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Wakefulness on the Civil Flight Deck: Evaluation of a Wrist-worn Alertness Device

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Wakefulness on the Civil Flight Deck: Evaluation of a Wrist-worn Alertness Device

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Wakefulness on the Civil Flight Deck: Evaluation of a Wrist-worn Device

Abstract

The study assessed the effectiveness of a wrist-worn alertness device based upon the principle that sustained periods of sleep are associated with wrist inactivity in excess of five minutes. The anticipated use of the device is in support of the management of fatigue in aircrew, where it would be used in the context of authorised cockpit napping to ensure that the non-napping pilot remained awake. The device is aimed at ensuring flight safety, and is not intended to replace the development of rosters that minimise the likelihood of sleepiness, or to extend current duty times. The alertness device was worn by 21 Air New Zealand pilots during the cruise phase of return flights between Auckland and Perth. The pilots assessed the device subjectively according to its effectiveness and usability. The presence of sleepiness and sleep was determined objectively by recordings of the electrical activity of the brain (electroencephalogram – EEG) and eye movements. The study demonstrated that the device is capable of awakening pilots from sleep on the flight deck, and also highlighted problems with the current design. The majority of the aircrew found the device acceptable to use, although a number of practical design problems were apparent. There were also incidences where relatively long periods of sleep occurred, due to brief movements during sleep resulting in the alertness alarm delay timer being reset. Overall, although the alertness device needs to be modified before operational use, the study has demonstrated that the device will improve safety by inhibiting unintentional sleep during flight.

Executive summary

1 Introduction

The report describes the findings of a study carried out by the QinetiQ Centre for Human Sciences (CHS) in collaboration with Air New Zealand (ANZ) to evaluate the effectiveness of a wrist-worn alertness device. The research was conducted on behalf of the UK Civil Aviation Authority as part of the research programme 'The sleep and wakefulness of the airline pilot', under contract number 7D/S/952/5. The report is a deliverable under item 11.4, 'Wakefulness on the civil flight deck'.

2 Background and aim of the study

The research was initiated because there is concern that undue levels of fatigue in aircrew could lead to the occurrence of involuntary sleep, posing a potential hazard to flight safety. The overall aim of the research was to recommend a practical method of detecting the presence of unplanned sleep during flight, and to develop an alertness device for use on the flight deck. The anticipated application of the device is in support of the management of fatigue in aircrew, where it could be used in combating involuntary sleep, when cockpit napping is not authorised and in the context of authorised cockpit napping to ensure that the non-napping pilot remains awake. Two in-flight studies have previously been carried out, involving the long-haul routes London-Miami-London and London-Chicago-London. These studies included investigating a number of possible methods, including measurement of head movement, wrist activity, skin resistance, eye movements and control inputs to the aircraft by the pilots. The findings were that measurement of wrist activity could be used to detect the presence of sleep for periods greater than five minutes, because when the pilots were awake, periods of wrist inactivity were extremely short (less than one minute for the majority of the time). Therefore, the recommendations of the research were to develop an alertness device based on wrist inactivity. The device is aimed at enhancing flight safety, and is not intended as a means of extending duty time and should not replace the development of rosters that minimise the likelihood of sleepiness. A prototype device has now been manufactured, and consists of an accelerometer to detect wrist motion and an auditory alarm. The aim of the present study was to assess the effectiveness of the alertness device in a normal scheduled civil air operation.

3 Methods

Twenty-one Air New Zealand pilots wore the alertness device during the cruise phase of flights between Auckland and Perth, which comprised daytime outward and overnight return flights lasting approximately seven and six hours respectively with a two-pilot (unaugmented) crew. They were asked to assess the device subjectively by completing a questionnaire. The presence of sleepiness and sleep was determined objectively by recording the electrical activity of the brain (electroencephalogram – EEG) and eye movements (via the electro-oculogram – EOG). The effectiveness of the device at detecting and preventing sleep was assessed.

4 Results

The study demonstrated that the device is capable of awakening pilots from sleep on the flight deck, and also highlighted problems with the current design. The majority of the aircrew found the device acceptable, although a number of practical problems were apparent, such as accidental switching on and off and the necessity to wear a second 'watch'. There were also incidences where relatively long periods of sleep occurred, due to brief movements during sleep resetting the alertness alarm delay timer.

5 Discussion

The present study has demonstrated the potential usefulness of the alertness device based upon wrist inactivity to awaken pilots from accidental sleep. The work was carried out during normal operational scheduled flights which included an overnight sector where sleepiness and, potentially, unintentional sleep may occur. Overall, the amount of sleepiness was less than in the two previous studies which investigated methodological aspects of developing an alertness device. Nevertheless, there was sufficient sleep observed in the group of pilots to demonstrate that the alertness device can prevent sleep, although the study also highlighted problems with the current design that need to be resolved. In the present study there were no incidences where one of the pilots planned to take a nap and the second pilot unintentionally fell asleep, which would have demonstrated the benefits of the device in conjunction with cockpit napping, that is, to ensure that the non-napping pilot remained awake.

6 Conclusions

While the alertness device operates effectively to awaken the pilot during flight, changes to the device are required as a result of the study. These include modifying the alarm delay timing algorithm and incorpration of the additional features indicated below. Overall, however, the study has demonstrated that use of the alertness device by the pilots during flight will improve safety by inhibiting unintentional sleep.

7 Recommendations

The following improvements to the design of the watch are recommended:

- modification of the software controlling the alertness alarm delay to take into account the occurrence of brief periods of movement during sleep, which currently allows periods of sleep longer than five minutes to occur;
- modification of the physical layout of the alertness device to prevent accidental switching on and off, for example, by incorporating a recessed button and an indicator that the device is active;
- provision of a facility for easily recharging the battery of the device;
- incorporation of a tactile alerting stimulus in addition to the existing auditory mode;
- provision of controls to enable the pilot to set the alertness alarm delay interval to enable use of the device in conjunction with planned cockpit napping;
- investigation of the feasibility of incorporating the alertness device into a sports watch;
- provision of the modified version of the alertness device for evaluation by aircrew in the context of cockpit napping.

Wakefulness on the Civil Flight Deck: Evaluation of a Wrist-worn Device

1 Introduction

1.1 Contract

The report describes the findings of a study carried out by the QinetiQ Centre for Human Sciences (CHS) in collaboration with Air New Zealand (ANZ) to evaluate the effectiveness of a wrist-worn alertness device. The work was carried out as part of the UK Civil Aviation Authority research programme entitled 'The sleep and wakefulness of the airline pilot', under contract number 7D/S/952/5. It comprises a deliverable under item 11.4, 'Wakefulness on the civil flight deck'. The study described is related to a collaboration agreement between QinetiQ and ANZ concerning research into aircrew fatigue.

1.2 Fatigue and involuntary sleep

Fatigue has been identified as a likely contributory factor in accidents within occupational settings where individuals work relatively long periods of duty that coincide with the circadian low of alertness [1, 2]. In addition, within civil air operations, aircrew experience circadian dysrhythmia due to crossing several time zones within a duty period [3, 4, 5]. These various influences can combine to produce relatively high levels of fatigue, and indeed aircrew have reported feelings of extreme sleepiness that could lead to involuntary sleep during flight [5].

Undoubtedly the key to eliminating or reducing fatigue is the careful management of the length and circadian timing of duty periods that also allows sufficient opportunity for adequate sleep [6]. As a further step, civil aviation organisations and airline operators are increasingly introducing active fatigue countermeasures. These include advice on pre-flight sleep and authorised cockpit napping to reduce the likelihood of low vigilance during cruise and to maximise alertness during critical phases of flight [7].

However, there may still be some instances where unintentional sleep could jeopardise safety, particularly during relatively long overnight flights. For this reason, there is a need to develop a reliable alertness alarm that warns the pilot of the occurrence of involuntary sleep. In addition, within the context of two-crew aircraft, such a device could be used in conjunction with authorised cockpit napping to ensure that the non-napping pilot remains awake. It is however important to be aware that use of an alertness device is aimed at enhancing safety and is not intended as an alternative to sensible rostering.

1.3 Previous studies

The present study is based upon research carried out for the CAA to determine possible approaches to monitoring sleepiness of aircrew on the flight deck, with a view to developing a device to detect and warn the pilot of involuntary sleep. The research previously involved two in-flight studies, and included the evaluation of a number of candidate measures that could be used to detect sleep. Both investigations involved long-haul three-crew operations in Boeing 747-100/200 series aircraft with each sector lasting approximately 9h.

The first study [8, 9], involving return flights between London and Miami, investigated a range of possible measures to detect sleep. These were galvanic skin resistance, head and wrist movement and control inputs to the aircraft flight management system by the pilot. The presence of sleepiness and sleep were determined objectively from the electrical activity of the brain (electroencephalogram, EEG) and eye movements (via the electro-oculogram, EOG). The pilots were asked to follow their normal pattern of activities during flight, which may have included taking a nap.

The study concluded that the measurement of eye movements would provide the most sensitive alarm, and that a device based upon detection of wrist inactivity could prevent sustained periods of sleep lasting longer than five minutes. While eye movements are clearly a sensitive measure of sleepiness and sleep, they cannot as yet be recorded unobtrusively on a routine basis within a civil airline operation. Consequently measuring eye movements as the basis of an alertness device was not considered further in the current research.

