ALT SEL BLUE ARMED with MISS APPROACH ALT set
Flap 15 indicated	The point where FLAP 15 is in the commanded position
Gear retracted	The point where gear is retracted
	The point where target go around torque is achieved
Acceleration altitude	The point where power lever 1+2 = notch

Event group	Customised event
	The point where PWR MGT CLB is selected
	The point where BLEEDS are selected on
	The point where the Taxi & T.O. LIGHT is selected off
	The point when SEL_SPEED_MAGENTA = 170kts
Target speed associated with flap retraction	The point when the aircraft reaches WHITE BUG speed
	The point where flap is selected up
Flap retracted	The point where flap is retracted
Altitude above 1000ft	The point when the aircraft is above 1000ft

APPENDIX K SLEEP/DUTY DIARY

EVALUATION OF SIMULATED FLIGHT DATA EVENTS AS MEASURES OF FATIGUE RISK

PILOT DUTY/SLEEP DIARY

Contact: Cameron Dyer

ID ☐☐☐☐

WHEN TO DO WHAT

	Sleep / Duty Diaries + Activity Monitor											
Non-rested SIM then Rested SIM	OFF	FLY	FLY	FLY	FLY/SIM 18:00 - 20:00	PAX HOME BASE / OFF	**FLY**	**FLY (early finish)**	MOF	MOF	SIM 20:00 - 22:00	PAX HOME BASE / OFF
DAY	1	2	3	4	5	6	7	8	9	10	11	12

ON DAY ONE OF THE STUDY____________________________Fill out your duty/sleep diary, whether at home or on layover and complete the relevant section of your duty/sleep diary each day for each of the 11 days during the study. Answer the pre-study questionnaire. Complete the look back report.

ONLY FILL OUT DETAILS ABOUT YOUR FLIGHT DUTY PERIOD ON DAYS 2 THROUGH 5

FOR THE FOUR DAY FLIGHT DUTY PERIOD [DAYS 2 – 5]:
Before the **first** flight___________________________________Rate your fatigue and sleepiness.
At the end of the **last** flight (on the flight deck)________________Rate your fatigue and sleepiness. Complete the NASA Task Load Index (TLX) questionnaire and detail flights flown during the flight duty period.

FOR YOUR FIRST SIMULATOR SESSION [DAY 5]:
Before the simulator session______________________________Complete a 1min trial performance test (PVT) and complete a 10min performance test (PVT). Rate your Fatigue and Sleepiness.

After the simulator session_______________________________Complete the NASA Task Load Index (TLX) questionnaire. Complete a 10min performance test (PVT). Rate your Fatigue and Sleepiness.

FOR YOUR LAST SIMULATOR SESSION [DAY 11]:
Before the simulator session______________________________Complete a 10min performance test (PVT). Rate your Fatigue and Sleepiness.

After the simulator session_______________________________Complete the NASA Task Load Index (TLX) questionnaire. Complete a 10min performance test (PVT). Rate your Fatigue and Sleepiness.

FOR EACH DAY DURING THE STUDY _____________________Fill out your duty/sleep diary, whether at home or on layover.

INFORMATION ABOUT WEARING THE ACTIGRAPH

Information about wearing the actigraph:

The small watch-sized object you will be wearing on your wrist is an actigraph. It contains an accelerometer and memory chip and records movement. The data from the actigraph is analysed along with the information from the duty/sleep diary to determine sleep duration and timing.

1. Wear the actigraph on your non-dominant wrist (the hand you don't write with). It is important that you do not change wrists as this may significantly change the information that we get from the actigraph.
2. The actigraph should be attached reasonably firmly so that it does not move about on your wrist. If it does move about, tighten the strap slightly.
3. The actigraph must be removed for any contact with water (e.g. showering, swimming), but it is very important that you put it back on again afterwards.
4. If you take the actigraph off for any reason (for showering, to take a swim etc) then please note this in your duty/sleep diary.
5. If you forget to put the actigraph back on at any stage then put it on as soon as you remember. Please write in the diary the time when you put the actigraph back on.
6. **We cannot tell what you are doing from the actigraphy data. We can only tell whether you are moving or not.**
7. On the top of the actigraph there is a small circle shaped button; this is the event marker. If you push this, a small mark will appear on the data output. It does not stop or start the actigraph. The actigraph will keep recording the entire time you are wearing it.
8. We would like you to push the event marker when you start trying to sleep and again when you stop trying to sleep. Please do this whenever you intend to sleep for **10 minutes or longer**.

INFORMATION ABOUT COMPLETING THE DUTY/SLEEP DIARY

Information about filling out the duty/sleep diary

1. We are interested in **any** sleep that is 10 minutes or longer. It does not matter whether this is during the day or during the night.

2. The information that is important to us are the times that you **begin trying to sleep** and when you **finish trying to sleep** after any sleep that is **10 minutes or longer.**

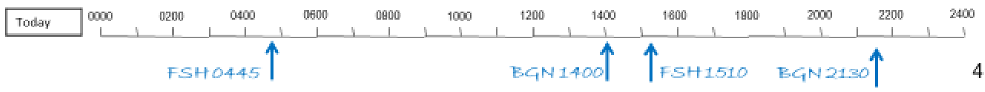
3. **Record all times in local time, using the 24-hour clock.**

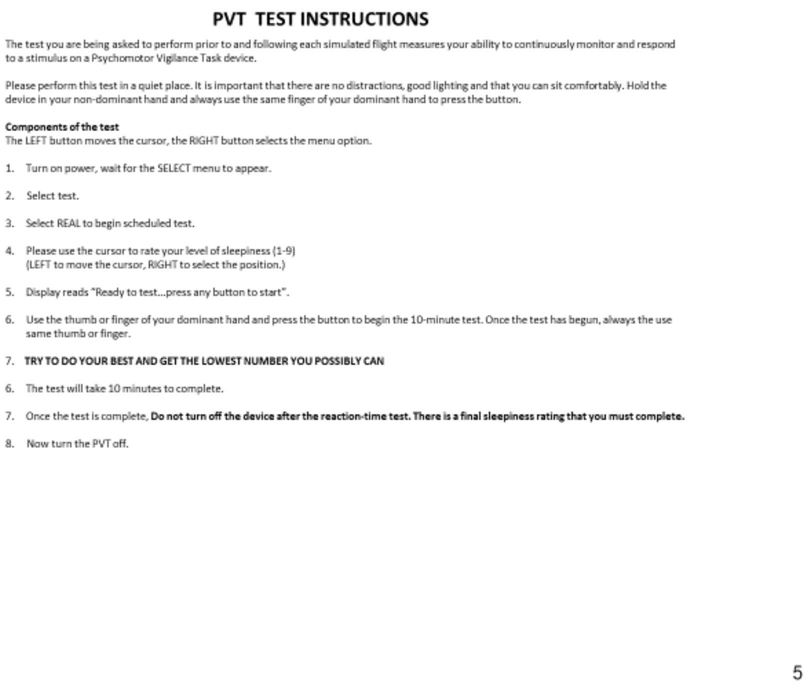
4. When you are about to **begin trying to sleep:**
   a. Mark the time on the timeline and record the time above/below it, i.e. BGN 2255.
   b. Beginning (BGN) is the time when you begin trying to sleep. Some people may get into bed and read etc, but we do not need to know this, we only need to know when you begin trying to go to sleep.

5. When you have **finished trying to sleep:**
   a. Mark the time on the timeline and record the time above/below it, i.e. FSH 0545.
   b. Finished (FSH) is when you wake up and are no longer trying to sleep. At this time you may either get out of bed or begin to read etc, but you are no longer trying to sleep.

6. **Beginning** and **Finish** are the times we would like you to push the event marker on the actigraph.

7. If you wake up during your sleep to get a drink, go to the toilet etc, you do not need to write anything in the duty/sleep diary. If you get up for **more than 10 minutes** then please treat any later sleep as a new sleep period.





PVT TEST INSTRUCTIONS

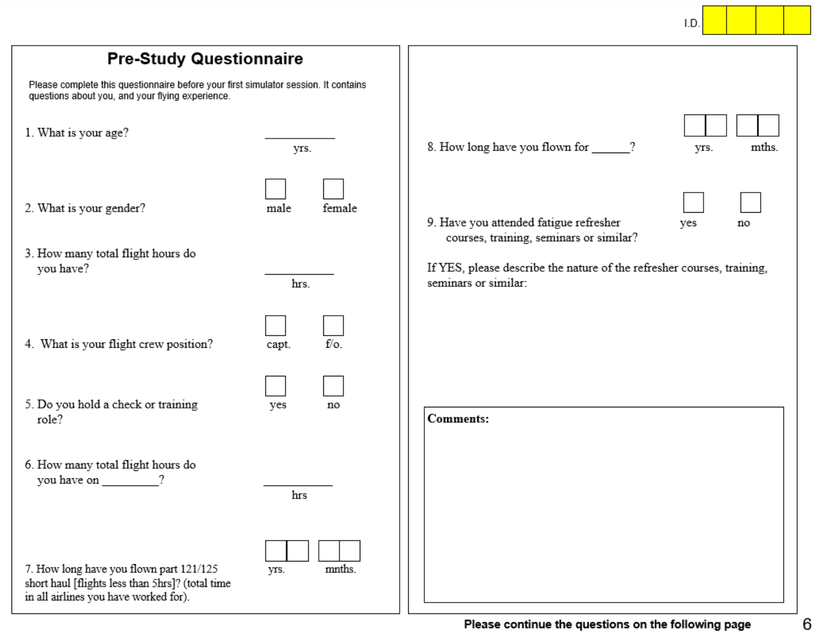
The test you are being asked to perform prior to and following each simulated flight measures your ability to continuously monitor and respond to a stimulus on a Psychomotor Vigilance Task device.

Please perform this test in a quiet place. It is important that there are no distractions, good lighting and that you can sit comfortably. Hold the device in your non-dominant hand and always use the same finger of your dominant hand to press the button.

Components of the test
The LEFT button moves the cursor, the RIGHT button selects the menu option.

1. Turn on power, wait for the SELECT menu to appear.
2. Select test.
3. Select REAL to begin scheduled test.
4. Please use the cursor to rate your level of sleepiness (1-9)
   (LEFT to move the cursor, RIGHT to select the position.)
5. Display reads "Ready to test...press any button to start".
6. Use the thumb or finger of your dominant hand and press the button to begin the 10-minute test. Once the test has begun, always the use same thumb or finger.
7. **TRY TO DO YOUR BEST AND GET THE LOWEST NUMBER YOU POSSIBLY CAN**
6. The test will take 10 minutes to complete.
7. Once the test is complete, **Do not turn off the device after the reaction-time test. There is a final sleepiness rating that you must complete.**
8. Now turn the PVT off.

5



I.D. ☐☐☐☐

Pre-Study Questionnaire

Please complete this questionnaire before your first simulator session. It contains questions about you, and your flying experience.

1. What is your age? ________ yrs.

2. What is your gender? ☐ male ☐ female

3. How many total flight hours do you have? ________ hrs.

4. What is your flight crew position? ☐ capt. ☐ f/o.

5. Do you hold a check or training role? ☐ yes ☐ no

6. How many total flight hours do you have on ________? ________ hrs

7. How long have you flown part 121/125 short haul [flights less than 5hrs]? (total time in all airlines you have worked for). ☐☐ yrs. ☐☐ mnths.

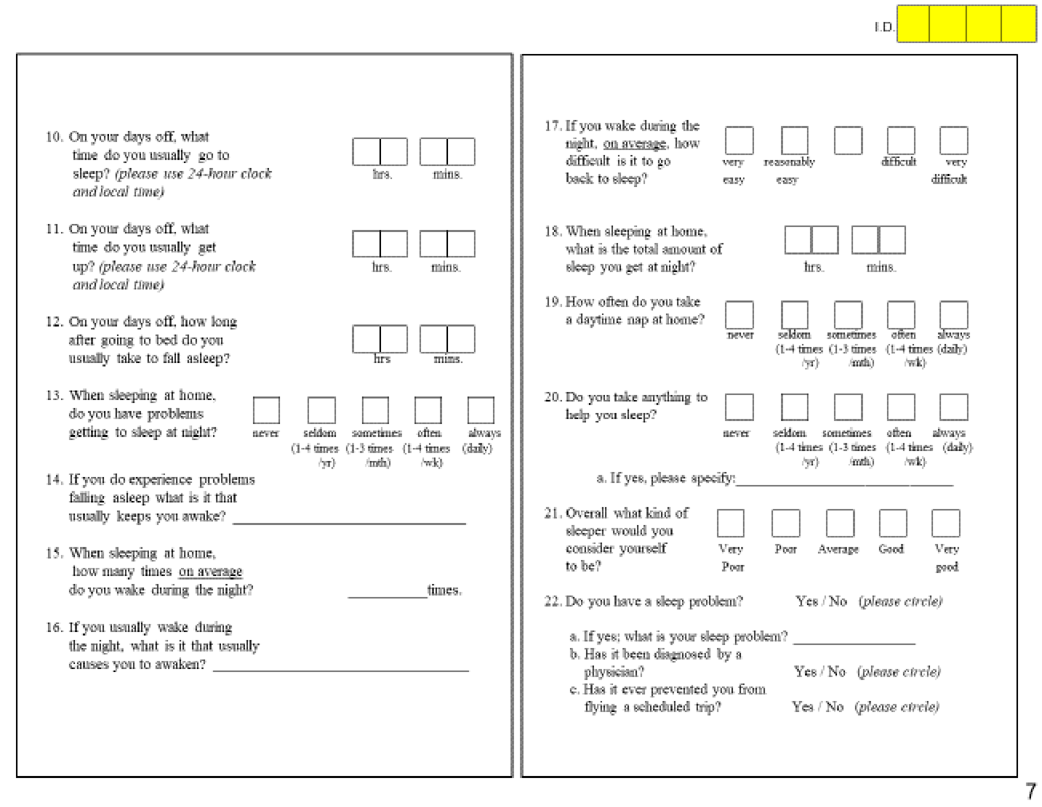
8. How long have you flown for ______? ☐☐ yrs. ☐☐ mths.

9. Have you attended fatigue refresher courses, training, seminars or similar? ☐ yes ☐ no

If YES, please describe the nature of the refresher courses, training, seminars or similar:

Comments:

Please continue the questions on the following page 6



I.D. ☐☐☐☐

10. On your days off, what time do you usually go to sleep? *(please use 24-hour clock and local time)* ☐☐ hrs. ☐☐ mins.

11. On your days off, what time do you usually get up? *(please use 24-hour clock and local time)* ☐☐ hrs. ☐☐ mins.

12. On your days off, how long after going to bed do you usually take to fall asleep? ☐☐ hrs ☐☐ mins.

13. When sleeping at home, do you have problems getting to sleep at night? ☐ never ☐ seldom (1-4 times /yr) ☐ sometimes (1-3 times /mth) ☐ often (1-4 times /wk) ☐ always (daily)

14. If you do experience problems falling asleep what is it that usually keeps you awake? ______________________

15. When sleeping at home, how many times on average do you wake during the night? __________times.

16. If you usually wake during the night, what is it that usually causes you to awaken? ______________________

17. If you wake during the night, on average, how difficult is it to go back to sleep? ☐ very easy ☐ reasonably easy ☐ ☐ difficult ☐ very difficult

18. When sleeping at home, what is the total amount of sleep you get at night? ☐☐ hrs. ☐☐ mins.

19. How often do you take a daytime nap at home? ☐ never ☐ seldom (1-4 times /yr) ☐ sometimes (1-3 times /mth) ☐ often (1-4 times /wk) ☐ always (daily)

20. Do you take anything to help you sleep? ☐ never ☐ seldom (1-4 times /yr) ☐ sometimes (1-3 times /mth) ☐ often (1-4 times /wk) ☐ always (daily)

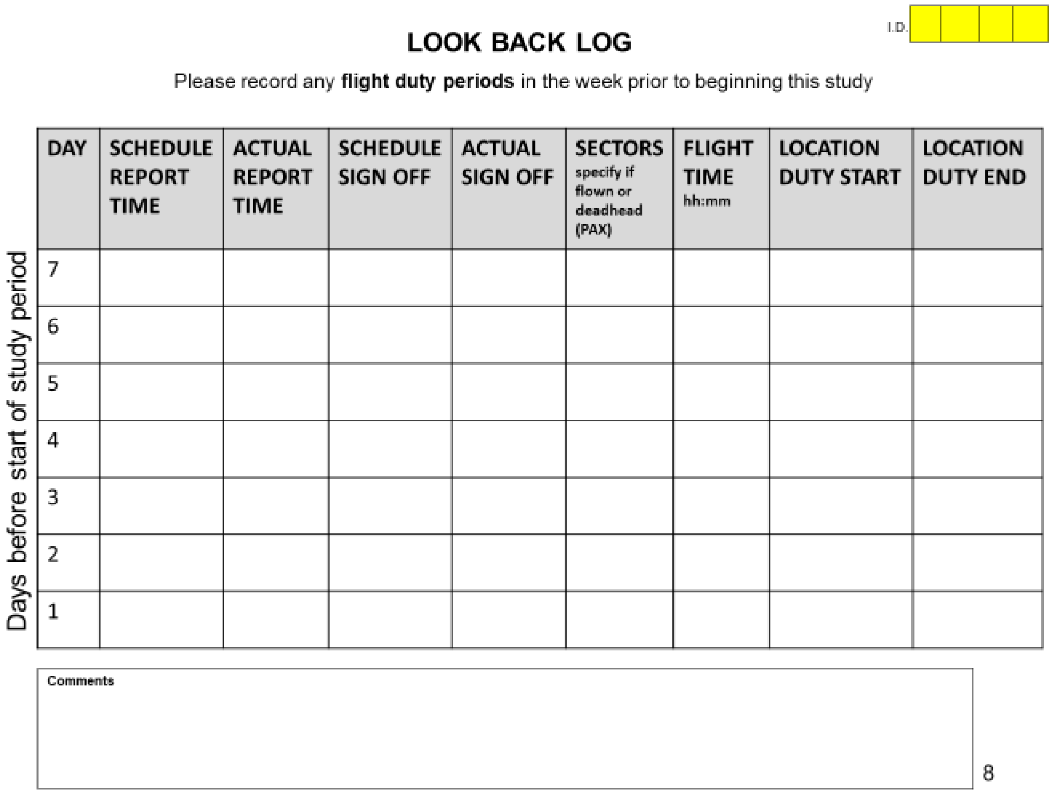
   a. If yes, please specify:______________________

21. Overall what kind of sleeper would you consider yourself to be? ☐ Very Poor ☐ Poor ☐ Average ☐ Good ☐ Very good

22. Do you have a sleep problem? Yes / No *(please circle)*

   a. If yes; what is your sleep problem? ______________
   b. Has it been diagnosed by a physician? Yes / No *(please circle)*
   c. Has it ever prevented you from flying a scheduled trip? Yes / No *(please circle)*

7



I.D. ☐☐☐☐

LOOK BACK LOG

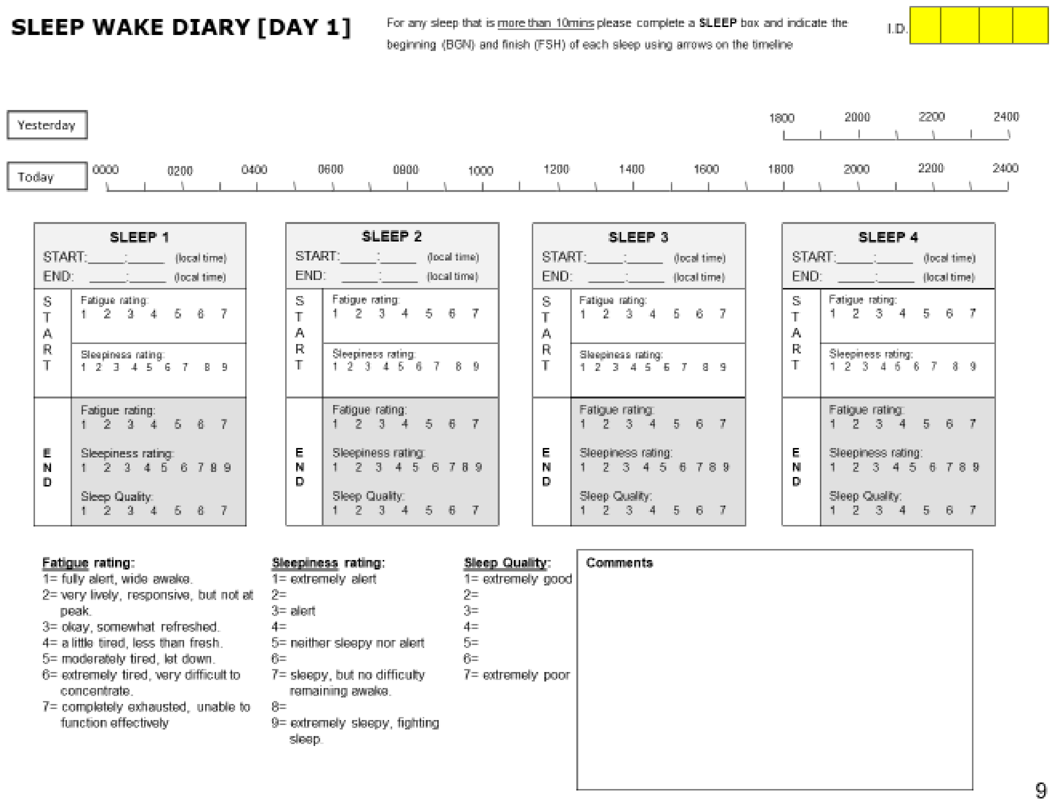
Please record any **flight duty periods** in the week prior to beginning this study

Days before start of study period

DAY	SCHEDULE REPORT TIME	ACTUAL REPORT TIME	SCHEDULE SIGN OFF	ACTUAL SIGN OFF	SECTORS specify if flown or deadhead (PAX)	FLIGHT TIME hh:mm	LOCATION DUTY START	LOCATION DUTY END
7								
6								
5								
4								
3								
2								
1								

Comments

8



SLEEP WAKE DIARY [DAY 1]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D. ☐☐☐☐

	SLEEP 1	**SLEEP 2**	**SLEEP 3**	**SLEEP 4**
	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

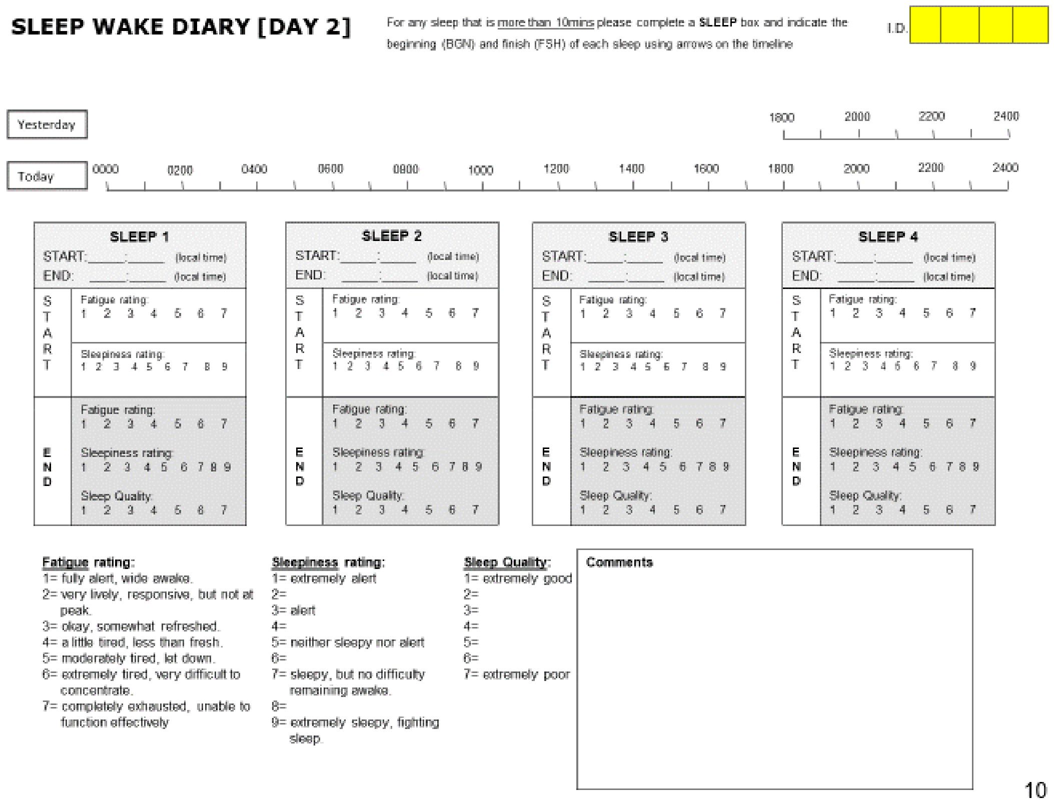
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

9



SLEEP WAKE DIARY [DAY 2]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D. ☐☐☐☐

	SLEEP 1	**SLEEP 2**	**SLEEP 3**	**SLEEP 4**
	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

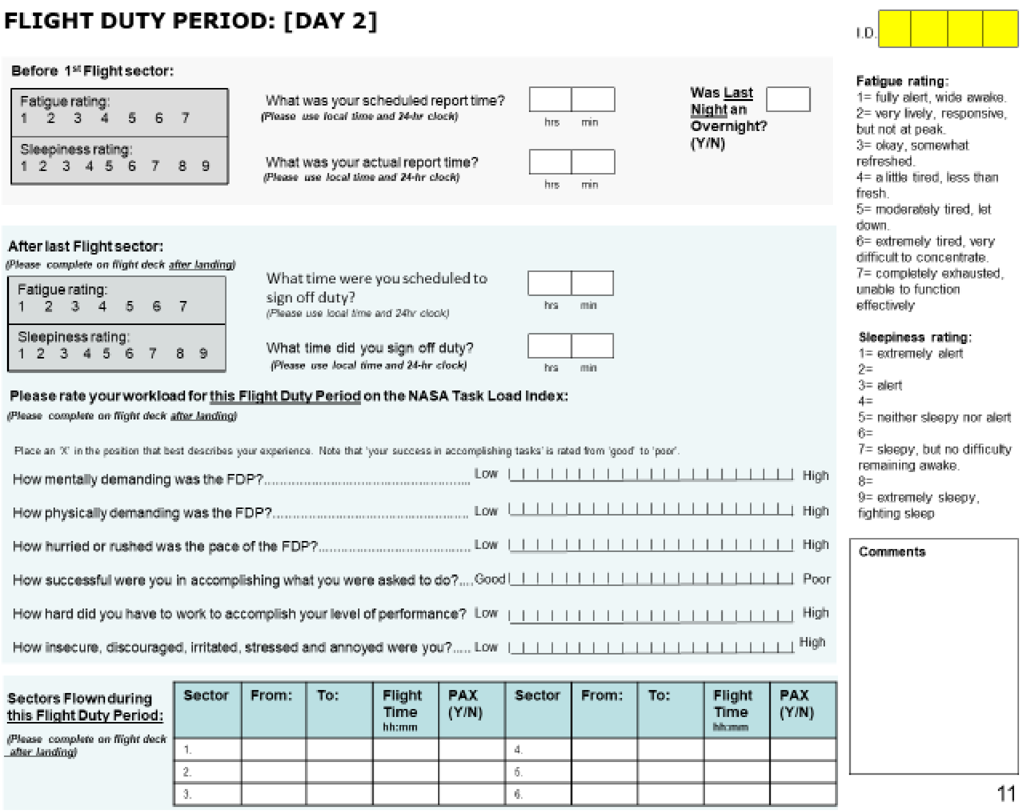
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

10



FLIGHT DUTY PERIOD: [DAY 2]

I.D.

