The alertness of aircrew on the London-Sydney route: comparison with predictions of a mathematical model

DERA/CHS/PPD/CR/990261/1.0

Cover + x + 30 pages

November 1999

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This document was produced by DERA for the Civil Aviation Authority under Order/Contract reference 7D/S/952/2

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Record of changes

Issue	Date	Detail of Changes
Draft	July 99	
1.0	Nov 99	

Executive summary

E.1 Background

E.1.1 This report describes a study carried out to validate the CHS Alertness Model, using data collected on the return trip between London and Sydney via Bangkok. It has been produced for the Safety Regulation Group of the CAA under contract number 7D/S/952/2.

E.1.2 The CHS Alertness Model forms the core element of a computer program which has been designed to provide an automatic procedure for determining whether existing or proposed roster patterns are acceptable. It is based on several years of research into the development of fatigue during irregular schedules of rest and activity. Before the program is made more widely available to the airline industry, it is important that the underlying model is validated with respect to current operations, and some initial validation has already been carried out using data supplied by the German Institute of Aerospace Medicine (DLR).

E.1.3 Validation against the Sydney route was important because of its duration, the number of time-zones crossed, and its reported effects on patterns of sleep. In addition, the 10-hour eastward time-zone shift between London and Sydney had already been shown, in non-aircrew volunteers, to generate high levels of fatigue that were not predicted by the model. This route therefore provided an opportunity to investigate the performance of the model using a type of schedule where there was already a suspicion that the model may be inadequate. In addition, the study enabled a simple procedure for monitoring aircrew alertness to be tested.

E.2 Methodology

E.2.1 The subjects were 12 aircrew from British Airways, who completed the tour of duty in 6 groups of 2 on 6 successive days. They flew overnight from London to Bangkok, where they spent two nights, before flying on to Sydney, landing at 06:20 local time. On the first full day in Sydney, they flew a shuttle to Melbourne, and later the following day they flew back to Bangkok, where they landed at 22:30 local time. After another two nights in Bangkok, they returned overnight to London at the end of the third day. All flights except the shuttle were augmented by one additional crew member. At the time of the trial, Bangkok was 7 hours, and Sydney 11 hours, in advance of London time.

E.2.2 The evaluation of levels of fatigue was based on information from three sources:

i. Diaries that the aircrew completed from 2 days before the outward flight until 3 days after the return. These provided information on the timing and quality of all sleep periods, including naps, together with the subjective evaluation of alertness before going to sleep and on waking.

ii. Information from small hand-held computers that the aircrew carried with them on the flight deck. They completed a session on the computer before and after each flight, and at one hour intervals during the 4 main flights, except when they were sleeping. In each session they completed a fatigue assessment, based on the Samn-Perelli 7-point scale, and performed two tasks, one a tracking task which lasted for 2 minutes, the other a test of sustained attention that lasted for 3 minutes.

iii. An actimeter, which is a device, similar in size to a wristwatch, that the aircrew wore on their wrist throughout the study. This provided corroboration of the timing of sleep, as well as information on inactive periods on the flight deck that may have indicated involuntary napping.

E.3 Results

E.3.1 Subjective levels of alertness varied between flights and with time into flight. The least fatiguing flight was the outward leg between Bangkok and Sydney, while the most fatiguing was the final leg between Bangkok and London. The increase in fatigue during the flights was most marked during the return phase, when the recuperative value of sleep in the bunk facilities was less than on the initial outward leg. Sleep was disrupted throughout the schedule, and levels of alertness on waking were particularly low after the first two sleep periods in Sydney.

E.3.2 The model was able to explain just over a quarter of the total within-subject variation in the subjective assessments of alertness. However, the gradual increase in fatigue throughout the schedule, that was present in the data, was not predicted by the model. In addition, the model did not anticipate the high levels of fatigue at the end of the last three duty periods, and particularly at the end of the final leg.

E.3.3 These predictions were based on estimates by the model of the trends in the adaptation of the circadian rhythm to the various time-zone transitions. These trends varied between individuals since they were dependent on the precise timing of periods of wakefulness. For example the model predicted that, during the period in Sydney, when the amplitude of the rhythm was very low, some aircrew may have adapted by a phase delay rather than a phase advance.

E.4 Conclusions

E.4.1 The results from this study provide a key source of information for testing different hypotheses concerning the development of fatigue in long-haul operations, and this should lead to the development of a model with significantly improved performance. Two initial improvements are immediately indicated:

i. the method of estimating the circadian adaptation to time-zone changes needs to be reassessed in the light of recent research findings,

ii methods for relating the recuperative value of sleep to the degree of circadian disruption need to be investigated.

If modifications based on these two approaches prove to be insufficient to account for the differences that this study has highlighted, then other hypotheses, including the effect of the loss of REM sleep, may need to be considered.

E.4.2 This study has helped to establish a simple procedure for the assessment of alertness on the flight deck that is acceptable to the crews and which does not require arecordist to be present to monitor the crews.

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1 Introduction

1.1 Terms of reference

1.1.1 This report describes a study carried out to validate the CHS Alertness Model, based on data collected on the return trip between London and Sydney via Bangkok. It has been produced for the Safety Regulation Group of the CAA under contract number 7D/S/952/2.

1.2 Background

1.2.1 The CHS is currently developing a computer program to assess the fatigue implications of airline rosters [1]. The aim of this program is to provide the CAA, and eventually the operators, aircrew and others, with an automatic procedure for determining whether existing or proposed patterns of working are acceptable. An initial version of the program is now available in the form of a proof-of-concept prototype. However, for the reasons that will be outlined below, it has not yet been developed to the point where it is ready for general use.

1.2.2 The basis of the program is the CHS Alertness Model [2]. This model was originally developed from the results of a series of laboratory studies of the effects of irregular patterns of work and rest on alertness and performance. It has been adapted for civil operations by including information that has been collected as part of the current research programme for the CAA.

1.2.3 The details of the model have been described elsewhere. Essentially, it contains two components, one related to the predicted pattern of sleep and wakefulness, the other to the circadian rhythm or 'body clock'. The circadian rhythm is normally entrained to the 24-hour day as defined by the clock time in the local environment. However, after a time-zone change this entrainment is initially lost and, depending on the size and direction of the transition, several days may elapse before readaptation is complete. The accurate representation of this phenomenon in the model is a key element in the prediction of levels of fatigue in long-haul operations.

1.3 Validation of the model

1.3.1 One reason why the present version of the program can only be considered as a proof-of-concept prototype is that there are many situations where information about the development of fatigue is currently lacking. Moreover, many of the predictions of the model rely on extrapolations from work patterns studied in the laboratory, rather than from those in civil air operations, and these require justification. There is, therefore, an immediate requirement for the model to be validated with reference to the levels of alertness of aircrew in current operations.

1.3.2 Studies have been carried out over a number of years into the effects of long-haul schedules on the quality of the sleep of aircrew, both in-flight and on layover. These have provided useful information on the impact of different rosters on sleep and hence, indirectly, on alertness. However, it is only comparatively recently that levels of alertness on the flight deck have been monitored directly.

1.3.3 One of the first studies of alertness on the flight deck was carried out by the Institute of Aerospace Medicine (DLR, Cologne), using crews from two German airlines, LTU-Süd and Condor [3]. Information was collected on three main routes: the east-coast return between Düsseldorf and Atlanta, the west-coast return between Hamburg and Los Angeles, and the north-south return between Frankfurt and the Seychelles. The data from all three routes were made available to the CHS, and were used to validate the model.

1.3.4 The results of this initial validation were encouraging [4]. The main differences between actual and predicted alertness levels occurred on the Seychelles route, which consisted of two consecutive night flights. The model slightly underestimated alertness on the first night and overestimated it on the second night. However, alertness levels on the transatlantic trips, which included a layover of three nights in the USA, were generally well predicted, although there was some suggestion that the model may have underestimated the reduction in alertness with time on duty.

1.4 The Sydney route

1.4.1 Until the current study was carried out, there was no information that could be used to validate the model with respect to long eastward time-zone changes. Anecdotal evidence suggests that individuals may have greater difficulty adapting to eastward (advancing) than to westward (delaying) transitions, and this has been confirmed by several studies of non-aircrew volunteers [e.g. 5]. In addition, sleep patterns after eastward transitions are considerably more disrupted, with many crews unable to sleep at the normal local time of day [6].

1.4.2 There were several reasons why the London-Sydney route was chosen for this study. As well as being the longest eastward transition (11 hours in the winter months in the northern hemisphere) currently operated by British Airways, it is the most disruptive for sleep [6]. Moreover, an early field trial with non-aircrew volunteers showed that a long eastward transition was associated with a marked deterioration in performance that persisted for a least 6 days [7]. The failure of the model to predict the extent of this deterioration was of some concern, and this study has provided the opportunity to investigate whether this disparity extends to aircrew on the flight deck.