The second investigation [10, 11], carried out during return flights between London and Chicago, further examined the potential of wrist activity to be used as the basis of a practical alertness device. As in the previous study, the EEG and eye movements were used to determine the presence of sleepiness and sleep. During the flights, the aircrew were requested to remain awake unless sleep was required in the interests of safety. This was in contrast with the previous study [8], where sleep occurred on a number of occasions. The change in instructions was made because the morphology of sleep onset for a planned nap is likely to differ from that of an unintentional sleep episode. These differing patterns could affect the assessment of the reliability of an alarm based upon wrist inactivity.

The findings of the study ascertained that detecting periods of wrist inactivity can be used to identify episodes of sustained sleep lasting approximately five minutes. The method, although relatively insensitive to sleepiness, would prevent the occurrence of lengthy periods of sleep. Therefore, the recommendations of the research were to develop and assess an alertness device based on wrist inactivity. A prototype device has now been produced, and consists of an accelerometer to detect wrist motion and an auditory alarm. It is approximately the same size as a conventional watch, and is attached to the pilot by a wrist-watch strap. The alarm activates automatically after a period of five minutes of wrist inactivity (see ‘Methods’ for a full description).

1.4 Aim and scope of the present study

In addition to combating involuntary sleep, when cockpit napping is not authorised, the alertness device could be used as a safety aid when cockpit napping is permitted, to ensure that the non-napping pilot remains awake. In an operational context, the non-napping pilot would wear the alertness device set at a wrist inactivity interval of five minutes, and the napping pilot’s device would be deactivated. Alternatively, the inactivity interval of the latter device could be set to the planned duration of the nap. However, before the alertness device is used operationally, it is necessary to evaluate its effectiveness at awakening a pilot who has inadvertently fallen asleep and its utility in an airline flight-deck environment.

The aim of the present study was therefore to assess the alertness device during flight. The research involved recording data on a series of non-stop daytime and overnight sectors between Auckland and Perth. Both pilots on each flight were asked to wear the alertness device, and also to assess it subjectively by completing a questionnaire. The EEG and eye movements were recorded during flight to determine accurately the presence of sleepiness and sleep, in the same way as in the previous studies [8, 10]. The pilots also reported their subjective levels of alertness.

2 Methods

2.1 Flights and subjects

The study was carried out during twelve non-stop return flights between Auckland and Perth, a two-pilot operation with Boeing 767-300 series aircraft. The outbound daytime flight was scheduled to depart from Auckland (AKL) at 1415h (New Zealand Daylight Saving Time – NZ DST) and arrive in Perth (PER) at 1640h local time (Western Australia Time; 2140 NZ DST). The return overnight flight was scheduled to depart at 1800h local time (2300h NZ DST), arriving in Auckland at 0525h NZ DST. The duration of the outbound sector was approximately six hours forty minutes, and the return flight about six hours twenty-five minutes. The layover period between the outward and return sectors was 46h 20min, and included two local nights. Although a bunk is provided on the aircraft, there is no rest opportunity with unaugmented (two-pilot) crews. However a procedure is provided for cockpit napping in the event of unexpected fatigue in-flight: under controlled conditions, one pilot may nap in the seat for up to 45 minutes.

The subjects were 21 Air New Zealand pilots and data were recorded from both the Captain and First Officer during nine of the flights, and from the First Officer only for three flights. The Captains were aged between 45 and 57 (mean 50.8) years and the First Officers between 39 and 53 (mean 44.9) years. One female and 20 male pilots participated. The study was approved by the QinetiQ Ethics Committee, and each pilot gave written informed consent before participating following an explanation of the purpose and procedures of the study. The subjects were assured of the confidentiality of their individual identity and data.

2.2 Measures, sensors and recording devices

2.2.1 Wrist-worn alertness device: description

The alertness device (‘Actiwatch-Alert’, Cambridge Neurotechnology Ltd, UK) is a wrist-worn unit that comprises an accelerometer, auditory alarm and signal processing electronics. The device, shown in Figure 1, is about the size of a conventional watch, with a button to cancel the alarm should it be activated. It continuously records occurrences of wrist movement above an acceleration level of 0.05g and activates the auditory alarm when no wrist movement is detected within a specified time interval. The latter alarm delay can be set to 1, 2, 5 or 10 min, and based upon information from the two previous investigations [8, 10], the delay was set at five minutes in the present study. The sound intensity of the alarm is 95dbA at 30cm, and the device was set to record wrist activity with a time scale of 15s. Wrist inactivity intervals that are equal to the specified alarm delay cause the alarm to be activated until cancelled by pressing a button on the front surface of the device. The signal processing software stores accelerometer values, the time of alarm activation and the time taken to cancel the alarm.

The pilots were asked to wear the alertness device on their non-dominant wrist, and the device was not worn during take-off or landing. After each return flight, the data stored by the alertness device for each pilot were downloaded to a PC for further analysis.

2.2.2 EEG and EOG

Sleep and sleepiness were identified using the EEG and EOG, in a manner identical to that used in the previous studies [8, 10]. The EEG was recorded from central and occipital regions of the brain, which are known to be sensitive to the onset of sleep [14, 15]. The electrode sites used were C3-A1, O1-A1 and O2-Cz according to the 10-20 International System [12] for electrode placement. The electrodes were silver-

silver chloride and were attached to the pilot using a stretchable fabric headband. Eye movements were recorded from tin electrodes sited above and below each eye, 1cm lateral to the outer canthus, giving vertical, horizontal and oblique derivations of the EOG. The electromyogram (EMG) was recorded from the neck. These seven physiological signals were recorded continuously on a portable 8-channel digital recorder (Embla, Flaga Medical Devices Limited, Iceland; 200Hz sample rate) located at the back of the pilot's cockpit seat. The Embla recorder and the alertness device were synchronised by simultaneously pressing an event button on each device.

2.2.3 Subjective alertness

The pilots completed subjective assessments of alertness using a visual-analogue scale [13] at the top of ascent and at the end of the cruise phase. This comprised firstly a 6.8cm line with extremes labelled 'extremely alert' (6.8) and 'extremely sleepy' (0), and the pilots were asked to consider the mid-point as their normal state. They were also asked to assess their sleep quality on the night before each trip and during the layover, including both the main sleep periods and any naps taken. The pilots were asked to record any planned napping and awareness of unintentional sleep during flight.

The pilots completed further subjective alertness assessments using the Karolinska Sleepiness Scale and the abbreviated Samn-Perelli scale on a Palmtop electronic device.

2.2.4 Vigilance performance task

A vigilance performance task was also undertaken at the top of climb, mid-cruise and prior to approach, using the Palmtop device. The task consists of a choice reaction task with a visual stimulus presented at pseudorandom intervals in one of four locations and response buttons in four corresponding locations. The data were analysed for mean reaction times.

2.3 Experimental procedure

The pilots were briefed about the purpose and procedures of the study at the start of their outbound duty period. The alertness device and all measurement sensors were attached to the pilots during the flight at the top of ascent, and the physiological electrodes removed after landing. The alertness device was de-activated and removed from the pilot before descent commenced. Data were recorded continuously from each pilot during the cruise phase, while they carried out their normal pattern of activities as crew members, including taking planned naps as required. When preparing to take a nap, the napping pilot was asked to de-activate his alertness device. An experimenter was present on the flight deck to attach and remove the physiological sensors at the beginning and end of the flights but not during cruise.

2.4 Analysis

2.4.1 Assessment of alertness during flight

Segments of EEG during the cruise phase of flight were analysed using frequency analysis to give an indication of the overall level of alertness, omitting any times when the pilots were taking a planned nap. For each pilot on every flight, three epochs of approximately five minutes of data containing no physiological artefacts (for example, due to body movement) were selected by examination of the EMG signal to indicate when the pilots were keeping still. They were chosen to be near the top of ascent, mid-cruise and near the end of cruise. The subjective assessments of alertness by the pilots were also analysed.

2.4.2 Determination of periods of sleepiness and sleep from the EEG and EOG

2.4.2.1 Preliminary analysis of the EEG and EOG

The EEG, EMG and EOG variables were analysed with a time resolution of 1s. The EEG was described by variables corresponding to frequency ranges known to be related to alertness and sleepiness [14]. The variables delta, theta, alpha and beta were defined as 0.5-3 Hz, 3-7.5 Hz, 7.5-13 Hz, 13-30 Hz respectively. The EOG signal was characterised by calculating the square of the first derivative of signal amplitude with respect to time (that is, the rate of change in amplitude) integrated over 1s. Root mean square (RMS) of EMG amplitude was calculated for 1s epochs and used to identify artefacts due to body movement.

2.4.2.2 Classification of wakefulness and sleep during flight using the EEG and EOG

For each subject, the EEG and EOG recordings were scanned visually to identify periods of sleepiness and sleep. The data were subsequently classified (see next paragraph) according to a four-point scale of wakefulness ranging from 0 to 2, using a time resolution of 1s. The levels of the scale were 0 (wakefulness), 0.5 (sleepiness), 1 (drowsy sleep) and 2 (sleep). These levels, described in detail below, were defined according to features similar to conventional criteria for the visual analysis of sleep [15] which in contrast uses a time resolution of 30s. The scale of wakefulness used in this study was based on information from the quantitative analysis of alertness on a shorter time scale, of the order of a few seconds [16]. The EEG and EOG patterns that represent the four levels of wakefulness are shown in Figure 2. Figure 3 shows examples of the EEG and EOG recordings during flight and demonstrates typical features seen during the transitions between alertness, sleepiness and sleep.

