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Nicola A Wright
J Coldwell
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Nicola A Wright
J Coldwell
Amanda S McGown
DRA Centre for Human Sciences
Farnborough, Hampshire, GU14 6TD
A N Nicholson
Royal Air Force School of Aviation Medicine
Farnborough, Hampshire, GU14 6SZ

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EXECUTIVE SUMMARY

Practical methods for monitoring sleepiness on the civil flight deck were investigated with the aim of recommending the basis of an alerting system to warn pilots of involuntary sleep. The study, involving twelve First Officers as subjects, was carried out on long-haul flights in Boeing 747-100/200 series aircraft flying between London and Miami during outbound daytime flights and return sectors overnight.

The electrical activity of the brain (electroencephalogram, EEG), electro-oculogram (EOG), electromyogram (EMG), electrocardiogram (ECG), skin resistance and wrist and head movements were measured for the duration of each flight, as well as control inputs to the aircraft by the pilot. Sleepiness and sleep were identified from the EEG and EOG.

Sleepiness and sleep were evident in most of the subjects, the extent being consistent with that expected for the flight timing with respect to duration and time of day. Wrist and head movements were markedly reduced during sleep and there were changes in the characteristics of skin resistance, while sleepiness was not detected by any of these variables.

On the basis of this, two separate possible methods for monitoring alertness are proposed, the first based on wrist activity and the second on eye movements. A system that detects absence of wrist activity and activates an alarm after a preset interval would prevent lengthy periods of sleep. While being relatively simple to implement and unobtrusive to the pilot, wrist activity only detects sleep after it has developed and is insensitive to sleepiness. Lapses in wakefulness lasting short periods of time are not detected, and sleepiness or sleep could be allowed to persist for several minutes. Eye activity however is a sensitive detector of sleepiness and measurement of eye movements would prevent any unintentional sleep.

These findings should be qualified by the following points. In this study the subjects were asked to fall asleep in order to enable the assessment of several possible methods of monitoring sleep. The morphology of intentional sleep is however likely to differ from that seen when the pilot is asked to remain awake. It is therefore suggested that a second investigation be carried out to address the question of unintentional sleep. The objective would be to assess the effectiveness of monitoring wrist activity in a realistic simulation of a two crew situation where only one crew member is required to be awake.

Contents

1 INTRODUCTION

Impaired vigilance and sleepiness during long haul operations is of potential concern in civil aviation particularly when long periods of duty occur against a background of irregularity of work and rest related to round the clock schedules and time zone change. The effects of these various influences can be minimised by careful planning of flight schedules which limit duty hours and take into consideration the adverse effects of the juxtaposition of duty hours and the circadian nadir of performance, thus enabling aircrew to obtain adequate sleep and rest [1–8].

However it may be inevitable that fatigue will occur despite careful attention to all these issues, owing to external factors such as operational delays and other unavoidable circumstances. In any event, the problem of low vigilance and in the extreme the flight crew falling asleep is still seen as a major factor influencing air safety, despite flight time limitation regulations designed to avoid fatigue. The introduction of an alertness monitor on the flight deck to warn pilots of involuntary sleep would at least prevent the worst-case situation whereby the flight crew fall asleep unintentionally.

The issue of involuntary sleep is particularly relevant to current trends in the aviation industry to allow 'controlled rest' in two crew aircraft during cruise on specified routes [9], with the assumption that at least one pilot remains awake at any given time. Such rest is reported to be beneficial to subsequent alertness, and is not intended to enable duty hours to be extended [9], rather an acceptance that however well-planned operations are, pilots do, for many reasons, become sleepy particularly during long monotonous flights [10]. Allowing 'controlled rest' at times during cruise when workload is low can assist pilots to feel more alert during critical phases of flight such as descent and landing. However, the assumption that while one pilot sleeps the other is awake is unjustified and therefore assured wakefulness by means of an alertness alarm system may be required before the practice of cockpit rests is authorised by many airlines.

Since the early 1950s methods of monitoring alertness and sleepiness in occupational settings with a view to devising an alarm have been considered, including recording the electrical activity of the brain and performance of the actual operational task or alternatively a secondary task. Although many physiological measures are correlated with arousal, their sensitivity and specificity to the onset of sleepiness and sleep have not been established, particularly in the aviation environment. Furthermore there are many difficulties with implementing a warning system that is both sensitive and reliable with respect to false alarms and sufficiently unobtrusive to be acceptable to pilots. Secondary tasks are in general considered to be an unwanted intrusion and ineffective in preventing loss of vigilance.