1.5 The monitoring of alertness

1.5.1 This study was the first carried out by the CHS in which levels of alertness were monitored during flight. Part of the objective, therefore, was to establish the methodology that would be used for future work and for the further validation of the model.

1.5.2 The monitoring of alertness has been based on three components: subjective assessments, actigraphy and performance measurements. These are described in detail in the following section.

2 Methodology

2.1 The schedule

2.1.1 Volunteers from the British Airways B747-400 fleet completed one return trip to Australia. The trip length was 10 days and included 6 flights: London to Bangkok, Bangkok to Sydney, Sydney to Melbourne, Melbourne to Sydney, Sydney to Bangkok, Bangkok to London. The sequence of flights is given in Table 2-1, and the pattern of the schedule is indicated by the black bars in Figure 4-1.

2.1.2 A total of 6 trips were monitored. All flights carried a 3-man flight crew, including one relief flight crew member, with the exception of the shuttle flights within Australia which carried a flight crew of 2. The 6 trips were taken out of the bid-line and one captain and one first officer were assigned to each one, completing all flights within the trip together. The 6 crews departed from the UK at approximately 21:30 on 6 consecutive days.

2.1.3 Two studies of the London to Sydney route were completed, one in March 1997 and the other in January 1998. A number of problems were encountered during the first study. The schedule of flights was disrupted, which meant that some individuals did not complete the shuttle flights in Australia, and one aircraft was diverted due to mechanical failure. Consequently, only a few individuals completed the route as originally planned. The study was repeated in January 1998, when all crews followed the same duty pattern. This report is concerned only with the second trial.

2.1.4 At the time of the trial the time zone change between London (LHR) and Bangkok (BKK) was +7 hours, between LHR and Sydney (SYD) +11 hours and LHR and Melbourne (MEL) +11 hours.

2.1.5 The duration of the flights, flying duty periods (FDPs) and layover periods are given in Table 2-1.

Flight	Departure time		Arrival time		Layover (hours)	Flight duration (hours)	Flying duty period (hours)
	GMT	*Local*	GMT	*Local*			
LHR-BKK	21:30	*21:30*	08:55	*15:55*	48:00	11:25	13:15
BKK-SYD	10:25	*17:25*	19:20	*06:20*	23:40	08:55	10:25
SYD-MEL	20:30	*07:30*	22:05	*09:05*		01:35	
MEL-SYD	03:25	*14:25*	04:55	*15:55*	23:45	01:30	09:55
SYD-BKK	06:10	*17:10*	15:30	*22:30*	47:59	09:20	10:50
BKK-LHR	16:59	*23:59*	05:55	*05:55*		12:56	14:26

Table 2-1; Flight and duty times during the operation

2.2 Subjects

2.2.1 Twelve healthy, male, aircrew from the British Airways B747-400 fleet took part in the study. They were aged between 39 and 54 (mean 48.0) years, and were selected from a larger pool of volunteers to provide an age distribution which closely matched that of crews operating the B747-400 fleet.

2.2.2 The 12 subjects comprised 6 captains and 6 first officers. The mean age of the captains was 51.7 (range 49-54) years and the first officers 44.2 (39-51) years. Subjects provided informed consent before taking part in the study.

2.3 Flight crew diary

2.3.1 The diary provided volunteers with details of the study and how to complete all the required tasks. It was divided into three sections: sleep pages, a Psion test schedule and a duty schedule. Individuals were identified by a subject number and were asked to provide the following information: Captain / First Officer, age and last flying duty before the study started. On a daily basis, details of sleep and, if applicable, duty were requested (Appendix A). Example pages for the sleep section were included for reference.

2.3.2 **Sleep pages:** Individuals provided information about the timing and quality of their sleep on two pages, one to be completed before and the other after sleep. They were asked to complete the sleep pages for every planned sleep period from 2 nights before to 3 nights after the trip, no matter how long or where it was taken, either on the ground or during a flight.

2.3.3 Immediately before attempting to sleep, subjects were asked to rate their current level of alertness and their average alertness since their last sleep period. They were required to place a vertical mark across an 80mm scale, where the extremes corresponded to 'extremely alert' (80) and 'extremely tired' (0). If they were on duty, they were asked to rate their overall workload during the duty period on a similar scale (extremely low = 0 to extremely high = 80). They rated their feelings of jet lag since they last went to bed (none, slight, moderate, severe) and indicated their reasons for retiring to bed (tiredness, flight schedule, local bedtime, other).

2.3.4 On waking, the crews were asked to estimate the time spent in bed and the time spent asleep. Ratings of sleep quality (extremely poor = 0 to extremely good = 80), whether they wanted to sleep more or less (much more = 0 to much less = 80), and how they felt on waking (extremely tired = 0 to extremely alert = 80) were requested. They were asked to indicate the reason for their awakening (natural, planned, disturbance, other) and, if they woke during the night for a significant period of time, to estimate the time spent awake. The definition of a significant period of time was unspecified, so that individuals could determine for themselves what they considered to be significant. A small section for comments was provided at the bottom of each page.

2.3.5 **Psion test schedule:** During each flight, individuals were asked to indicate the times that they had completed the Psion tests and the timing of any rest periods.

2.3.6 **Flight duty times:** Details of the timing of all duty periods were requested, including report time, push back and engines off, together with information on positioning and crew augmentation.

2.4 Psion sessions

2.4.1 The selection of tasks presented on the Psion was based on experience from laboratory studies investigating the effects of fatigue on performance. In addition to being sensitive to fatigue, the tasks also needed to fulfil some operational criteria. In particular, the amount of time that any one crew member spent completing the tasks needed to be kept to a minimum. Tasks also needed to be chosen that did not require extensive training to achieve peak levels of performance.

2.4.2 The sessions lasted approximately 6 minutes and included: a subjective rating of fatigue (Samn-Perelli); subjective ratings of alertness, anxiety and sociability; a tracking task and a short vigilance task.

2.4.3 Crews were instructed to complete the Psion tasks approximately 1 hour before take-off. Once in flight they were completed an hour after take-off and every hour thereafter until an hour before landing (subject to rest periods). After landing, one further session was undertaken at the earliest convenient time. The only exception to this procedure was the internal flight in Australia when crews were asked to complete one test before each flight, one after, and one approximately halfway through the flight.

2.4.4 **Samn-Perelli fatigue rating:** The fatigue rating was a modified version of a 7-point scale based on the Samn-Perelli Checklist [8], which has been validated in air operations and has been used in previous studies of aircrew fatigue [3]. Aircrew were asked to choose the number between 1 and 7 which most closely related to their current fatigue level, as follows:

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.

2.4.5 **Sustained attention task:** This task has been used previously in numerous laboratory experiments at DERA CHS and has been shown to be sensitive to the effects of fatigue [9]. It was adapted from a task designed by Rosvold [10] to measure sustained attention. For this particular study it was modified further so that it ran for 3 minutes instead of the original 10 minutes. This was to ensure that the total time of the tasks presented on the Psion did not exceed 6 minutes.

2.4.6 The task consisted of a random sequence of letters which was presented one at a time on the Psion screen at a rate of one per second. Two letters (the critical stimulus) were displayed continuously at the top left-hand corner of the screen. Subjects were required to press the space bar whenever the letters of the critical stimulus were presented consecutively during the random sequence. Response times and the nature of the responses (correct or incorrect) were recorded during the 3-minute task.

2.4.7 **Unstable tracking task:** When used in the laboratory this task is usually completed using a joystick [11]. For the purposes of the current study it was modified so that subjects used the left and right shift keys to position a horizontally moving cross within a fixed target area displayed in the centre of the screen. The duration of the task was also modified so that it ran for 2 minutes instead of the original 3. The average error score proportional to the distance of the cross from the target area and measured in arbitrary units was recorded, together with the number of times the cross reached the outer limits of the target area.

2.5 Activity monitoring

2.5.1 Activity was recorded using Cambridge Neurotechnology AW4-32K actiwatches which are lightweight, wrist-worn monitors. An accelerometer within the watch records the occurrence and degree of motion and integrates this information to produce activity counts. The accelerometer is sensitive to movements of 0.01g in any direction. Data were integrated and recorded at 2-minute intervals.

2.5.2 A marker button is recessed in the case of the watch and, when it is depressed, the activity record is marked with the time and date. Subjects were asked to press the button every time they put on or took off the watch. This allowed periods when the watchwas being worn to be identified. Data from the watches were used to confirm periods of sleep and to determine episodes of inactivity during duty.