Before 1st Flight sector:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What was your scheduled report time? hrs min
(Please use local time and 24-hr clock)

What was your actual report time? hrs min
(Please use local time and 24-hr clock)

Was Last Night an Overnight? (Y/N)

After last Flight sector:
(Please complete on flight deck after landing)

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time were you scheduled to sign off duty? hrs min
(Please use local time and 24hr clock)

What time did you sign off duty? hrs min
(Please use local time and 24-hr clock)

Please rate your workload for this Flight Duty Period on the NASA Task Load Index:
(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the FDP?........ Low | | | | | | | | | | | | | | | | | | | | | High

How physically demanding was the FDP?........ Low | | | | | | | | | | | | | | | | | | | | | High

How hurried or rushed was the pace of the FDP?........ Low | | | | | | | | | | | | | | | | | | | | | High

How successful were you in accomplishing what you were asked to do?.... Good | | | | | | | | | | | | | | | | | | | | | Poor

How hard did you have to work to accomplish your level of performance? Low | | | | | | | | | | | | | | | | | | | | | High

How insecure, discouraged, irritated, stressed and annoyed were you?..... Low | | | | | | | | | | | | | | | | | | | | | High

Sectors Flown during this Flight Duty Period:
(Please complete on flight deck after landing)

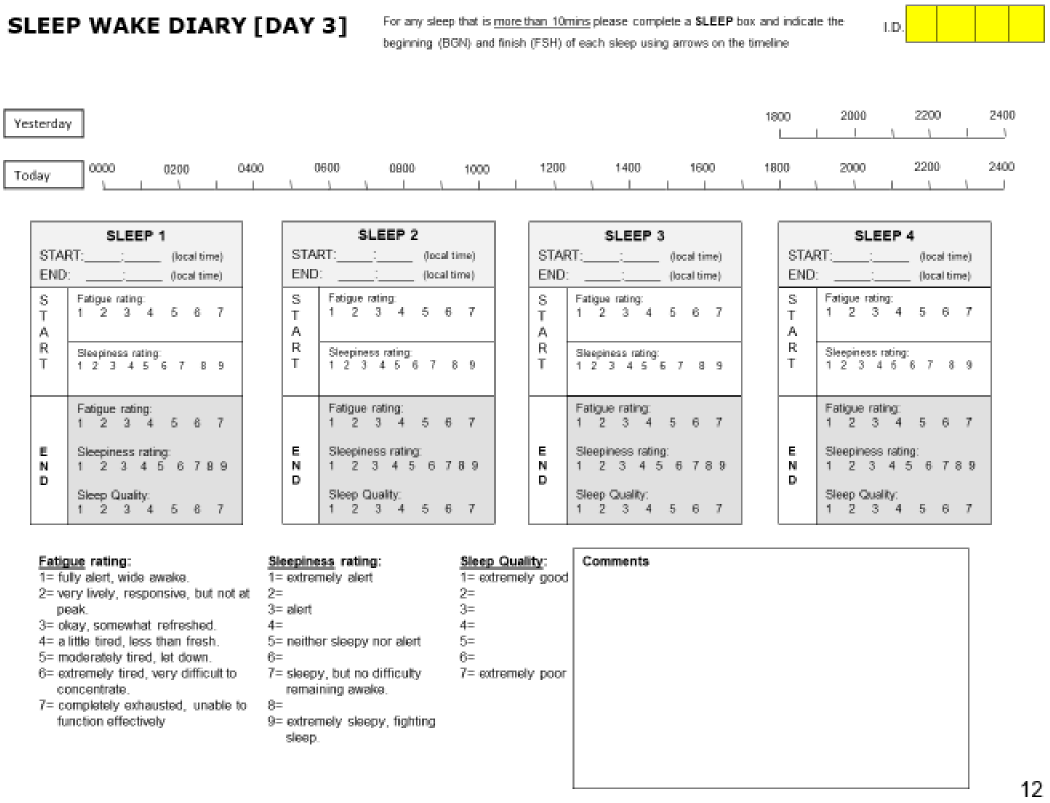
Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)	Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)
1.					4.				
2.					5.				
3.					6.				

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

Comments

11



SLEEP WAKE DIARY [DAY 3]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

SLEEP 1
START: ____:____ (local time)
END: ____:____ (local time)
START – Fatigue rating: 1 2 3 4 5 6 7
START – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Fatigue rating: 1 2 3 4 5 6 7
END – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Sleep Quality: 1 2 3 4 5 6 7

SLEEP 2
START: ____:____ (local time)
END: ____:____ (local time)
START – Fatigue rating: 1 2 3 4 5 6 7
START – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Fatigue rating: 1 2 3 4 5 6 7
END – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Sleep Quality: 1 2 3 4 5 6 7

SLEEP 3
START: ____:____ (local time)
END: ____:____ (local time)
START – Fatigue rating: 1 2 3 4 5 6 7
START – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Fatigue rating: 1 2 3 4 5 6 7
END – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Sleep Quality: 1 2 3 4 5 6 7

SLEEP 4
START: ____:____ (local time)
END: ____:____ (local time)
START – Fatigue rating: 1 2 3 4 5 6 7
START – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Fatigue rating: 1 2 3 4 5 6 7
END – Sleepiness rating: 1 2 3 4 5 6 7 8 9
END – Sleep Quality: 1 2 3 4 5 6 7

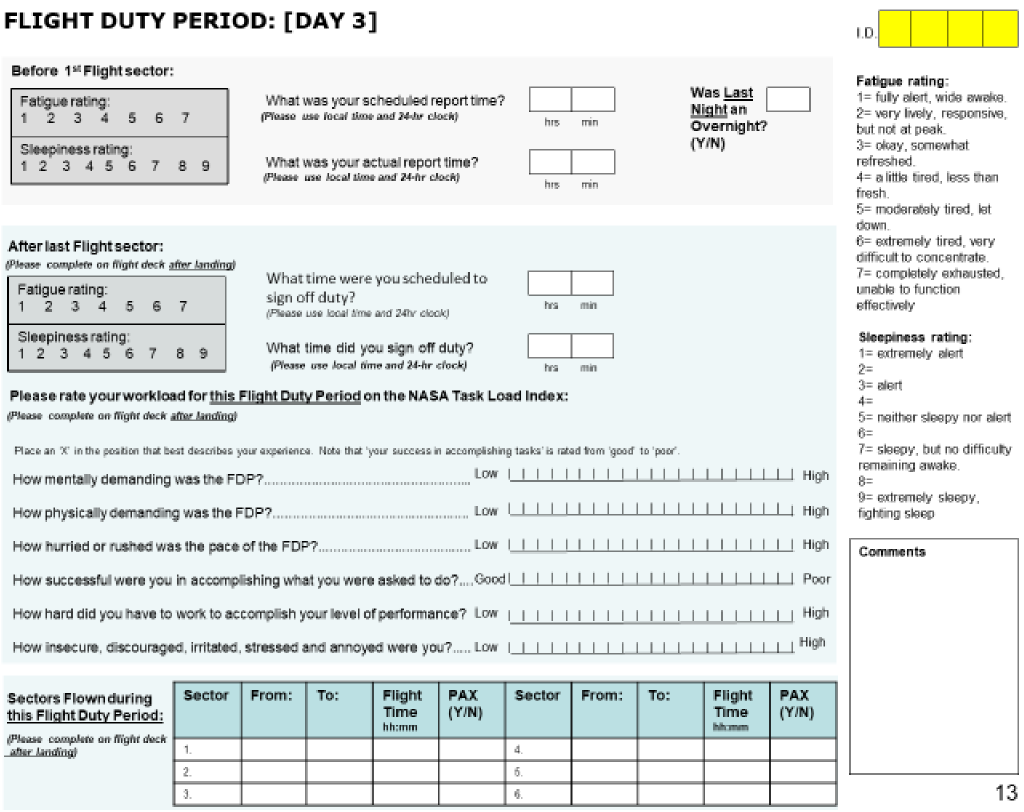
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

12



FLIGHT DUTY PERIOD: [DAY 3]

I.D.

Before 1st Flight sector:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What was your scheduled report time? hrs min
(Please use local time and 24-hr clock)

What was your actual report time? hrs min
(Please use local time and 24-hr clock)

Was Last Night an Overnight? (Y/N)

After last Flight sector:
(Please complete on flight deck after landing)

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time were you scheduled to sign off duty? hrs min
(Please use local time and 24hr clock)

What time did you sign off duty? hrs min
(Please use local time and 24-hr clock)

Please rate your workload for this Flight Duty Period on the NASA Task Load Index:
(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the FDP?.......... Low | | | | | | | | | | | | | | | | | | | | | High
How physically demanding was the FDP?.......... Low | | | | | | | | | | | | | | | | | | | | | High
How hurried or rushed was the pace of the FDP?.......... Low | | | | | | | | | | | | | | | | | | | | | High
How successful were you in accomplishing what you were asked to do?.... Good | | | | | | | | | | | | | | | | | | | | | Poor
How hard did you have to work to accomplish your level of performance? Low | | | | | | | | | | | | | | | | | | | | | High
How insecure, discouraged, irritated, stressed and annoyed were you?..... Low | | | | | | | | | | | | | | | | | | | | | High

Sectors Flown during this Flight Duty Period:
(Please complete on flight deck after landing)

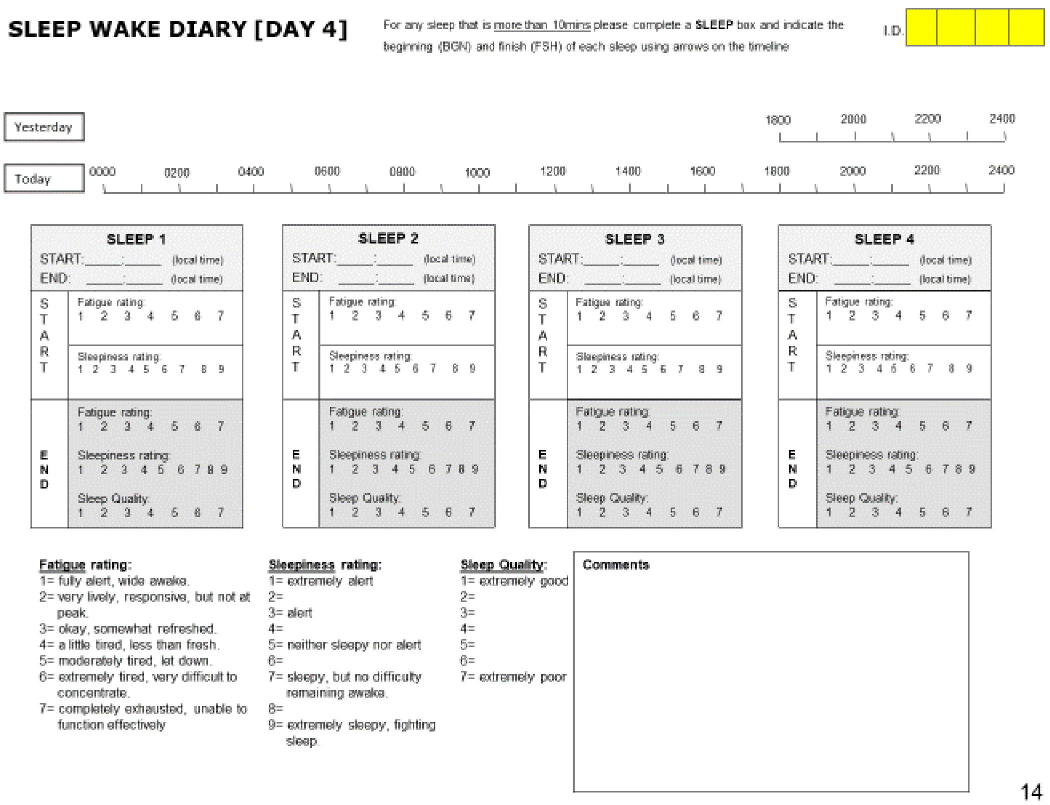
Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)	Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)
1.					4.				
2.					5.				
3.					6.				

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

Comments

13



SLEEP WAKE DIARY [DAY 4]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

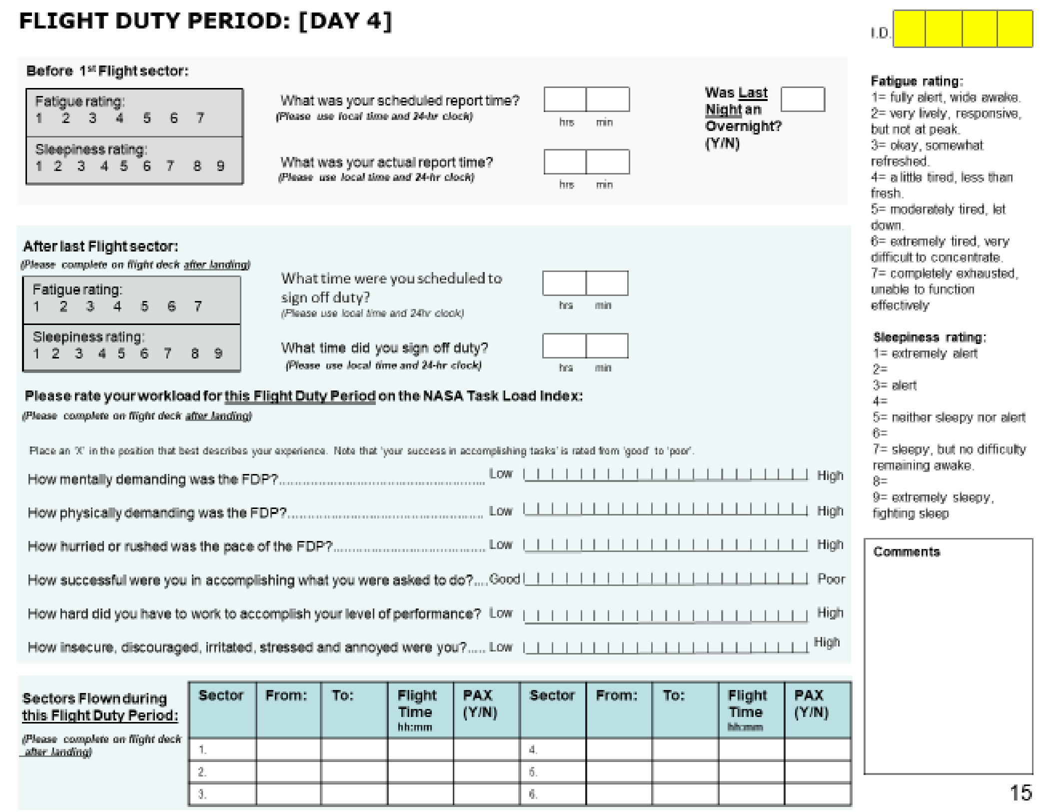
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

14



FLIGHT DUTY PERIOD: [DAY 4]

I.D.

Before 1st Flight sector:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What was your scheduled report time? hrs min
(Please use local time and 24-hr clock)

What was your actual report time? hrs min
(Please use local time and 24-hr clock)

Was Last Night an Overnight? (Y/N)

After last Flight sector:
(Please complete on flight deck after landing)

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time were you scheduled to sign off duty? hrs min
(Please use local time and 24hr clock)

What time did you sign off duty? hrs min
(Please use local time and 24-hr clock)

Please rate your workload for this Flight Duty Period on the NASA Task Load Index:
(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High
How physically demanding was the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High
How hurried or rushed was the pace of the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High
How successful were you in accomplishing what you were asked to do?.... Good |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| Poor
How hard did you have to work to accomplish your level of performance? Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High
How insecure, discouraged, irritated, stressed and annoyed were you?..... Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Sectors Flown during this Flight Duty Period:
(Please complete on flight deck after landing)

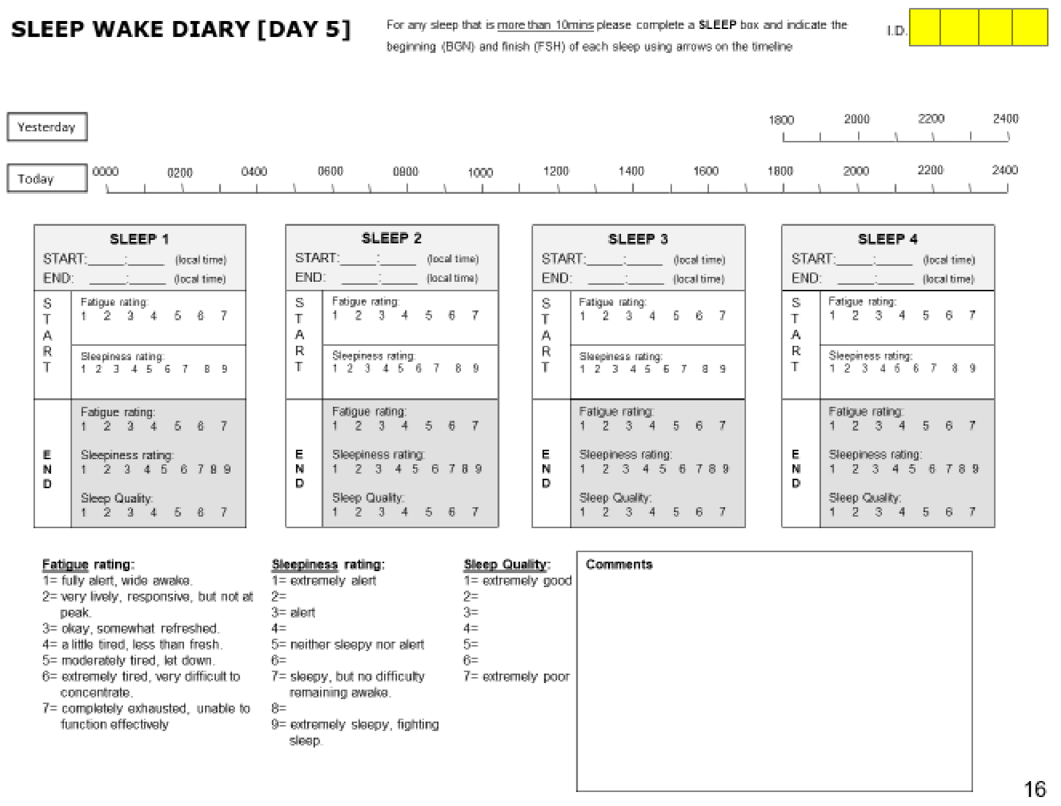
Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)	Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)
1.					4.				
2.					5.				
3.					6.				