An alertness monitor based on information about the physiological state of the pilot combined with some aspect of performance of the operational task has been suggested. The present study investigates possible approaches to detecting sleepiness and sleep on the flight deck, with the overall aim of recommending the basis of a practical alertness monitoring system for use in aviation. The electrical activity of the brain, electro-ocular activity, the electrocardiogram and electromyogram, wrist activity, head movements and skin resistance were measured during long-haul flights in the daytime and overnight. Control inputs to the aircraft by the pilot were recorded by an observer on the flight deck.

2 METHODOLOGY

2.1 Subjects

The subjects were twelve First Officers between 29 and 48 (mean 39.0) years of age (eleven males and one female), who were currently engaged in flying long-haul operations with British Airways. They gave written informed consent to participate following explanation of the purpose and procedures of the study, in accordance with requirements of the RAF Institute of Aviation Medicine Ethics Committee. The subjects were assured of confidentiality regarding their individual identity and were allocated a number unrelated to order of participation. For the purpose of the investigation subjects were, with the consent of the Captain, allowed to sleep on the flight deck.

2.2 Flights

The study was carried out during twelve non-stop flights between London and Miami over the period from Nov 92 to Jun 93, a three-crew operation covered by Boeing 747-100/200 series aircraft. For each subject, data were recorded from an outbound westward flight during the daytime and the return eastward sector, a predominantly overnight flight. The westward flight departed at 1115h GMT and arrived at 1600h EST (2100h GMT), while the return eastward sector was either an early evening departure (subjects 8–12) leaving at 1800h EST (2300 GMT) and arriving at 0725h GMT, or a later flight (subjects 1–7) leaving at 2230h EST (0330h GMT) and arriving at 1150h GMT. The layover period between outbound and return sectors was either 26 or 30.30h for the departure times respectively.

2.3 Procedures

Measurement sensors were attached to the subject before the crew carried out pre-flight checks and were detached immediately after landing. Data were recorded continuously from the subject from before takeoff until after landing, while he carried out his normal pattern of duties as a crew member.

Control recordings to assess the physiological state of the pilot were carried out on two occasions during each flight, one during the early part of the cruise phase and the second towards the end before descent commenced. Each control period consisted of a recording with eyes open lasting 2 min, followed by 2 min with eyes closed, during which time the pilot was asked to remain still and relax. No control data was recorded for the first two pilots who participated.

An observer was present on the flight deck at all times to monitor activities of the subject, and to maintain a written log of events throughout the flight. A copy of the flight recorder output was obtained for each flight to provide information specific to phase of flight and activity of the aircraft.

2.4 Measures and sensors

Electroencephalographic activity (EEG) from occipital and parietal regions of the brain was recorded, together with vertical and horizontal electro-oculographic activity (EOG), the electromyogram (EMG) from the neck and a bipolar electrocardiogram (ECG). These were registered using silver–silver chloride disc electrodes applied to the skin, with inter-electrode resistances maintained at less than 10 kohms.

Galvanic skin resistance was recorded by measuring transmission of constant voltage across a pair of nickel electrodes attached to the volar surface of the third digit. Wrist activity was measured by a single-axis accelerometer on each wrist, and head movement by two inclinometers sited orthogonally on the subject's head.

Control inputs to the aircraft by the pilot were logged by the observer, and included inputs to the flight management system, communications, autopilot status, phase of flight, environmental conditions and general cockpit activities.

The subjects completed subjective assessments of alertness by placing a mark on an analogue line with the extremes 'very tired' and 'very alert'. These were carried out before takeoff and after landing for each flight, and they retrospectively estimated their alertness during the flight after landing. They were also asked to indicate whether they were aware of having fallen asleep and whether any sleep had been intentional. In addition they completed a log of their nocturnal sleep periods and naps before the outward flight and during the layover period, including estimated duration and quality of sleep and subjective alertness after awakening.

Temperature and humidity were recorded at time intervals of 30min during flight using a digital hand-held thermometer/hygrometer.