2.6 Organisation of rest during the duty period

2.6.1 All aircraft flown during the study were fitted with a bunk. Crews were able to rest during the flights except for the shuttle between Melbourne and Sydney. During the time spent on the ground at Melbourne crews were provided with a hotel room and were able to sleep if they chose.

2.6.2 In general, the calculation for the amount of time available to each crew member for in-flight rest was based on subtracting approximately 1.5 hours (an hour from the departure time and half an hour from the landing time) from the total flight time and dividing by 3 (3-man crew). However, this was subject to change as a result of operational circumstances.

2.7 Organisation of the study

2.7.1 A week prior to departure, volunteers received the diary and detailed information about the study by post. They were asked to complete the diary for two days prior to departure and for three days after returning to the UK.

2.7.2 A member of staff from DERA CHS met volunteers at the airport prior to the first flight. Aircrew were asked to report approximately half an hour earlier than usual in order to be briefed about the in-flight phase of the study and to be issued with an actiwatch and Psion computer. During the briefing the Psion tasks were demonstrated and crews were asked to complete at least one training session. On arrival back in the UK, staff from CHS met and debriefed the subjects.

3 Method of analysis

3.1 Alertness

3.1.1 The assessments of alertness during the 5 individual duty periods were analysed by unbalanced analysis of variance (ANOVA), where the random factor was 'subject' (n=12) and the fixed factor was 'time'. The levels of the factor 'time' numbered 12 for the two flights between London and Bangkok (1 pre-flight, 10 in-flight and 1 post-flight), 10 for the two flights between Bangkok and Sydney (1 pre-flight, 8 in-flight and 1 post-flight) and 6 for the Sydney-Melbourne shuttle (1 pre-flight, 1 in-flight and 1 post-flight on both legs). The analysis was unbalanced because no assessments were obtained during in-flight sleep, which occurred at different times during the flights.

3.1.2 The analysis was repeated with the amount of sleep already achieved during the flight included as a covariate. This was to investigate the value of in-flight sleep in sustaining alertness, and also enabled estimates to be made of the reduction in alertness that might have occurred if no sleep had been taken.

3.1.3 A separate ANOVA was run which included the 4 long flights in the same analysis. The fixed factor was 'flight' (n=4) and, in addition to the length of previous in-flight sleep, both linear and quadratic components of time into flight were included as covariates.

3.2 Performance

3.2.1 The two variables extracted from the performance tasks for analysis were the reaction time for correct responses (CRT) on the sustained attention task and the root mean squared error (RMS) on the tracking task. The method of analysis was the same as that described above for alertness. However, both variables were transformed prior to analysis to ensure homogeneity of variance. The transformations used were log(CRT) and 1/(RMS-1).

3.2.2 The relationship between performance and subjective alertness was investigated by regression analyses, combined across subject, of the performance measures as functions of linear and quadratic components of alertness.

3.3 Sleep

3.3.1 Four variables obtained from the subjective evaluation of sleep were analysed by balanced ANOVA. These were the duration and quality of the sleep period, the requirement for more sleep, and subjective alertness on waking. Separate analyses were carried out for in-flight sleep and for the other main sleep periods.

3.3.2 The analysis of bunk sleep was based on a 12 by 4 design, with 12 subjects and 4 sleep periods corresponding to the 4 different flights. To allow for multiple comparisons, the Newman-Keuls procedure was used to test differences between sleep on different flights.

3.3.3 The analysis of the other main sleep periods was based on a 12 by 12 design, with 12 subjects and 12 main sleep periods. The sleep periods comprised two in London preceding the outward flight (L1 and L2); four in Bangkok, two on the outward leg and two on return (B1, B2, B3 and B4); a daytime nap in Sydney on arrival (SN), followed by two night-time sleeps (S1 and S2); and a daytime nap on return (RN), followed by two overnight sleep periods (R1 and R2). Values for L1 and L2 were averaged and used as a baseline for comparison with the other sleep periods. To allow for multiple comparisons, Dunnet's procedure was used for the comparison of the sleep variables for individual periods with baseline.

3.4 The fatigue model

3.4.1 Levels of alertness predicted by the model were obtained at all times corresponding to the test sessions. To achieve this, information was required about the two factors that constitute the inputs to the model, namely the timing of all the sleep periods, including naps, and the phase and amplitude of the circadian rhythm of each individual.

3.4.2 Information on the timing of the sleep periods was obtained from the diaries and confirmed with reference to the activity data. The phase and amplitude of the circadian rhythms were then predicted on the basis of the timing of both the time-zone transitions and the periods of sleep. The output from the model used in this analysis was in the form of a 100-point scale, where 0 and 100 represented the lowest and highest levels of alertness that are theoretically achievable.

3.4.3 Regression analyses, combined across subjects, were used to investigate the relationship between observed levels of alertness, on the Samn-Perelli scale, with predicted levels on the 100-point scale. Other factors, such as time on task, time through the schedule and predicted circadian amplitude, were included as independent variables in the analyses to determine whether there were any systematic discrepancies between the observed and predicted values. In these analyses, all time points within an hour of awakening were excluded, because of the greater difficulty in estimating levels of alertness that may be affected by sleep inertia.

3.4.4 Finally, for each time point, the mean levels of subjective alertness were compared with the mean levels obtained from the model, using the best estimates from the regression analysis described above.

4 Results

4.1 Sleep

4.1.1 The pattern of sleeping throughout the period of the operation is shown in Figure 4-1, which includes naps as well as the main periods of wakefulness during sleep.

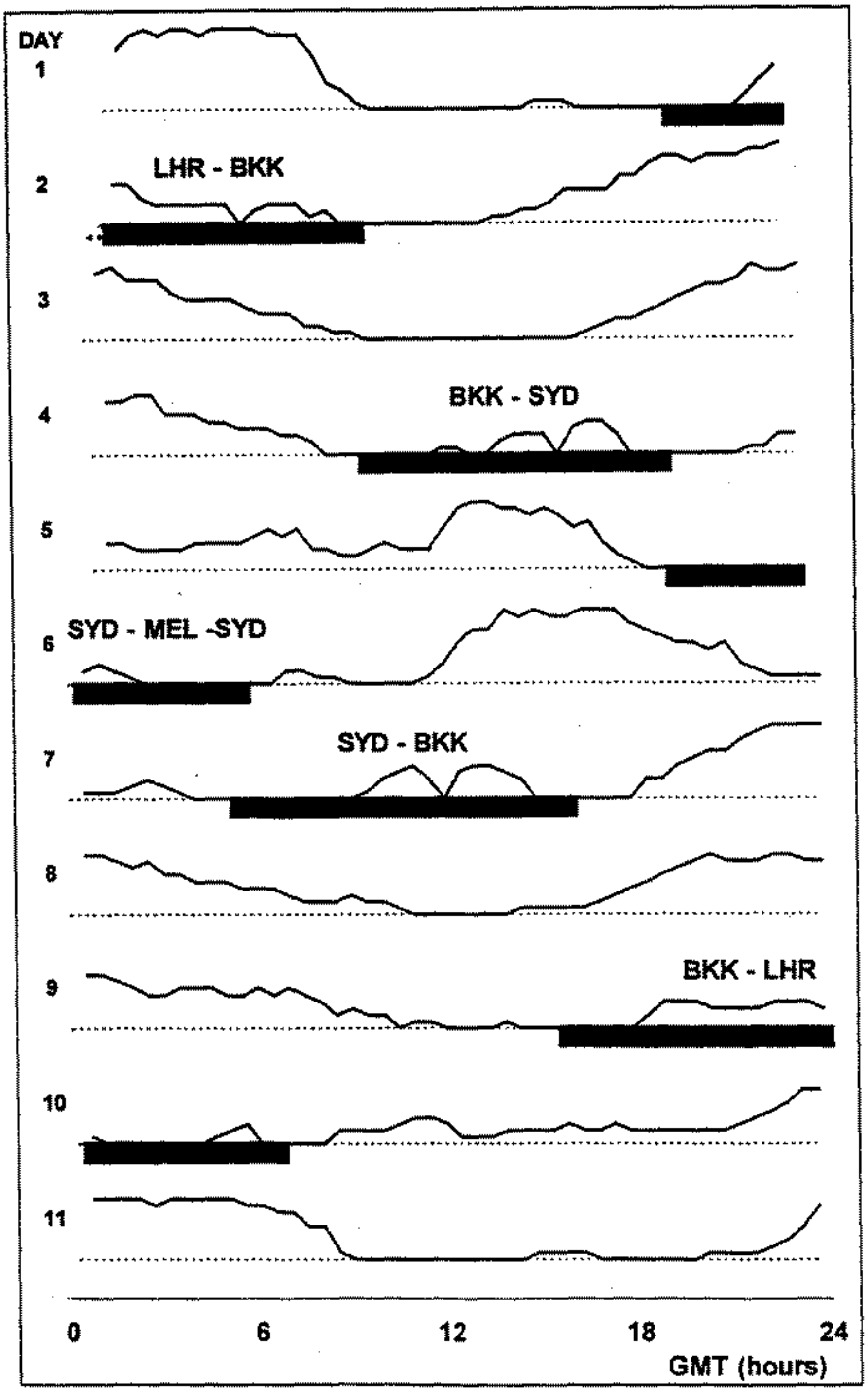

Figure 4-1; Pattern of sleep during the operation

The solid bars denote the duty periods. The continuous lines indicate the proportion of aircrew asleep at a particular time.