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

Comments

15



SLEEP WAKE DIARY [DAY 5]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

SLEEP 1	**SLEEP 2**	**SLEEP 3**	**SLEEP 4**
START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)
START Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	START Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	START Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	START Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	END Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	END Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	END Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

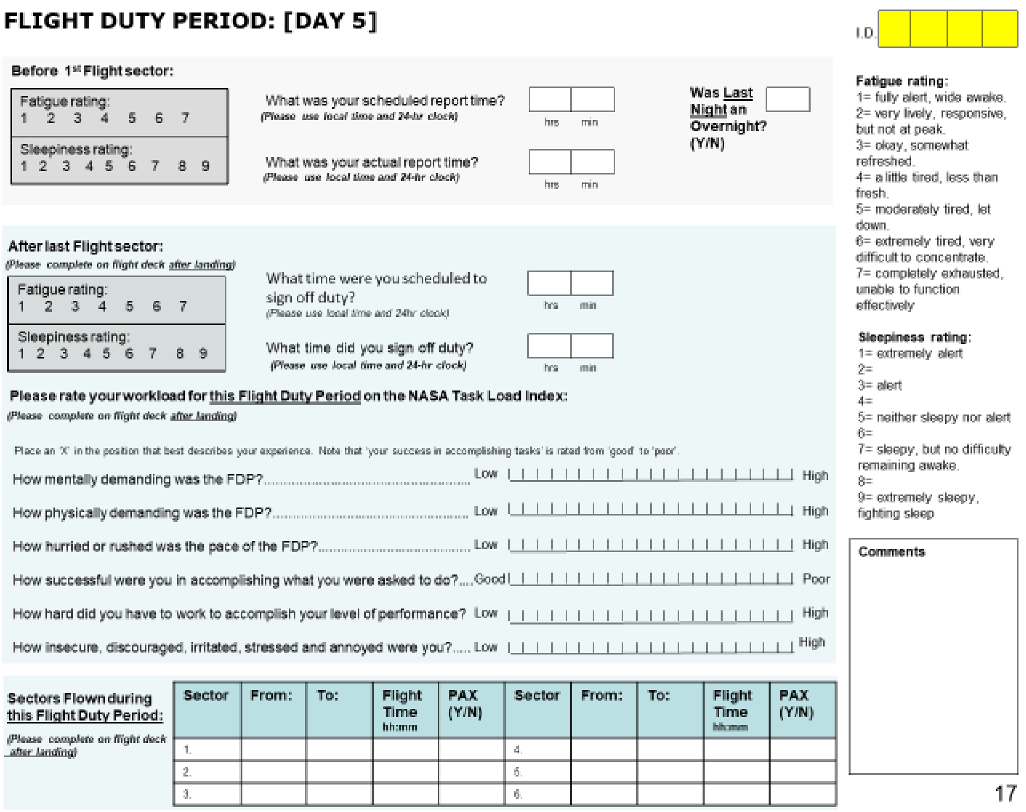
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

16



FLIGHT DUTY PERIOD: [DAY 5]

I.D. ☐☐☐☐

Before 1st Flight sector:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What was your scheduled report time? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

What was your actual report time? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

Was Last Night an Overnight? (Y/N) ☐

After last Flight sector:
(Please complete on flight deck after landing)

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time were you scheduled to sign off duty? ☐ hrs ☐ min
(Please use local time and 24hr clock)

What time did you sign off duty? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

Please rate your workload for this Flight Duty Period on the NASA Task Load Index:
(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How physically demanding was the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How hurried or rushed was the pace of the FDP?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How successful were you in accomplishing what you were asked to do?.... Good |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| Poor

How hard did you have to work to accomplish your level of performance? Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How insecure, discouraged, irritated, stressed and annoyed were you?..... Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Sectors Flown during this Flight Duty Period:
(Please complete on flight deck after landing)

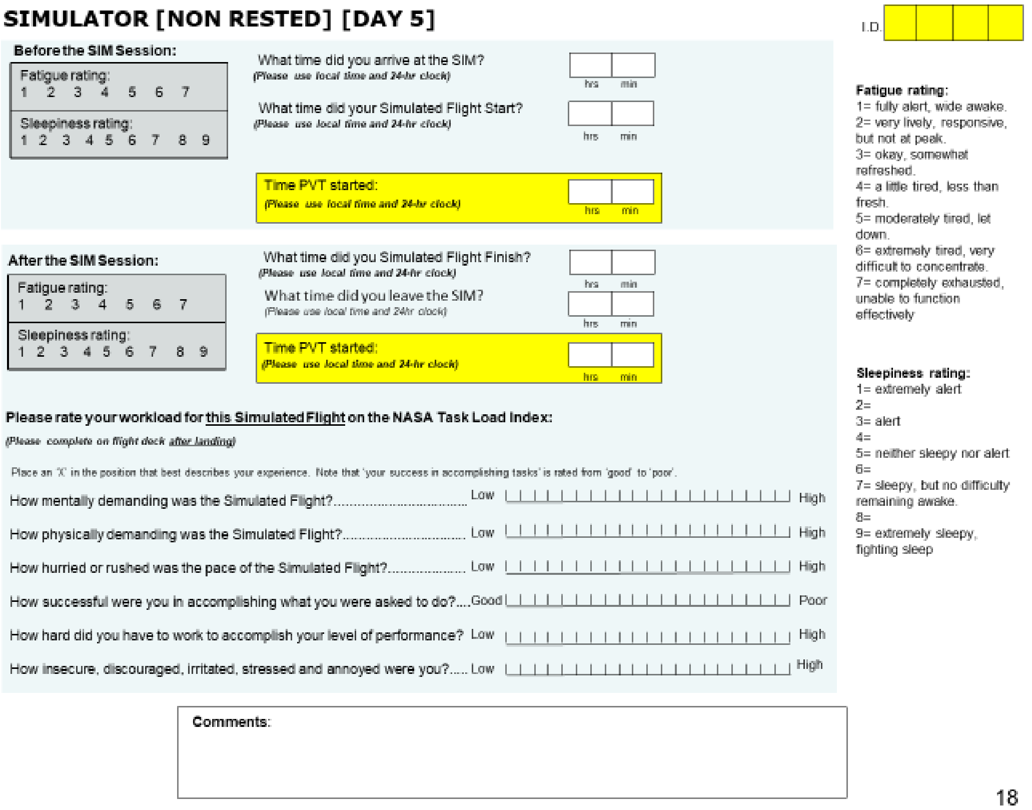
Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)	Sector	From:	To:	Flight Time hh:mm	PAX (Y/N)
1.					4.				
2.					5.				
3.					6.				

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

Comments

17



SIMULATOR [NON RESTED] [DAY 5]

I.D. ☐☐☐☐

Before the SIM Session:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time did you arrive at the SIM? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

What time did your Simulated Flight Start? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

Time PVT started: ☐ hrs ☐ min
(Please use local time and 24-hr clock)

After the SIM Session:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time did you Simulated Flight Finish? ☐ hrs ☐ min
(Please use local time and 24-hr clock)

What time did you leave the SIM? ☐ hrs ☐ min
(Please use local time and 24hr clock)

Time PVT started: ☐ hrs ☐ min
(Please use local time and 24-hr clock)

Please rate your workload for this Simulated Flight on the NASA Task Load Index:
(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the Simulated Flight?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How physically demanding was the Simulated Flight?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How hurried or rushed was the pace of the Simulated Flight?........ Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

How successful were you in accomplishing what you were asked to do?.... Good |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| Poor

How hard did you have to work to accomplish your level of performance? Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

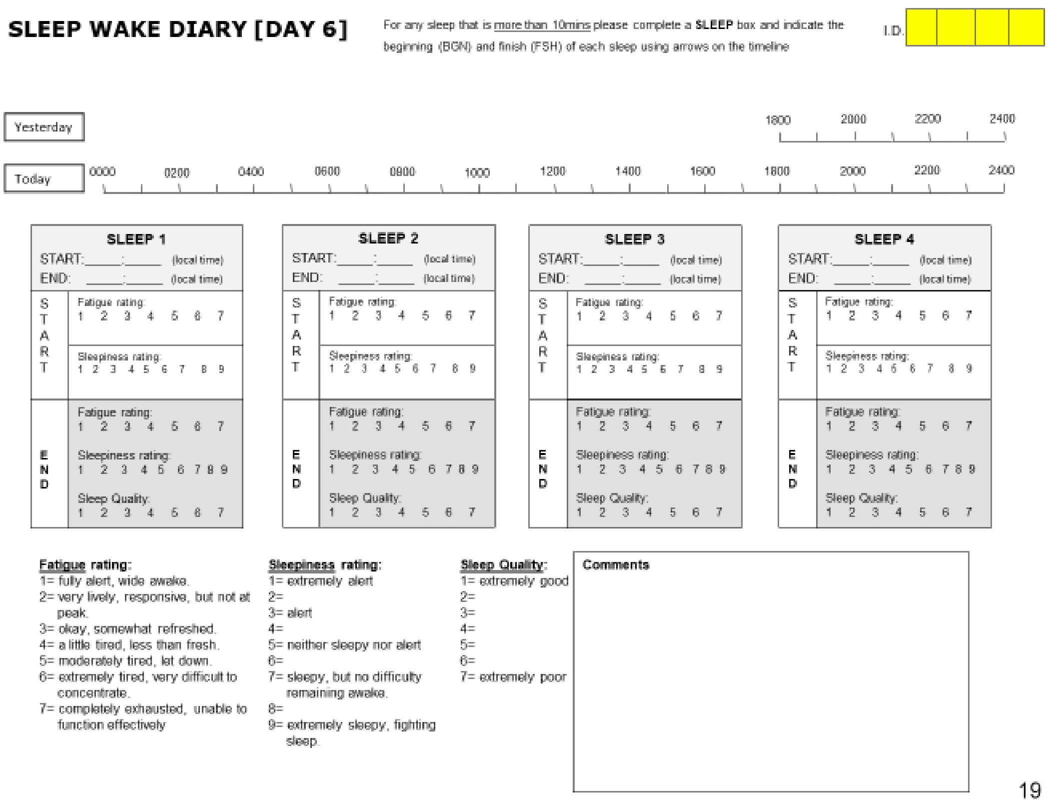
How insecure, discouraged, irritated, stressed and annoyed were you?..... Low |_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_|_| High

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

Comments:

18



SLEEP WAKE DIARY [DAY 6]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

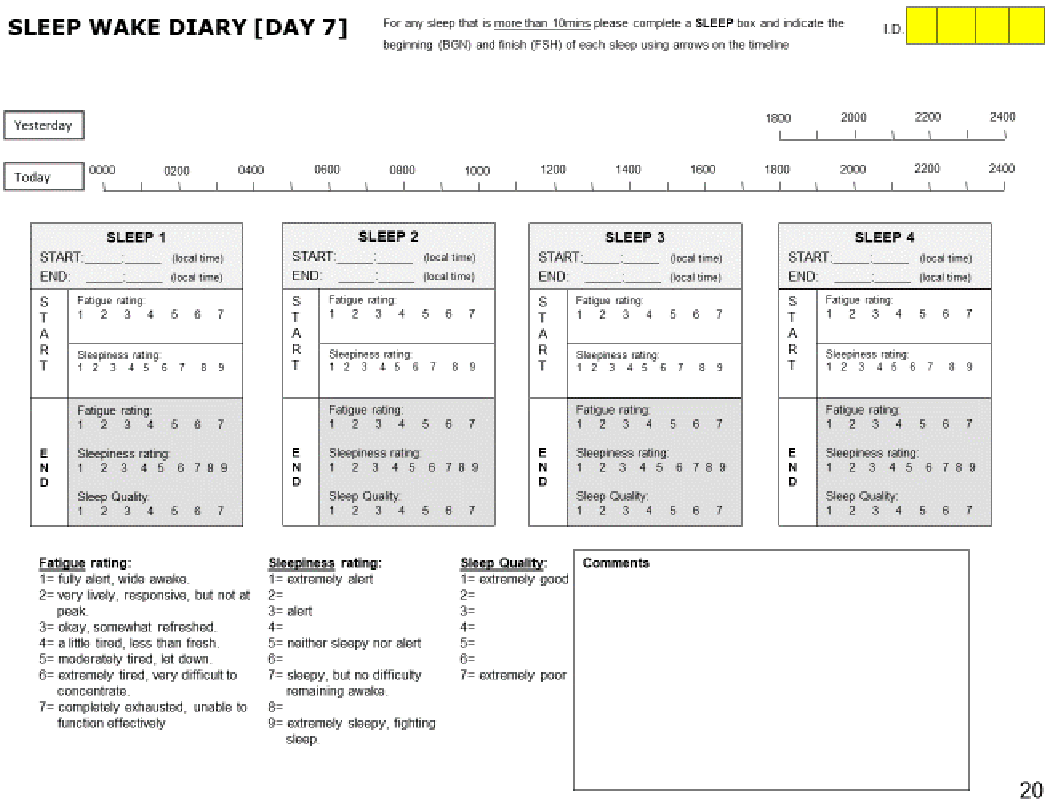
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

19



SLEEP WAKE DIARY [DAY 7]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

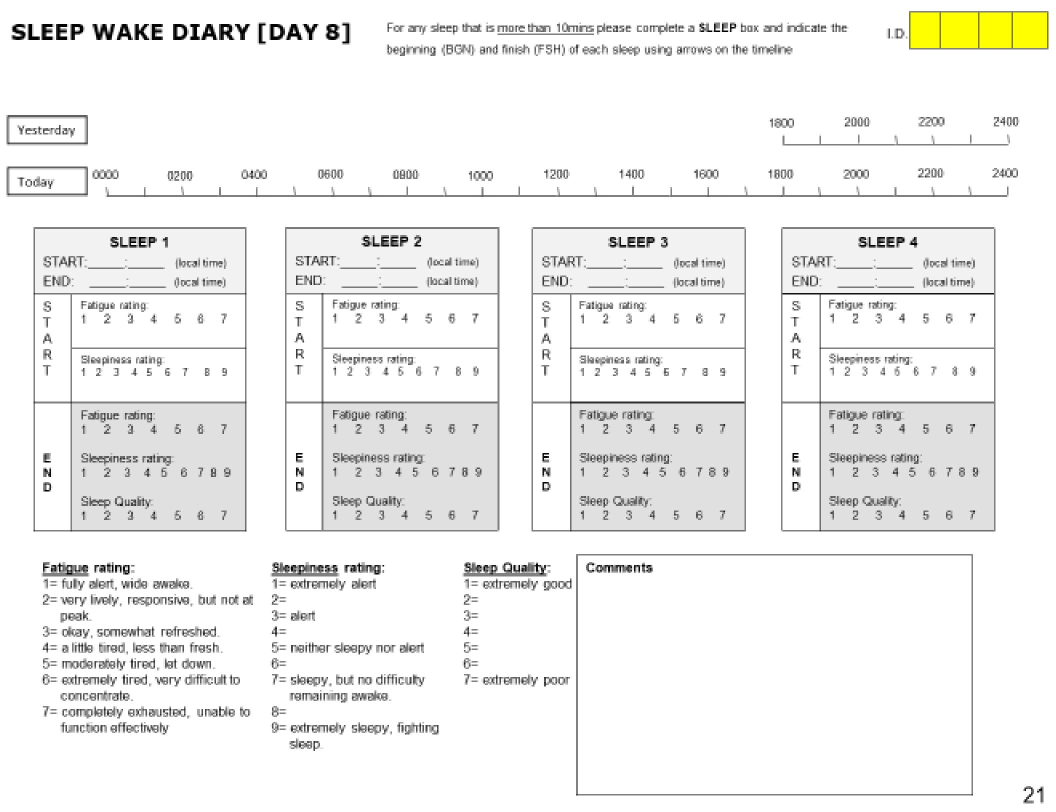
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

20



SLEEP WAKE DIARY [DAY 8]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

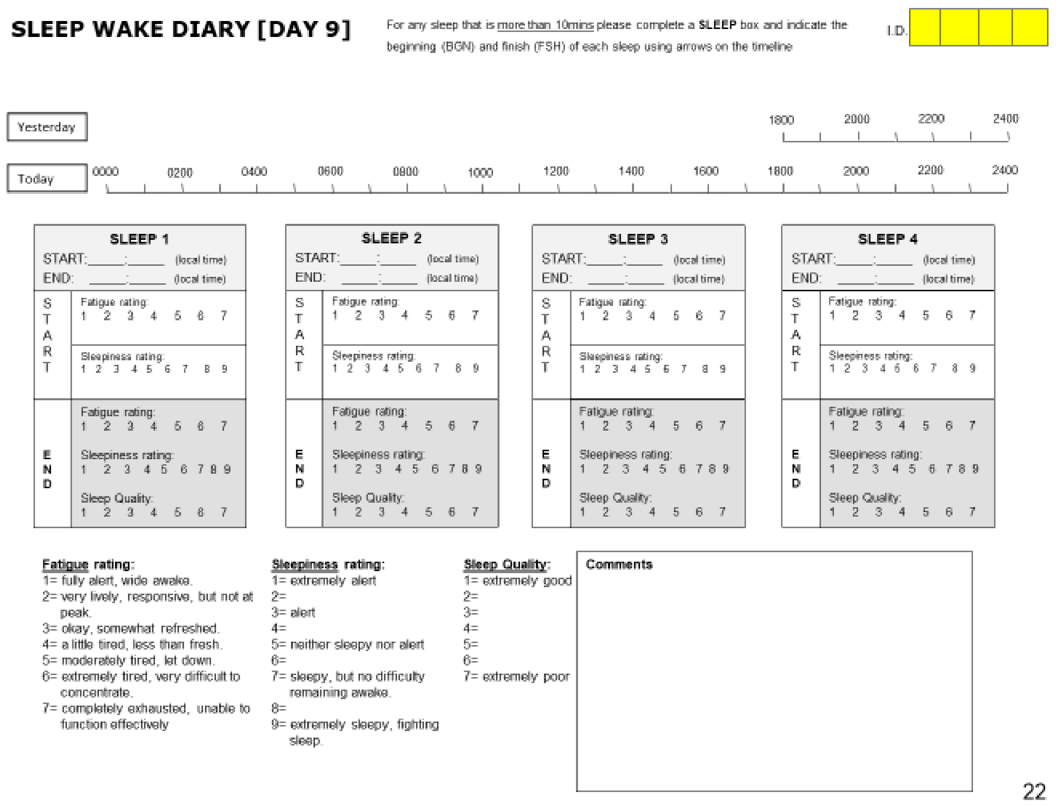
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

21



SLEEP WAKE DIARY [DAY 9]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)	START:____:____ (local time) END: ____:____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

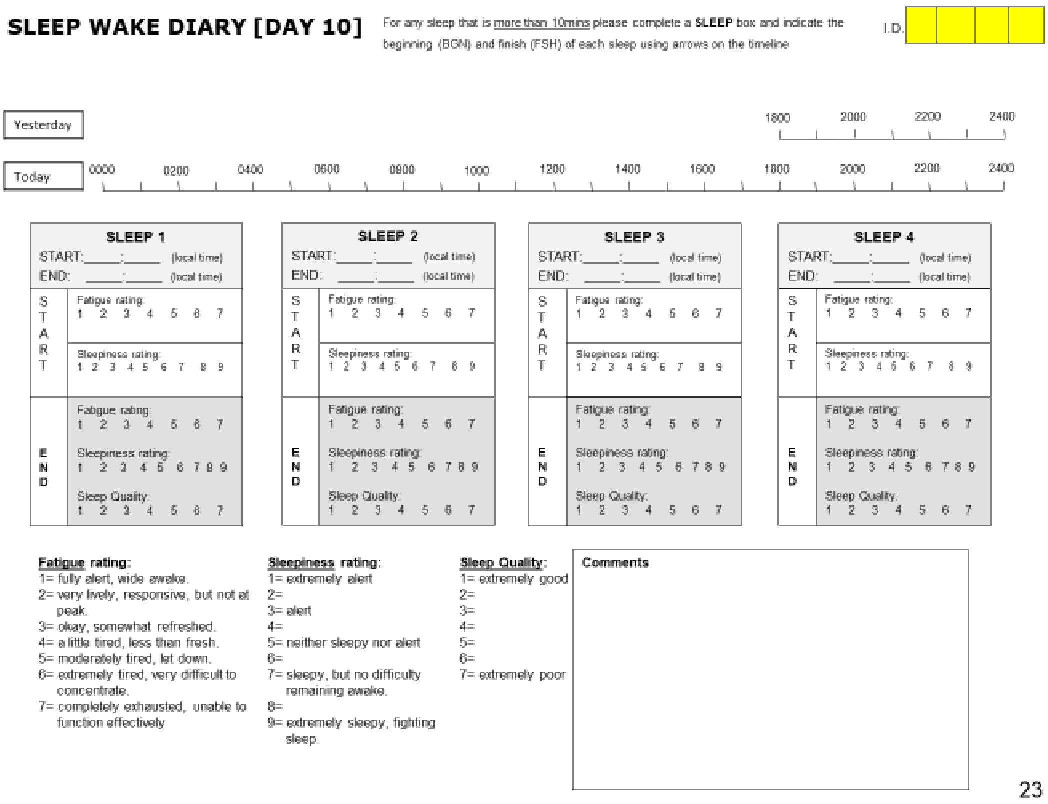
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

22



SLEEP WAKE DIARY [DAY 10]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

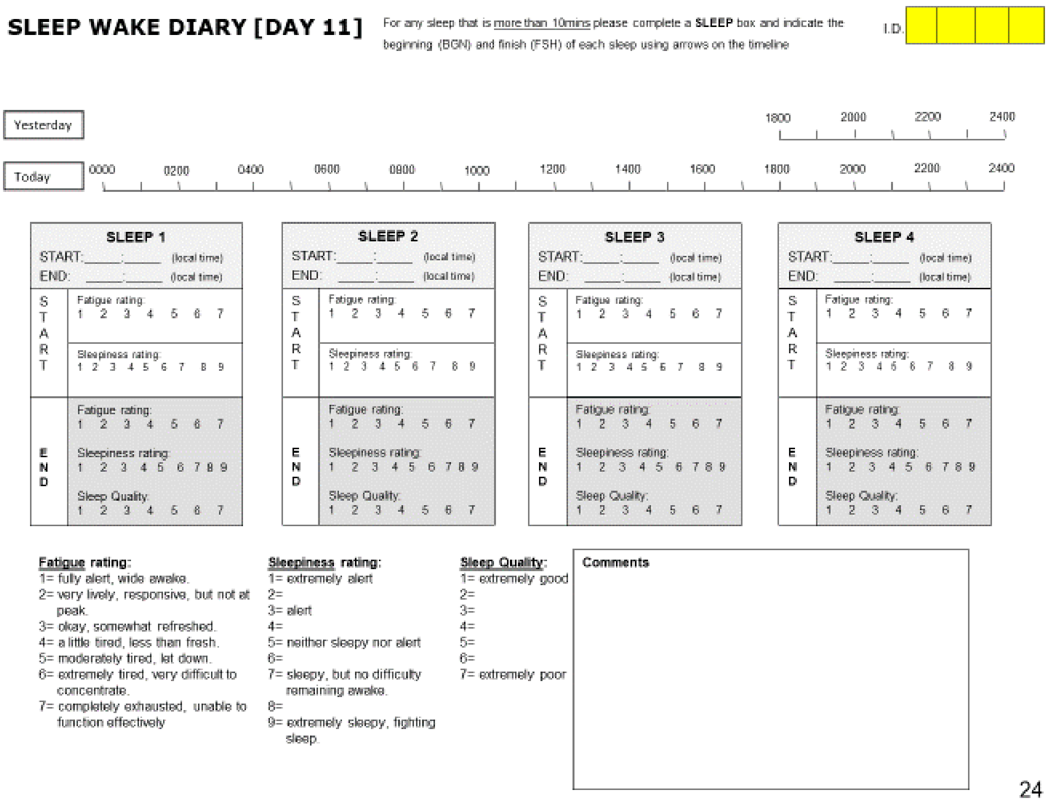
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

23



SLEEP WAKE DIARY [DAY 11]

For any sleep that is more than 10mins please complete a **SLEEP** box and indicate the beginning (BGN) and finish (FSH) of each sleep using arrows on the timeline

I.D.

Yesterday 1800 2000 2200 2400

Today 0000 0200 0400 0600 0800 1000 1200 1400 1600 1800 2000 2200 2400

	SLEEP 1	SLEEP 2	SLEEP 3	SLEEP 4
	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)	START:_____:_____ (local time) END: _____:_____ (local time)
START	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9
END	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7	Fatigue rating: 1 2 3 4 5 6 7 Sleepiness rating: 1 2 3 4 5 6 7 8 9 Sleep Quality: 1 2 3 4 5 6 7

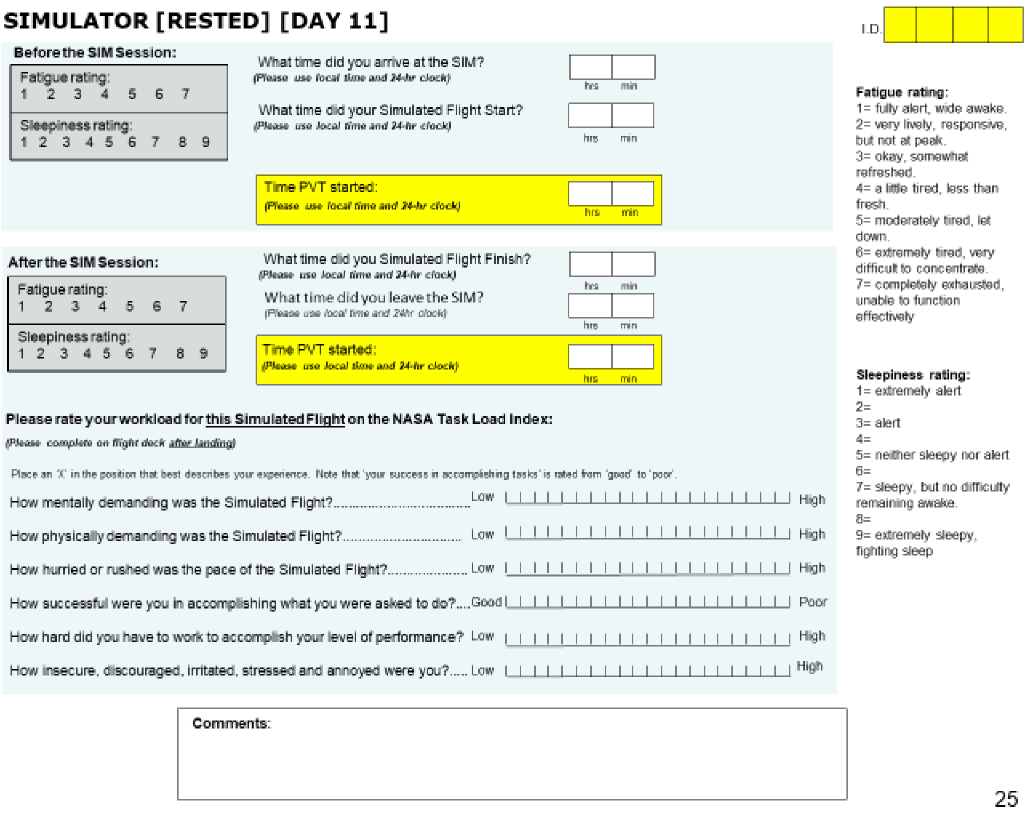
Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep.