Based upon these four levels of wakefulness, the EEG and EOG data for the whole of the cruise of each flight were analyzed quantitatively, using discriminant analysis according to the following method. Periods of data representing each of the wakefulness levels were identified visually and used in the training phase of a discriminant analysis. The variables used in the discriminant analysis were delta, theta, alpha and beta activity of the EEG and the derived measure of eye movements (see para 2.4.2.1). A separate discriminant function was derived for each subject to allow for individual differences. The data for each flight were then classified using the resultant discriminant functions. The segments of data classified as representing wakefulness, sleepiness or sleep by the discriminant analysis were also verified visually. The minimum period for classifying each recording was 1s to allow for the incidence of short periods of sleepiness.

A detailed description of the EEG and EOG criteria for the four levels of wakefulness, used previously [8, 10] is as follows:

Level 0: alert wakefulness, with no clear evidence of sleepiness. This level is characterized by EEG activity comprising predominantly alpha and beta frequencies and the presence of saccadic eye movements (associated with changes in the point of gaze to enable focus on an object) and blinks in the EOG.

Level 0.5: some evidence of sleepiness in both the EEG and EOG, in the form of increased rhythmic EEG alpha activity and slowing of eye movements. These slow eye movements (SEMs) do not necessarily involve eye closure, rather the lack of accurate saccadic eye movements. The SEMs at this level of wakefulness have a relatively high amplitude and are typically in the frequency range 0.5 to 1.0 Hz. Incidences of level 0.5 activity frequently only last several seconds, often occur in sequences and are termed ‘microsleeps’ when the duration is short. Alternatively, these EEG and EOG patterns may appear as the first overt sign in the transition between wakefulness and drowsy sleep.

Level 1: presence of theta activity in the EEG and slow rolling eye movements. The amplitude and frequency of these eye movements are lower than for level 0.5 activity, with frequencies of around 0.1 to 0.3 Hz. Level 1 activity is analogous to the characteristics of stage 1 sleep according to Rechtschaffen and Kales [15] criteria and represents light, drowsy sleep.

Level 2: periods of continuous relatively high amplitude theta or delta activity. This classification starts either from cessation of slow eye movements or from a K-complex (which is a characteristic EEG waveform used to signify sleep onset) and lasts until some indication of decreasing depth of sleep. This may be an increase in frequency of the EEG indicating an awakening or the development of slow eye movements, saccades or blinks in the EOG. Level 2 activity is similar to stage 2 sleep [15].

2.4.3 Association between wrist activity and levels of wakefulness and sleep

The times of occurrence of wrist inactivity, together with the durations of inactivity, were determined from the alertness device accelerometer recordings for each subject and flight. These periods of inactivity were then compared on a 15s basis with the incidences of wakefulness, sleepiness and sleep (levels 0, 0.5, 1 and 2). Since the latter were classified on a scale of 1s, the wakefulness level for each wrist inactivity epoch was taken as the level representing the highest present. For example, if any part of the EEG and EOG during the 15s wrist epoch was classified as level 0.5, and the remainder was level 0, then the 15s epoch was considered to be level 0.5.

2.4.4 Assessment of the alertness device

2.4.4.1 Quantitative assessment of the accuracy of sleep detection

The number of correct positive and false positive alarm activations were identified. Correct positives were defined as periods of wrist inactivity lasting five minutes coinciding with wakefulness levels of 0.5 and higher. False positives occurred where periods of wrist inactivity lasting five minutes were associated with wakefulness levels of ‘0’. False negatives were also considered in terms of the duration of sleep that occurred (see para 3.5.1).

2.4.4.2 Subjective evaluation of the alertness device by the pilots

The pilots were asked to evaluate the alertness device for usability, effectiveness and comfort, and to provide comments and opinions. For each of the outward and return flights they were asked the following series of questions:

“Were you aware of having fallen asleep unexpectedly during flight ? “

“Did you waken naturally or were you woken by the alertness device ? “

“Were you aware that the alarm sounded at any time when you were awake, and if so how many times ? “

“Please comment on the alertness device, including its use, comfort, operation and any other aspect”.

3 Results

3.1 Estimated sleep time during the layover period

Among the group of 21 subjects, the individual pilots reported having slept between 4h and 10h 30min (mean 7.76h) on the first layover night, and between 6h and 10h (mean 7.90h) on the second night. 17 pilots took a nap before the return flight, and their estimated sleep times were between 10min and 3h 30min. 6 pilots also took a second nap, with estimated sleep durations between 45min and 2h 15min.

3.2 Alertness during flight

The mean values of EEG and EOG variables corresponding to the start, middle and end of the cruise phase are shown in Table 1, together with subjective estimates of alertness and performance on the vigilance task. These measures were provided as an indicator of the levels of fatigue that the aircrew experienced.

Table 1 Alertness during flight

	Day flight (AKL-PER)			**Night flight (PER-AKL)**		
Measure	**Time 1**	**Time 2**	**Time 3**	**Time 1**	**Time 2**	**Time 3**
	start of cruise	**mid-cruise**	**end of cruise**	**start of cruise**	**mid-cruise**	**end of cruise**
EEG theta activity (μV)	0.409	0.638	0.456	0.397	0.396	0.349
EEG alpha activity (μV)	0.536	0.710	0.575	0.508	0.540	0.464
EEG beta activity (μV)	0.656	0.807	0.722	0.665	0.713	0.655
EOG $(dy/dt)^2$ (μV^2)	1077.8	1629.8	1522.6	2608.2	1966.3	1816.7
Subjective alertness[1]	48.0		27.9	40.0		22.2
Samn-Perelli Alertness Scale	2.38	3.10	3.84	2.95	4.05	4.52
Karolinska Sleepiness Scale	3.14	4.14	4.42	4.15	5.76	6.52
Vigilance task (mean reaction time)	572	558	550	522	549	559

1. 0 = extremely sleepy; 68 = extremely alert

3.3 Incidence of sleepiness and sleep during flight

Table 2 shows the incidence, duration and timing of sleep and sleepiness among the group of 21 subjects for the Perth to Auckland night flight. Three pilots slept during the night flight while a further eight showed evidence of sleepiness. Of those showing sleep in their EEG, two were aware of having slept, and one of these had planned to take a nap. Three pilots showed short periods of sleepiness during the Auckland to Perth daytime flights but no sleep was present.

Table 2 Incidence of sleepiness and sleep during the night flight

Subject number	Take-off time (NZ DST)	Time of start of earliest sleep (hours into flight)	Time of end of latest sleep (hours into flight)	Duration of sleep level (min)			Total sleep time (min)	Aware of sleep	Planned nap
				0.5	**1.0**	**2.0**			
3	23:33	1.36	3.41	0.5			0.5	no	
4	23:33	2.78	3.80	0.9			0.9	no	
7	23:20	1.77	3.44	8.0	11.7	26.0	45.7	yes	no
10	23:29	2.31	3.33	4.8			4.8	no	
12	0:15	4.22	5.27	1.2			1.2	no	
15	23:13	3.20	3.31	2.3	3.6		5.9	yes	yes
18	23:14	2.31	2.90	2.6	0.0	23.4	26.0	yes	yes
22	23:46	3.05	5.22	0.6			0.6	no	
23	23:17	2.00	4.48	8.7	11.6	8.8	29.1	see below[1]	
24	23:17	3.56	3.86	0.3			0.3	no	

1. The sleep duration for pilot 23 includes a nap of 10min 6s.

Figure 4 shows the distribution of durations of sleepiness and sleep for levels 0.5, 1 and 2. The majority of ocurrences of sleepiness lasted less than 20s, while sleep levels 1 and 2 lasted between 11s and 11min 20s. The intervals of sleep in excess of five minutes occurred because of brief periods of movement during sleep that resulted in the alarm delay timer being reset (see '*Assessment of the alertness device*' below).

3.4 Association between wrist activity and levels of wakefulness

The number of wrist inactivity epochs of various durations for each wakefulness level was calculated, and is shown in Figure 5. It can be seen that the majority of wrist inactivity durations are less than 2.5-3min. during wakefulness. By the nature of the study, there are no inactivity durations above 5min because the alertness device prevented this from happening. One interval of 5min (shown as 20 epochs in Figure 5) occurred during 'wakefulness' in subject 9 during the night flight. This is represented by the last symbol on the curve representing 'wakefulness'; there were 20 one-second epochs of inactivity associated with this point.

3.5 Assessment of the alertness device

3.5.1 Accuracy of sleep detection

The number of activations of the alertness alarm is shown in Table 3. During the daytime flights, there were no false alarms or activations due to sleep. Those that occurred were explained by the pilots testing the alarm to check its correct operation, for example, during periods of turbulence. During the night flights, there was one false positive alarm which occurred because the pilot remained still but fully awake for five minutes. Eight correct alarm activations occurred owing to the presence of sleep lasting less than or equal to five minutes. Two further alarm activations occurred in association with periods of reduced alertness. In one of these, there was increased alpha activity in the subject's EEG lasting for a short period of time but with no accompanying change in the EOG. In the second, the EOG pattern showed characteristics typical of sleepiness for approximately 3.5-4min but there was no EEG evidence of sleepiness. During the night flights, there were also four alarm activations due to the pilots testing the device.

Table 3 Number of activations of the alertness alarm

Number of activations of the wrist-worn alertness alarm (five minute wrist inactivity delay)		
	Day flight (AKL-PER)	Night flight (PER-AKL)
Total number of activations	7	15
Extraneous alarms	7	4
False alarms	0	1
Alarms related to reduced alertness	0	2
Correct positives	0	8

Footnote to table:

'Extraneous alarms' include demonstrations and tests by experimenter and/or pilot

'False alarms' represent activations when no signs of reduced alertness or sleepiness were present.

'Alarms related to reduced alertness' represent activations where there were some signs of reduced wakefulness (for example, increased alpha activity in the EEG or slow eye movements in the EOG) but present for only a short period of time, or only in either the EEG or EOG rather than both.