2.5 Recording devices

A schematic diagram of the recording devices is shown in Figure 1. The EEG, EOG, EMG and ECG were recorded continuously on a portable 8-channel analogue recorder (Medilog 9200, Oxford Medical Limited) sited adjacent to the subject's seat. Galvanic skin resistance, wrist activity, and head movement were logged at a sampling rate of 25Hz by a purpose-built digital physiological data recorder (DPDR, Cavendish Automation Limited) situated behind the flight engineer's panel, with signals from the subject routed to the digital recorder via an umbilical. The two devices were synchronised by a time code marker generated by the digital recorder and recorded on one channel of the Medilog recorder. A portable control panel linked to the digital recorder enabled activities of the pilot, including control inputs, to be logged by the observer, according to pre-assigned codes. Data from the DPDR was down-loaded to a lap-top PC at the end of each flight.

2.6 Analysis

2.6.1 *Signal processing*

All data were analysed by a Hewlett Packard HP720 computer, using a commercially available signal processing package (DATS, Prosig Computer Consultants Limited).

Analogue tapes containing EEG, EOG, EMG and ECG signals were replayed at 60 times real-time using a Medilog 9200 Replay System (Oxford Medical Limited). These signals were digitised at a sampling rate of 7680 Hz (equivalent to 128 Hz real-time).

All variables other than ECG were analysed with a time resolution of 1s. The EEG was described by variables corresponding to frequency ranges known to be related to sleepiness and alertness, namely delta (0.5–3Hz), theta (3–7.5Hz), alpha (7.5–13Hz) beta1 (13–20Hz) and beta2 (20–30Hz) activity. The EOG was characterised by absolute activity, defined as the square of the first derivative of signal amplitude with respect to time integrated over 1s. This variable shows marked differences in magnitude for the fast eye activity that is typical of wakefulness, including saccades and blinks, compared with that seen during sleepiness and sleep. Root mean square (RMS) of EMG amplitude was calculated for 1s epochs to screen EEG and EOG data for artefacts due to body movement. Mean level of skin resistance and integrated EMG, wrist activity and head movement were calculated over 1s epochs. For wrist and head data, presence or absence of activity are of more interest than absolute level and therefore periods of inactivity were detected also. Heart rate was measured in beats per minute from the ECG recording.

2.6.2 *Estimates of alertness at beginning and end of flights*

These estimates are intended to indicate the overall alertness experienced by the pilots during the trips and are not related to instances of falling asleep. In this way the findings can be interpreted more generally and also confirm that the levels of alertness and sleepiness are typical of those expected, given the slightly unusual circumstances of the flights. The analyses assume that the pilots were well-rested and alert at the beginning of the outbound flight.

Estimates of fatigue were obtained by measurements carried out while the pilot was inactive during the control recordings and also during periods at the start and end of cruise while he carried out normal flight deck activities ('active recordings'). In addition, each pilot assessed his sleepiness subjectively.

(a) *Control recordings* Each variable described in para 2.6.1, excluding wrist and head movement, was meaned over the two minute periods for the four control recordings. Data recorded with eyes open and with eyes closed were analysed separately, because characteristics of the EEG and EOG differ under the two conditions and also subjects often fall asleep when asked to close their eyes. The following factors were considered in the analysis: time into flight (start versus end), day versus night, and time of return departure (early or late).

(b) *Active recordings* Mean values were obtained for each variable during the first hour of cruise, usually immediately after the control recording, and for one hour before descent commenced. These estimates of fatigue were used in addition to the controls because the latter are atypical of data during flight operations. Comparisons analogous to those for control recordings with respect to day versus night and start versus end of flight were made.

(c) *Subjective assessments* Subjectively assessed levels of alertness were analysed relating to start, during and end of flight for early and late departures.

2.6.3 *Classification of wakefulness and sleep in flight*

For each subject, periods of sleepiness and sleep were identified from the EEG and EOG, and subsequently characterised according to a four-point scale ranging from 0 to 2, with levels of 0, 0.5, 1 and 2 defined according to features similar to conventional criteria used for the visual analysis of sleep [11]. The data were classified statistically using discriminant analysis and periods identified as representing sleepiness or sleep were verified visually. The minimum period for classifying each recording was 5s to allow for the incidence of short periods of sleepiness seen during this investigation. The levels of wakefulness and sleep were defined as:

0 – alert wakefulness, with no clear evidence of sleepiness. This level is characterised by EEG activity of predominantly alpha and beta frequencies and the presence of saccades and blinks in the EOG.