Sleep Quality:
1= extremely good
2=
3=
4=
5=
6=
7= extremely poor

Comments

24



SIMULATOR [RESTED] [DAY 11]

I.D.

Before the SIM Session:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time did you arrive at the SIM?
(Please use local time and 24-hr clock)
hrs min

What time did your Simulated Flight Start?
(Please use local time and 24-hr clock)
hrs min

Time PVT started:
(Please use local time and 24-hr clock)
hrs min

After the SIM Session:

Fatigue rating:
1 2 3 4 5 6 7

Sleepiness rating:
1 2 3 4 5 6 7 8 9

What time did you Simulated Flight Finish?
(Please use local time and 24-hr clock)
hrs min

What time did you leave the SIM?
(Please use local time and 24hr clock)
hrs min

Time PVT started:
(Please use local time and 24-hr clock)
hrs min

Please rate your workload for this Simulated Flight on the NASA Task Load Index:

(Please complete on flight deck after landing)

Place an 'X' in the position that best describes your experience. Note that 'your success in accomplishing tasks' is rated from 'good' to 'poor'.

How mentally demanding was the Simulated Flight?.................................... Low High

How physically demanding was the Simulated Flight?.............................. Low High

How hurried or rushed was the pace of the Simulated Flight?..................... Low High

How successful were you in accomplishing what you were asked to do?....Good Poor

How hard did you have to work to accomplish your level of performance? Low High

How insecure, discouraged, irritated, stressed and annoyed were you?..... Low High

Comments:

Fatigue rating:
1= fully alert, wide awake.
2= very lively, responsive, but not at peak.
3= okay, somewhat refreshed.
4= a little tired, less than fresh.
5= moderately tired, let down.
6= extremely tired, very difficult to concentrate.
7= completely exhausted, unable to function effectively

Sleepiness rating:
1= extremely alert
2=
3= alert
4=
5= neither sleepy nor alert
6=
7= sleepy, but no difficulty remaining awake.
8=
9= extremely sleepy, fighting sleep

25

APPENDIX L ACTIGRAPHY SCORING PROTOCOL AND DOUBLE SCORING

APPENDIX L, section L1 Actigraphy Scoring Protocol (manual identification of rest interval start and end times)

The accepted standard for analysing actigraphy records is to use both sleep/duty diary entries and actigraphy to identify rest intervals (International Civil Aviation Organisation, 2015). Rest interval start and end times were determined using three sources of information:

- Change in actigraphy activity data
- Event marker
- Sleep/duty diary entries

When sources of information did not match, the following criteria was applied to determine which source to prioritize:

- Actigraphy and event marker match, sleep/duty diary does not match:

  Use actigraphy and event marker.

- Actigraphy and sleep/duty diary match, event maker does not match:

  Use actigraphy and sleep/duty diary.

- Event marker and sleep/duty diary match, actigraphy does not match:

  Use event marker and sleep/duty diary.

- None match:

  Use actigraphy, followed by the event marker, followed by the sleep/duty diary.

APPENDIX L, section L2 Scoring an off-wrist period during a sleep period (as indicated by the sleep/duty diary)

Off-wrist periods were determined by the absence of actigraphy data and a reduction in case temperature. Off-wrist periods that occurred during a period of wakefulness were ignored. Off-wrist periods that occurred during sleep (as confirmed by sleep/duty diary entries) were scored as a rest interval but were marked as “bad” to exclude the off-wrist period rest interval from analysis.

APPENDIX L, section L3 Double Scoring Procedure

Actigraphy records were scored by a staff member at the Sleep/Wake Research Centre with 20% of those records being double scored by the researcher. For double scored actigraphy records, if a rest interval time differed by 15 minutes or more, both the staff member and the researcher rescored the actigraphy record. If the rest interval time still differed by 15 minutes or more, the actigraphy record was re-scored by a second staff member at the Sleep/Wake Research Centre who determined the correct rest interval time. Following rescoring, if an actigraphy record was amended to include a corrected rest interval time, a new actigraphy record prefixed by “scored_corrected”, was created. The overall agreement rate for double scored actigraphy records between the staff member at the Sleep/Wake Research Centre and the researcher was 89.5%.

APPENDIX M SIMULATOR STUDY TIMELINE

Date	Description
2011	Initial discussions with Massey University Sleep/Wake Research Centre.
2012 February	Enrolment at Massey University in paper 252.702 Sleep, Fatigue Risk Management and Occupational Safety and Health.
2012 June	Completion of paper 252.702.
2012 June	Initial discussions with the operators Fatigue Safety Action Group regarding the research proposal.
2012 October	Investigation regarding simulator recording capability .
2012 December	Presentation to FSAG who were supportive of the research proposal.
2013 January	Presentation to the operators Chief Flight Operations and Safety Officer who was supportive of the research proposal.
2013 January	Discussion with the Technical Director of one of the Pilot Unions who was supportive of the research proposal.
2013 March	Presentation to a Pilot Union Council who were not supportive of the research proposal. Concerns included a cross section of opinion and security of data.
2013 November	A research proposal addressing concerns with supporting documentation was provided to that Pilot Unions Board of Management (as a follow up to the presentation in 2013 March). The researcher was advised that he required council approval.
2013 December	Simulator recording capability demonstration for one of the Pilot Unions.
2013 December	The researcher was informed that initial concept planning for the purchase of a simulator included the inclusion of a more advanced debriefing system which included a SOQA system[108].
2014 January	Discussion with the operators Flight Operations Manager who was supportive of the research proposal.
2014 May	A research proposal was provided (a second time) to that Pilot Unions council.
2014 June	That Pilot Unions council are supportive of the research proposal.

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[108] This represents a critical step within the research process. Without the SOQA system, this research would likely have been impractical due to the absence of a suitable software program to acquire and analyse simulated flight data.

Date	Description
2014 June	Enrolment in PhD programme.
2015 July	SOQA Training Course (7th – 10th July).
2015 September	To aid initial development of the simulated flight scenarios / profiles the researcher spoke with an academic who supports the operators pilot training programme and the operators Training Manager.
2015 September	Initiation of work with each Pilot Union to establish a SOQA Agreement.
2016 May	Discussion with the operators Head of Airline and General Manager Pilots who were supportive of the research proposal.
2016 July	Following on from council approval in June 2014, that Pilot Unions Board of Management was supportive of the research proposal subject to 1) the development of an agreed deidentification process and 2) a Temporary SOQA Agreement.
2016 July	Massey University confirmation of move to Full Registration.
2016 August	The operators Flight Operations Manager approves the use of pilot resource to conduct the research.
2016 August	Data collection planned for February and March 2017.
2016 September	Discussion with the Admin Head from each Pilot Union who are supportive of the research proposal.
2016 October	Simulator recording capability demonstration for each Pilot Union including SOQA demonstration.
2016 November	To further develop simulated flight scenarios / profiles, a second discussion was held with the academic who supports the operators pilot training programme, the operators Training Manager and Deputy Training manager.
2016 November	Data collection delayed until May and June 2017 due to operator workforce requirements.
2016 November	Massey University Human Ethics Committee provide Ethical Approval for the simulator study.
2016 December	A simulated flight was undertaken to aid with validation of the proposed simulated flight scenario / profile. This represented the first trial simulated flight.
2017 February	A simulated flight which included simulator instructor and flight crew (participants) was undertaken to aid with further validation of the proposed simulated flight scenario / profile. This represented the second trial simulated flight.
2017 March	Discussion with another academic who provided further input into the development of the simulated flight scenarios / profiles.

Date	Description
2017 March	Data collection delayed until July - October 2017 due to operator workforce requirements.
2017 April	SOQA Brief Debrief Station (BDS) testing by CAE Engineers.
2017 June	Data collection postponed due to operator workforce requirements.
2017 August	Temporary Agreement (12 month) Relating to SOQA System signed between each of the Pilot Unions, the operator and the Researcher.
2018 January	SOQA Training Course (31st January – 2nd February).
2018 March	Discussion with the operators General Manager Airlines and Head of Operations Delivery who were supportive of the research proposal[109].
2018 April	Discussion with the operators Flight Operations Manager, Crew Planning Manager Airlines and Senior Crew Planner Airline Training to initiate development / inclusion of the flight duty period protocol within the published roster.
2018 June	Two simulator sessions booked to help with validation of parameters and customised events.
2018 August	The temporary agreement (12 month) relating to the SOQA system signed between one of the Pilot Union's, the operator and the researcher is extended by six months with an expiry of March 1st, 2019.
2018 August	The temporary agreement (12 month) relating to the SOQA system signed between one of the Pilot Union's, the operator and the researcher is extended by 12 months with an expiry of August 1st, 2019.
2018 September	Simulator sessions booked (including allocation of a simulator instructor) for January and February 2019.
2018 November	Start of recruitment.
2018 November	As a result of the initiation of recruitment, a legal advisor from one of the Pilot Union's raises the following concerns: - Methodology to be applied - Consequential risks and liabilities that could arise for participants - The need for appropriate risk mitigation assessment and agreement prior to the start of data collection A signed written undertaking was required from the operator and the researcher.
2019 January	A signed written undertaking was provided by the acting Airline Flight Operations Manager, and the researcher which satisfied the

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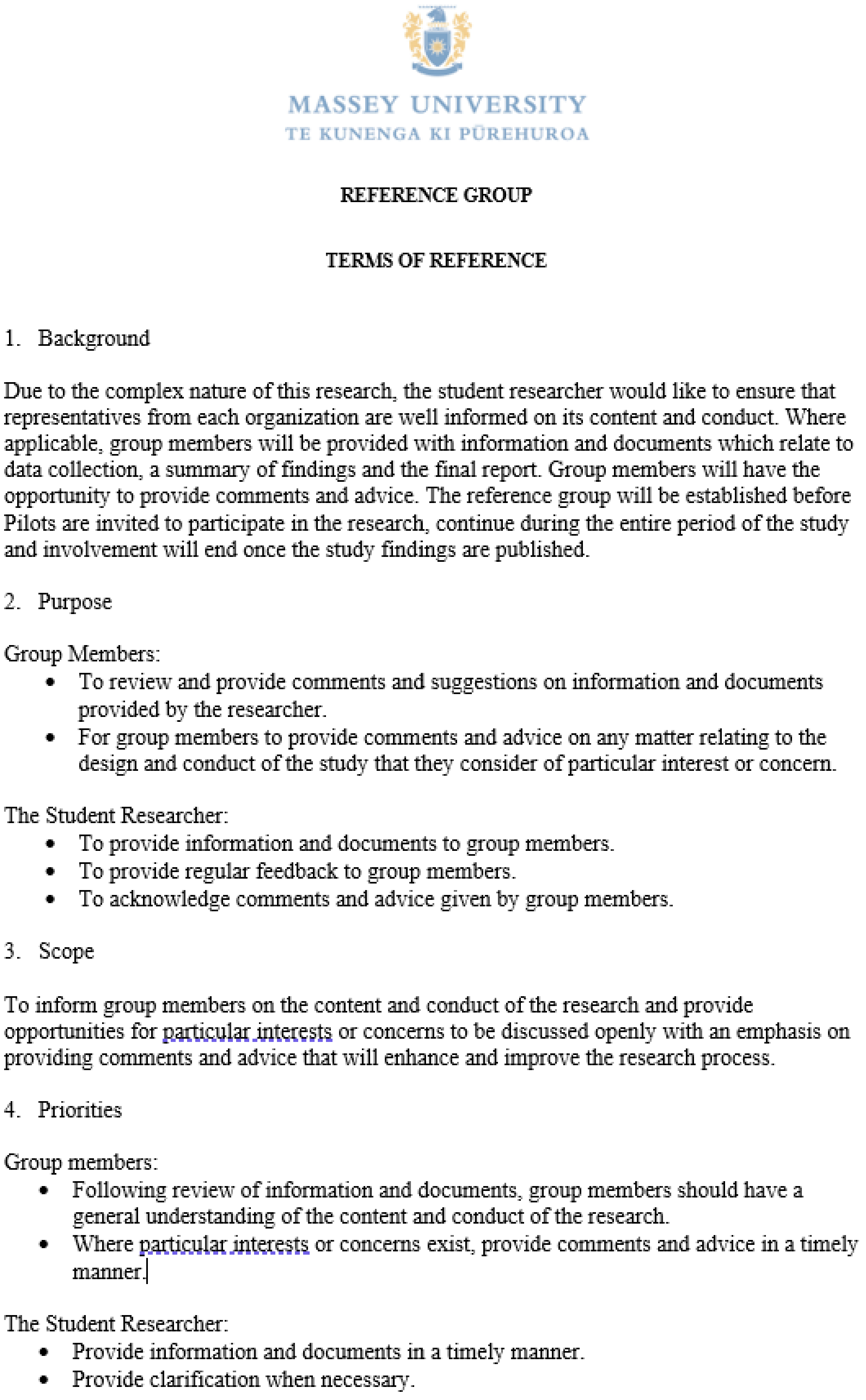
[109] This represents a critical part of the research process. It confirmed that Airline Operations was supportive of the research and ensured that data collection was prioritised during the roster build.

Date	Description
	legal advisors concerns. Subsequently, that Pilot Union was supportive of the simulator study.
2019 January	Start of data collection.
2019 February	One of the Pilot Unions approves an exception to the temporary agreement relating to the SOQA system allowing data collection to be extended.
2019 May	Completion of Data Collection.
2020 June	Expected Date of Completion delayed due to disruption associated with Covid-19.
2024 August	PhD thesis submission.

APPENDIX N PROJECT REFERENCE GROUP – TERMS OF REFERENCE



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REFERENCE GROUP

TERMS OF REFERENCE

1. Background

Due to the complex nature of this research, the student researcher would like to ensure that representatives from each organization are well informed on its content and conduct. Where applicable, group members will be provided with information and documents which relate to data collection, a summary of findings and the final report. Group members will have the opportunity to provide comments and advice. The reference group will be established before Pilots are invited to participate in the research, continue during the entire period of the study and involvement will end once the study findings are published.

2. Purpose

Group Members:

- To review and provide comments and suggestions on information and documents provided by the researcher.
- For group members to provide comments and advice on any matter relating to the design and conduct of the study that they consider of particular interest or concern.

The Student Researcher:

- To provide information and documents to group members.
- To provide regular feedback to group members.
- To acknowledge comments and advice given by group members.

3. Scope

To inform group members on the content and conduct of the research and provide opportunities for particular interests or concerns to be discussed openly with an emphasis on providing comments and advice that will enhance and improve the research process.

4. Priorities

Group members:

- Following review of information and documents, group members should have a general understanding of the content and conduct of the research.
- Where particular interests or concerns exist, provide comments and advice in a timely manner.

The Student Researcher:

- Provide information and documents in a timely manner.
- Provide clarification when necessary.

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- Ensure that there are no surprises in relation to the content or conduct of the research.

5. Membership

Representatives from the following Organizations:

- Massey University
-
-
-
-

Subject matter experts (SME) may be invited to contribute where applicable.

6. Conditions of Membership

- Members must represent their Organization.
- Participation is voluntary.
- Reimbursement for participation will not be offered.
- Members will declare conflicts of interest.

7. Meetings

The majority of correspondence (via email) will fall between meetings to ensure timelines are achieved. The purpose of holding 6 monthly meetings (via teleconference) is to review and document correspondence following the previous meeting. Emphasis will be placed on the recording of comments and advice for inclusion within an appendix of the thesis. The date and time for each meeting will be decided during the previous meeting.

8. Expectations of Members

- To provide comments and advice via email.
- To participate in email correspondence.
- To participate in 6 monthly meetings.
- To promote awareness of interests or concerns to other group members.
- Where differences exist, group members should work towards consensus.
- To respect decisions made by the research team regarding a particular issue or concern.
- To keep confidential, ALL information and documents distributed by the researcher.
- To keep confidential, ALL discussions relating to correspondence between members via email, in person or teleconference.

9. Administration

- The researcher is responsible for all administrative functions.

APPENDIX O VALIDATED PARAMETERS

All TAWS/EGPWS alerts[110]

All TCAS alerts[111]

Flight Guidance and Control Panel push button and rotary knob selections, i.e. selected altitude

Index Control Panel push button and rotary knob selections, i.e. manual speed control

Decision Height / Minimum Descent Altitude rotary knob selection

Flight Mode Annunciator mode arm, mode change, mode capture and mode hold[112]

Very High Frequency (VHF) 1 and 2 Active Frequency

AP Quick Disconnect push button

Flight Director pitch and roll order

TLU LO Speed

Mode Select Auto push button[113]

Engine bleed push button (Left and Right)

Push to talk selector Left and Right

Nose wheel steering control handwheel

Anti Ice Status

De Ice Status

Icing AOA push button

Engine Anti Icing and Wing De Icing Panel push button selections

Baro setting control push STD[114] (Left and Right)

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[110] Terrain Avoidance Warning System / Enhanced Ground Proximity Warning System.

[111] Traffic Alert and Collision Avoidance System.

[112] Annunciation of icing status information, lateral modes, vertical modes and engagement status of autopilot.

[113] A push button represents a depress, i.e. the button is pushed then released.

[114] Standard atmospheric pressure is 1013.2hpa (STD). Local atmospheric pressure is variable. Below transition, local atmospheric pressure is set. Above transition, 1013.2hpa is set. The BARO SET internal rotary knob allows barometric pressure to be set. By pushing the rotactor button, the barometric setting is set to STD (Avions de Transport Regional, 2014, p. 1.10.05).

Landing light switch (Left and Right)

Taxi and take off light switch

Power Management rotary selector

Go around push button

VHF transmission in progress

Touch Control Steering push button

APPENDIX P SIMULATED FLIGHT DESCRIPTIONS

APPENDIX T provides an explanation of terms used in the following descriptions.

APPENDIX P, section P1 First Trial Flight: Simulated Flight Description [Christchurch to Wellington]

The aircraft takes off from Christchurch runway 02. The standard instrument departure (SID) flown is NUBKA THREE PAPA (NUBKA3P) with GRETA transition. The standard route clearance (SRC) is Christchurch Wellington 1 (CHWN1). The standard arrival route (STAR) flown is WARDS 2A and the instrument approach flown is the instrument landing system distance measuring equipment runway 34 (ILS/DME RWY 34). The aircraft lands on Wellington runway 34. The weather in Christchurch is overcast with a cloud base of 4000ft. Visibility is greater than 10km in light rain. Temperature is 22 deg C and the wind is from the northwest at 10kt. The 2000ft wind is from the southwest at 14kt. Mean aerodynamic cord (MAC) is 27% and the aircraft weight is 22600kg which is near its maximum take off weight when it departs Christchurch runway 02. Once airborne, wind speed increases and the direction changes to the southwest resulting in a tailwind of 12kt at an altitude of 500ft. The aircraft is required to cross NUBKA to the north of the runway at an altitude of 2000ft. An increase in tailwind, high temperature and high take off weight will reduce aircraft climb performance. The aircraft enters cloud at 4000ft and while climbing through 6400ft, a TCAS[115] Traffic Advisory (TA) is enunciated followed by a "DESCEND" Resolution Advisory (RA). Crew should stop climb and descend at a rate in the green (fly to) band on the primary flight display vertical speed scale. After separation has become adequate, the TCAS system will issue a "CLEAR OF CONFLICT" RA. At this point, crew should re-establish the aircraft's climb. While passing through 7000ft, the aircraft exits cloud and reaches top of climb in clear air at 17000ft. Cruise is of short

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[115] TCAS is an airborne Traffic alert and Collision Avoidance System that interrogates transponders in nearby aircraft and generates appropriate aural and visual advisories to flight crew to provide adequate separation (Avions de Transport Regional, 2014, p. 2.02.15 P01).

duration with a tailwind of 42kt which reduces flight duration. On descent, the aircraft enters cloud at 7000ft. The cloud base in Wellington is 1000ft with broken towering cumulus clouds. Visibility is greater than 10km however this reduces to 4000m in heavy showers of rain. Temperature is 15 deg C and the surface wind is from the northwest at 20kt. The 2000ft wind is from the northwest at 30kt. On passing WARDS, ATC request that the aircraft maintain 160kt until passing 5DME. Having crossed JONAH and with 3.4nm to run prior to UMAGA, the crew are alerted both aurally and visually to an un-commanded autopilot disconnect. A second iteration of this scenario is trialled[116] which occurs as the aircraft is turning left to intercept the localiser. At this point, the aircraft is at 3000ft, with a crosswind of 13kt and a head wind of 35kt. In both iterations, there is no fault with the autopilot system and the autopilot is available for immediate re-engagement. Once established inbound, flight crew maintain 160kt until 5DME as requested by ATC when passing WARDS. The approach above 1000ft has consistent wind speed and direction with light turbulence where it is unlikely that wind conditions will contribute to approach stability. Four approaches are flown to help determine appropriate wind shear settings that should prompt crew to initiate go around. The approaches start at 1000ft and stop around 300ft. Below 1000ft, windspeed becomes variable and turbulence increases. Below 500ft, fluctuation in aircraft airspeed because of wind shear and increasing turbulence should prompt the crew to initiate go around below 500ft. Turbulence is moderate. The Wind Shear / Microburst Recovery Procedure should be initiated. The aircraft climbs to 4000ft during the missed approach. ATC provide vectors to UMAGA. With just over 2mins remaining until the aircraft crosses UMAGA, ATC request the aircraft enter a righthand[117] holding pattern at UMAGA. On passing UMAGA at 4000ft, ATC clear the aircraft to descend to 3000ft. The aircraft should turn right onto the outbound entry heading before making a right-hand turn to intercept

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[116] Although multiple un-commanded autopilot disconnections were trialled, only one is intended for each planned simulated flight.

[117] The hold direction is opposite to that published on the Instrument Approach Plate.

the inbound holding track[118]. ATC then clear the aircraft for the ILS DME runway 34 approach. An uneventful approach is flown.