'Correct positives' are alarms when the EEG showed sleepiness or sleep for the majority of the 5 min wrist inactivity epoch preceding the alarm.

While only one false positive alarm occurred, there were a several instances of 'false negatives' where sleep was allowed to persist for a relatively long period of time. This happened because the interval timer controlling the alarm delay, set at five minutes, was reset by the pilot moving briefly after having been asleep. The false negatives occurred with subjects 7 and 23 who both slept during the night flight, with sleep persisting for 33 and 13min 30s respectively. The wrist inactivity durations, wakefulness levels and alertness alarm activations for these two subjects are shown in Figures 6a and 6b, and demonstrates both correct alarm activations and problems associated with the alertness device (see below for explanation using examples from two subjects). The problems were related to brief movements during sleep that reset the alertness device delay timer.

For subject 7, there were four correct alarm activations, at 2h 31min, 2h 56min, 3h 3min and 3h 8min into flight. Also, at 1h 46min into flight, there was a non-contiguous period of sleepiness lasting 9min 15s, which did not result in an alarm activation because the pilot only remained still continuously for 3min 45s. The first alarm was associated with sleepiness lasting for 2min 5s, demonstrating correct alarm activation. However, the three remaining alarms were associated with a non-contiguous period of sleep lasting 33 min. Each time the alarm sounded, the pilot awoke briefly, for up to 3, 3 and 4 fifteen second epochs, and then resumed sleep. A further arousal of 5 fifteen second epochs occurred, and the pilot then deactivated the alarm.

A similar pattern was seen with subject 23. There were four alarm activations, at 2h 9min, 3h 48min, 4h 23min and 4h 28min. The first alarm was associated with 9.5min of interrupted sleepiness, and this was followed by a 10min 15sec nap during which time the alertness device was de-activated. The second alarm coincided with a 2min 45s period of sleepiness. The last two alarm activations were associated with interrupted sleep lasting 13min 30s, comprising a sleep lasting 8min 30s, followed by an arousal lasting for 3 fifteen second epochs caused by the alarm and a subsequent 5min period of sleep.

With subject 18, there was a malfunction of the alertness device or an accidental de-activation resulting in no data being recorded for this pilot during the night flight.

3.5.2 Subjective evaluation by the pilots

The opinions of the pilots included both favourable comments regarding the alertness device and potential problems. These are shown in Table 4, together with their frequency. While wearing the device was not generally seen as a problem, several design features, including accidental alarm de-activation, the sound intensity of the alarm and the effect of turbulence on the accelerometer, need to be considered.

Table 4 Comments on the alertness device by the pilots

Comments on alertness device made by the pilots	Frequency of occurrence
No problem or discomfort with wearing watch	9
Considered device useful	3
Stated alarm activated when awake but still	2
Stated preference for wearing watch on upper wrist or other wrist	2
Design of alarm requires change (accidental on/off)	1
Sound level too low if arms folded when asleep	1
Expressed concern that turbulence would affect alarm operation	2

4 Discussion

4.1 Overview

The present study has demonstrated the potential usefulness of an alertness device based upon wrist inactivity to awaken pilots from accidental sleep. The work was carried out during normal operational scheduled flights which included an overnight sector where sleepiness and, potentially, unintentional sleep may occur. Overall, the amount of sleepiness and sleep was less than in the two previous studies which investigated methodological aspects of developing the alertness device [8, 10]. Nevertheless, there was sufficient sleep seen in the group of pilots to demonstrate that the alertness device can prevent sleep, although the study also highlighted problems with the current design that need to be resolved. In the present study there were no incidences where one of the pilots planned to take a nap and the second pilot unintentionally fell asleep, which would have demonstrated the benefits of the device in conjunction with cockpit napping.

4.2 Alertness measures

In the present study approximately half the pilots showed evidence of sleepiness, based upon the EEG and EOG, and three of them slept during the overnight sector. This differs from the previous studies, where the majority of pilots were either sleepy or fell asleep during the night flights. The differences may be explained by the longer flights, these being approximately 9h for the Miami-London and Chicago-London routes in contrast with 5-6h overnight between Perth and Auckland. The previous trips also had relatively shorter layover periods of between 25 and 30h, including only one local night, compared with around 47h and two local nights in the present study. The physiological measures, subjective assessments of alertness and response times in the vigilance performance task indicated that the overnight flights led to reduced alertness. The pattern of sleepiness events (i.e. occurrences of level 0.5) among the three studies was similar with the majority of these events lasting less than 20s. Also in accordance with the previous findings, the associations between wrist activity and wakefulness, sleepiness and sleep demonstrated a similar pattern, with marked differences in inactivity durations between these states, as shown in Figure 5.

4.3 Performance of the alertness device and proposed improvements

The alertness alarm operated in accordance with expectations in many respects. Excluding operational tests, eleven alarm activations occurred during the flights, and of these, ten were associated with sleep, sleepiness or reduced alertness as determined by the EEG. The alarms associated with sleepiness and reduced alertness are valuable because they alert the pilot to the fact that he or she could soon inadvertently fall asleep. One false alarm occurred in the study, which covered approximately 200 hours of operation during the cruise phase of flight.

Subjectively, the pilots found the device acceptable, although some design aspects require change. They were asked to wear the alertness device on their non-dominant wrist, and so this interfered with wearing a wrist-watch. The button for activating and de-activating the alertness device currently has a raised profile on the front face, and this requires change to avoid accidentally switching it on or off. Many of the pilots expressed concern that the accelerometer in the alertness device would detect turbulence during flight and therefore prevent alarm activation when the pilot remained still during sleep in the presence of turbulence. However, tests during the flights as well as data collected in the two previous studies indicated that the accelerometer used in the alertness device is insensitive to turbulence, at least under the flight conditions experienced to date. This is because the frequency and amplitude of turbulence differs from the frequencies and amplitude threshold that the alertness device responds to in order to detect wrist activity.

In addition to the design aspects discussed above, the alertness alarm needs to be modified to handle brief periods of movement during sleep. Figure 6 shows examples where periods of sleep in excess of five minutes can develop as a result of short arousals and movement during sleep. Therefore the algorithm controlling the alarm delay timing requires change to take into account these brief periods of movement. Arousals occur naturally as part of sleep particularly when the subject is sleeping in a seat rather than in a bed. Also, the alarm woke two of the pilots, resulting in movement, but they continued to sleep after a short period of wakefulness to de-activate the alarm. Analysis of the data where arousals during sleep occurred suggests that up to one minute of movement should be ignored by the algorithm if the 15s-epochs are preceded and followed by long periods of inactivity indicating the likelihood of sleep. Figure 5, showing the differences in distributions of wrist inactivity durations between wakefulness, sleepiness and sleep, also suggests that the ability to detect sleepiness, in contrast with sleep, may be increased by ignoring longer incidences of wakefulness within periods of sleep, for example, up to 2 min. Determining the parameters of an improved algorithm should be investigated statistically, although also bearing in mind the potential for false positives.

As a result of the study, several other changes to the alertness device were identified to improve its operational usefulness. For example, incorporating a tactile stimulus (vibration) in addition to the auditory alarm may be beneficial. Although the intensity of the alarm (95dbA) would appear to be adequate for the cockpit environment of the Boeing 767 aircraft, this may not be the case in noisier cockpit environments and when the alertness device is covered by clothing. Use of a tactile stimulus in combination with the auditory alarm may be useful in these circumstances. Also, if the device is intended for use during cockpit napping by the non-napping pilot, it may arguably be desirable to use a tactile alarm to avoid waking the napping pilot.

Other design features of the alertness device should be incorporated, such as the ability to recharge the unit easily and the provision of a recessed button to avoid switching the device on and off accidentally. Timing controls are also required to enable the pilot to change the alarm delay interval for use in conjunction with cockpit napping. The alertness device could potentially be incorprated into a normal watch, for example, one similar to a sports watch, which would already have some of the timing features and physical control buttons, such as ‘start’, ‘stop’, ‘reset’ and the facility to set different alarm delay intervals.

4.4 Proposed use of the alertness device

It is considered that the development of a reliable, unobtrusive alertness device which is acceptable to pilots would enhance flight safety. In particular, use of such a device in conjunction with authorised cockpit napping would reduce the risk of both pilots being asleep at the same time. While the device based upon wrist inactivity as investigated in this study will not warn the pilot of imminent sleep and indeed may allow some sleep to occur, it will, when modified in accordance with the present findings, inhibit the development of relatively long, sustained episodes of sleep.

Any unintentional sleep during flight is clearly undesirable; however, the use of a five minute alarm delay interval is based upon the relatively low incidence of false positive alarms with this period of time. The advantage of the device is that it can be worn unobtrusively in the form of a wrist-watch, and therefore may be acceptable to aircrew. Such a device would appear to be a workable trade-off between non-intrusiveness and the ability to detect sleep.

Use of more sensitive measures, such as eye movements, that detect sleepiness at an early stage would clearly be an improvement. Research has been conducted to detect changes in eye movements from the analysis of video recordings [17, 18] and to monitor eyelid movement using infra-red sensors mounted in spectacle frames [19]. However, despite considerable effort within the research community and industry, there would still at present appear to be practical difficulties associated with detecting drowsiness-related eye movements reliably on a routine basis in work settings.

5 Conclusions

An in-flight study has been conducted to assess the effectiveness of a wrist-worn alertness device. The study demonstrated that the device is capable of awakening pilots from sleep on the flight deck, and also highlighted problems with the current design. Subjectively, the majority of the aircrew found the device acceptable to use, although a number of practical problems were apparent, such as accidental switching on and off and the necessity to wear ‘two watches’.