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 characteristics frequently last only several seconds, often occur in sequences and are termed microsleeps when the duration is short. Alternatively, such patterns may appear as the first overt sign in the transition between wakefulness and drowsy sleep.

1 – presence of theta activity in the EEG and slow rolling eye movements. This is analogous to the characteristics of stage 1 sleep according to conventional criteria [11] and represents light, drowsy sleep.

2 – periods of continuous relatively high amplitude theta or delta activity starting either from cessation of slow eye movements or from a K-complex and lasting until some indication of decreasing depth of sleep, such as increased frequency of the EEG indicating an arousal or the development of slow eye movements, saccades or blinks in the EOG. This classification is similar to stage 2 sleep.

Typical EEG and EOG waveforms characterising each of these four levels are shown in Figures 2(a), (b), (c) and (d) respectively.

The total durations of sleep levels 0.5, 1 and 2 were calculated for each subject and flight. For each continuous period of sleep that included level 1 or 2, the time into flight, latency from wakefulness to sleep and duration of sleep were calculated. The durations of periods of sleepiness (level 0.5) that were not followed by sleep were measured.

2.6.4 *Correlation of variables with wakefulness and sleep*

The patterns of each variable during sleep were investigated by identifying all segments of data for each level of sleep (0.5, 1 and 2) and comparing the variables with data when the subject was classified as being awake (level 0). Two separate estimates of 'awake' were used: the 'active' level (denoted 'A') estimated from a segment of data lasting 1h taken early during cruise of the daytime flight (described under Analysis 2.6.2 'Estimates of alertness') representing the state of the pilot carrying out flight-related activities when alert and well rested; a 'local' wake state (denoted 'L') just before the pilot becomes sleepy or actually falls asleep. The latter represents the state that an alarm system would need to distinguish from sleepiness or sleep. States 'A' and 'L' are likely to be different because alertness varies across a continuum between 'fully alert' ('A') and 'awake' just preceding sleepiness ('L') rather than being a single state.

The distribution of variables during each level of sleep were investigated and mean values calculated and compared with data relating to wakefulness. An analysis of variance (ANOVA) was carried out, with factors 'subject' and 'sleep level' (0-'A', 0-'L', 0.5, 1 and 2).

2.6.5 *Investigation of an alertness monitoring system*

This was carried out initially by examining the responses of variables during the transition to sleep and from amplitude distributions of variables during wakefulness. In this instance, wakefulness for each subject was investigated for a period lasting 3h starting early during cruise of the daytime flight to represent alertness. The durations of periods of inactivity were examined for wrist and head movement. Threshold levels and time intervals for activating an alarm system were considered with respect to false positives and negatives.

3 RESULTS

3.1 Sleep and flight times

Figure 3 shows the pre-flight and layover sleeps, naps and flight times of individual subjects. No data relating to these sleeps was obtained for subject 3. For the late departure return flights (subjects 1–7), four of the six pilots took pre-flight naps as well as an overnight sleep in local time. The return flight for subject 1 was delayed by 6.5 hours for operational reasons and therefore his data for this sector was atypical of the group of subjects in that he was able to take a long pre-flight nap. Three subjects reported sleep of poor quality before the flights, two before the outbound flight and one during the layover period.

3.2 Estimates of alertness

Subject 1 was omitted from these analyses because of the operational delay. Tables 1 and 2 show the mean levels for variables during control (9 subjects) and active recordings (11 subjects) respectively. Figure 4 shows subjectively assessed alertness.

Overall, alertness was lower for the late return flight than the early return ($p<0.05$). This effect was seen with eye activity (eyes open resting and 'active' recording), beta 1 activity (eyes closed resting) and skin resistance (both resting and 'active' recordings). This was the only effect in which statistically significant differences were seen.

During the control recordings with eyes closed, only four pilots showed signs of sleepiness, subject 4 on all four occasions and subjects 9, 10 and 12 at the end of the return flight.

3.3 Wakefulness and sleep during flight

Figure 5 shows the sleepiness profiles for individual subjects, indicating incidence and timing of sleepiness and sleep during flight. The durations of sleep at levels 0.5, 1 and 2 are given in Table 3.