APPENDIX P, section P2 First Trial Flight: Simulated Flight Description [Wellington – Christchurch]

The aircraft departs from Wellington runway 16. The standard instrument departure flown is PEGAS THREE DEPARTURE (PEGSA3). The standard route clearance (SCR) is Wellington Christchurch 3 (WNCH3). The standard arrival route flown is MESIX SIX BARVO (MESIX6B) and the instrument approach flown is the instrument landing system distance measuring equipment runway 20 (ILS/DME RWY 20). The aircraft lands on Christchurch runway 20. The temperature in Wellington Is 16 deg C, cloud is overcast at 4000ft with light rain, visibility is greater than 10km and the wind is from the south at 5kt. The 2000ft wind is from the southwest at 9kt. Mean aerodynamic cord (MAC) is 28% and the aircraft take off weight is 22600kg. Prior to take off from Wellington runway 16, the aircraft is cleared to 4000ft on the PEGSA3 standard instrument departure. On passing 2500ft, ATC request the aircraft levels off at 3000ft and on reaching PEGSA, track direct SABDA and climb to 16000ft. A tailwind of 40kt is maintained when above 11000ft to reduce flight time. The aircraft's cruise altitude is 16000ft. The aircraft enters cloud at 4000ft and enters icing conditions in the vicinity of 7000ft which requires the anti-ice system to be engaged. Light ice accretion occurs during both the climb and descent which requires the de-ice system to be engaged. Severe ice accretion does not occur. During descent the wind direction changes from the northwest to a southerly direction and wind speed increases from 60 to 70kt at 10000ft and gradually reduces to 20kt gusting 35kt at surface level. At 2000ft the wind is from the south at 30kt. The temperature in Christchurch is 15 deg C, cloud is broken at 1000ft with visibility reducing to 4000 meters in heavy showers of rain. Wind is from a southerly direction at 20kt gusting 35kt. ATC

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[118] The hold entry is consistent with holding pattern requirements outlined in section 3.4.3 (offset entry) of the Aeronautical Information Publication (Aeropath, 2013, pp., ENR 1.5 - 15).

clear the aircraft to fly the MESIX6B standard arrival route (STAR) and are told that ILS/DME runway 20 is in use. On passing KABGO, ATC request the aircraft track direct to VIKEX and to maintain 4000ft. On passing VIKEX, ATC request the aircraft turn right onto 236M to intercept the localiser for ILS DME 20. In addition, the aircraft is cleared to descend to 2000ft and is requested to maintain 160kt until 5DME. This scenario may result in the aircraft intercepting the glideslope before the localiser. If this occurs, the aircraft cannot descend until intercepting the localiser which will contribute to the aircraft becoming high on profile. Four approaches are flown to determine a realistic scenario. During each iteration, the aircraft tracks ILS/DME runway 20 with a head wind of 45kt and a cross wind of 15kt. Following the fourth iteration, a go around is prompted by ATC at 300ft. Passing 2700ft during the go around, the aircraft is vectored left hand downwind to VIKEX and levels off at 4000ft. While tracking towards VIKEX, with just over 2mins remaining until the aircraft crosses VIKEX, ATC request the aircraft enter a righthand[119] holding pattern at ODISI. On passing ODISI at 4000ft, ATC clear the aircraft to descend to 3000ft. The aircraft should be turned right onto the outbound entry heading before making a right-hand turn to intercept the inbound holding track[120]. ATC then clear the aircraft for the ILS DME runway 20 approach. An uneventful approach is flown.

APPENDIX P, section P3 Second Trial Flight: Simulated Flight Description [Christchurch to Wellington]

The aircraft takes off from Christchurch runway 02. The standard instrument departure (SID) flown is NUBKA THREE PAPA (NUBKA3P) with GRETA transition. The standard route clearance (SCR) is Christchurch Wellington 1 (CHWN1). The standard arrival route (STAR) flown is WARDS 2A and the instrument approach flown is the instrument landing system distance measuring equipment runway 34 (ILS/DME RWY 34). The aircraft lands on Wellington runway 34. In Christchurch, the cloud base is broken at 4000ft. Visibility is

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[119] The hold direction is opposite to that published on the instrument approach plate.

[120] The hold entry is consistent with holding pattern requirements outlined in section 3.4.3 of the Aeronautical Information Publication (Aeropath, 2013, pp., ENR 1.5 - 15).

greater than 10km in light rain. Temperature is 22 deg C and the wind is from the northwest at 10kt. The 2000ft wind is from the southwest at 14kt. Mean aerodynamic cord (MAC) is 28% and aircraft weight is 22600kg. During initial climb, the aircraft is required to cross NUBKA to the north of the runway at an altitude of 2000ft. The increase in tailwind, high temperature and high take off weight reduce aircraft climb performance requiring crew intervention to ensure the aircraft complies with the altitude constraint. During climb, the aircraft enters cloud at 4000ft and while climbing through 5200ft, a TCAS Traffic Advisory (TA) is enunciated followed by a “DESCEND” Resolution Advisory (RA). Crew should stop climb the and descend at a rate in the green (fly to) band on the primary flight display vertical speed scale. After separation has become adequate, the TCAS system issues a “CLEAR OF CONFLICT” RA. At this point, crew should re-establish the aircraft’s climb. The aircraft exits cloud when climbing through 7000ft and does not enter atmospheric icing conditions. Cruise is of short duration with a tailwind of 40kt that reduces flight duration. During descent, the aircraft enters cloud at 7000ft however remains clear of atmospheric icing conditions. The cloud base in Wellington is 1000ft with broken towering cumulus clouds. Visibility is greater than 10km however does reduce to 4000m in heavy showers of rain. Temperature is 20 deg C. The 2000ft wind is from the northwest at 35kt and the surface wind is also from the northwest at 20kt. On passing WARDS[121], ATC request that the aircraft maintain 160kt until passing 5DME. On crossing JONAH[122], the crew are alerted both aurally and visually to an un-commanded autopilot disconnect. There is no fault with the autopilot system and the autopilot is available for immediate re-engagement. The approach above 1000ft has consistent wind speed and direction with light turbulence. It is unlikely that environmental conditions will destabilise the approach. Below 500ft, fluctuation in aircraft airspeed and increasing

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[121] WARDS is a waypoint located 41.8nm (77.4km) from Wellington. The ATC speed constraint instruction was provided when the aircraft crossed WARDS, which is 10 minutes before the aircraft will cross 5DME on the ILS/DME RWY34 instrument approach.

[122] JONAH is 11.15nm from Wellington and 5nm from UMAGA.

turbulence should result in crew initiating a go around due to wind shear. Turbulence is moderate. The Wind Shear / Microburst Recovery Procedure should be actioned as the aircraft climbs to 3000ft during the missed approach. ATC provide vectors to UMAGA. With just over 2mins remaining until the aircraft crosses UMAGA, ATC request the aircraft enter a righthand[123] holding pattern at UMAGA. On passing UMAGA at 3000ft, ATC clear the aircraft to descend to 2000ft. The aircraft should turn right onto the outbound entry heading before making a right hand turn to intercept the inbound holding track[124]. ATC then clear the aircraft for the ILS DME runway 34 approach. An uneventful approach is flown.

APPENDIX P, section P4 Second Trial Flight: Simulated Flight Description [Wellington to Christchurch]

The aircraft takes off from Wellington runway 16. The standard instrument departure flown is PEGSA THREE DEPARTURE (PEGSA3). The standard route clearance (SCR) is Wellington Christchurch 3 (WNCH3) and the standard arrival route flown is MESIX SIX BARVO (MESIX6B). The instrument approach flown is the instrument landing system distance measuring equipment runway 20 (ILS/DME RWY 20). The aircraft lands on Christchurch runway 20. The temperature in Wellington is 20 deg C, cloud is broken at 4000ft with light rain, visibility is greater than 10km and the wind is from the south at 10kt. The 2000ft wind is from the northwest at 15kt. Mean aerodynamic cord (MAC) is 28% and the aircraft take off weight is 22400kg. Prior to take off from Wellington runway 16, the aircraft is cleared to 10000ft on the PEGSA3 standard instrument departure. Light ice accretion occurs between 7000ft and 14000ft which requires engagement of anti-ice and de-ice systems. During cruise at 16000ft, a tailwind of 28kt reduces flight duration. During descent, wind direction gradually changes from a north westerly to a southerly and wind speed decreases from 40kt at 10000ft to 20kt at surface level. Light ice accretion

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[123] The direction of the hold is opposite to that on the instrument approach plate.

[124] The hold entry is consistent with holding pattern requirements outlined in section 3.4.3 (offset entry) of the Aeronautical Information Publication (Aeropath, 2013, pp., ENR 1.5 - 15).

occurs between 14000ft and 8000ft which requires engagement of anti-ice and de-ice systems. On passing 10000ft during descent[125], ATC instruct the aircraft to enter a righthand[126] holding pattern at KABGO at 8000ft. The temperature in Christchurch is 17 deg C, cloud is broken at 1500ft, and visibility is 6000 meters in light rain. Wind is from the southwest at 20kt. ATC clear the aircraft to fly the MESIX6B standard arrival route (STAR) and indicate that the crew can expect the ILS/DME runway 20 instrument approach. When crossing CH409[127], the flight crew are alerted both aurally and visually to an un-commanded autopilot disconnect[128]. Having crossed CH409, ATC advise the aircraft to expedite descent[129] to 3000ft. The approach clearance provided by ATC is for the localiser but not the glide slope. The implication is that the aircraft can track inbound towards the runway however cannot descend below 3000ft. The crew receive clearance to descend at 8 DME[130] when the aircraft is 300ft above profile. Headwind during the approach is 17kt with a 14kt cross wind component. Turbulence is light to moderate. At 300ft, a TAWS/EGPWS warning “TOO LOW GEAR”[131] occurs, which should prompt the flight crew to go around. On passing 3000ft, ATC then vector the aircraft righthand downwind for a second ILS/DME RWY 20 approach which is normal.

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[125] The aircraft is 7nm from KABGO which allows roughly two minutes for the crew to prepare to enter the holding pattern.

[126] The direction of the holding pattern is opposite to the holding pattern depicted on the standard arrival plate.

[127] CH409 is 16.6nm from Christchurch and 5nm from waypoint ODISI.

[128] The intention was for the autopilot to be available for immediate re-engagement. This represented a misunderstanding between the researcher and the simulator instructor that was corrected following the initial simulated flight protocol.

[129] Expedite implies that the requested action should start immediately.

[130] This had the effect of delaying flight crew preparation for the approach however sufficient time was likely available to allow the crew to stabilise the aircraft prior to reaching the 1000ft stable gate.

[131] The operators standard operating procedure for a TAWS/EGPWS “TOO LOW GEAR” alert is for the flight crew to commence the go around/missed approach procedure (Operator Documentation, 2018, pp. 6B-27).

APPENDIX P, section P5 Final Flight: Simulated Flight Description [Christchurch to Wellington]

The aircraft takes off from Christchurch runway 02. The standard instrument departure flown is NUBKA FIVE PAPA (NUBKA5P) with GRETA transition[132]. The SRC is Christchurch Wellington 1 (CHWN1). The standard arrival route flown is WARDS 2A and the instrument approach flown is the instrument landing system distance measuring equipment runway 34 (ILS/DME RWY 34). The aircraft lands on Wellington runway 34. Christchurch has broken cloud at 4000ft with light rain and a visibility greater than 10km. Temperature is 22 deg C and the wind from the northwest at 10kt. The 2000ft wind is from the southwest at 15kt. Mean aerodynamic cord (MAC) is 28% and the aircraft weight is 22520kg which is near its maximum take off weight. Once airborne, wind speed increases and the direction changes to the southwest resulting in a tailwind of 12kt at an altitude of 500ft. The aircraft is required to NUBKA to the north of the airfield at an altitude of 2000ft. An increase in tailwind, high temperature and high take off weight will reduce aircraft climb performance. Climbing through 4000ft the aircraft enters cloud and when climbing through 7000ft, the aircraft enters icing conditions[133] which requires engagement of anti-ice systems. Following ice accretion, engagement of the de-icing system is required. Severe ice accretion does not occur. A tailwind of 28kt is maintained passing 11000ft. On passing 14000ft, the aircraft exits icing conditions and reaches top of climb in clear air at 17000ft. Cruise is of short duration and on descent, the aircraft enters icing conditions at 14000ft which requires reactivation of anti-ice and de-ice systems. Severe icing accretion does not occur. At 10000ft the tailwind component has reduced to 10kt and although remaining in cloud, the aircraft exits icing conditions. In Wellington, cloud is broken at 4000ft and scattered at 2000ft. Visibility is 7000m in light rain,

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[132] The location where the aircraft completes the standard instrument departure and transitions to the enroute phase of flight.

[133] Inflight icing conditions are defined when the total air temperature is 7 deg C or less while flying through visible moisture where visible moisture is defined as clouds, fog with visibility of 1800m or less, rain, snow, sleet or ice crystals (Operator Documentation, 2018, section 4.9.1).

temperature is 19 deg C and the surface wind and 2000ft wind is from the northwest at 20kt[134]. On passing WARDS, ATC request that the aircraft maintain 160kt until passing 5DME. JONAH is 11.15nm from Wellington and is 5nm from UMAGA. When crossing JONAH, the aircraft is on an eastward heading and will need to turn left to intercept the ILS localiser[135] before reaching UMAGA. On crossing JONAH, the aircraft should be above 3000ft with a tailwind of 18kt. At this point, the flight crew are alerted both aurally and visually to an un-commanded autopilot disconnect. There is no fault with the autopilot system and the autopilot is available for immediate re-engagement. The flight crew turn the aircraft to the left and intercept the localiser. Once established inbound[136], flight crew should maintain 160kt until 5DME[137] as requested by ATC when passing WARDS. Headwind during the approach is 10kt with a small cross wind component and turbulence is light. At 300ft ATC instruct the aircraft to go around. ATC then vector the aircraft for a second ILS/DME RWY 34 approach which is normal.

APPENDIX P, section P6 Final Flight: Simulated Flight Description [Wellington to Christchurch]

The aircraft departs from Wellington runway 16. The standard instrument departure flown is TAXUP TWO QUEBEC (TAXUP2Q) with a SABDA transition. The SRC is Wellington Christchurch 3 (WNCH3). The standard arrival route flown is MESIX SIX BARVO (MESIX6B) and the instrument approach flown is the instrument landing system distance measuring equipment runway 20 (ILS/DME RWY 20). The aircraft lands on Christchurch runway 20. The weather in Wellington is warm with a temperature of 20 deg C. The cloud base is broken at 4000ft, visibility is greater than 10km with light rain and the wind is

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[134] Wellington features a predominantly strong wind from either a northerly or southerly direction. The northerly wind blows 60% of the time with winds averaging 50 – 60kt when preceding a cold front (Wagtendonk et al., 2000b).

[135] The localiser (abbreviated LOC) provides directional guidance along the extended approach path centreline to the landing runway (Wagtendonk et al., 2000a).

[136] An aircraft is not considered to be established on the localizer until it is within a half scale deflection of the ILS localiser (Aeropath, 2019, ENR 1.5, 4.13.5 (f)).

[137] This has the effect of delaying flight crew preparation for the approach however sufficient time was likely available to allow the crew to stabilise the aircraft prior to reaching the 1000ft stable gate.

southwest at 10kt. The 2000ft wind is from the southwest at 15kt. Mean aerodynamic cord (MAC) is 28% and the aircraft take off weight is 22400kg. Prior to take off, ATC instruct the crew to cross TAXUP at or above 4000ft[138]. On passing 2000ft, the wind direction changes to the northwest resulting in a tailwind of 14kt when passing 2500ft. The aircraft enters cloud at 4000ft and enters icing conditions in the vicinity of 7000ft which requires the anti-ice system to be engaged. Light ice accretion occurs during climb which requires the de-ice system to be engaged. Severe ice accretion does not occur. Passing 11000ft, windspeed increases to 45kt which results in a tailwind of 23kt. The aircraft exits icing conditions at 14000ft and reaches top of climb at 16000ft. The cruise portion of the flight is of short duration. During descent, the aircraft enters icing conditions at 14000ft which requires activation of anti-ice and de-ice. Light ice accretion occurs during descent which requires the de-ice system to be engaged. The aircraft exits icing conditions at 9000ft however remains in instrument meteorological conditions. The weather in Christchurch is cool with a temperature of 15 deg C. The wind is southwest at 20kt, cloud base is broken at 1000ft, and visibility is 6000m in light rain. The 2000ft wind is from the southwest at 25kt. ATC request the aircraft fly the MESIX SIX BARVO (MESIX6B) standard arrival route. The runway in use at Christchurch is runway 20 and the approach in use is the ILS/DME RWY 20. When crossing CH409, the flight crew are alerted both aurally and visually to an un-commanded autopilot disconnect. CH409 is 16.6nm from Christchurch and 5nm from ODISI. There is no fault with the autopilot system and the autopilot is available for immediate re-engagement. Having crossed CH409, ATC advise the aircraft to expedite descent to 3000ft. The aircraft is required to turn left to intercept the localiser and level off at 3000ft. The approach clearance provided by ATC is for the localiser but not the glide slope. The implication is that the aircraft can track inbound towards the runway however cannot descend below 3000ft. The crew

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[138] TAXUP has a published ATC altitude restriction of between 3000ft and 6000ft (Aeropath, 2018). Requiring the aircraft to cross TAXUP at 4000ft results in a required climb gradient of 8.1% (500ft per nm) between lift off and 4000ft.

receive clearance to descend at 8 DME. The aircraft is 300ft above the glide slope. Headwind during the approach is 15kt with a 12kt cross wind component and turbulence is light to moderate. At 300ft ATC instruct the aircraft to go around. ATC then vector the aircraft righthand downwind for a second ILS/DME RWY 20 approach which is normal.

APPENDIX Q SIMULATED FLIGHT SCENARIOS

APPENDIX Q, section Q1 Scenarios Included in the First Trial of the Simulated Flights

Table Q 1 Scenarios included in the First Trial of the Christchurch Wellington Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Tailwind during initial climb.	2000ft wind 240M 15kt Cloud overcast 4000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 22 deg C.	Initial climb.	Environmental conditions conducive to decreased climb performance.	During initial climb, a wind shift occurs resulting in an unexpected tailwind of 12kt at 500ft.	The aircrafts path is modified to ensure the 2000ft altitude constraint at NUBKA is complied with.	If crew contact ATC and indicate that they cannot comply with the altitude constraint at NUBKA, ATC will request that the aircraft level off at 2000ft.	Scenario flown as planned. Sub scenario not applicable.
Traffic alert and Collision Avoidance System Resolution Advisory.	Instrument Meteorological Conditions. Light turbulence. 11 deg C.	Climb.	Traffic alert Collision Avoidance System Resolution Advisory at 6500ft.	Aural and visual information provided to the flight crew.	The aircrafts path is modified to ensure the aircrafts vertical speed is adjusted to equal the resolution required vertical speed.	Nil.	Scenario flown as planned.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Un-commanded autopilot disconnect prior to being established on ILS/DME RWY 34 instrument approach.	Wind at 4000ft, 320M 38kt. Cloud broken 1000ft. Moderate Turbulence. Heavy rain. Temperature 15 deg C.	Descent.	Un-commanded autopilot disconnection.	Audio and visual AUTOPILOT OFF warnings.	Immediate re-engagement of autopilot.	Nil.	Scenario flown as planned.
Speed restriction during ILS/DME RWY34 instrument approach above 1000ft.	2000ft wind 320M 30kt. Cloud Broken 1000ft. Moderate Turbulence. Wind shear reported. Visibility 4000m in heavy showers of rain. Temperature 15 deg C.	Approach.	ATC issue the crew with a speed instruction at WARDS to maintain 160kt until 5DME.	Maintaining 160kt until 5DME will delay crew in completing the before landing checklist.	Crew comply with stable approach criteria airspeed requirements before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the aircraft to climb to and maintain 3500ft.	Multiple approaches trialled. Scenario flown as planned. Sub scenario not applicable.
Go around	2000ft wind 320M 30kt. Cloud Broken 1000ft. Moderate Turbulence. Wind shear reported. Visibility 4000m in heavy showers of rain. Temperature 15 deg C.	Approach.	Rapid loss of airspeed and increasing turbulence associated with negative wind shear.	Push the power lever go around button. OR Rotate to go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	If the approach is continued, ATC will instruct the aircraft to go around.	Scenario flown as planned. Sub scenario not applicable.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Holding Pattern.	4000ft wind 320M 40kt. Cloud broken at 1000ft. Moderate turbulence.	Descent / Initial Approach.	ATC instruct the aircraft to enter a holding pattern at UMAGA. On passing UMAGA, ATC instruct the aircraft to descend to 3000ft.	On passing UMAGA, the aircraft turns right onto the outbound entry heading then turns right to intercept the inbound holding track.	Crew comply with Sector 2 Entry Procedures (Offset Entry) as outlined in Aeropath (2013, pp., ENR 1.5 - 15).	Nil.	Scenario flown as planned.

Table Q 2 Scenarios included in First Trial of the Wellington Christchurch Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Aircraft handling following unexpected change to flight path.	2000ft wind 230M 10kt C loud overcast 4000ft. Light turbulence. Visibility > 10km. Temperature 16 deg C.	Initial climb.	Having passed 2500ft during departure, ATC request the aircraft to level off at 3000ft until passing PEGSA[139].	Selected altitude changed from 4000ft to 3000ft. OR Autopilot disengagement.	Aircraft climb is stopped at 3000ft.	Nil.	Scenario flown as planned.

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[139] PEGSA is located 10nm from Wellington. The aircraft would be 5.4nm from Wellington when passing 2500ft and 4.6nm from PEGSA.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Ice accretion during climb and descent.	Climb: Instrument Meteorological Conditions. Total Air Temperature < 7 deg C at 6500ft. Cloud tops 14000ft. Descent: Instrument Meteorological Conditions. Total Air Temperature > 7 deg C at 8500ft. Cloud base 1000ft.	Climb. Descent.	Environmental conditions conducive to atmospheric icing conditions.	1. Entering Icing Conditions. 2. Ice Accretion and as long as atmospheric icing conditions exist. 3. Leaving Icing Conditions. 4. When the aircraft is visually verified clear of ice.	Crew complete checklists associated with: 1. entering icing conditions, 2. ice accretion, 3. when leaving icing conditions and 4. when the aircraft is verified clear of ice.	Nil.	During climb, the rate of ice accretion contributed to a change in flight path. Ice accretion was heavier than planned.
Height restriction during ILS/DME RWY20 instrument approach above 1000ft.	Surface wind 180M 20kt. Cloud broken at 1000ft. Moderate turbulence. Visibility 4000m in heavy showers of rain. Temperature 15 deg C.	Approach.	ATC request the aircraft maintain 160kt to 5DME. In addition, ATC provide vectors which result in GS capture before LOC capture.	Aircraft cannot descend until established on the localiser which prevents the aircraft from descending.	Crew recover the vertical path before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the crew to climb and maintain 3500ft.	In the planned scenario, ATC clear the aircraft for the localiser which prevents the aircraft from descending. Surface wind is 230M20kt with light turbulence. Sub scenario not applicable.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Go around.	Surface wind 180M 20kt. Cloud broken at 1000ft. Moderate turbulence. Visibility 4000m in heavy showers of rain. Temperature 15 deg C.	Approach.	ATC instruct the aircraft to go around at 300ft.	Push the power lever go around button. OR Rotate to the go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	Nil.	In the planned scenario, surface wind is 230M20kt with light turbulence.
Holding Pattern.	4000ft wind 180M 40kt. Cloud broken at 1000ft. Moderate turbulence.	Descent / Initial Approach.	ATC instruct the aircraft to enter a holding pattern at ODISI. On passing ODISI, ATC instruct the aircraft to descend to 3000ft.	On passing ODISI, the aircraft turns onto the outbound entry heading then intercepts the inbound holding track.	Crew comply with Sector 2 Entry Procedures (Offset Entry) as outlined in Aeropath (2013, pp., ENR 1.5 - 15).	Nil.	Scenario flown as planned.

APPENDIX Q, section Q2 Scenarios Included in the Second Trial of the Simulated Flights

Table Q 3 Scenarios included in the Second Trial of the Christchurch Wellington Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Tailwind during initial climb.	2000ft wind 240M 15kt. Cloud Broken 4000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 22 deg C.	Initial climb.	Environmental conditions conducive to decreased climb performance.	During initial climb, a wind shift occurs resulting in an unexpected tailwind of 12kt at 500ft.	The aircrafts path is modified to ensure the 2000ft altitude constraint at NUBKA is complied with.	If crew contact ATC and indicate that they cannot comply with the altitude constraint at NUBKA, ATC will request that the aircraft level off at 2000ft.	Scenario flown as planned. Sub scenario not required.
Traffic alert and Collision Avoidance System Resolution Advisory.	Wind at 6000ft, 240M 30kt. Instrument Meteorological Conditions. Light turbulence. Light rain. 12 deg C.	Climb.	Traffic alert Collision Avoidance System (TCAS) Resolution Advisory (RA) at 5500ft.	Aural and visual information provided to the flight crew.	The aircrafts path is modified to ensure the aircrafts vertical speed is adjusted to equal the resolution required vertical speed.	Nil.	Scenario flown as planned. Timing and nature of the TCAS advisory and weather differ from first trial flight.
Un-commanded autopilot disconnect when passing JONAH[140].	2000ft wind 300M 30kt. Cloud broken 1000ft. Moderate Turbulence. Light rain. Temperature 16 deg C.	Descent.	Un-commanded autopilot disconnection.	Audio and visual AUTOPILOT OFF warnings.	Immediate re-engagement of autopilot.	Nil.	Scenario flown as planned.