There were also incidences where relatively long periods of sleep occurred, due to brief movements during sleep resetting the alertness alarm delay timer. Therefore, changes to the timer algorithm are required to ignore these brief movements within a sustained period of sleep. The alertness device would be further improved by including a tactile alerting stimulus in addition to the existing auditory mode.

A facility that enables the pilot to change the alarm delay interval is also required for use in conjunction with planned cockpit napping. Incorporation of the alertness device within a normal 'sports watch' may be appropriate, since some of the required timing and physical controls would already be present.

The anticipated application of the device is in combating unintentional sleep and in support of the management of fatigue in aircrew, where authorised cockpit napping is permitted, to ensure that the non-napping pilot remains awake. In this way, the device would ensure that unintended or unauthorised napping does not take place or is detected in a timely manner. The device is aimed at improving flight safety, and is not intended to replace the development of rosters that minimise the likelihood of sleepiness.

Overall, the study has shown that an alertness device based upon wrist inactivity can operate effectively to awaken pilots during flight, and that use of such a device will improve safety in civil air operations by inhibiting unintentional sleep.

6 Recommendations

The following recommendations arose from the study:

- the software controlling the alertness alarm should be modified to take into account the occurrence of brief periods of movement during sleep, as this currently allows periods of sleep longer than five minutes to occur;
- the physical layout of the alertness device should be modified to prevent accidental switching on and off, for example, by incorporating a recessed button and an indicator to show that the device is active;
- a facility for easily recharging the battery of the device should be provided;
- a tactile alerting stimulus in addition to the existing auditory mode should be incorporated. This could be an option for the pilot to choose to use, or alternatively could be used in combination with the auditory alarm, for example, if sleep persisted after an initial alarm;
- controls to enable the pilot to set the alertness alarm interval should be included, for use in conjunction with planned cockpit napping;
- the feasilbiliy of incorporating the alertness device into a sports watch should be investigated;
- aircrew should be provided with the modified version of the alertness device for evaluation in the context of cockpit napping.

7 Acknowledgements

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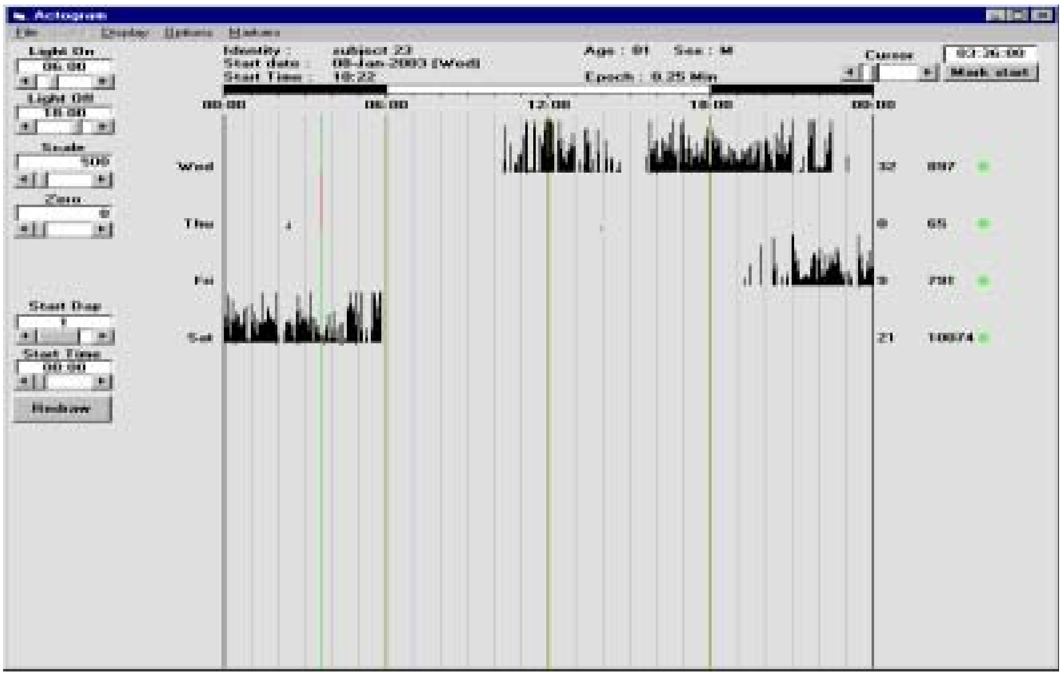

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Start Time : 10:22
Age : 61 Sex : M
Epoch : 0.25 Min
Cursor 07:26:00
Light On 06:00
Light Off 18:00
Scale 500
Zero 0
Start Day 1
Start Time 00:00