There was no evidence of sleepiness or sleep in subjects 1 and 8 on either the outbound or return sectors, and subjects 9 and 10 showed only sleepiness (level 0.5) rather than sleep. During the overnight flights, seven pilots showed sleep at level 2 for periods ranging from 7.5 to 54.5 min, all except one of these returning on the later evening departure. Subject 12 slept for approximately one hour during the return flight while no data was being recorded due to technical problems, and therefore this period is not represented in the figure or table; this subject did not sleep at any other time on either flight during data recordings. In addition three pilots slept during the daytime flights, one for 29.9 min at level 2.

Table 4 shows the time interval (latency) from wakefulness (level 0) to sleep (level 2) during flight for those pilots who slept, the duration of each sleep and the time into sector that sleep occurred. The durations of periods of loss of wakefulness that included sleep level 2 ranged from 12.7 to 77.3 min, while latencies ranged from 2.6 to 32.5 min. The durations in seconds of periods of sleepiness (level 0.5) for all subjects is given in Figure 6 and shows that the majority lasted for less than 40s.

3.4 Correlation of variables with wakefulness and sleep

All data from both flights for one subject (number 6) are shown as time series for each variable (Figure 7), including the sleepiness profile. This subject showed the most sleep on both the outbound and return sectors, with a total of 49.0 and 90.2 min respectively. With respect to covariation between individual time series data, this pilot was typical of the subjects as a group. Data for all other subjects are contained in the Appendix (subjects 1–5 and 7–12).

Figure 8(a)–(i) shows all the data for subjects who slept for any significant amount of time, and includes a section of 'awake' data before and after the subject fell asleep so that transitions between 'awake' and 'sleep' can be seen. Data from one subject (number 3) for the night flight was omitted from this section of the analysis because synchronisation between the Medilog and digital recorder was lost.

During periods classified as sleep level 1 or 2, the EEG showed increased alpha and theta activity and markedly reduced eye activity according to the way sleepiness was classified (see Methods, para 2.6.3 of Analysis). The change in eye activity was generally abrupt when sleepiness or sleep occurred while increases in EEG alpha and theta were often more gradual. Arousals of short duration in episodes of sleep were indicated by an increase in eye activity and by a change in the EEG.

As the subjects fell asleep, skin resistance increased gradually and then dropped rapidly upon awakening. During sleep resistance was higher relative to the 'local' awake baseline value; however it could also be at a similarly high value when subjects were awake at other times during the flights. In nine subjects out of the twelve, mean skin resistance during the last 3h of cruise was higher for the night flight than during the daytime. Changes in resistance are likely to indicate tiredness, fatigue and low arousal in a general way rather than being directly related to the incidence of sleepiness and sleep.

During sleep, wrist and head movement were absent for long periods of time separated by sporadic activity in contrast with high levels of activity during wakefulness. The reductions in activity with these measures were abrupt rather than gradual, and also occurred during sleepiness when a period of sleep followed.

For instances of sleepiness (level 0.5), changes in variables other than the EEG and EOG did not follow a consistent pattern other than when sleepiness developed into sleep.

The amplitude distributions of EEG theta, eye activity, wrist activity and skin resistance for wakefulness and each sleep level are shown in Figures 9(a)–(d) corresponding to the data shown in Figure 8. These indicate the degree of overlap between each sleep level and wakefulness and the extent to which the sleep levels differ from wakefulness.

Mean values of each variable are given in Table 5 for wakefulness, represented as both 'active' ('A') and 'local' ('L') states, and for sleep levels 0.5, 1 and 2. There was a significant effect of sleep level for EEG delta ($p<0.05$), theta ($p<0.05$), eye activity ($p<0.001$), wrist ($p<0.001$) and head ($p<0.001$) movement, and skin resistance ($p<0.001$). Eye activity, wrist and head movement were higher during wakefulness (level 0) than during each sleep level (.5, 1 and 2). EEG delta and theta were both higher in sleep level 2 compared with sleepiness (level 0.5). There were no differences between skin resistance during wakefulness state 'L' and any level of sleep, although all sleep levels were higher than awake state 'A'.

3.5 Investigation of an alertness monitoring system

Based on practical concerns and findings reported earlier in the report, wrist, head and eye activity are possible candidates for a monitor. Since wrist and head parameters showed similar characteristics, both being indictors of physical activity, only wrist movement will be considered in detail here because of ease of implementation.

The amplitude distribution of wrist activity was examined to enable a threshold level to be set for an alarm system. Intervals of time when activity is below this threshold when the subject is alert enable a reasonable time parameter for activation of an alarm to be set to avoid false positives.