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[140] Waypoint JONAH (JONAH) is 11.15nm from Wellington and is 5nm from UMAGA.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Speed restriction during ILS/DME RWY34 instrument approach above 1000ft.	2000ft wind 280M 30kt. Cloud Broken 1000ft. Moderate Turbulence. Wind shear reported. Visibility 7000m Moderate rain. Temperature 16 deg C.	Approach.	ATC issue the crew with a speed instruction at WARDS[141] to maintain 160kt until 5DME.	Maintaining 160kt until 5DME will delay crew in completing the before landing checklist.	Crew comply with stable approach criteria airspeed requirements before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the aircraft to climb to and maintain 3500ft.	Scenario flown as planned. Sub scenario not required.
Go around.	2000ft wind 280M 30kt. Cloud Broken 1000ft. Moderate Turbulence. Wind shear reported. Visibility 7000m Moderate rain. Temperature 16 deg C.	Approach.	Rapid loss of airspeed and increasing turbulence associated with negative wind shear.	Push the power lever go around button. OR Rotate to the go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	If the approach is continued, ATC will instruct the aircraft to go around.	Scenario flown as planned. Sub scenario not required.

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[141] WARDS is located 41.8nm (77.4km) from Wellington. The ATC speed constraint instruction was provided when the aircraft crossed WARDS, which was 10 minutes before the aircraft would cross 5DME on the ILS/DME RWY34 instrument approach.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Holding Pattern.	3000ft wind 300M 20kt. Cloud broken at 1000ft. Moderate turbulence.	Descent / Initial Approach.	ATC instruct the aircraft to enter a holding pattern at UMAGA. On passing UMAGA, ATC instruct the aircraft to descend to 2000ft.	On passing UMAGA, the aircraft turns right onto the outbound entry heading then turns right to intercept the inbound holding track.	Crew comply with Sector 2 Entry Procedures (Offset Entry) as outlined in Aeropath (2013, pp., ENR 1.5 - 15).	Nil.	Scenario flown as planned.

Table Q 4 Scenarios included in the Second Trial of the Wellington Christchurch Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Ice accretion during climb while in level flight at 10000ft.	Climb: Instrument Meteorological Conditions. Total Air Temperature < 7 deg C at 8000ft. Cloud tops 13000ft.	Climb.	Environmental conditions conducive to atmospheric icing conditions. The aircraft is in level flight at 10000ft for 140sec during ice accretion.	1. Entering Icing Conditions. 2. Ice Accretion and as long as atmospheric icing conditions exist. 3. Leaving Icing Conditions. 4. When the aircraft is visually verified clear of ice.	Crew complete checklists associated with: 1. entering icing conditions, 2. ice accretion, 3. when leaving icing conditions and 4. when the aircraft is verified clear of ice.	Nil.	Scenario flown as planned.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Holding Pattern.	7000ft wind 270M 35kt. Cloud broken at 1000ft. Moderate turbulence.	Descent / Initial Approach.	ATC instruct the aircraft to enter a holding pattern at KABGO. On passing KABGO, ATC instruct the aircraft to descend to 7000ft.	On passing KABGO, the aircraft is turned to follow the holding pattern.	Crew comply with Sector 3 Entry Procedures (Direct Entry) as outlined in Aeropath (2013, pp., ENR 1.5 - 15)	Nil.	Scenario flown as planned.
Un-commanded autopilot disconnect prior to crossing CH409[142].	Surface wind 230M 20kt. Cloud Broken 1000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 17 deg C.	Descent.	Un-commanded autopilot disconnection.	Audio and visual AUTOPILOT OFF warnings.	Immediate re-engagement of autopilot.	Nil.	Autopilot not re-engaged. Flight crew attempt to re-engage the autopilot however it was mistakenly disabled by the simulator instructor.
Height restriction during ILS/DME RWY20 instrument approach above 1000ft.	Surface wind 230M 20kt. Cloud Broken 1000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 17 deg C.	Approach.	ATC clear the aircraft for the localiser which prevents the aircraft from descending. At 8DME, the aircraft is cleared for the approach which allows it to descend.	One DOT high on glide slope at 8mn equates to 300ft above path.	Crew recover the vertical path before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the crew to climb and maintain 3500ft.	Scenario hand flown. Sub scenario not required.

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[142] CH409 is 16.6nm from Christchurch and 5nm from ODISI.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario	Comments
Go around.	Surface wind 230M 20kt. Cloud Broken 1000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 17 deg C.	Approach.	At 300ft on ILS/DME RWY20 approach, Spurious TAWS/EGPWS Warning “TOO LOW GEAR”[143].	Push the power lever go around button. OR Rotate to the go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	Nil.	Scenario hand flown.

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[143] The operators standard operating procedure for TAWS/EGPWS “TOO LOW GEAR” alert is for the flight crew to commence the standard go around/missed approach procedure (Operator Documentation, 2018, pp. 6B-27) however acceleration must be delayed until all TAWS/EGPWS warnings have ceased and the aircraft is at or above the nominated acceleration altitude.

APPENDIX Q, section Q3 Scenarios Included in the Final Simulated Flights

Table Q 5 Scenarios included in the Final Christchurch Wellington Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario
Tailwind during initial climb.	2000ft wind 240M 15kt. Cloud Broken 4000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 22 deg C.	Initial climb.	Environmental conditions conducive to decreased climb performance.	During initial climb, a wind shift occurs resulting in an unexpected tailwind of 12kt at 500ft.	The aircrafts path is modified to ensure the 2000ft altitude constraint at NUBKA is complied with.	If crew contact ATC and indicate that they cannot comply with the altitude constraint at NUBKA, ATC will request that the aircraft level off at 2000ft.
Ice accretion during climb and descent.	Climb: Instrument Meteorological Conditions. Total Air Temperature < 7 deg C at 7000ft. Cloud tops 14000ft. Descent: Instrument Meteorological Conditions. Total Air Temperature > 7 deg C at 10000ft. Cloud base 4000ft.	Climb Descent	Environmental conditions conducive to atmospheric icing conditions.	1. Entering Icing Conditions 2. Ice Accretion and as long as atmospheric icing conditions exist. 3. Leaving Icing Conditions 4. When the aircraft is visually verified clear of ice.	Crew complete checklists associated with: 1. entering icing conditions, 2. ice accretion, 3. when leaving icing conditions and 4. when the aircraft is verified clear of ice.	Nil.

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario
Un-commanded autopilot disconnect when passing JONAH[144].	2000ft wind 300M 30kt. Cloud broken 4000ft. Moderate Turbulence. Light rain. Temperature 16 deg C.	Descent.	Un-commanded autopilot disconnection.	Audio and visual AUTOPILOT OFF warnings.	Immediate re-engagement of autopilot.	Nil.
Speed restriction during ILS/DME RWY34 instrument approach above 1000ft.	Surface wind 330M 20kt. Cloud Broken 4000ft. Moderate turbulence. Light rain. Visibility > 10km. Temperature 16 deg C.	Approach.	ATC issue the crew with a speed instruction at WARDS[145] to maintain 160kt until 5DME.	Maintaining 160kt until 5DME will delay crew in completing the before landing checklist.	Crew comply with stable approach criteria airspeed requirements before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the aircraft to climb to and maintain 3500ft.
Go around.	Surface wind 330M 20kt. Cloud Broken 4000ft. Moderate turbulence. Light rain. Visibility > 10km. Temperature 16 deg C.	Approach.	ATC instruct the aircraft to go around at 300ft.	Push the power lever go around button. OR Rotate to the go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	Nil.

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[144] JONAH is 11.15nm from Wellington and is 5nm from UMAGA.

[145] WARDS is located 41.8nm (77.4km) from Wellington. The ATC speed constraint instruction was provided when the aircraft crossed WARDS, which is 10 minutes before the aircraft will cross 5DME on the ILS/DME RWY34 instrument approach.

Table Q 6 Scenarios included in the Final Wellington Christchurch Simulated Flight

Planned scenario	Weather	Phase of flight	Problem input	Problem indication	Problem output	Sub scenario
Tailwind during climb.	2000ft wind 200M 10kt. Cloud Broken 4000ft. Light turbulence. Light rain. Visibility > 10km. Temperature 20 deg C.	Climb.	Prior to take off, ATC request that the aircraft cross TAXUP at or above 4000ft. Environmental conditions conducive to decreased climb performance.	At 2000ft, a wind shift occurs resulting in an unexpected 14kt tailwind at 2500ft.	The aircrafts path is modified to ensure the altitude constraint at TAXUP is complied with.	If crew contact ATC and indicate that they cannot comply with the altitude constraint at TAXUP, ATC will request that the aircraft level off at 4000ft.
Ice accretion during climb and descent.	Climb: Instrument Meteorological Conditions. Total Air Temperature < 7 deg C at 7000ft. Cloud tops 14000ft. Descent: Instrument Meteorological Conditions. Total Air Temperature > 7 deg C at 9000ft. Cloud base 1000ft.	Climb. Descent.	Environmental conditions conducive to atmospheric icing conditions.	1. Entering Icing Conditions. 2. Ice Accretion and as long as atmospheric icing conditions exist. 3. Leaving Icing Conditions. 4. When the aircraft is visually verified clear of ice.	Crew complete checklists associated with: 1. entering icing conditions, 2. ice accretion, 3. when leaving icing conditions and 4. when the aircraft is verified clear of ice.	Nil.
Un-commanded autopilot disconnect prior to crossing CH409[146].	2000ft wind 260M 25kt. Cloud broken 1000ft. Light Turbulence. Light rain. Temperature 15 deg C.	Descent.	Un-commanded autopilot disconnection.	Audio and visual AUTOPILOT OFF warnings.	Immediate re-engagement of autopilot.	Nil.

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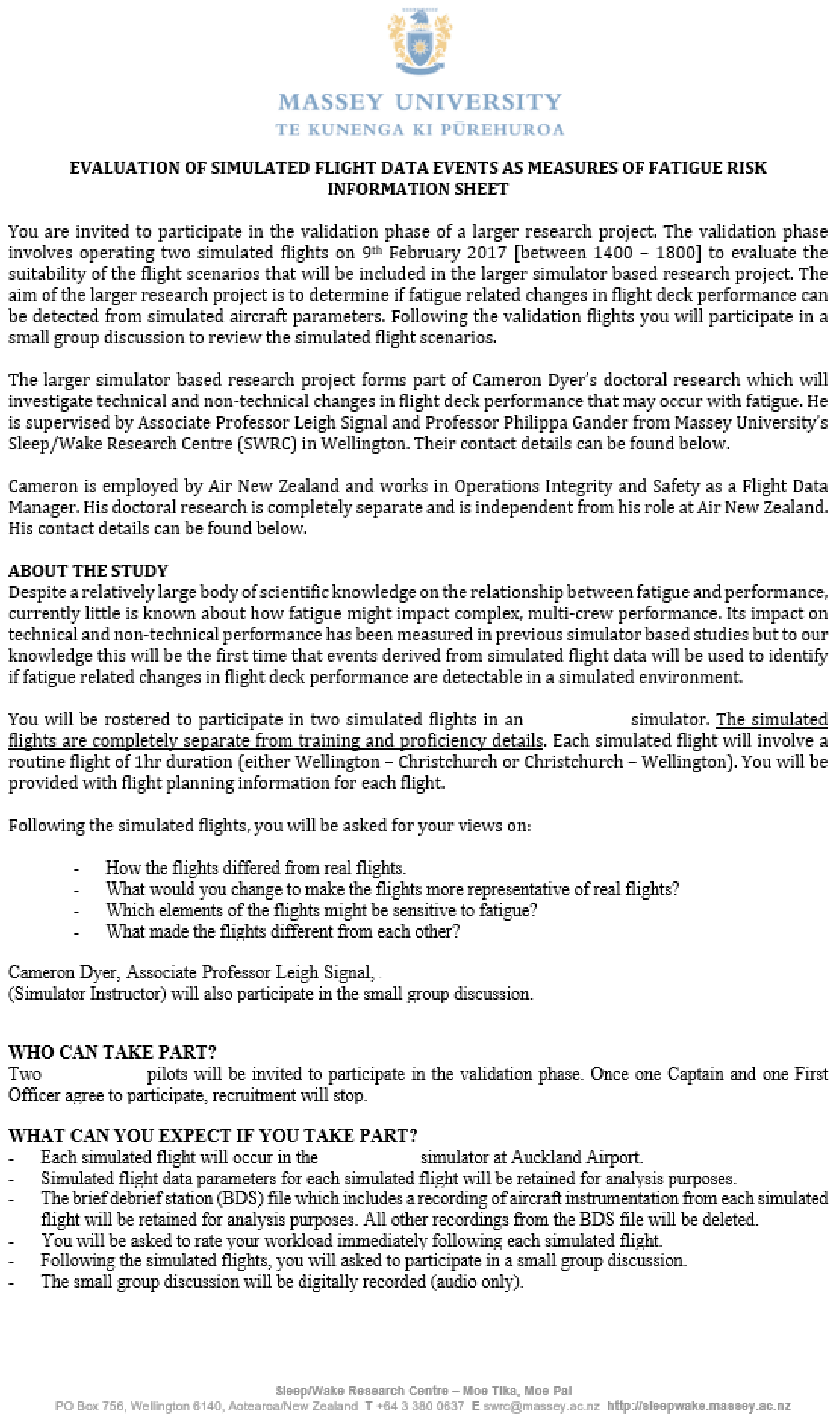
[146] CH409 is 16.6nm from Christchurch and 5nm from ODISI.

Planned scenario	**Weather**	**Phase of flight**	**Problem input**	**Problem indication**	**Problem output**	**Sub scenario**
Height restriction during ILS/DME RWY20 instrument approach above 1000ft.	Surface wind 230M 20kt. Cloud Broken 1000ft. Light turbulence. Light rain. Visibility 6000m. Temperature 15 deg C.	Approach.	ATC clear the aircraft for the localiser which prevents the aircraft from descending. At 8DME, the aircraft is cleared for the approach which allows it to descend.	One DOT high on glide slope at 8mn equates to 300ft above path.	Crew recover the vertical path before reaching the 1000ft approach stable gate.	If crew contact ATC and state they are not able to comply, ATC will instruct the crew to climb and maintain 3500ft.
Go around.	Surface wind 230M 20kt. Cloud Broken 1000ft. Light turbulence. Light rain. Visibility 6000m. Temperature 15 deg C.	Approach.	ATC instruct the aircraft to go around at 300ft.	Push the power lever go around button. OR Rotate to the go around pitch attitude on the flight director. OR Set both PLs to the RAMP.	Crew complete checklists associated with go around.	Nil.

APPENDIX R VALIDATION STUDY INFORMATION SHEET



MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA

EVALUATION OF SIMULATED FLIGHT DATA EVENTS AS MEASURES OF FATIGUE RISK
INFORMATION SHEET

You are invited to participate in the validation phase of a larger research project. The validation phase involves operating two simulated flights on 9th February 2017 [between 1400 – 1800] to evaluate the suitability of the flight scenarios that will be included in the larger simulator based research project. The aim of the larger research project is to determine if fatigue related changes in flight deck performance can be detected from simulated aircraft parameters. Following the validation flights you will participate in a small group discussion to review the simulated flight scenarios.

The larger simulator based research project forms part of Cameron Dyer's doctoral research which will investigate technical and non-technical changes in flight deck performance that may occur with fatigue. He is supervised by Associate Professor Leigh Signal and Professor Philippa Gander from Massey University's Sleep/Wake Research Centre (SWRC) in Wellington. Their contact details can be found below.

Cameron is employed by Air New Zealand and works in Operations Integrity and Safety as a Flight Data Manager. His doctoral research is completely separate and is independent from his role at Air New Zealand. His contact details can be found below.

ABOUT THE STUDY
Despite a relatively large body of scientific knowledge on the relationship between fatigue and performance, currently little is known about how fatigue might impact complex, multi-crew performance. Its impact on technical and non-technical performance has been measured in previous simulator based studies but to our knowledge this will be the first time that events derived from simulated flight data will be used to identify if fatigue related changes in flight deck performance are detectable in a simulated environment.

You will be rostered to participate in two simulated flights in an simulator. The simulated flights are completely separate from training and proficiency details. Each simulated flight will involve a routine flight of 1hr duration (either Wellington – Christchurch or Christchurch – Wellington). You will be provided with flight planning information for each flight.

Following the simulated flights, you will be asked for your views on:

- How the flights differed from real flights.
- What would you change to make the flights more representative of real flights?
- Which elements of the flights might be sensitive to fatigue?
- What made the flights different from each other?

Cameron Dyer, Associate Professor Leigh Signal, .
(Simulator Instructor) will also participate in the small group discussion.

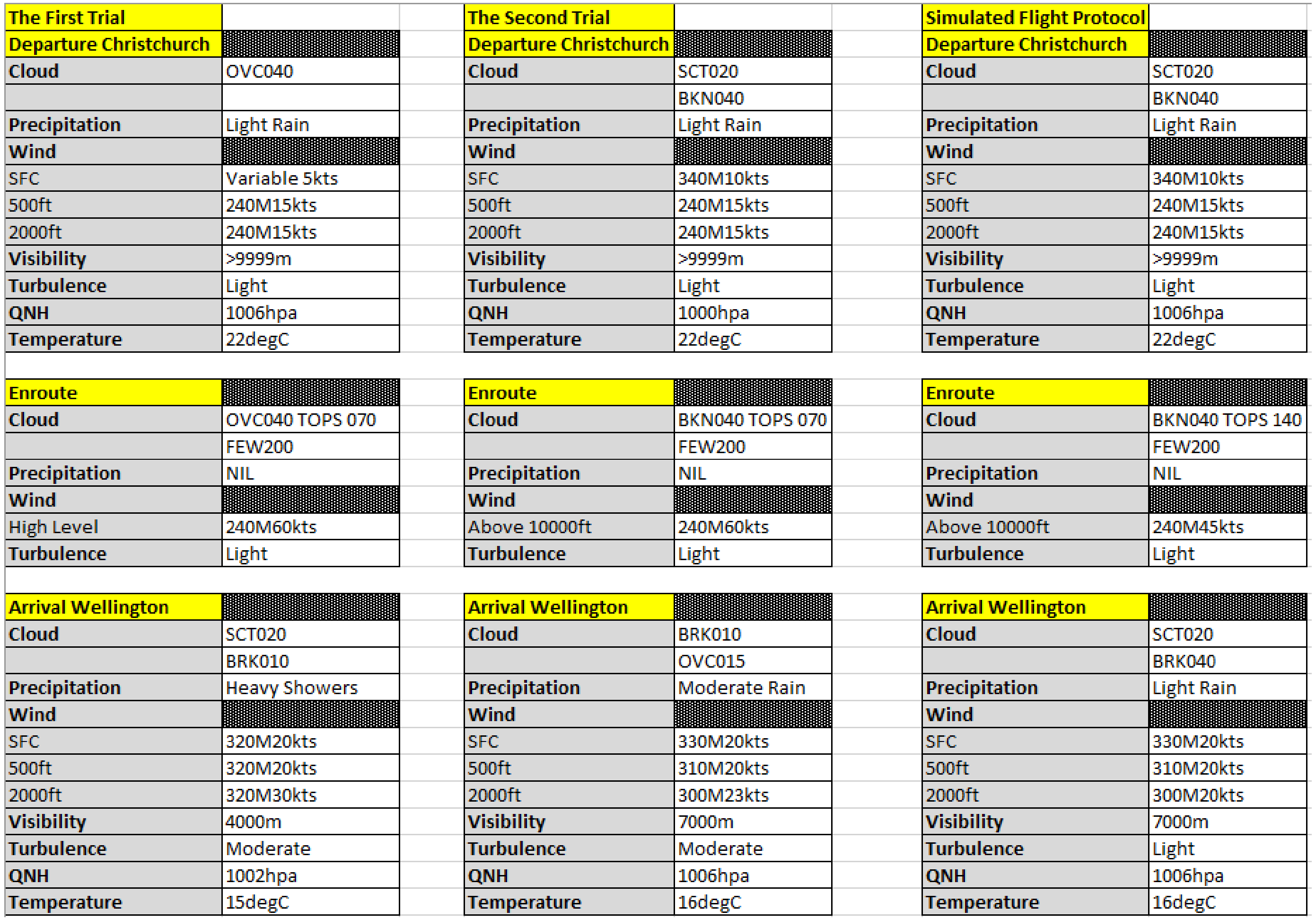
WHO CAN TAKE PART?
Two pilots will be invited to participate in the validation phase. Once one Captain and one First Officer agree to participate, recruitment will stop.

WHAT CAN YOU EXPECT IF YOU TAKE PART?
- Each simulated flight will occur in the simulator at Auckland Airport.
- Simulated flight data parameters for each simulated flight will be retained for analysis purposes.
- The brief debrief station (BDS) file which includes a recording of aircraft instrumentation from each simulated flight will be retained for analysis purposes. All other recordings from the BDS file will be deleted.
- You will be asked to rate your workload immediately following each simulated flight.
- Following the simulated flights, you will asked to participate in a small group discussion.
- The small group discussion will be digitally recorded (audio only).

Sleep/Wake Research Centre – Moe Tika, Moe Pai
PO Box 756, Wellington 6140, Aotearoa/New Zealand T +64 3 380 0637 E swrc@massey.ac.nz http://sleepwake.massey.ac.nz

APPENDIX S SIMULATED FLIGHT WEATHER CONDITIONS

Christchurch - Wellington



The First Trial		**The Second Trial**		**Simulated Flight Protocol**	
Departure Christchurch		**Departure Christchurch**		**Departure Christchurch**	
Cloud	OVC040	**Cloud**	SCT020	**Cloud**	SCT020
			BKN040		BKN040
Precipitation	Light Rain	**Precipitation**	Light Rain	**Precipitation**	Light Rain
Wind		**Wind**		**Wind**	
SFC	Variable 5kts	SFC	340M10kts	SFC	340M10kts
500ft	240M15kts	500ft	240M15kts	500ft	240M15kts
2000ft	240M15kts	2000ft	240M15kts	2000ft	240M15kts
Visibility	>9999m	**Visibility**	>9999m	**Visibility**	>9999m
Turbulence	Light	**Turbulence**	Light	**Turbulence**	Light
QNH	1006hpa	**QNH**	1000hpa	**QNH**	1006hpa
Temperature	22degC	**Temperature**	22degC	**Temperature**	22degC
Enroute		**Enroute**		**Enroute**	
Cloud	OVC040 TOPS 070	**Cloud**	BKN040 TOPS 070	**Cloud**	BKN040 TOPS 140
	FEW200		FEW200		FEW200
Precipitation	NIL	**Precipitation**	NIL	**Precipitation**	NIL
Wind		**Wind**		**Wind**	
High Level	240M60kts	Above 10000ft	240M60kts	Above 10000ft	240M45kts
Turbulence	Light	**Turbulence**	Light	**Turbulence**	Light
Arrival Wellington		**Arrival Wellington**		**Arrival Wellington**	
Cloud	SCT020	**Cloud**	BRK010	**Cloud**	SCT020
	BRK010		OVC015		BRK040
Precipitation	Heavy Showers	**Precipitation**	Moderate Rain	**Precipitation**	Light Rain
Wind		**Wind**		**Wind**	
SFC	320M20kts	SFC	330M20kts	SFC	330M20kts
500ft	320M20kts	500ft	310M20kts	500ft	310M20kts
2000ft	320M30kts	2000ft	300M23kts	2000ft	300M20kts
Visibility	4000m	**Visibility**	7000m	**Visibility**	7000m
Turbulence	Moderate	**Turbulence**	Moderate	**Turbulence**	Light
QNH	1002hpa	**QNH**	1006hpa	**QNH**	1006hpa
Temperature	15degC	**Temperature**	16degC	**Temperature**	16degC

Wellington - Christchurch

The First Trial		**The Second Trial**		**Simulated Flight Protocol**	
Departure Wellington		**Departure Wellington**		**Departure Wellington**	
Cloud	OVC040	**Cloud**	SCT020	**Cloud**	SCT020
			BKN040		BKN040
Precipitation	Light Rain	**Precipitation**	Light Rain	**Precipitation**	Light Rain
Wind		**Wind**		**Wind**	
SFC	160M05kts	SFC	200M10kts	SFC	200M10kts
500ft	180M05kts	500ft	200M10kts	500ft	200M10kts
2000ft	230M10kts	2000ft	300M15kts	2000ft	300M15kts
Visibility	>9999m	**Visibility**	>9999m	**Visibility**	>9999m
Turbulence	Light	**Turbulence**	NIL	**Turbulence**	Light
QNH	1006hpa	**QNH**	1008hpa	**QNH**	1002hpa
Temperature	16degC	**Temperature**	20degC	**Temperature**	20degC

Enroute		**Enroute**		**Enroute**	
Cloud	BRK040 TOPS 140	**Cloud**	BKN040 TOPS 140	**Cloud**	BKN040 TOPS 140
	FEW200		FEW200		FEW200
Precipitation	NIL	**Precipitation**	NIL	**Precipitation**	NIL
Wind		**Wind**		**Wind**	
High Level	320M60kts	Above 10000ft	320M60kts	Above 10000ft	320M40kts
Turbulence	Light	**Turbulence**	Light	**Turbulence**	Light

Arrival Christchurch		**Arrival Christchurch**		**Arrival Christchurch**	
Cloud	BRK010	**Cloud**	BRK010	**Cloud**	BRK010
			OVC015		
Precipitation	Heavy Showers	**Precipitation**	Light Rain	**Precipitation**	Light Rain
Wind		**Wind**		**Wind**	
SFC	180M20kts	SFC	230M20kts	SFC	230M20kts
500ft	180M30kts	500ft	250M25kts	500ft	250M25kts
2000ft	180M40kts	2000ft	260M25kts	2000ft	260M25kts
Visibility	4000m	**Visibility**	6000m	**Visibility**	6000m
Turbulence	Moderate	**Turbulence**	Light	**Turbulence**	Light
QNH	1002hpa	**QNH**	1002hpa	**QNH**	1002hpa
Temperature	15degC	**Temperature**	17degC	**Temperature**	15degC

APPENDIX T CONTEXTUAL INFORMATION TO SUPPORT INTERPRETATION OF SIMULATED FLIGHT PROTOCOL SCENARIOS

Aircraft Flight Path Information

Altitude is measured in feet (ft) and reflects height above sea level. As the aircraft climbs, the distance between the aircraft and the ground increases which is reflected as increasing altitude. Radio Altitude is measured in feet (ft) and reflects height above the ground. Vertical Speed indicates the aircrafts rate of climb or rate of descent. It measured in feet per minute. Airspeed is measured in knots (kt) and reflects the aircraft speed through the air, as opposed to true airspeed or ground speed. One knot is the equivalent of 1.85 kilometres per hour. Ground speed is measured in knots and reflects the aircrafts speed over the ground. Heading represents the direction in which the aircraft is pointing and is expressed with reference to degrees magnetic[147]. Track represents the path of the aircraft over the ground and is expressed with reference to degrees magnetic. Roll is measured in degrees and indicates that the aircraft is turning. Pitch is measured in degrees and indicates that the aircraft is in level flight, climbing or descending.