Figure 1 Wrist-worn alertness device and example accelerometer output

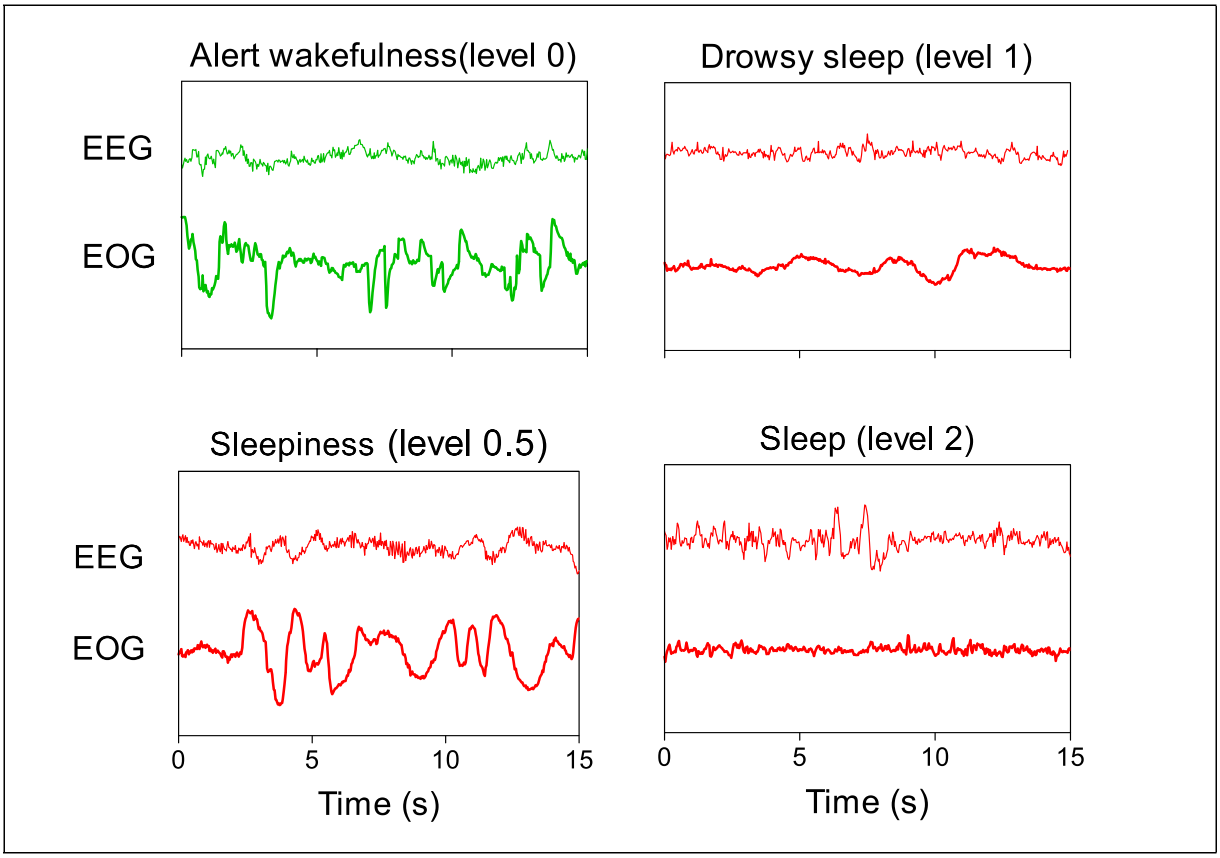


Figure 2 Four alertness levels

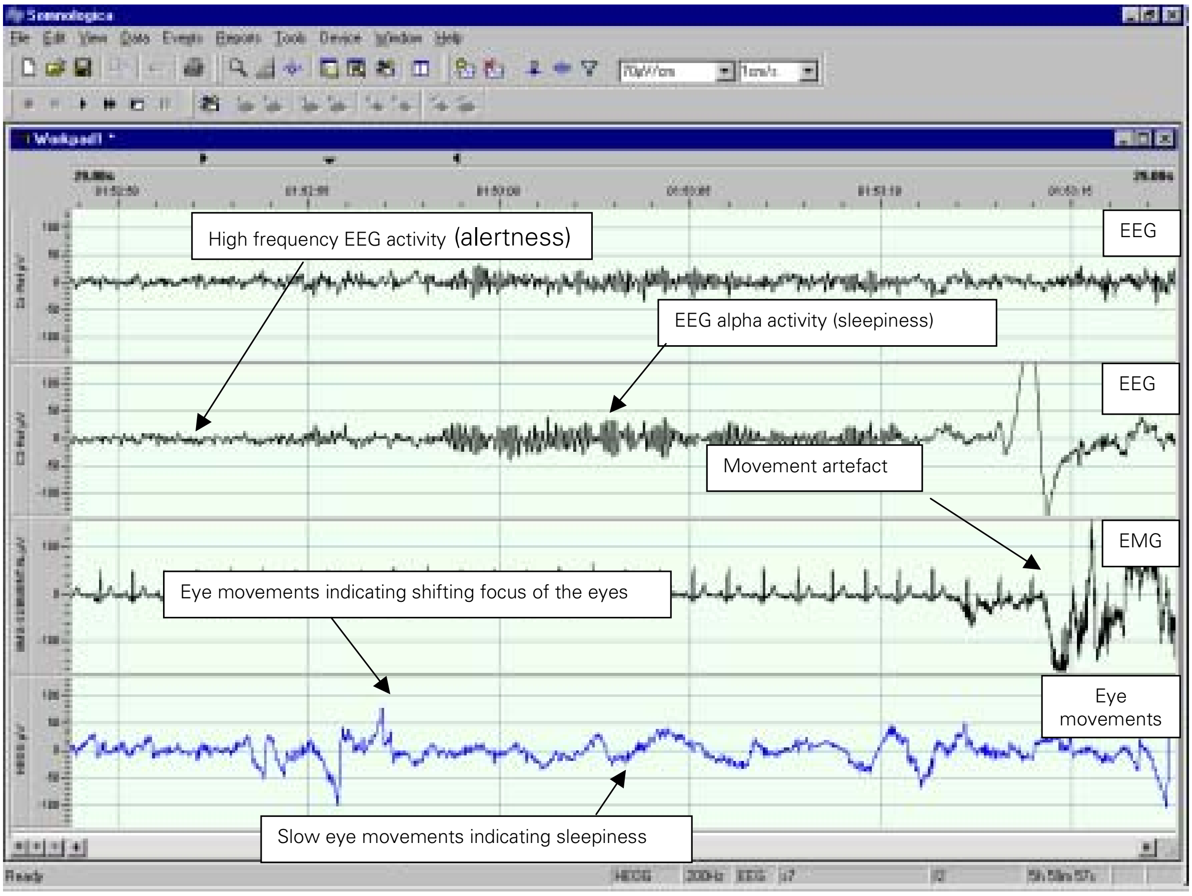


Figure 3a Example of EEG recording showing the transition between alertness to sleepiness.

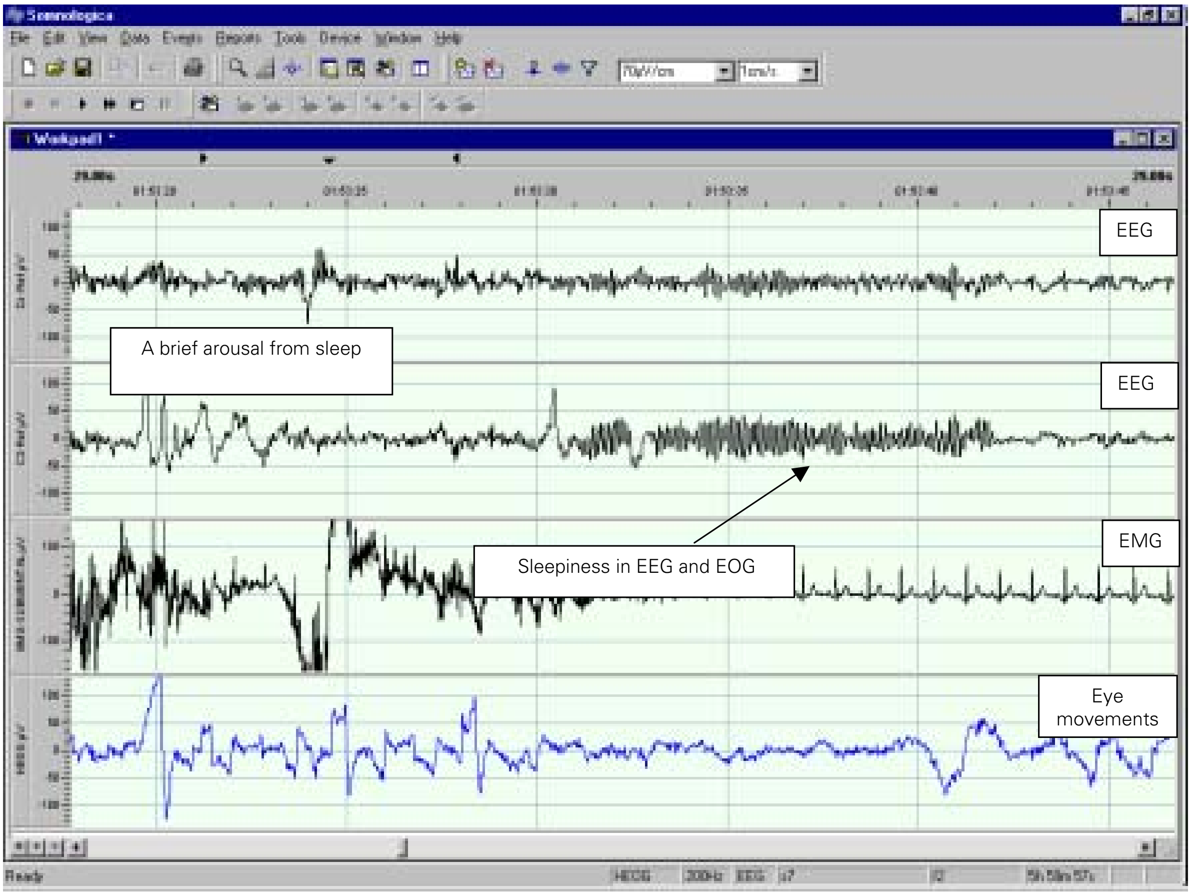
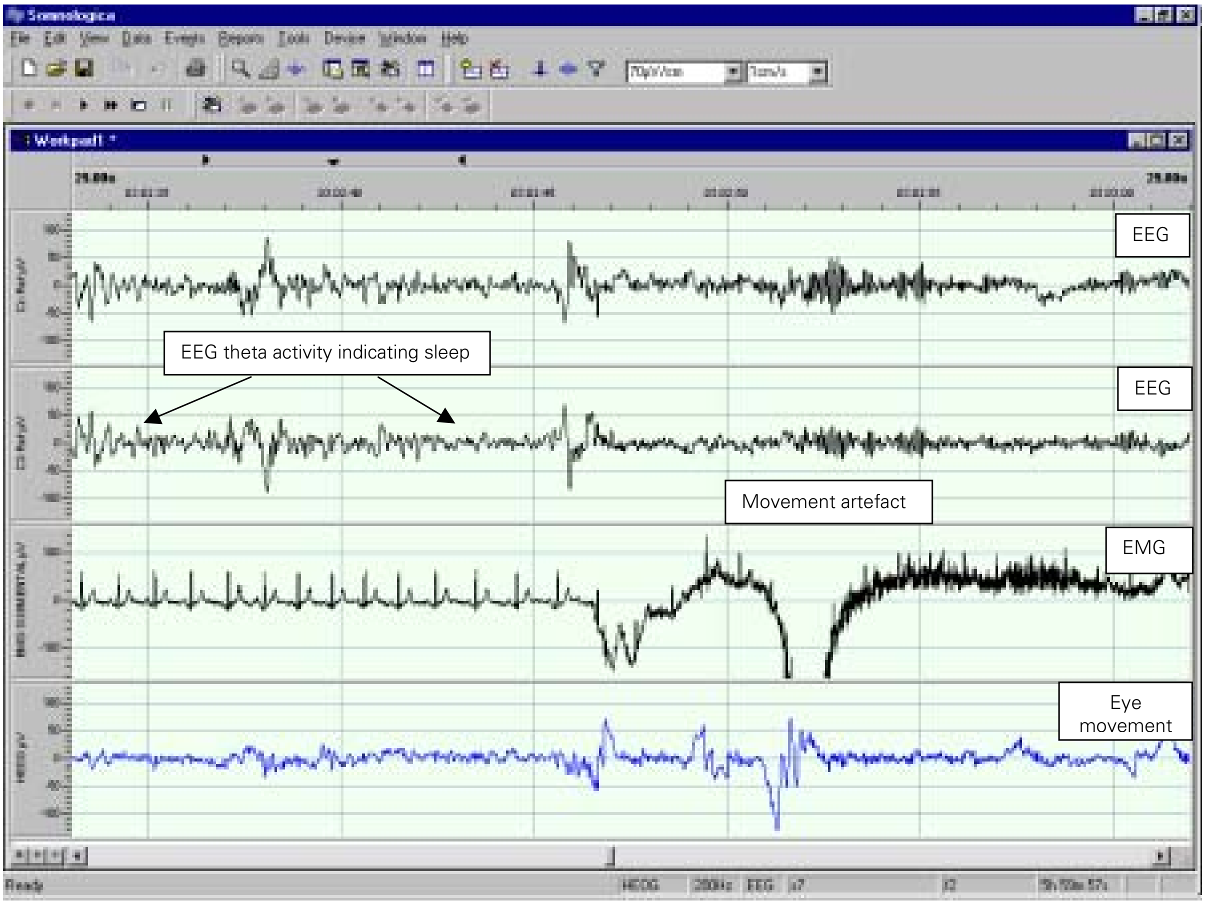


Figure 3b Example of EEG recording showing sleepiness following a brief awakening



EEG

EEG theta activity indicating sleep

EEG

Movement artefact

EMG

Eye movement

Figure 3c Example of EEG recording showing the presence of sleep followed by an arousal.