4.1.2 The timing of sleep was extremely variable in Bangkok during both the outward and the return phases of the operation. Some sleep periods were close to the normal local time for sleep, and others to the normal home time, while the majority fell between these two extremes. A total of 4 additional naps were taken in Bangkok, during the 48 days covered by the study.

4.1.3 Nine out of the 12 crew members slept during the day on arrival in Sydney, as well as during the following night. The average duration of the daytime sleep was 3.27 hours, while for the overnight sleep it was 5.20 hours. Between the shuttle and the return flight to Bangkok, 3 individuals took a nap, and one took two naps, in addition to their normal overnight sleep.

4.1.4 A summary of the subjective evaluation of the main sleep periods is given in Table 4-1. The duration of sleep on the first night in Bangkok was significantly longer than on baseline ($p < .05$). Apart from the daytime sleep on arrival in Sydney (see above), after waking from which the desire for more sleep was greater than after any other sleep period ($p < .05$), the only sleep period that was significantly short was the daytime nap on arrival in London ($p < .01$). Levels of alertness were low after both the first two sleeps in Sydney ($p < .05$), as well as after the nap on arrival in London ($p < .05$). However, the quality of the nap in London was rated more highly than the poorest sleep on layover, which was on the first night in Sydney ($p < .05$).

Sleep identifier	Location	Duration (hours)	Quality	Requirement for more sleep	Alertness on waking
L1	LHR	6.91	46.7	28.0	38.9
L2	LHR	7.64	54.9	33.8	51.8
B1	BKK	9.67†	55.8	32.6	40.0
B2	BKK	7.11	44.5	32.4	36.8
SN	SYD	3.27**	54.4	12.8**	24.1**
S1	SYD	5.20	37.8††	33.8	30.9**
S2	SYD	6.26	45.5	29.6	36.4
B3	BKK	7.50	45.5	25.9	34.6
B4	BKK	7.54	43.7	34.0	36.4
RN	LHR	4.25**	59.5	23.4	32.9*
R1	LHR	7.84	51.2	30.1	38.5
R2	LHR	6.60	56.3	31.6	37.1

* *poorer than baseline (mean of L1 and L2) ($p < .05$)*
** *poorer / shorter than baseline ($p < .01$)*
† *longer than baseline ($p < .05$)*
†† *poorer than RN ($p < .05$)*

Table 4-1; Subjective evaluation of main sleep periods

4.1.5 A summary of the subjective evaluation of in-flight sleep is given in Table 4-2. All the aircrew attempted to sleep in the bunk at least once during the 4 main flights. One individual went into the bunk twice during the outward flight between London and Bangkok, and three went in twice on the return from Bangkok. Four individuals also attempted to nap in Melbourne during the shuttle operation between Melbourne and Sydney. One failed to get to sleep at all, while the mean duration of the other three naps was 1.31 hours.

Flight	Duration (hours)	Quality	Requirement for more sleep
LHR–BKK	2.31	41.5	15.0
BKK-SYD	1.18***	28.5	23.2
SYD-BKK	1.45*	36.3	23.1
BKK-LHR	1.83	26.8	27.5

* *shorter than LHR-BKK ($p < .05$)*
*** *shorter than LHR-BKK ($p < .001$)*

Table 4-2; Subjective evaluation of in-flight sleep

4.2 Alertness

4.2.1 The results of the analysis of subjective alertness within the 5 individual duty periods are summarized in Table 4-3. With the exception of the return flight from Sydney to Bangkok, the main effect of time within duty was significant for all duty periods. The mean values corresponding to different times during the flight, together with their standard errors, are shown in Figure 4-2.

Duty	Probability of time sequence effect in ANOVA table	Improvement in alertness per hour of in-flight sleep†	Probability of time sequence effect in ANOVA table (adjusted for in-flight sleep)
LHR–BKK	0.0274	0.57***	0.0024
BKK-SYD	0.0024	-0.07 NS	0.0265
SYD-MEL-SYD	0.0000	0.00 NS	0.0000
SYD-BKK	0.0650	0.38 NS	0.0731
BKK-LHR	0.0104	0.13 NS	0.0165

*** *greater than zero ($p < .001$)*
NS *not significantly different from zero*
† *For the shuttle duty, this refers to sleep taken between the two flights.*

Table 4-3; Subjective alertness during individual duty periods

4.2.2 The beneficial effect of in-flight sleep was only evident during the first flight ($p < .001$), when each hour of sleep had the effect of reducing fatigue by 0.57 on the Samn-Perelli scale. The mean reduction associated with sleep periods longer than 2.5 hours was 1.7, and that associated with sleep periods between 1.5 and 2.5 hours was 0.5. No sleep periods during this flight were shorter than 1.5 hours. Based on this analysis, if no sleep had been taken in flight, the increase in fatigue throughout the duty period would have been much greater (Figure 4-3).

4.2.3 When the duty periods corresponding to the 4 long flights were included in the same analysis, the effect of time on duty, after correcting for in-flight sleep, was similar for each duty period, amounting to a linear increase of 0.15 per hour. However, the mean level of fatigue for the second flight (3.32) was lower than for the first, third and fourth (4.26, 4.43 and 4.36 respectively, all $p < .001$). In this analysis, the correction for sleep amounted to a reduction of 0.34 per hour on the alertness scale ($p < .001$) on the first flight, 0.33 per hour on the third ($p < .01$) and 0.20 per hour on the fourth ($p < .01$). Sleep had no significant effect on alertness during the second flight.