Weather Condition Information

Temperature is measured in degrees Celsius, wind speed is measured in knots, wind direction is measured in degrees true[148], visibility is measured in meters and

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[147] Degrees magnetic refers to the north magnetic pole.

[148] Degrees true refers to the north geographic pole.

ceiling[149] is measured in feet above ground level. Overcast cloud is where no sky is visible, broken cloud refers to a cloud base that covers between 5/8 and 7/8 of the sky, scattered cloud refers to a cloud base that covers between 3/8 to 4/8 of the sky and few suggests cloud coverage of between 1/8 and 2/8 of the sky (Wagtendonk et al., 2000b). Cloud base is associated with the minimum descent altitude (MDA) [150]. If the cloud base is below MDA, the approach must be discontinued. The operator defines light turbulence as a condition of the atmosphere in which there occurs bumpiness accompanied by slight erratic changes in attitude or altitude. Moderate turbulence is associated with changes in altitude, airspeed fluctuates but positive control of the aircraft is maintainable at all times. Occupants feel a definite strain against seat belts or shoulder straps, unsecured objects move and food service and walking is difficult (Operator Documentation, 2018, pp. 4-47). APPENDIX S shows differences in weather conditions between the initial simulated flight protocol and the final simulated flight protocol.

Simulated Flight Information

Each simulated flight includes a standard instrument departure (SID), a standard route clearance (SRC) and a standard arrival route (STAR). A SID is defined as a published departure procedure that provides routing to avoid most high terrain that may be in relatively close proximity to the aerodrome (Aeropath, 2013, pp. 1.5 - 4). A SRC is a standard clearance that depicts a designated route between two destinations and defines the route to be flown (Aeropath, 2016, pp. 1.1 - 16). A STAR specifies both in diagrammatic and narrative form routing, to a point where an

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[149] Ceiling (also referred to as cloud base) is defined as the height above the ground or water of the base of the lowest layer of cloud below 20,000ft which covers more than half the sky (Aeropath, 2021, GEN 2.2 - 34).

[150] Minimum Descent Altitude is a specified altitude or height during a non-precision approach where descent must not be made without the required visual reference (Aeropath, 2021, pp. GEN 2.2 - 36).

instrument approach can be flown to the destination and may include a transition route and a arrival route (Aeropath, 2013, pp. 1.5 - 20). The approach type flown at both airports was an Instrument Landing System (ILS) associated with a Distance Measuring Equipment (DME). An ILS is a precision approach aid which provides both glideslope and localiser guidance. A glideslope provides descent path guidance to the runway on a descent slope of 3 deg which is approximately 300ft per nautical mile. A localiser provides tracking guidance along the extended centreline of the approach path to the runway. Deviation above or below the glideslope or to the left or right of the localiser will result in indications being provided to flight crew to correct their path (Wagtendonk et al., 2000a). DME provides an accurate and continuous indication of range (measured in nm) between the aircraft and the selected ground station. During an approach, the operator requires that the aircraft shall be configured and stable from the nominated stable gate. A go around represents an aborted landing where the aircraft climbs away from the airport and shall be carried out if the approach is unstable at, or becomes unstable below, the stable gate. An approach in instrument meteorological conditions (IMC) requires that the before landing checklist is complete by 1000ft above aerodrome level and that stable approach criteria are met by 1000ft above aerodrome level. The operator's stable approach criteria, at the time of data collection, included the following criteria:

- Airspeed not less than 5kt below velocity approach (Vapp)[151] and not greater than 20ks above Vapp.
- Rate of descent is not greater than 1000ft /min.

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[151] Velocity Approach represents a target speed which is calculated for each approach. Once calculated, it is a constant whereas airspeed is variable. To meet stable approach criteria, airspeed must be greater than -5kt below Vapp and less than 20kt above Vapp.

- The aircraft is established on the correct flight path.
- The aircraft is in the correct landing configuration.
- Gear down by 1000ft.
- Landing flap in commanded position by 1000ft.
- The before landing checklist is complete.

APPENDIX U CHECKLISTS ASSOCIATED WITH THE CONFIGURATION OF THE CHRISTCHURCH – WELLINGTON AND WELLINGTON – CHRISTCHURCH SIMULATED FLIGHTS.

APPENDIX U, section U1 Christchurch – Wellington Simulated Flight

Weight	22600kg
TOMAC	28%

Action	Complete:
Ensure the simulator is configured to reflect weather at CHC and aircraft weight and CG is set as per above.	Complete:
PRESS RECORDING button to START BDS recording.	Complete:
The Wind Vector AT 500ft BARO is 24015kts. NOTE: the wind shift from 34010 to 24015 should not start at 500ft, the wind should be 24015 at 500ft BARO. Activate the wind change at V1.	Complete:
If crew indicate they are unable to make the 2000ft constraint, ATC to request they level off at 2000ft. Once level at 2000ft, instruct crew to resume climb.	Complete:
Ensure the simulator is configured to reflect weather during the climb and cruise. WLG WX set.	Complete:
Ensure icing conditions are present at 7000ft however only “normal procedure” required. Ice accretion checklist.	Complete:
At 12000ft during descent, ensure the simulator is configured to reflect weather at WLG. Ice accretion checklist.	Complete:

Action	Complete:
AP momentary disconnect when passing JONAH.	Complete:
When turning onto the LLZ [in vicinity of UMAGA] ATC request aircraft maintain 160knots to 5DME. ACT instructs this passing Wards on 119.3	Complete:
ATC instruct go around at 300ft due Runway incursion with the intruder aircraft proceeding to line up on RW34. Radar vectored WLG ILS 34 to land.	Complete:
PRESS RECORDING button to STOP BDS recording.	Complete:

APPENDIX U, section U2 Wellington – Christchurch Simulated Flight

Weight	22400kg
TOMAC	28%

Action:	Complete:
Ensure the simulator is configured to reflect weather at WLG and aircraft weight and CG is set as per above.	Complete:
Ensure the clearance includes a requirement for the aircraft to be at or above 4000ft at TAXUP. “addition to clearance”.	Complete:
PRESS RECORDING button to START BDS recording.	Complete:
The Wind Vector AT 2500ft is 30015kts. NOTE: the wind shift from 20010 to 30015 should not start during the take off roll, rather the wind shift should be initiated at 2000ft to ensure the wind is 30015 at 2500ft.	Complete:
If crew indicate they are unable to make the 4000ft constraint at TAXUP, ATC to request they level off at 4000ft. Once level at 4000ft, ATC to instruct aircraft to resume climb.	Complete:
Ensure the simulator is configured to reflect weather during the climb and cruise. CHC WX	Complete:
Ensure icing conditions are present at 7000ft however only “normal procedure” required. Ice accretion checklist	Complete:
At 12000ft during descent, ensure the simulator is configured to reflect weather at CHC. Ice accretion checklist	Complete:
AP momentary disconnect when passing CH409. “Expedite descent to 3000ft” (just before CH409).	Complete:

Action:	**Complete:**
Once inbound, having passed ODISI, the aircraft is cleared for the LLZ but not the GS. The aircraft is level at 3000ft. At 8DME the aircraft is cleared for the approach. NOTE: The aircraft should be 300ft high at 8DME based on the advisory altitude.	Complete:
ATC instruct go around at 300ft. Radar vectors CHC ILS 20.	Complete:
PRESS RECORDING button to STOP BDS recording.	Complete:

APPENDIX V SIMULATED FLIGHT PROTOCOL DEVELOPMENT

APPENDIX V, section V1 The First Trial of the Initial Simulated Flight Protocol

The first trial included the simulator instructor and the researcher. It consisted of a four hour simulator slot with both the Christchurch Wellington and Wellington Christchurch flights being flown by the simulator instructor[152] with the researcher acting as an observer Table Q 1 and Table Q 2 (within APPENDIX Q) outline scenarios that were investigated during the first trial. The tables include a column called “COMMENTS” to indicate if the scenario that occurred during flight was different from the planned scenario. Table V 1 (see APPENDIX V) shows paired scenarios included in the first trial. Sub scenarios were not applicable as the first trial was an opportunity to run through the planned scenarios. The un-commanded autopilot disconnect scenario during the Christchurch – Wellington flight did not include a paired scenario. The purpose of including this scenario was to determine if the location of the autopilot disconnection contributed to time taken to re-engage the autopilot.

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[152] The simulator instructor performed both the pilot flying and pilot monitoring duties.

Table V 1 Comparison of Scenarios During the First Trial of the Initial Simulated Flight Protocol

		CHRISTCHURCH – WELLINGTON FLIGHT	WELLINGTON – CHRISTCHURCH FLIGHT
Paired scenario	**Scenario comparability**	**Scenario name**	**Scenario name**
Change in environmental conditions.	Similar.	Tailwind During Initial Climb.	Ice Accretion During Climb.
Change in flight path.	Similar.	Traffic alert and collision avoidance system resolution advisory.	Aircraft handling following unexpected change to flight path.
Excess Energy during Approach.	Similar.	Speed restriction during ILS/DME RW34 instrument approach above 1000ft.	Height restriction during ILS/DME instrument approach above 1000ft.
Go Around.	Similar.	Go Around.	Go Around.
Holding Pattern.	Near identical.	Holding Pattern.	Holding Pattern.
-	-	Un-commanded autopilot disconnect prior to passing UMAGA.	No corresponding scenario.

The following scenarios were trialled multiple times during the session:

Excess Energy during Approach

During the Christchurch – Wellington flight, four approaches were flown with the aircraft between 900ft and 300ft and less than 3nm from the airport. The magnitude and location of the onset of wind shear differed during each approach. The effect of wind shear on the flight was to destabilise the approach. These iterations helped determine the initiating altitude and magnitude of wind shear which subsequently influences the point where go around is initiated. During the Wellington –

Christchurch flight, four approaches were flown with the aircraft between 4000ft and 2000ft and not closer than 8nm from the airport. These iterations helped determine the initiating altitude and extent of glide slope deviation for the scenario that includes a height restriction during ILS/DME RWY20 instrument approach above 1000ft.

Change in environmental conditions: Ice Accretion during Climb

During the Wellington Christchurch flight, variation in ice accretion rates was undertaken to determine what temperature and altitude should be used to initiate the scenarios that include ice accretion during climb and descent. The Christchurch Wellington flight did not enter atmospheric icing conditions.

Change in Flight Path: Un-commanded disconnection of autopilot

During the Christchurch Wellington flight, multiple un-commanded disconnections of the autopilot were trialled to determine if the location of the un-commanded disconnection contributed to time taken to re-engage the autopilot. All disconnections occurred within 5nm of UMAGA while tracking toward the instrument landing system (ILS) localiser or during intercept of the instrument landing system localiser. Un-commanded disconnection of the autopilot did not occur during the Wellington Christchurch flight.

APPENDIX V, section V2 Changes to Scenarios following the First Trial of the Initial Simulated Flight Protocol

Changes to scenarios following the first trial of the initial simulated flight protocol from Christchurch to Wellington include the following:

Changes to weather conditions: The surface wind direction and velocity at Christchurch was changed from variable at 5kt to 340 deg M at 10kt (8kt headwind component) to improve aircraft climb performance. This was done to reduce the likelihood of crew focusing on SID compliance due to the tailwind during initial climb scenario. The visibility, cloud base and wind direction and velocity at Wellington were changed to reflect slightly more favourable conditions to reduce likelihood that crew may divert following the go around scenario.

The location of the un-commanded autopilot disconnect scenario was changed to occur while crossing JONAH as opposed to occurring while in the turn to capture the localiser. Despite trialling various locations during the first trial, autopilot re-engagement duration was short and consistent which limited the duration where the aircraft was flown by hand. The focus of the scenario therefore changed from monitoring the accuracy of manual flying where the disconnection of the autopilot represented the start point and re-engagement of the autopilot represented the end point to monitoring time taken to re-engage the autopilot, e.g. reaction time. The paired scenario, un-commanded autopilot disconnect, was added to the second trial flight.

Changes to scenarios following the first trial of the initial simulated flight protocol from Wellington to Christchurch include the following:

Changes to weather conditions: The surface wind direction and velocity, 500ft wind velocity and 2000ft wind velocity at Wellington were changed to reflect the same wind angle and velocity at Christchurch during the Christchurch – Wellington flight[153]. This would allow comparison of acceleration altitude values during initial climb for both flights. The visibility, cloud base and wind velocity at Christchurch

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[153] At both airports, the wind angle relative to the runway was 40 degrees and the wind velocity was 10 knots.

were changed to reflect slightly more favourable conditions to reduce likelihood that crew may opt to divert following the go around scenario.

Within the paired scenario, change in flight path, the aircraft handling following unexpected change to flight path scenario was replaced with a spurious TAWS/EGPWS Warning TOO LOW GEAR scenario. This change resulted in the trigger for the start of each scenario being near identical, i.e. both scenarios are triggered by the same automated alert. Paired scenario compatibility is still categorised as similar due to differences in the amount of prior warning, the phase of flight and the aircraft configuration associated with the two scenarios.

A scenario where an un-commanded autopilot disconnect occurs prior to crossing CH409 was included. This was to allow the incorporation of the paired scenario, un-commanded autopilot disconnect, during the second trial simulated flight. The location of the holding pattern was changed in the second scenario and occurred prior to the go around during descent into Christchurch. This provided an opportunity to ask flight crew if the holding pattern location contributed to differences between execution of the holding patterns.

The trigger that initiates the go around was changed from an ATC instruction to go around to a spurious TAWS/EGPWS Warning TOO LOW GEAR alert. The change was to facilitate the change in trigger for the paired scenario, change in flight path.

The circuit direction following go around was changed to right hand to reflect the published circuit direction.

APPENDIX W THE SECOND TRIAL OF THE INITIAL SIMULATED FLIGHT PROTOCOL

The purpose of the second trial was to evaluate changes to scenarios following the first trial and to seek feedback from two line pilots who flew both simulated flights, on the similarities and differences between scenarios within a paired scenario. The trial consisted of a four hour simulator slot (1400 – 1800). The captain was pilot flying and the first officer, pilot monitoring. The simulator instructor was present within the simulator cab to facilitate the simulated flight protocol. Participants completed paper based[154] flight planning tasks (as described in section 3.6) and following the simulated flights, and participated in a small group discussion (as discussed in APPENDIX W, section W1). Table Q 3 and Table Q 4 (within APPENDIX Q) outline scenarios that were trialled during the second trial. A column ("COMMENTS") is included to indicate if the scenario flown was different from the planned scenario. Table W 1 (in APPENDIX W) shows scenarios included in the second trial of Christchurch Wellington simulated flights and Wellington Christchurch simulated flights.

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[154] The operator has an electronic flight planning process. It was not possible to incorporate electronic flight planning for the purposes of this study.

Table W 1 Comparison of Scenarios During the Second Trial of the Initial Simulated Flight Protocol

		CHRISTCHURCH–- WELLINGTON FLIGHT	**WELLINGTON – CHRISTCHURCH FLIGHT**
Paired scenario	**Scenario comparability**	**Scenario name**	**Scenario name**
Change in environmental conditions.	Similar.	Tailwind during initial climb.	Ice accretion during climb.
Change in flight path.	Similar.	Traffic alert and collision avoidance system resolution advisory.	Spurious TAWS/EGPWS Warning TOO LOW GEAR.
Un-commanded autopilot disconnect.	Near identical.	Un-commanded autopilot disconnect prior to crossing JONAH.	Un-commanded autopilot disconnect prior to crossing CH409.
Excess energy during approach.	Similar.	Speed restriction during ILS/DME RWY34 instrument approach above 1000ft.	Heigh restriction during ILS/DME instrument approach above 1000ft.
Go around.	Similar.	Go around.	Go around.
Holding pattern.	Similar.	Holding pattern.	Holding pattern.

APPENDIX W, section W1 Small Group Discussion

This section reviews results from a small group discussion following the second trial of the initial simulated flight protocol. The discussion informed decisions that determined which scenarios would be paired together within the final simulated flight protocol. It comprised of an operational debrief, facilitated by the simulator instructor and a discussion regarding similarities between paired scenarios, facilitated by the researcher. The following question was asked:

For each pair of scenarios, are they similar enough to represent the same thing?

A separate ethics application was not required to collect data from this phase of the research as an amendment to ethics notification SOA 16/64 was approved by the Chair of the Massey University Human Ethics Committee: Southern A on the basis that the following recruitment process would be followed:

- The operator's Training Manager will identify and contact potential participants who will be provided with an information sheet.
- If interested, the potential participants will then contact the researcher who will provide them with a consent form and confidentiality agreement form.
- If interested, the potential participants will then sign both forms and return these to the researcher.
- On receiving the signed forms, the researcher will contact the operators training planning team to roster participants for the trial simulated flights.

The information sheet provided to participants is included in APPENDIX R. The audio recording from the small group discussion was transcribed verbatim by the researcher. Transcripts were anonymised and provided to the simulator instructor and participants to review, edit or withdraw their contributions. Transcript release authority and confidentiality agreement[155] forms were completed by the simulator instructor and participants. Data extracts included a reference to its source (Small group discussion ID). Where irrelevant information is excluded from a data extract, this is represented as […]. Pauses are represented as "…"

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[155] The simulator instructor and participants agreed to keep confidential all information concerning the project and agreed not to retain or copy any information involving the project.

APPENDIX W, section W2 Paired Scenario: Change in environmental conditions

Tailwind during Initial Climb (Christchurch – Wellington): There is an expectation that pilots always comply with this SID: “there's also an expectation [laughs] from the pilots that you always make NUBKA. It’s like, ‘oh we always make it’ so there’s that anticipation in your head” (Small group discussion 4). However, “The good old aircraft doesn’t always achieve it” (Small group discussion 8). Environmental conditions and aircraft weight should prompt crew to consider the aircraft’s performance: “when you look at the wind at 340 at 10 so you’re looking at 5kt of headwind at 22600kg take off weight, temperature 22 degrees. You know, that’s sort of a bit of a catalyst to go mm that’s going to be close” (Small group discussion 8). Weather information relating to the flight as per flight planning material and an automatic terminal information service (ATIS) broadcast[156] indicated that the 2000ft wind was 240 degrees at 15kt. The pilots considered the abruptness of the wind shift to be unexpected: “the Christchurch NUBKA departure feels more like a catch where the wind probably wouldn’t swing around that quickly um to catch you out like I mean um yeah” (Small group discussion 12). Despite the weather conditions and aircraft weight, compliance with the SID is likely achievable if crew take action to improve aircraft performance: “The temperature was fine, we could have elected to take speed manual, 150kt to assure that” (Small group discussion 4).

Several outcomes are possible:

- The crew complies with the SID.
- The crew do not comply with the SID.

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[156] The automatic provision of current, routine information to arriving and departing aircraft throughout a 24 hour period.

- The crew contact ATC to mention that they cannot comply with the SID and ATC request the aircraft level off at 2000ft as per the ATC instruction (sub scenario).

Ice Accretion During Climb (Wellington Christchurch): This scenario requires crew to complete two checklists, one when entering atmospheric icing conditions, and another at first indication of ice accretion. Completion of these checklists ensures compliance with the aircraft flight crew operating manual (FCOM) requirements for flight within atmospheric icing conditions and ice accretion (Avions de Transport Regional, 2014, p. 2.02.08). The ice accretion during climb scenario "is a very normal thing to happen, like extremely normal because you're climbing into cold air" (Small group discussion 12). The crew will likely be waiting to engage the anti-ice system: "we're waiting for it to get to 7 degrees before turning it on" (Small group discussion 4). Several outcomes are possible:

- A check list is completed correctly at the correct time.
- A check list is completed incorrectly at the correct time.
- A checklist is completed correctly at the incorrect time.
- A check list is completed incorrectly at the incorrect time.

Paired Scenario Compatibility: The tailwind during initial climb scenario and ice accretion during climb scenario occur during different phases of flight: "like your just airborne you're running through your um your procedure, you after take off checks […] where the other one is um, you're climbing away, you know you're in moisture so you sort of waiting for that temperature to come back" (Small group discussion 4). Workload between the scenarios is different: "the SID is it's a high workload as well […] it so it's sort of a higher workload area, the first one as opposed to waiting for the icing" (Small group discussion 4). There is also a difference in expectation associated with each environmental condition. There is an expectation that you will get icing: “mmm I’d also say um there’s an expectation for that pilots that you get the icing” (Small group discussion 12) However, there is also an expectation that a wind shift below 500ft will not occur: “we don’t really expect that to swing around to a tail at 500ft” (Small group discussion 12). It feels like a catch: “to have a tailwind swing around and then catch you out on that […] the Wellington, ah sorry the Christchurch NUBKA departure feels more like a catch” (Small group discussion 12). When questioned what would be like the tailwind during climb scenario, one pilot suggested: “Out of Wellington, the only other one that was kind of similar um is when you don’t get any input from ATC and it’s up to you to intercept your track onto the SID” (Small group discussion 12). The other pilot agreed: “Yeah, so that way you could see if crews would request a direct or whether they just, call it, you know course intercept SABDA with a 30 degrees cut ah, or or the flight management system will do it for you, but it might test to see what, what would they do. Whether they just carry on with the requirement or um, or just contact ATC for a direct to or something” (Small group discussion 4). The suggested scenario was not incorporated into the final simulated flight protocol as the intention of this pair of scenarios was to monitor flight crew actions following a change in environmental conditions.