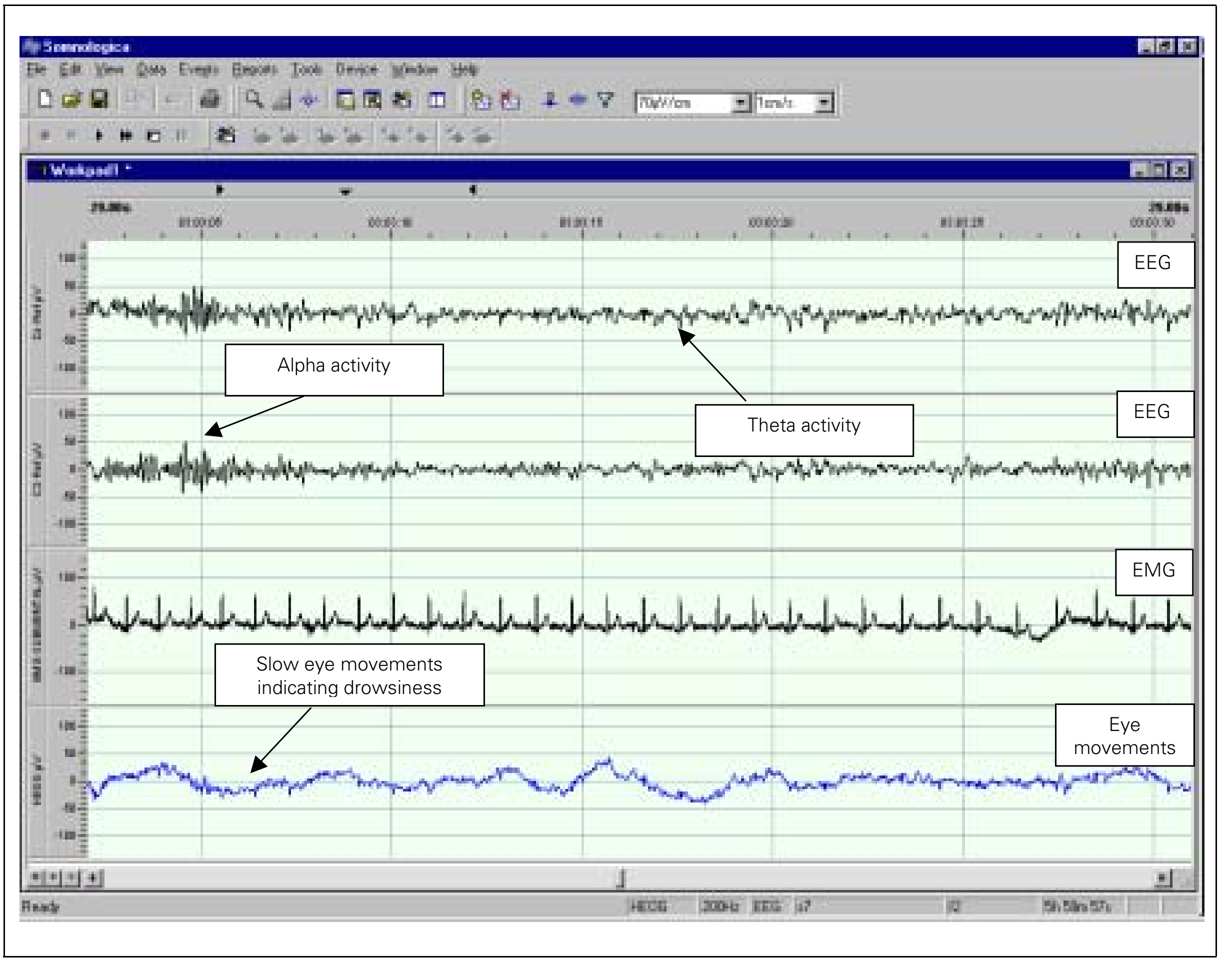


Figure 3d Example of EEG recording showing sleepiness and sleep.

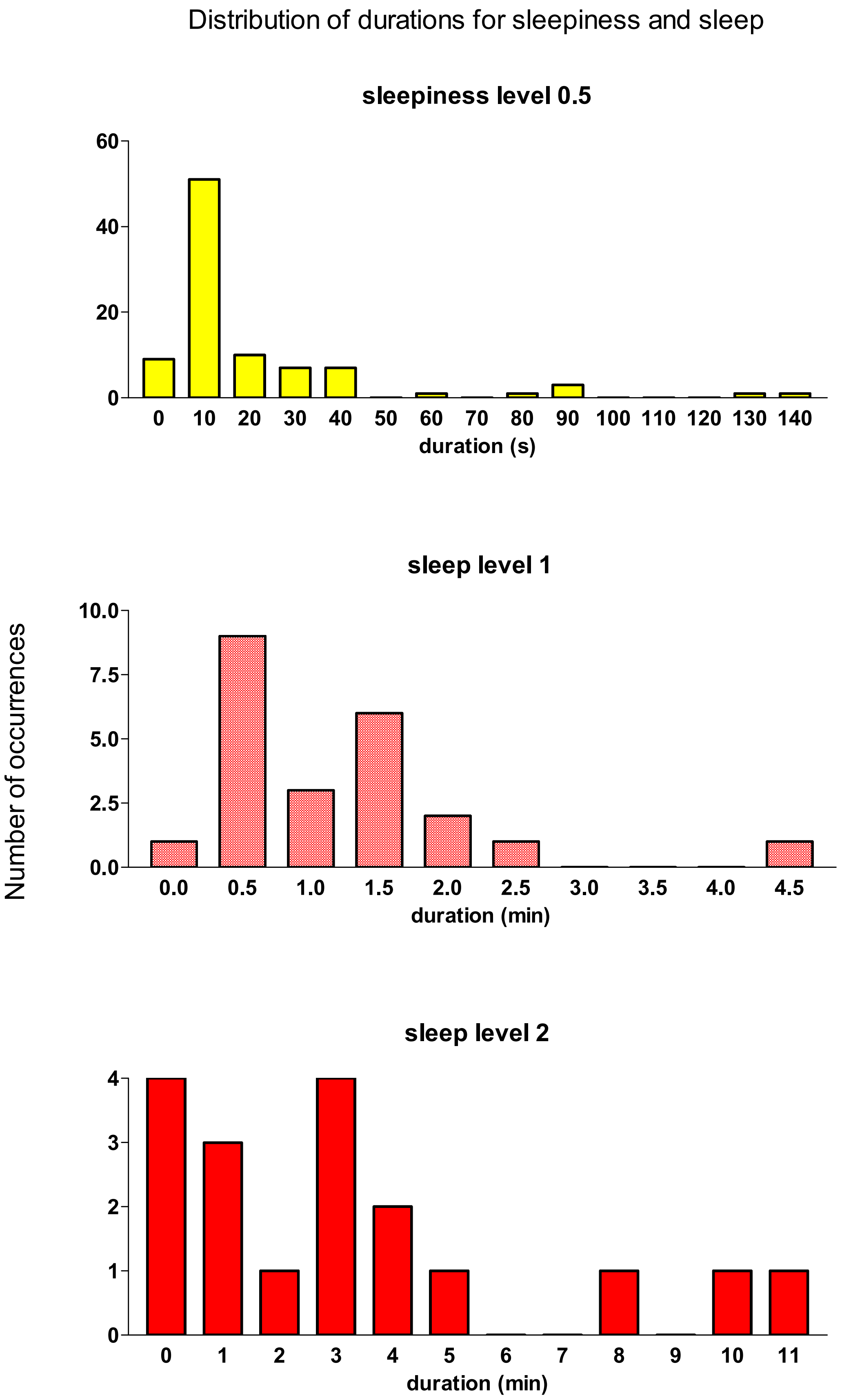


Figure 4 The distribution of the durations of sleepiness events and periods of sleep