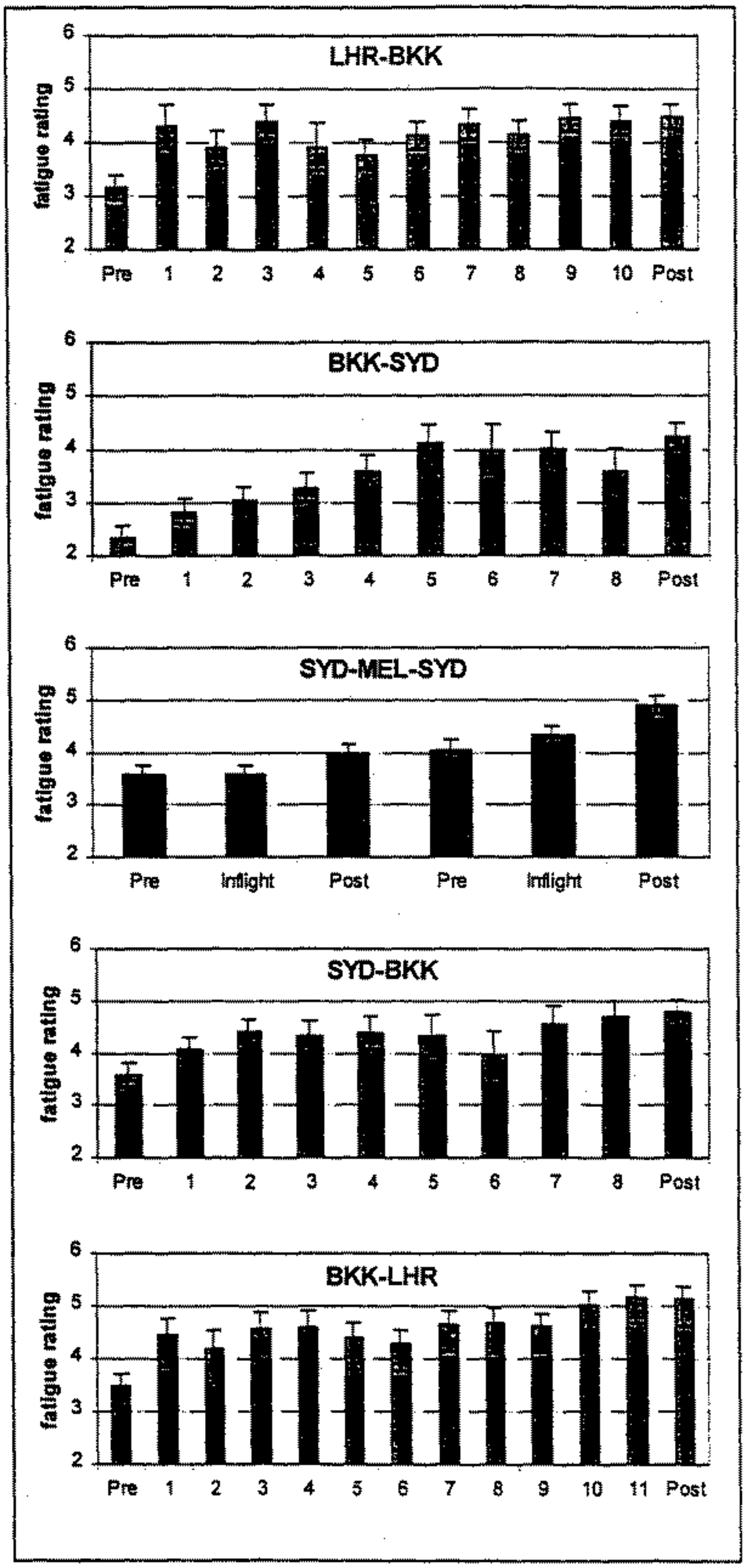

Figure 4-2; Subjective fatigue during the 5 duty periods

Where Pre = pre flight rating; numbers correspond to hourly ratings inflight; post = post flight rating

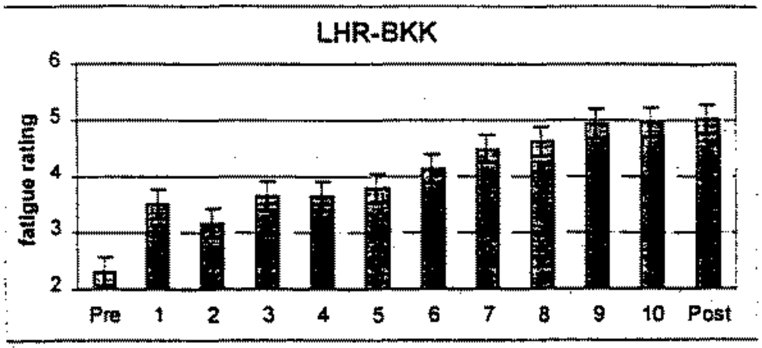

Figure 4-3; Predicted levels of fatigue during the LHR-BKK sector (if no sleep taken in-flight)

4.2.4 When the duty periods corresponding to the 4 long flights were included in the same analysis, the effect of time on duty, after correcting for in-flight sleep, was similar for each duty period, amounting to a linear increase of 0.15 per hour. However, the mean level of fatigue for the second flight (3.32) was lower than for the first, third and fourth (4.26, 4.43 and 4.36 respectively, all $p < .001$). In this analysis, the correction for sleep amounted to a reduction of 0.34 per hour on the alertness scale ($p < .001$) on the first flight, 0.33 per hour on the third ($p < .01$) and 0.20 per hour on the fourth ($p < .01$). Sleep had no significant effect on alertness during the second flight.

4.3 Performance

4.3.1 The response time on the sustained attention task was strongly correlated with subjective alertness ($p < .001$). The inclusion of a quadratic term in alertness improved the quality of the fit ($p = .012$), suggesting that the relationship was non-linear. On the basis of the best quadratic fit, reaction times corresponding to Samn-Perelli scores of 1, 2 and 3 were similar, while those corresponding to scores of 4, 5, 6 and 7 were increased by 1.7%, 5.3%, 10.9% and 18.6% respectively.

4.3.2 The only duty period during which the response time varied with time into duty was the Sydney shuttle. The time taken to respond was significantly longer during the two post-flight sessions than during the Melbourne to Sydney leg ($p < .05$).

4.3.3 The mean response times for each duty period are shown in Figure 4-4. Performance was better on the shuttle than on all the other flights apart from the outward flight between Bangkok and Sydney ($p < .001$). In addition, performance was better on the Bangkok to Sydney flight than on the other three long flights (LHR-BKK $p < .01$; SYD-BKK $p < .05$; BKK-LHR $p < .01$).

4.3.4 The tracking task was not correlated with subjective fatigue, nor did it vary significantly between flights or at different times on the same flight.

4.4 Predictions of the alertness model

4.4.1 The changes in the phase and amplitude of the circadian rhythm throughout the schedule, as predicted by the model, are shown in Figures 4-5 and 4-6 respectively. The 7-hour time-zone shift on the first flight caused the phase of all individuals to advance slowly, but the trends diverged during the period in Sydney. At this stage, the circadian rhythm of some individuals changed rapidly, possibly by a phase delay rather than a phase advance, and the amplitude of many of the rhythms was very low. The return to

London was followed by a slow readaptation via a phase delay.

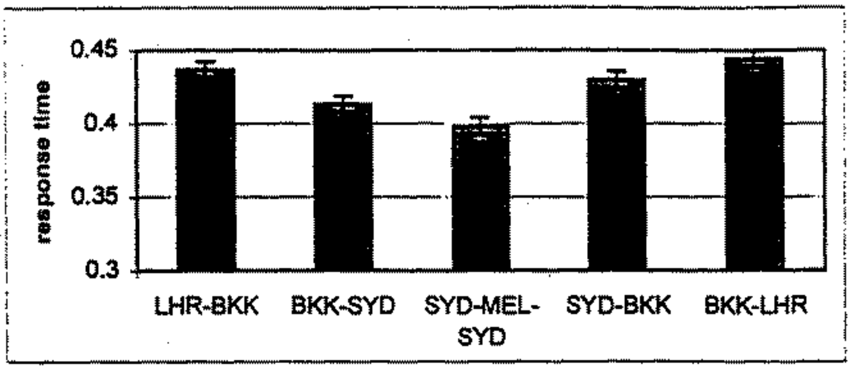

Figure 4-4; Mean response times during the 5 duty periods

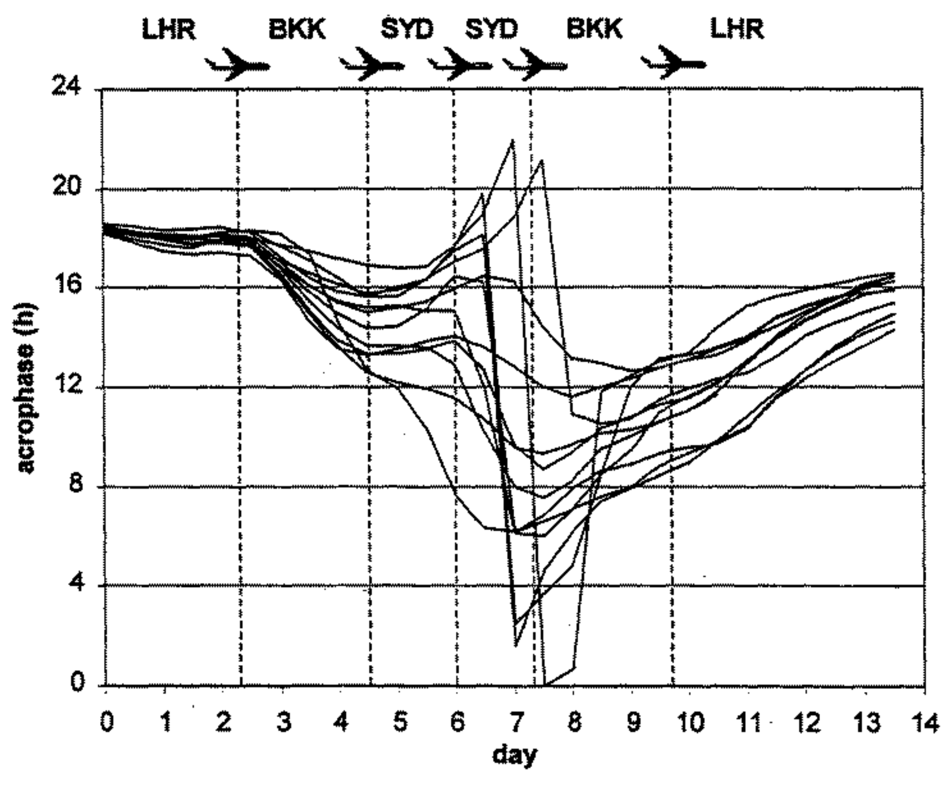

Figure 4-5; Predicted changes in the phase of the circadian rhythm during the operation (12 subjects)