From the distributions of wrist activity at each level of sleep (Figure 9(c)), a threshold for wrist 'inactivity' was set at 2.0. The distribution of time intervals of inactivity during alertness when each parameter was continuously below the threshold is shown in Figure 10 and Table 6. The majority of intervals were less than 20s, three were longer than 2 min and none were greater than 5 min. Since 5 min is likely to be too long for sleep to remain undetected, an interval of 2 min was tested. From latency values in Table 4, this duration would prevent the occurrence of sleep at level 2.

A running RMS level of wrist activity was estimated over 2 min, updated every 15s to compare with the alarm threshold of 2.0, and tested on data from subject 6 during the night flight when he was becoming sleepy (Figure 11). The first two episodes of sleepiness were ignored by the alarm, while the second instance of sleep level 1 at 48 min into the data segment was detected. However, by that time the subject had been fluctuating between wakefulness and sleepiness for approximately eight minutes. Additionally an integration interval of 2 min gave three false positive alarms in 35h with the subjects tested in this study.

Further aspects of an alarm system will be considered in the discussion.

4 DISCUSSION

The present study suggests that eye, wrist and head activity may be used to provide a way to prevent involuntary sleep on the civil flight deck, while skin resistance is related in a more general way to fatigue rather than to the specific occurrence of sleep. These findings have been determined in a long-haul operation that showed levels of sleepiness and loss of alertness generally consistent with those expected for the flight duration and duty times with respect to GMT and layover local time. Although the amount of sleep seen during flights varied considerably between individual pilots, effects of sleep on the parameters under investigation were similar for the group. However, degree of sensitivity to reduced alertness differed between parameters, with eye activity detecting the onset of sleepiness while wrist and head movement only detected sleep. In this respect, the importance of lapses in wakefulness in contrast with actual sleep needs to be considered in the aviation context – at what stage in the development of sleep should an alarm system activate to warn the pilot ?

The optimal way to monitor sleepiness and sleep would appear to be by measuring eye movements. We believe the slowing of eye movements to be one of the most sensitive and reliable biological markers of the onset of sleepiness, and more specific to sleepiness than changes in the occipital EEG. In contrast with saccadic eye movements and blinks that are controlled or influenced by the cortex, these rhythmic slowed eye movements are likely to be of sub-cortical origin, and represent loss of the ability to fixate on targets [12]. Experiments in the laboratory have shown that such patterns of eye activity are associated with 40–60% error rates over short periods of time in activities requiring sustained attention [13]. Evidence of the frequency with which these physiological changes occur occupationally [14–16] has now accumulated.

Lapses in wakefulness often occur over short periods of time lasting less than 30–60s and the subject may well be unaware of them and only subsequent events, such as realising that he has missed information, bring the lapse to his attention. Alternatively, sleepiness may develop into sleep, depending on how tired the subject is, the immediate demands of flying the aircraft and other factors such as general activities in the cockpit. The importance of lapses in alertness, for example during cruise needs to be considered.

However, irrespective of sensitivity, the ways and means for measuring eye activity unobtrusively in occupational settings do not currently exist, although such measurements may be technologically feasible in the near future. An engineering solution is required that is likely to include sensor development, telemetry and refinements in physiological signal processing.

Therefore, for an immediately available method to prevent unintentional sleep on the flight deck, the present study examines the effectiveness of alternative solutions. It would appear that simple measures of physical activity, such as wrist or head movement are possible. As well as sensitivity, design considerations for an alarm system need to focus on reliability in terms of false alarms and acceptability to the pilot. Each of these is equally important to the successful integration of such a system into future aircraft design.

Based on findings of the investigation, these factors will be discussed with respect to wrist and eye activity. When the subjects were awake, wrist activity was almost continuous, while in contrast when they slept, there were relatively long intervals of time when movement was absent, with any activity isolated and sporadic. Wrist inactivity may or may not coincide with periods of sleepiness since no direct relationship exists between activity and alertness. It would not in any case be possible to design an alarm that activated on the basis of wrist inactivity during periods of sleepiness as short as 30s because when the pilot is awake and alert, inactivity of this duration occurs too frequently (Figure 10 and Table 6). Therefore reliably detecting 'microsleeps' within periods of wakefulness is not feasible using wrist activity.