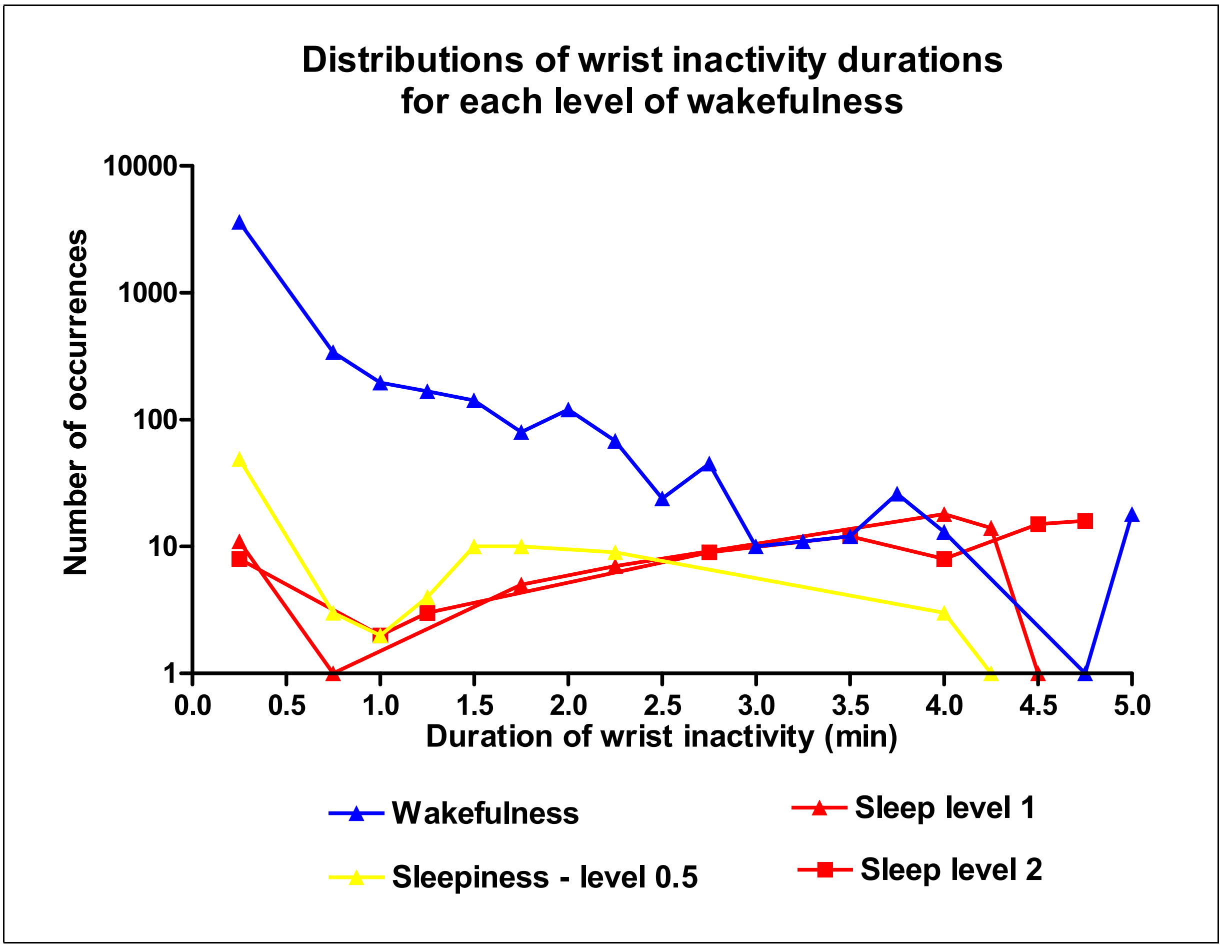


Figure 5 The distribution of wrist inactivity durations for each level of alertness

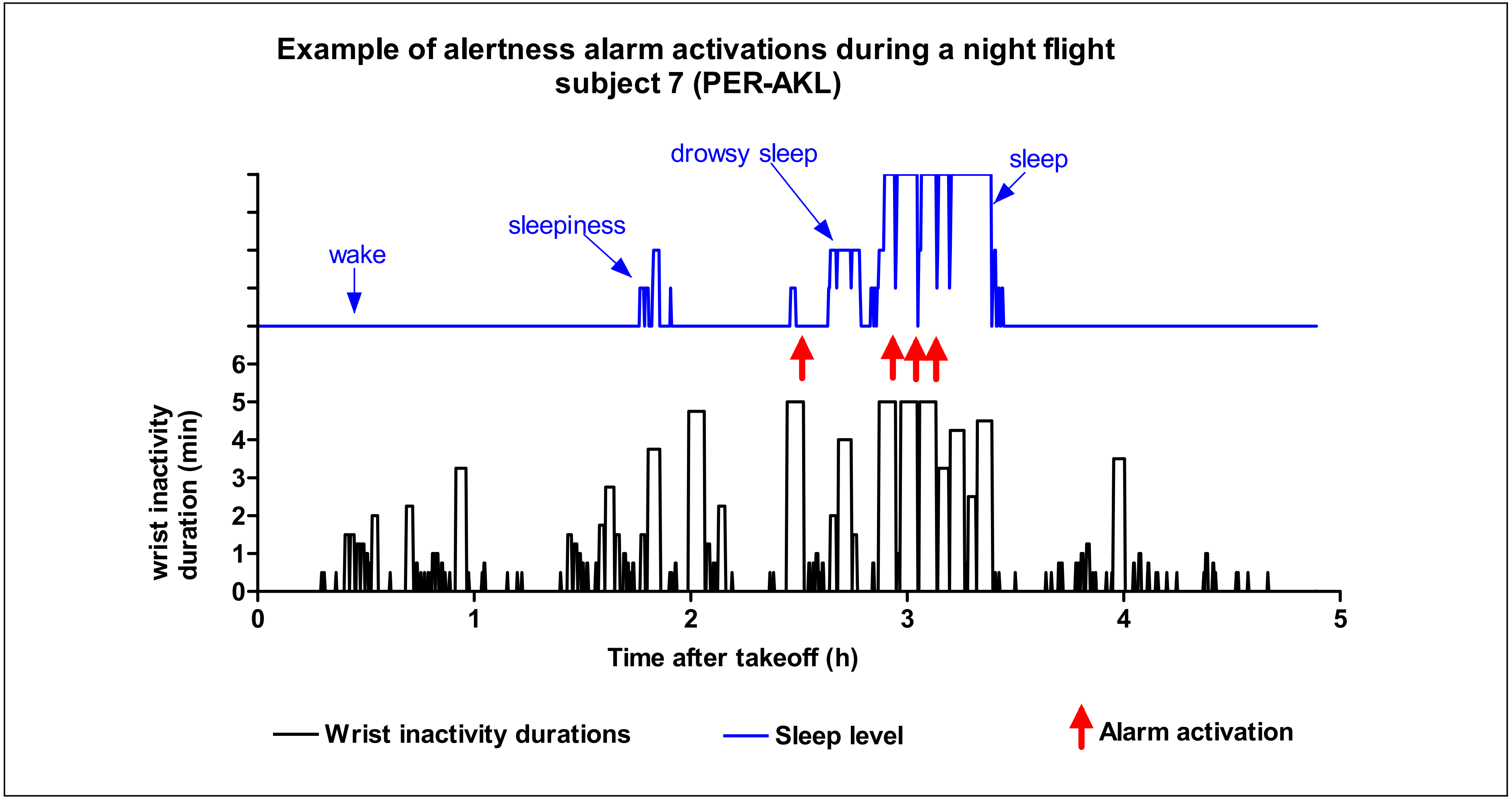


Figure 6a Alertness alarm activations for subject 7

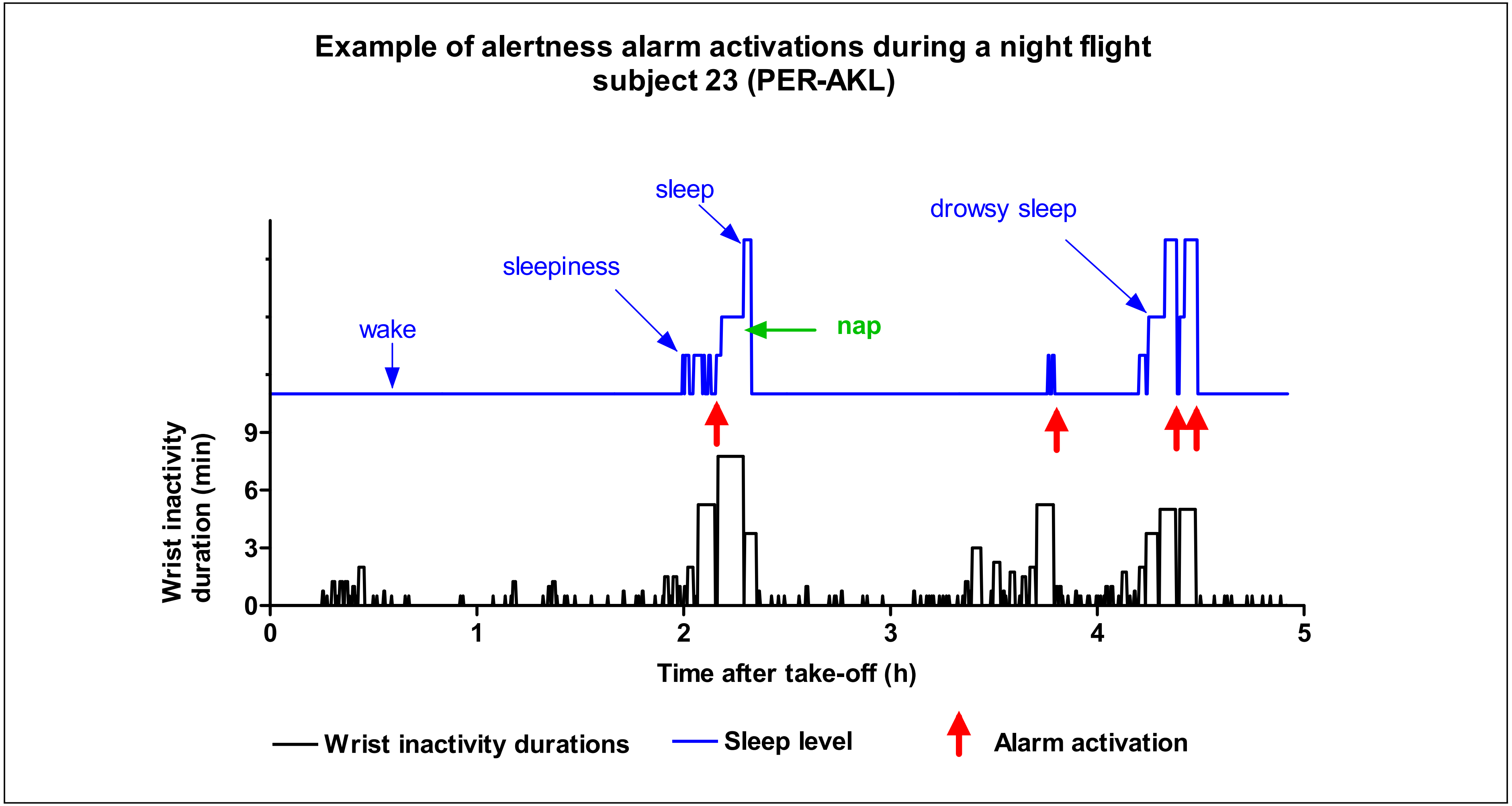


Figure 6b Alertness alarm activations for subject 23