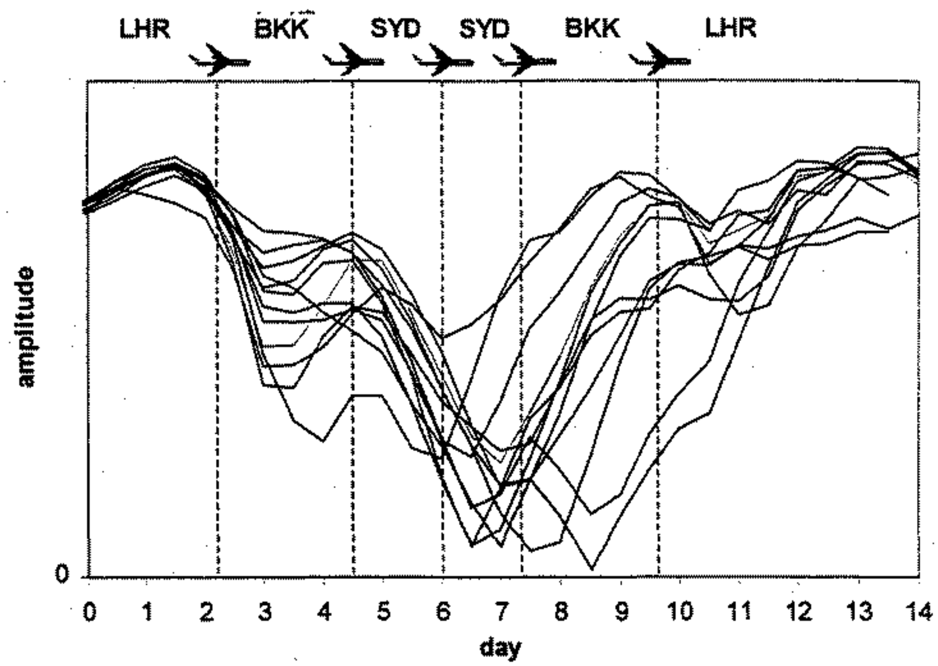

Figure 4-6; Predicted changes in the amplitude of the circadian rhythm during the operation (12 subjects)

4.4.2 The model accounted for just over a quarter of the total within-subject variation in the subjective assessment of alertness ($r^2 = .261$, $p < .001$). However, the changes in alertness that were unexplained by the model were correlated with time through the schedule ($p < .001$). After correcting for the model predictions, alertness reduced with time. In other words, there was a reduction in alertness throughout the schedule that the model failed to predict. The strength of this effect depended on the predicted level of alertness ($p < .01$). At the start of the flight from London, the relationship between observed and predicted levels of alertness was strong. By the end of the schedule, however, the relationship was weaker, due to a reduction in alertness at times when it was predicted to be high. This relationship is illustrated in Figure 4-7.

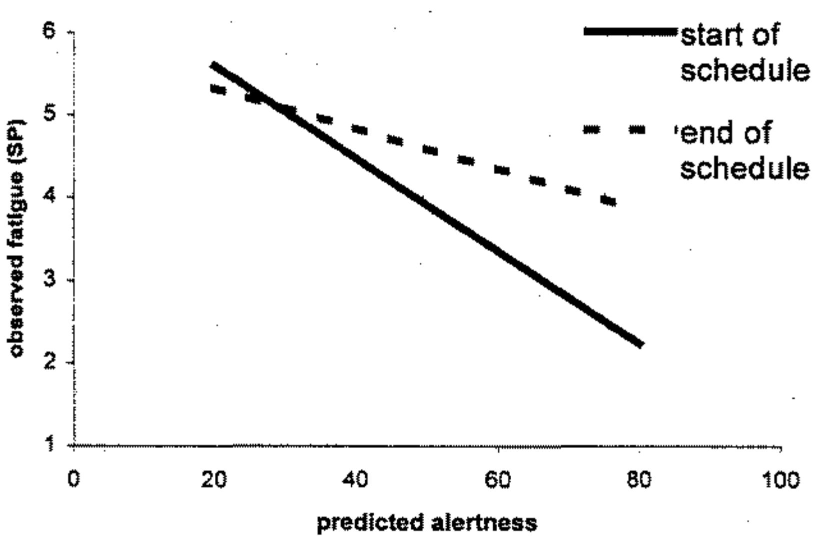

Figure 4-7; Relationship between the predicted and observed ratings of alertness at the beginning and end of the schedule

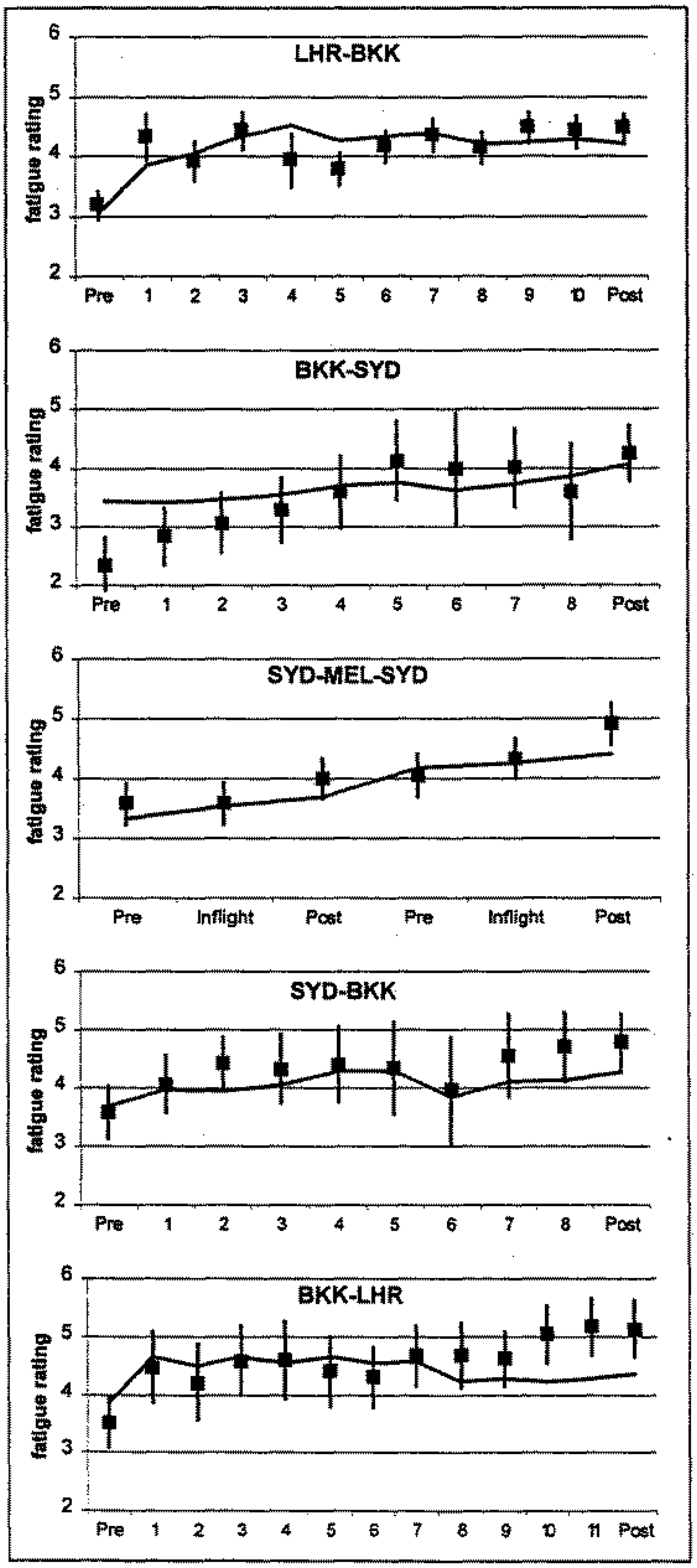

Figure 4-8; Observed and predicted levels of fatigue during the 5 duty periods

The square symbols denote the observed fatigue ratings (± 2 S.E.) and the continuous lines indicate the predicted alertness levels during the duty period.

4.4.3 The fit of the basic model to the data is illustrated in Figure 4-8. The overall correlation between the two sets of mean values was 0.79 ($r^2 = .632$, $p < .001$). While in the majority of cases the predictions were within two standard errors of the mean, there were discrepancies. The main ones were the underestimation of alertness in the middle of the first flight and at the start of the second, and the overestimation of alertness at the end of the two return flights, particularly the Bangkok to London flight. Alertness was also overestimated post-flight, after the return to Sydney on the shuttle.