The alarm system tested in the Results section gave three false positive alarms in 35h of flying for this group of subjects, which is far too high. Although sleep level 1 was detected, a relatively long period of low alertness, approximately eight minutes, was allowed before alarm activation, and this is likely to be considered unacceptable if only one pilot is required to be awake. The system could probably be improved with respect to false positive and negatives by numerically optimising alarm parameters, such as integration interval, update rate and threshold, based on the distributions of wrist activity amplitude when awake and asleep and from inactivity distributions. This involves testing randomly generated time series of activity with the estimated distributional properties against sleepiness profiles using a range of parameter settings to minimise false alarms. In this way, a more effective sleep monitor could be developed, although the duration of sleep allowed before an alarm is activated may still be unacceptable.

Problems with false alarms would however be unlikely to occur with a monitoring system based on eye movements. Waveforms of low frequency in the EOG that characterise sleepiness (Figure 2a) are specific to this behavioural state and can be described using signal processing techniques [17]. Therefore epochs of EOG signal lasting 30–60s when the subject is alert but fast eye activity is absent, caused for example by suppression of eye movements during visual information processing, could be correctly assigned as alert rather than causing a false positive alarm. Consequently monitoring eye movements could provide an optimal system by identifying sleepiness as it occurs.

It would therefore appear that two methods for monitoring alertness on the flight deck can be considered. The first, based on wrist activity is a simple, immediately available solution that detects sleep but not sleepiness. An alternative solution, technically much more difficult and costly, is to design an alertness system using eye movements to provide a sensitive, optimal solution that prevents any unwanted sleep.

Obviously an alertness monitoring system is only designed to be used during cruise, when the probability of an emergency occurring is orders of magnitude lower than during descent and landing. However, if the unlikely does happen in cruise and the pilot has just been awakened suddenly by an alarm from stage 2 or 3 sleep then the certain fact is that he will be less able to cope quickly with an emergency than if an alarm had prevented him falling asleep at all. This is the trade-off between an expensive, difficult solution based on eye movements, and a relatively simple one using wrist activity monitoring.

This raises the important questions of sleep inertia and of how quickly stage 2 or 3 sleep can develop from wakefulness. The literature describing sleep inertia is extensive [18–23] and deficits in performance are generally considered to persist for several minutes after an abrupt awakening from sleep, depending on factors including depth of sleep and time of day. The range of latencies to sleep level 2, which behaviourally can be considered the same as stage 2, was from 2 to 32 min in the pilots we studied. The gradient of sleep development depends on many factors, including duration of prior wakefulness, circadian influences and general ease with which individuals fall asleep [24, 25]. Certainly stage 2 sleep can be achieved by some well-rested individuals in less than 5 min. These considerations dictate realistic time settings for an alertness detector.

The recommendations should be interpreted cautiously at this stage, particularly with respect to wrist activity. We find the results both during wakefulness and during sleep in the cockpit surprising, although more generally correlation between waking, sleeping and motor activity is accepted (26) and is used to record rest and activity patterns over several days. However, with the time resolution required for our application, more periods of relative inactivity were expected during alert wakefulness, as well as more restlessness during sleep given that cockpit seats are not designed for restful sleep. Nevertheless, in this group of subjects, flying this particular aircraft, an alarm system based on wrist activity would prevent the worst-case situation whereby lengthy periods of sleep occur.

Again in terms of caution, these findings may not carry over to more highly automated aircraft, although wrist and eye movements are associated as much with general cockpit activities as with directly controlling the aircraft. Lastly, the number of subjects and total duration of sleep observed here are relatively small, and therefore a more extensive dataset is highly desirable to fully assess the effectiveness particularly of wrist activity.

In summary, the present study suggests that a monitoring system based on detection of either eye movements or wrist activity would prevent the development of long periods of involuntary sleep on the flight deck, while changes in skin resistance, though reflecting fatigue in a general way, are not sufficiently specific to sleep. While wrist activity has the advantage of being relatively simple to implement, lapses in wakefulness could persist for several minutes. Monitoring eye movements is more sensitive, detecting sleepiness before sleep develops, although the technology for unobtrusive day-to-day measurement of eye activity is not yet available.