Based on this feedback, in the final simulated flight protocol, the tailwind during climb and ice accretion scenarios were not paired together due to differences in phase of flight, workload and expectation. The tailwind during initial climb scenario (Christchurch – Wellington) was paired with a new scenario, tailwind during climb (Wellington - Christchurch. Details regarding the new paired scenario are outlined in section 3.8.1.

APPENDIX W, section W3 Paired Scenario: Change in Flight Path

Traffic alert and collision avoidance system resolution advisory (Christchurch – Wellington): When passing 5500ft during climb, a traffic alert collision avoidance system (TCAS) corrective resolution advisory[157] (RA) is enunciated. The operator's standard operating procedure states the pilot flying must follow any resolution advisory unless doing so would jeopardise the immediate safety of the flight (Operator Documentation, 2018, p. 6B.12). There is no sub scenario that prevents the pilot from modifying the aircraft's path to ensure aircraft vertical speed is adjusted to equal the resolution required vertical speed. The crew were aware of the possibility of a resolution advisory (RA) when a traffic advisory (TA) was enunciated: "climbing up we got traffic in towards us. Got ready for it". (Small group discussion 4). The crew then responded correctly to the resolution advisory: "Um, worked through the conflict and then established ourselves back on track into the climb" (Small group discussion 4). Several outcomes were possible:

- The aircraft's path is modified to ensure aircraft vertical speed equals the resolution required vertical speed.
- The aircraft's path is modified however aircraft vertical speed does not equal the resolution required vertical speed.
- No change is made to the aircraft's vertical path.

Spurious TAWS/EGPWS warning TOO LOW GEAR (Wellington Christchurch): At 300ft on ILS/DME RWY20 approach, a spurious TAWS/EGPWS (GPWS) warning "TOO LOW GEAR" is enunciated. The operators standard operating procedure

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[157] A message given to the pilot containing information relevant to collision avoidance. A corrective resolution advisory advises the pilot to deviate from the current vertical speed (Avions de Transport Regional, 2014, p. 1.05.20).

following this alert is for the crew to commence the go around / missed approach procedure (Operator Documentation, 2018, p. 6B.10). There is no sub scenario that prevents crew from either going around or landing. The crew complied with the standard operating procedure: “you know, you’re not sure if you've got an unsafe indication or not so go around […] so it’s just that initial thing is regardless if it’s at 500ft or 50ft it’s a, a go around and then make sure you can confirm three greens” (Small group discussion 4). An unintended consequence of the scenario was that the “TOO LOW GEAR” annunciation resulted in the crew working through a process with Maintenance Operations Control (MOC) to confirm that neither the primary panel or overhead panel included erroneous gear status indications: “ah followed the go around, […] and then ran through some um sorta ran after take off checks and then decided that we might check-in with Engineering, make sure they’re happy with the process of the gear um and ran through the checklist for ourselves just to umm make sure we weren’t missing anything” (Small group discussion 4). Additional track miles were not flown[158] however the crew did spend time to resolve the perceived issue. Several outcomes were possible:

- A go around is conducted.
- A go around is not conducted, and the aircraft continues to land.

Paired Scenario Compatibility: In both scenarios, the operator has a standard operating procedure that outlines the expected response. During the scenarios, aircraft configuration is different: “You know, you in in the go around you you most likely configured um with the with the RA you’re clean […] um configuration would be the only difference” (Small group discussion 4). Differences in aircraft

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[158] The crew did not enter a holding pattern, orbit or request vectors to lengthen the flight. They did not request additional time to resolve the issue.

configuration may influence manoeuvrability which could contribute to variation in time taken to respond to TCAS RA or GPWS alerts. Workload at the point when the scenarios are initiated is different: “in the case we had with the autopilot off and the approach, ATC restrictions then the go around, its um quite physically and mentally demanding for the pilot flying. Umm, if you’re you’re trying to keep that situation awareness as well as handling um and you know […] if you don’t get that support from your offsider, um it can turn hairy pretty quick. Um where a TCAS is, it’s um, it’s well it’s, we’ve got a standard operating procedure for it. We follow the procedure and we do it” (Small group discussion 4). The scenarios differ in their level of abruptness. The EGPWS alert was abrupt and unexpected, no cues existed prior to the alert. For the TCAS RA, crew will have been monitoring movement of oncoming traffic and were prepared for the possibility of a TCAS RA alert: “ah so from there we got ready for an RA which had the TA then the RA and so responded to that” (Small group discussion 12). As a result of differences mentioned above, the paired scenario was excluded from the final simulated flight protocol. The event that triggers the go around in Christchurch was changed to an ATC instruction that instructs crew to perform a go around at 300ft.

APPENDIX W, section W4 Paired Scenario: Un-commanded Autopilot Disconnect

Un-commanded autopilot disconnect when passing JONAH: On crossing JONAH, an un-commanded autopilot disconnect occurs. There is no fault with the autopilot, and it is available for immediate re-engagement. The crew do not mention this autopilot disengagement during the small group discussion. The autopilot is re-engaged promptly, and the approach continued. Several outcomes were possible:

- The autopilot is re-engaged.
- The autopilot is not re-engaged.

Un-commanded autopilot disconnect when passing CH409: The autopilot was not available to be re-engaged following this scenario which represented a misunderstanding between the researcher and the simulator instructor: "it it depends how you read this as well, that that could well be me here because it says disconnect but it doesn't say anything about reselecting [inaudible] reengaging it so I made the assumption that you wanted it disconnected and left disconnected" (Small group discussion 8). To account for this, the simulator instructor checklist was updated in the final simulated flight protocol to ensure the autopilot was available for reselection. The loss of the autopilot was one of several issues for the crew: "Ah, we lost the autopilot as well so quite a few things going on there" (Small group discussion 4). Rather than discontinue the approach or request vectors, the approach was continued with the autopilot disengaged. Several outcomes were possible:

- The autopilot is re-engaged.
- The autopilot is not re-engaged.

Paired Scenario Compatibility: Following an un-commanded autopilot disconnection, pilots will try to re-engage the autopilot: "well we should, I mean if it, the first think you'd do if it pops out is try and put it back in" (Small group discussion 4). This represents: "just the normal procedure […] doesn't work, forget it" (Small group discussion 8). There was a suggestion that: "the only thing with the SIM is that you know ssst stuff supposed to go wrong in the SIM so you go oh no, 'I don't think it's going to work anyway' so you sort of your in than mindset that you don't want to try and re-engage it cos the examiner is going to be like 'well, that was a silly idea because its broken'" (Small group discussion12). It was reiterated that: "in the SIM, far as I'm concerned, the SIM is the aircraft […] shouldn't be any different" (Small group discussion 8) of which both pilots agreed: "yeah yeah, absolutely" (Small group discussion 12), "yeah so […] we should be trying to reen (sic), put it back in" (Small group discussion 4).

The scenarios are near identical, they occur during the same phase of flight, weather conditions were similar and workload comparable following a normal descent. A crucial factor with these scenarios is that the autopilot must be re-engaged. If the autopilot cannot be re-engaged, it is not possible to compare both scenarios and subsequent scenarios will be impacted on that flight as auto flight status will represent a difference between paired scenarios. No sub-scenario will be included within the final simulated flight protocol which prompts crew to re-engage the autopilot. Communication between MOC and flight crew regarding autopilot re-engagement is unlikely, especially if initiated by MOC. No changes were made to these scenarios during the final simulated flight protocol.

APPENDIX W, section W5 Paired Scenario: Go Around

Go around following Wellington ILS/DME RWY34 instrument approach: ATC alerted the crew to the presence of wind shear during approach: "ah you had a bit of a heads up that traffic in front had a bit of a moderate wind shear" (Small group discussion 8) and as the approach progressed, it became evident to the crew that they would experience wind shear: "we had quite a bit of sink, um and getting rocked around a bit" (Small group discussion 4). Several outcomes were possible:

- The crew go around and conduct the wind shear/microburst recovery procedure.
- The crew go around and conduct the go around/missed approach procedure.
- The crew continue the approach and land.

The go around involved high workload: “um, the first 75% of it was just a normal flight I guess, you know, just the standard thing the ATC or um TCAS if you, if you got one but yeah, the last 25% was defiantly um heavy workload” (Small group discussion 4). Workload was heavier than usual, but believable. The go around itself was busy: “missed the go around button […] I think it’s a bit busy, so I just pushed it myself to get it going. Um, I missed the NP from yeah, back to auto as part of the after take off checks and also after the climb procedure the white bug for the flap but […] picked that up. Um” (Small group discussion 4). The crew attributed omissions of some checklist items to recency: “Ah, mm well two engine go arounds aren’t really something that we do that often” (Small group discussion 4). When discussing completing checklist items out of sequence: “I’d probably just, yeah, went through the climb procedure and um then instead of confirming 170 magenta which would prompt me to, to then think white bug […] just missed that” (Small group discussion 4). A go around with a wind shear/microburst recovery procedure was conducted following increasing turbulence and wind shear at 300ft: “I mean yeah with that there’s no point trying, trying to hanging in […] I couldn’t press the button it was rocking too much” (Small group discussion 12).

Go around following Christchurch ILS/DME RWY20 instrument approach: passing 300ft, an EGPWS/TAWS TOO LOW GEAR alert occurs, several outcomes are possible:

- The crew go around and conduct the go around/missed approach procedure.
- The crew continue the approach and land.

A standard go around was conducted: “we had um the too low gear um aural alert so elected to go around from that, ah followed the go around” (Small group discussion 4). Despite the absence of turbulence and wind shear, workload contributed to the crew completing checklist items out of sequence: “the missed approach Christchurch was initially heading when we could have gone to LNAV um, but we got back on track and engaged LNAV […] the rest of its fine” (Small group discussion 4). It is likely that the absence of the autopilot during the go around contributed to an increased workload.

Paired Scenario Compatibility: The go around are due to different reasons. One is due to a TAWS/EGPWS TOO LOW GEAR alert and the other is due to wind shear. The operator’s standard operating procedure requires that the wind shear / microburst recovery procedure must be initiated if wind shear is of a severity that, if encountered, would exceed the performance capability of the aircraft. In the absence of a dedicated WINDSHEAR alert, identifying the presence of wind shear can be difficult: “wind shear can be quite you know, people can say ‘well how, how far are we going to take this, how bad does it have to get till we go’” (Small group discussion 4). The implication is that different crew, when experiencing the same simulated wind shear conditions, may action different procedures. Some will land, some will initiate the go around/missed approach procedure and some will initiate the wind shear / microburst recovery procedure: “it it depends, certain crews will view wind shear quite differently. I mean other crews could have today and gone, ‘let’s just go around, not even wind shear, it’s just turbulence’. I mean it all depends on who it is” (Small group discussion 8). However, there is no ambiguity associated with the need to go around following a TAWS/EGPWS TOO LOW GEAR alert: “that’s a mandatory go around irrespective of OPS notices or anything, we must go around […] get out of there, too low gear” (Small group discussion 8). The go around/missed approach procedure and wind shear/microburst recovery procedure are different. In the wind shear scenario: “trying to deal with the wind shear recoveries so it’s not a standard go around it's like quite a, you need to confirm that its, you've got the climb performance before changing the configuration of the aircraft" (Small group discussion 12). The presence of wind shear and turbulence increases workload: "it's quite a different go around because you have to ah meet the different criteria before you can start changing the ah aircraft configuration so that becomes, like that just adds to the workload as well" (Small group discussion. 12). Time taken to prepare for go around may differ between scenarios. In the wind shear scenario, crew were alerted to the presence of wind shear during approach: "halfway down the approach and got the report from moderate wind shear from the preceding aircraft" (Small group discussion 12) and immediately prior to the go around, weather conditions deteriorated: "well we had a bit of wind shear" (Small group discussion 4). Crew did not receive prior warning of the TAWS/EGPWS TOO LOW GEAR alert. In the final simulated flight protocol, the trigger that initiates the go around scenario during each flight is changed to an ATC instruction to go around. This removes ambiguity associated with the need to go around, ensures that the go around/missed approach procedure is undertaken, that environmental conditions are as similar as possible, and that crew become aware of the need to go around at the same point during each flight.

APPENDIX W, section W6 Paired Scenario: Excess Energy during Approach

Speed restriction during Wellington ILS/DME RWY34 instrument approach above 1000ft: On passing WARDS, ATC request that the aircraft maintain 160kt to 5 DME. This is a common request in Wellington: "we got descent in towards Wellington ah for the ILS approach with a speed constraint, quite normal isn't it" (Small group discussion 8), "yep, yeah especially Wellington" (Small group discussion 12). At 5 DME, the aircraft should be at 1630ft meaning that crew have 630ft to decelerate the aircraft to 150kt, select landing flap and complete the before landing checklist before reaching the 1000ft stable gate. Reducing time available to complete tasks can be inconvenient: “it is a pain if you are stable at, you know a 1000 cos you’ve got 500ft to get your speed back by 150 flap out and then finish the checks” (Small group discussion 4). However, is considered straight forward: “setup for the approach into Wellington ah mm, that was all straightforward” (Small group discussion 12). The aircraft maintained 160kt to 5 DME and was stable when passing the 1000ft stable gate. Several outcomes are possible:

- The crew go around.
- The crew indicate to ATC that they are unable to comply with the instruction whereby ATC request the aircraft to climb to 3500ft.
- The crew stabilise the aircraft above 1000ft and continue the approach (stable approach).
- The crew do not stabilise the aircraft by 1000ft and continue the approach (continued unstable approach).

Height restriction during Christchurch ILS/DME RWY20 instrument approach above 1000ft: Having crossed CH409 and while tracking towards ODISI, ATC clear the aircraft for the localiser, rather than for the instrument landing system (ILS). The crew’s reaction to that was “you’re getting mucked around by ATC coming into Christchurch on the first approach” (Small group discussion 12). This likely reflects an element of frustration given the infrequent likelihood of receiving such a clearance. Although, the crew acknowledge that “again, wh (sic), which is, isn’t a day to day thing but it’s not abnormal for that to happen […] they will do that especially if they have to hold somebody up before they start the descent” (Small group discussion 8), it is a legitimate option for ATC to manage aircraft traffic congestion. For example, “you know, it happens countless times” (Small group discussion 8).

The impact of being cleared for the localiser rather than the approach is that the aircraft cannot descend: “um ATC held us up until we were quite a bit above the glideslope and then gave us descent for the ILS to intercept the glideslope from above” (Small group discussion 12). At 8 DME, the aircraft was at 3000ft and 300ft high on profile. Being high on profile is considered a hassle: “Well it’s just a hassle cos you try, [inaudible] if your trying slow up, configure um we, we're lucky we had gear and flap out, it was just a matter of getting flap 30 out […] you know being high um is not as bad but you'd still want to be established and stable a fair way back” (Small group discussion 4). This situation can potentially be tough: “It’s just tough trying to meet those sta (sic), stable criteria if its starts getting out of hand” (Small group discussion 12), but it is achievable: “we managed to get on track um get back on glideslope pretty quickly, so I think for what it was, it was ok, achievable” (Small group discussion 4). The aircraft was stable in the vicinity of 2000ft which was 900ft above the 1000ft stable gate: “I think we were stable, well on the glideslope, established and stable by 2000 pretty much” (Small group discussion 4). Several outcomes are possible:

- The crew go around.
- The crew indicate to ATC that they are unable to comply with the instruction whereby ATC request the aircraft to climb to 3500ft.
- The crew stabilise the aircraft above 1000ft and continue the approach (stable approach).
- The crew do not stabilise the aircraft by 1000ft and continue the approach (continued unstable approach).

As part of the un-commanded autopilot disconnect scenario, the autopilot was disconnected as the aircraft crossed CH409. It was unable to be re-engaged which was unintended. The implication of this was that the height restriction scenario was more challenging for the crew to manage. If the autopilot had been available during the scenario: “it it makes it a whole lot simpler from a, um, well both of us like pilot flying me, I’m not, you know, I’m not just concentrating on flying it, I’m able to ssst (sic) keep my situation awareness um but also because I’m having to fly it, it makes [pilot monitoring] workload a hell of a lot more as well” (Small group discussion 4). The autopilot disconnect scenario (although unintentional) in combination with the height restriction scenario contributes to a feeling that the scenarios in combination were a setup: “you’re getting mucked around by ATC coming into Christchurch on the first approach and then […] having to hand fly so losing the autopilot um its sorta (sic) like that’s multiple failures” (Small group discussion 12).

Paired Scenario Compatibility: The scenarios are similar, but notification of each scenario occurred during different phases of flight. For the altitude restriction, crew were provided with roughly three minutes notice compared with roughly 10 minutes for the speed restriction. For the altitude restraint: “Um, well it was like right before, it was pretty much as we were 2 miles before establishing so it was, I guess um, it ATC were gonna (sic) do it, it would be nice to know that prior too, it was the localiser not the ILS” (Small group discussion 4). Both scenarios contributed to a reduction in time to complete tasks associated with approach and landing. However, the altitude restraint was more challenging: “yeah, so that’s um probably bordering on an undesirable event really” (Small group discussion 12). The crew acknowledge that if the aircraft was both fast and high, it would be like “pushing preverbal uphill cos you know you’re trying to catch glideslope but your airspeed going to increase” (Small group discussion 12). This could result in crew electing to go around which although not undesirable, would result in a loss of opportunity to record measures. For example, “I think, yeah potentially you could have some that would go around, they might just think ‘nah, look this is a little’, you know the lines of the cheese, the holes of the cheese are lining up, let’s just go around” (Small group discussion 4). Despite the differences mentioned above, only minor changes to environmental conditions were made to these scenarios during the final simulated flight protocol[159].

APPENDIX W, section W7 Paired Scenario: Holding Pattern

Holding Pattern at UMAGA (Christchurch – Wellington): Following the wind shear / microburst recovery procedure, the aircraft tracks downwind under radar vectors. ATC instruct the crew to enter a holding pattern at UMAGA at 3000ft. The direction of the hold is opposite to that published. The crew complied with the ATC instruction and following the wind shear / microburst recovery procedure, the flight was considered to be uneventful: “And the pretty much uneventful guys. We came around again, and you went dir (sic) direct to UMAGA, enter the hold in the opposite direction and a landing of 34. Or onto 34” (Small group discussion 8). Several outcomes were possible:

- The crew comply with the ATC hold instruction.
- The crew contact ATC and indicate that they are unable to comply with the hold instruction.
- The crew do not contact ATC and do not comply with the ATC hold instruction.

Holding Pattern at KABGO (Wellington – Christchurch flight): During descent, the aircraft is passing through 10000ft when ATC instruct the crew to enter a holding pattern at KABGO at 8000ft. The direction of the hold is opposite to that

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[159] This contributed to loss of data as most crew did not adhere to the speed constraint and the simulator instructor did not prompt crew to maintain 160 knots to 5nm.

published. The crew complied with the ATC instruction: “um, entered the hold. We did a descent in the hold which we did and then cleared fo (sic) for onwards and the approach” (Small group discussion 4). The clearance from ATC was considered to be late: “um, it was quite, um late from ATC to get a clearance like that so it was, it wasn’t a scramble, we had enough time to set it up and data check it properly […] being forced around a little bit by ATC in that situation was perhaps a bit of added pressure to it” (Small group discussion 12). However, the late clearance was understandable: “it’s not that often you have a lot of aircraft pilling up in in Christchurch and you know that it’s hard from them for get on the radio and sort their stuff out so they’re under a bit of undue pressure as well” (Small group discussion 8). Several outcomes were possible:

- The crew comply with the ATC hold instruction.
- The crew contact ATC and indicate that they are unable to comply with the hold instruction.
- The crew do not contact ATC and do not comply with the ATC hold instruction.

Paired Scenario Compatibility: When asked how challenging the scenario was a crew member said “well, the box does it all for us so um it’s just a matter of data entry and correctly data checking and then executing and so” (Small group discussion 4). The direction of the hold did not contribute to additional workload: “as long as we ah, yeah, if as long we’re cleared left or right then um we’re fine, it’s just a matter of pushing one button” (Small group discussion 4). Time between receiving the hold instruction and entering the hold was sufficient, although workload was higher for the hold at UMAGA as the procedure was not in the flight management system when the instruction was received: “the first one was enough definitely, the second time we were because we had um gone direct to BUTIN on the approach, to clean up the flight management system, we he cleared us to it wasn't in the flight management system so we had to re-enter that, so that just added another um element we had to put in, where with the first on KABGO was right there, hit the button, enter the hold, execute." (Small group discussion 4). To prevent UMAGA from being removed from the flight management system, the crew suggested vectoring the aircraft to UMAGA. This would ensure that the same data entry process was undertaken for both holding patterns: "you know, vector him via UMAGA for the ILS um so you're not expecting the hold, but you know that ok that's where we're going so if you're going to tidy up the box you can direct to UMAGA instead of direct BUTIN" (Small group discussion 4). Another factor which influences time taken to enter data into the flight management system is familiarity: "it just becomes to the knowledge of the system but yeah, knowing where to put the, the waypoint and how to tie that up, yeah. But still, that still shouldn't take any more than 10 seconds to rectify" (Small group discussion 4). The holding patterns occurred during different phases of flight. For example, one occurs during descent whereas the other occurs following a wind shear / microburst recovery procedure. Regarding the similarity of the two scenarios, a crew member said, "I'd say they're still, like they're definitely comparing apples with apples there so it's not um, not too far apart" (Small group discussion 12). The holding pattern scenarios were removed from the final simulated flight protocol as it was not possible to record keystrokes associated with flight management system data entry. Had this information been available, these scenarios would have likely been included within the final simulated flight protocol.

APPENDIX X CHANGES TO SCENARIOS FOLLOWING THE SECOND TRIAL OF THE INITIAL SIMULATED FLIGHT PROTOCOL

Where possible, scenarios within each paired scenario were constructed to be as similar as practically possible during the final simulated flight protocol. To improve paired scenario comparability, changes made to scenarios following the second trial of the Christchurch – Wellington flight include:

Changes to weather conditions:

- The cloud top height was increased from 7000ft to 14000ft to ensure the aircraft enters atmospheric icing conditions during climb and descent.
- Windspeed above 10000ft was reduced from 60kt to 45kt.
- The visibility, cloud base, turbulence and wind direction and velocity at Wellington were changed to reflect favourable conditions.
- No wind shear was reported or simulated.

The traffic alert and collision avoidance system resolution advisory scenario was removed from the final flight scenario due to incompatibility between the two scenarios within the paired scenario, change in flight path. This is discussed in the section, paired scenario compatibility, in APPENDIX W, section W3.

An ice accretion during climb and descent scenario was included in the final flight, despite not having been included in either trial flight. It was included to improve scenario compatibility with the ice accretion scenario in the Wellington – Christchurch flight. The section, paired scenario compatibility, within APPENDIX W, section W2, outlines the reasons which resulted in this change. Compatibility between the two scenarios in the final simulated flight protocol is discussed in section 3.8.2.

The trigger that initiates the go around scenario was changed from a rapid loss of airspeed and increasing turbulence associated with negative wind shear to an ATC instruction to go around at 300ft. Having a consistent trigger for the go around removes ambiguity regarding which procedure to initiate (see APPENDIX W, section W5).

The holding pattern scenario was removed due to an inability to capture flight management system key stroke data (see APPENDIX W, section W7).

Changes made to scenarios following the second trial of the Wellington – Christchurch flight include:

Changes to weather conditions:

- Windspeed above 10000ft was reduced from 60kt to 45kt.
- The visibility, cloud base, turbulence and wind direction and velocity at Christchurch were changed to reflect favourable conditions.

A tailwind during climb scenario was included which required the aircraft to cross TAXUP at 4000ft. This allows comparison with the tailwind during initial climb scenario during the Christchurch – Wellington flight. The paired scenario, tailwind during climb, is discussed in section 3.8.1. The paired scenario compliance with instructions following a change in environmental conditions was removed (see APPENDIX W, section W2). The ice accretion scenario was expanded to include descent and is included in the new paired scenario, ice accretion which is discussed in section 3.8.2. The trigger that initiates the go around scenario was changed from a spurious TAWS/EGPWS warning TOO LOW GEAR alert to an ATC instruction to go around at 300ft. This standardises the trigger which initiates the paired scenario, go around, as discussed in section 3.8.5. The holding pattern scenario was removed due to an inability to capture flight management system key stroke data (see APPENDIX W, section W7).