5 Discussion

5.1 Performance of the model

5.1.1 In several respects, there was reasonable agreement between the reported levels of alertness and the predictions of the model. The overall correlation of just over 0.5 between the observed and predicted levels is encouraging as it relates to the rawvalues which include the within-subject variation. The flight between Bangkok and Sydney was correctly identified as the least fatiguing, and the return from Bangkok to London as the most fatiguing, at least during the first half of the flight. The model also predicted reasonably well the rising trend in fatigue during the Australian shuttle and the initial increase to a plateau during the outward flight from London.

5.1.2 Nevertheless, it must be conceded that there are areas where the agreement is poor. Indeed, the main reason for conducting this study was the concern that the model would not be able to reproduce well the trends in fatigue on long tours of duty that included multiple (particularly eastward) time-zone changes. By far the most serious disagreement was during the last few hours of the return flight to London, where the model failed to reproduce the very high levels of fatigue that were reported. To some extent this underestimation of fatigue was replicated at the end of the previous flight and with the post-flight values at the end of the shuttle duty.

5.1.3 For the future development of the model it is essential that the reasons for these discrepancies are understood. There are at least three possibilities, any combination of which may provide the explanation:

i. There is a strong suggestion that the in-flight sleep on the final flight, and possibly also on the previous flight from Sydney to Bangkok, did not provide the recovery of alertness that would be expected, or that was achieved on the first outward flight. The poor sleep on the second flight, between Bangkok and Sydney, is understandable, as the requirement for sleep was low. On the return flights, however, and especially on the final flight, fatigue levels were already quite high before sleep was attempted. The model will have overestimated the recuperative value of the in-flight sleep and hence underestimated levels of fatigue at the end of the flight. Previous studies of in-flight sleep based on recordings of the electrical activity of the brain have suggested that good quality sleep can be achieved, even on flights to and from the Far East [12]. However, it is possible that, during a period of severe circadian disruption, as in the current study, such sleep is less recuperative.

ii. In the earlier study of the effects of a 10-hour eastward shift on the alertness and performance of non-aircrew volunteers, the increase in fatigue during the day was much larger than both baseline and the predictions of the [7]. The effects persisted for several days after the transition, until sleep, and particularly REM sleep, had fully recovered. The high fatigue levels at the end of the final duty period in this study seem to mirror this pattern. It is possible, therefore, that they may be the consequence of the preceding period of sleep disruption and the loss of REM sleep that would inevitably have occurred. In the present model, the recuperative value of sleep is related entirely to 'deep' or 'slow-wave' sleep, and does not include the influence of REM sleep. While this is consistent with most current thinking, it is possible that the loss of REM sleep could have an effect, particularly if it accumulated over several days, as is likely after a long time-zone transition.

iii. There was evidence of a general increase in levels of fatigue throughout the schedule. This appeared both in the subjective assessments of fatigue, which were increasingly underestimated by the model with time, and in the response times to the Psion tests, which increased on successive duty periods after the third (counteracting a learning effect which is the most likely explanation for the decrease over the first three duty periods). Moreover, the ability of the model to predict levels of alertness decreased with time. It appeared that on those occasions when alertness was predicted to be high, it deteriorated, while on those occasions when it was predicted to be low, it remained low. It is likely that the relationship between the circadian rhythm and alertness has started to break down as the schedule has progressed. This may reflect both inaccuracies in the prediction of changes in the rhythm (which may also explain the differences at the start of the second duty) and a change in relationship when the amplitude of the rhythm is low.

5.2 Further development of the model

5.2.1 The current study has clearly identified an important area where the present model is inadequate. The failure to predict levels of fatigue at the end of the schedule is serious, as the mean levels reached (over 5 on the Samn-Perelli scale) are high enough to cause some concern, at a time when the model would not recognize a problem.

5.2.2 The above discussion (section 5.1.3) has indicated the areas where the model might be developed to overcome these discrepancies. Firstly, it is proposed that the component of the model that predicts the pattern of adaptation to time-zone transitions should be updated to be consistent with the most recent research [13]. At the same time, modifications to the parameter space of this part of the model could be explored to investigate whether the performance of the model could be further improved.

5.2.3 Secondly, methods for relating the recuperative value of sleep to the degree of circadian disruption need to be investigated. It is possible that methods could be devised that would also explain the reduced benefit of daytime sleep, suggested by the analysis of the Frankfurt-Seychelles route [4]. Indeed, an alternative alertness model, based on laboratory studies in conditions of isolation, already incorporates an adjustment for the recovery of alertness during sleep as a function of the circadian rhythm [14].

5.2.4 It is possible that these two enhancements will alone be sufficient to provide a reasonable match with the results from this study. If so, then the next step will be to test the model against other schedules with long eastward transitions, for example between Europe and the Far East, preferably with layovers of different duration and flights at different times of day. If the changes are not sufficient, then other hypotheses will need to be considered, such as those involving the effects of REM loss.

5.3 Implications for the Sydney route

5.3.1 While the main purpose of this study was to validate the fatigue model, the results have some important implications for the management of fatigue on the London to Sydney schedules, as well as for flight time limitations more generally.

5.3.2 Prior to the study, there had been reports of problems with fatigue on the shuttle flights. However, these results suggest that high levels of fatigue were not reached until after the return to Sydney. Of course, this conclusion may only apply when the arrival back in

Sydney is in the middle of the afternoon. If the return is much later, then it is most likely that the rapid increase in fatigue throughout the day would continue into the evening, and that the crews would have considerable problems.

5.3.3 The main build-up in fatigue occurred during the return phase of the operation, and particularly towards the end of the Bangkok to London flight. The final two in-flight assessments, as well as the following post-flight assessment, averaged over 5 on the Samn-Perelli scale, which is a level that would not normally be regarded as acceptable. Normally, on an augmented flight with full rest facilities, the crews should have been able to obtain sufficient rest to remain reasonably alert. This was certainly the case on the outward flight between London and Bangkok. The provision of an extra crew member on the return flight is clearly indicated, so that each individual would have more time available for rest.

5.3.4 The accumulation of fatigue through the schedule appears to be associated with the continuous period of sleep disruption, although, following the discussion in section 5.1, the mechanism that is involved still needs to be established. Certainly the pattern of sleep is irregular in Bangkok, both on the outward and the return legs, and the quality of sleep in Sydney is poor. This suggests that fatigue on return would be reduced if the duration of the schedule, and hence the period of disruption, was less.

5.3.5 One method of reducing the duration of the schedule would be to spend one day less in Sydney by excluding the shuttle flight, and we understand that British Airways have now adopted this approach. Alternatively, or in addition, consideration could be given to reducing the layover time in Bangkok on the outward phase by 24 hours. The crews are able to sleep for longer than usual on the first night in Bangkok, and this should ensure that they will have overcome most of the sleep debt associated with the previous overnight flight. The timing of the flight from Bangkok is also favourable, as it coincides with daytime in London and, after only a 24-hour layover, the movement of the body clock to Bangkok time will be much reduced.

5.4 Implications for flight-time limitations

5.4.1 The accumulation of fatigue through the schedule is a factor that needs to be considered carefully in the context of the more general issue of flight time limitations. Until more information becomes available on other similar schedules, for example those operated by Air New Zealand between Auckland and various European destinations, we cannot be certain that this is a general phenomenon. However, the likelihood is that it will apply to those schedules which generate a continuous period of sleep disruption, and this would include most long tours of duty that involve long time-zone transitions, particularly in an eastward direction.

5.4.2 In these circumstances, it would be wise to insist on more stringent criteria for crew augmentation. These results would suggest a flight-time limit of around 10 hours, beyond which a full relief crew should be provided. The application of such a rule when tours of duty extend beyond 6 or 7 days should help to limit the build-up of fatigue on the flight deck by ensuring that sufficient time can be made available for sleep.

5.5 Methodology

5.5.1 Previous field studies of aircrew [3, 15] have used many more measures than in this study to assess the fatigue implications of specific duty schedules. Objective measures of sleepiness (brain activity), heart rate and heart rate variability have been collected as well as subjective measures of alertness, workload and sleep quality. In the current study, where far fewer variables were monitored, it was possible to detect similar trends in alertness to those observed in the earlier studies. Although the use of a greater variety of measures provided a comprehensive overview of an individual's response to the duty schedule, it is not always the most cost-effective way of assessing the fatigue implications of the operation.

5.5.2 This study has helped to establish the methodology for the assessment of alertness in-flight, which does not require a researcher to be present on the flight-deck.

5.5.3 *Alertness measures:* The modified version of the Samn-Perelli assessment was selected for inclusion in the current study because of its ease of administration and sensitivity to changes in alertness [16]. Results from the current study were correlated with the performance measures from the sustained attention task and, despite the relatively small sample size, the assessment has been shown to be a useful measure of alertness in-flight.

5.5.4 *Sustained attention task:* Athough the results from the task were correlated with alertness, it was not possible to detect any effect of time in to duty. However, the task has been shown to be sensitive to these effects during previous laboratory studies [9, 17, 18]. It was chosen because it was considered not to have strong alerting effects and because it could easily be administered in flight during long sectors. However, like the unstable tracking task, this task was modified for the field study and it ran for 3 minutes instead of the original 10. This reduction in duration was required for operational reasons and may have affected its sensitivity. The task has since been used successfully on the flight deck, using the full 10-minute version [19]. Another factor in the current study was that the limited training may have reduced the ability to detect trends within the flight.

5.5.5 *Unstable tracking task:* The results from the tracking task failed to show any significant variation between or within flights and did not correlate with subjective fatigue. The absence of variation in performance within flights may have been due to the alerting effect of the task. Some crew members reported that they enjoyed completing the task and found it more of a challenge than the sustained attention task. Based on the format in which the task was present and on these results the task is not considered suitable for inclusion in future in-flight assessments of aircrew alertness.

5.5.6 *Activity monitoring:* The data from the actiwatches did not form an essential part of the study. It did however provide a useful means of resolving some discrepancies relating to the diary data, for example when individuals reported that they were asleep in a hotel at the same time that they were on duty.

6 Conclusions

6.1 Based on the coefficient of correlation, the overall agreement between the reported levels of alertness and the predictions of the model was encouraging. Nevertheless, there were specific occasions during the schedule when the model did not reproduce the observed changes in the pattern of alertness. By far the most important of these was towards the end of the return flight to London, when the high levels of fatigue reported by the crew were not anticipated by the model.

6.2 The future development of the model will need to take into account the discrepancies highlighted by these results. Firstly, the method of estimating the circadian adaptation to time-zone changes needs to be reassessed in the light of recent research findings. Secondly, methods for relating the recuperative value of sleep to the degree of circadian disruption need to be investigated. If modifications based on these two approaches prove to be insufficient to account for the differences, then other possibilities will need to be considered, such as those involving the effects of REM loss over several days. Either way, the results from this study will continue to provide a key source of information for testing different hypotheses concerning the development of fatigue in long-haul operations.

6.3 There was an accumulation of fatigue through the schedule that appeared to be associated with the continuous period of sleep disruption that lasted throughout the time spent away from base. Problems on the return phase of the operation could be reduced by limiting the total duration of the schedule. This could be achieved by excluding the shuttle flight and spending one day less in Sydney, and we understand that British Airways have now adopted this approach. Alternatively, or in addition, the time spent in Bangkok on the outward phase could be reduced by 24 hours.

6.4 The accumulation of fatigue through the schedule is a factor that needs to be considered carefully in the context of the more general issue of flight time limitations. These results suggest that, when a tour of duty involving multiple time-zone transitions extends beyond 6 or 7 days, a full relief crew should be provided for flights longer than 10 hours. The application of such a limit would help to reduce levels of fatigue on the flight deck by ensuring that sufficient time is made available for sleep. This limit would not be necessary when crews are time-zone adapted.

6.5 This study has helped to establish a simple procedure for the assessment of alertness on the flight deck that is acceptable to the crews and which does not require a recordist to be present on the aircraft. The most important element is the subjective evaluation of fatigue based on the Samn-Perelli 7-point scale, which has revealed very clear trends in the development of fatigue in flight. The performance tasks have proved less sensitive. The tracking task does not appear to be useful in this environment, while the sustained attention task may provide more useful information if it is run for longer than the 3 minutes allowed in this study.

7 Acknowledgements

7.1.1 The authors are indebted to the British Airways crews who participated in the trial for their the effort and commitment. We would also like to thank SFO Mike Johnson for his help and assistance in the organisation and running of the study.

7.1.2 The authors would also like to thank Claire Spencer who was involved in the organisation of the information into a database and the preparation of data for analysis.

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A Appendix

A.1 Sleep section of diary

SECTION 1 - TO BE COMPLETED *BEFORE* EACH SLEEP

	day	*month*	*year*		*hrs*	*mins*
DATE:				**TIME:** LT *(or GMT in flight)*	:	

LOCATION: home ☐ hotel ☐ bunk ☐ seat ☐

HOW DO YOU FEEL RIGHT NOW?

extremely tired ________________________ extremely alert

ON AVERAGE, SINCE YOU LAST SLEPT, HAVE YOU FELT?

extremely tired ________________________ extremely alert

WERE YOU ON DUTY TODAY? Yes ☐ No ☐

PLEASE FILL IN THE APPROPRIATE DETAILS OF THE DUTY SCHEDULE ON THE BACK PAGE

WHAT WAS THE OVERALL WORKLOAD FOR THIS DUTY?

extremely low ________________________ extremely high

HOW WOULD YOU ASSESS YOUR FEELINGS OF JET LAG SINCE YOU LAST WENT TO BED?

none ☐ slight ☐ moderate ☐ severe ☐

symptoms ☐

WHAT IS THE REASON FOR RETIRING AT THIS TIME?

tiredness ☐ flight schedule ☐ local bedtime ☐ other ☐

COMMENTS:

SECTION 2 - TO BE COMPLETED *AFTER* EACH SLEEP

DATE (ON GETTING UP):

day		*month*		*year*	

	hrs	*mins*		*hrs*	*mins*
IN BED AT: LT (*or GMT in flight*)	•		**WAKE UP AT:** LT (*or GMT in flight*)	•	
ASLEEP AT: LT (*or GMT in flight*)	•		**GET UP AT:** LT (*or GMT in flight*)	•	

HOW WOULD YOU RATE THE OVERALL QUALITY OF YOUR SLEEP?

extremely poor ________________________________ extremely good

DID YOU WANT TO SLEEP MORE OR LESS THAN YOU DID?

much more ________________________________ much less

HOW DID YOU FEEL AFTER YOU WOKE UP?

extremely tired ________________________________ extremely alert

WHAT WAS THE REASON FOR YOUR AWAKENING?

natural awakening ☐ planned awakening ☐ disturbance ☐ other ☐

DID YOU WAKE UP DURING THE NIGHT FOR A SIGNIFICANT TIME?

If 'Yes', please complete table

			Approx Time *hrs*	Approx Time *mins*	Approx Duration *hrs*	Approx Duration *mins*
Yes	☐	Longest awakening	•		•	
No	☐	2nd longest	•		•	

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3. Contract number and period covered:	7D/S/952/2
4. Sponsor's Name and Location:	Civil Aviation Authority, Aviation House, Gatwick, West Sussex
5. Report Classification and Caveats in use:	6. Date written: November 1999 — Pagination: x + 30 — References: 19
7a. Report Title:	The alertness of aircrew on the London-Sydney route: comparison with predictions of a mathematical model
7b. Translation / Conference details (if translation give foreign title / if part of conference then give conference particulars):	
7c. Title classification:	Unclassified
8. Authors:	Spencer MB, Robertson KA
9. Descriptors / Key words:	aircrew, alertness, modelling

10a. Abstract. (An abstract should aim to give an informative and concise summary of the report in up to 300 words).

This report describes a study carried out to validate the CHS Alertness Model, using data collected on the return trip between London and Sydney via Bangkok. The subjects were 12 aircrew from British Airways, who completed the tour of duty in 6 groups of 2 on 6 successive days. They flew overnight from London to Bangkok, where they spent two nights, before flying on to Sydney, landing at 06:20 local time. On the first full day in Sydney, they flew a shuttle to Melbourne, and later the following day they flew back to Bangkok, where they landed at 22:30 local time. After another two nights in Bangkok, they returned overnight to London at the end of the third day. All flights except the shuttle were augmented by one additional crew member. At the time of the trial, Bangkok was 7 hours, and Sydney 11 hours, in advance of London time. Subjective levels of alertness varied between flights and with time into flight. The least fatiguing flight was the outward leg between Bangkok and Sydney, while the most fatiguing was the final leg between Bangkok and London. The increase in fatigue during the flights was most marked during the return phase, when the recuperative value of sleep in the bunk facilities was less than on the initial outward leg. Sleep was disrupted throughout the schedule, and levels of alertness on waking were particularly low after the first two sleep periods in Sydney. The model was able to explain just over a quarter of the total within-subject variation in the subjective assessments of alertness. However, the gradual increase in fatigue throughout the schedule, that was present in the data, was not predicted by the model. In addition, the model did not anticipate the high levels of fatigue at the end of the last three duty periods, and particularly at the end of the final leg.

10b. Abstract classification: UNCLASSIFIED	FORM MEETS DRIC 1000 ISSUE 5

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