The findings should be qualified by the following points. The aim of this work is to identify a method to ensure an acceptable level of alertness to be used in two crew operations when only one pilot is required to be awake. The present study was however carried out in a three crew aircraft, and it is therefore possible, though in our view unlikely, that the findings would have been different in a two crew aircraft. A more likely difficulty with the recommendations concerns the information and instructions given to the First Officer subjects. They were aware that we were interested in determining how various physiological measures related to sleepiness and sleep. Therefore they fell asleep intentionally, and in fact this was necessary in order to compare the various measures in terms of sensitivity to sleepiness and sleep. However, the development of unintentional sleep when the pilot is attempting to remain awake is likely to have a different morphological pattern over time from that seen when he decides to have a nap. Only one subject (number 6, night flight) in the present study showed the pattern of sleep that might be expected when a tired pilot is trying to stay alert ie. oscillations between 'awake' and short periods of drowsiness. Therefore, the findings, particularly regarding wrist activity, need to be verified when the subjects are asked to remain awake. It may be that performance characteristics of a device based on this measure would allow actual sleep to develop in some pilots, and therefore be unacceptable.

5 CONCLUSIONS

In the present study, sleepiness and sleep identified by patterns of the EEG and EOG were evident in most of the subjects, the extent being consistent with that expected for the flight timing with respect to duration and time of day. Wrist and head movements were markedly reduced during sleep and there were changes in the characteristics of skin resistance, while sleepiness was not detected by any of these variables.

Two separate methods for monitoring alertness are possible, the first based on wrist and the second on eye movements. An alarm system based on absence of wrist activity has the advantage of simplicity and would prevent lengthy periods of sleep. It would however be insensitive to sleepiness. In contrast, a system measuring eye activity could detect sleepiness and prevent any unintentional sleep.

6 RECOMMENDATIONS

The performance of a device based on wrist activity should be further investigated. The objective would be to determine whether such a device can identify periods of unintentional sleep or sleepiness without generating an unacceptably high level of false alarms. The study would assess the effectiveness of monitoring wrist activity in a realistic simulation of a two crew situation where only one crew member is required to be awake. EEG and EOG activity would need to be recorded also to indicate objectively when sleepiness and sleep has occurred.

7 ACKNOWLEDGEMENTS

This study was supported by the United Kingdom Civil Aviation Authority.

We would like to thank the British Airways Senior First Officers who participated as volunteer subjects, and the Captains and Senior Flight Engineers of the participating crews for their considerable assistance. We would like to thank Duncan Curwell, Clive Holland and Richard Knight for carrying out the studies with us and providing electronics support, and Steven Foster for technical assistance.

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Table 1 Variables during control recordings (mean values for 9 subjects)

Variable	*Return flight time*	*Day Flight*		*Night Flight*		
		Start	*End*	*Start*	*End*	*sd*
Eyes open						
EEG theta	early	3.299	3.625	3.003	3.027	1.257
(µV)	late	2.764	2.721	1.900	2.278	
EEG alpha	early	2.746	2.977	2.732	2.546	0.940
(µV)	late	3.021	2.459	1.840	2.257	
EEG beta1	early	2.557	2.711	2.312	2.192	0.785
(µV)	late	2.581	2.194	1.721	1.928	
Eye activity	early	184.3	168.7	207.3	197.6	69.09
(μV^2)	late	135.2	108.2	106.1	115.5	
Skin	early	109.5	79.5	87.4	134.3	61.85
resistance	late	117.2	123.3	177.3	167.3	
Eyes closed						
EEG theta	early	2.646	2.524	2.668	3.483	0.678
(µV)	late	2.801	2.774	2.480	2.569	
EEG alpha	early	4.856	4.082	4.954	5.044	2.004
(µV)	late	5.164	5.219	4.436	4.209	
EEG beta1	early	3.418	3.263	3.148	3.166	1.423
(µV)	late	2.668	2.793	2.298	2.257	
Eye activity	early	114.6	123.5	134.1	103.9	46.47
(μV^2)	late	103.4	83.8	88.2	102.7	
Skin	early	126.1	85.2	90.4	140.9	63.17
resistance	late	125.4	129.7	188.9	184.4	

Table 2 Variables during 'active' recordings (mean values for 11 subjects)

Variable	Return flight time	Day Flight Start	Day Flight End	Night Flight Start	Night Flight End	sd
EEG theta	early	4.422	4.795	4.682	4.698	1.999
(µV)	late	3.821	4.723	3.247	3.817	
EEG alpha	early	3.404	3.665	3.264	3.263	1.166
(µV)	late	3.065	3.444	2.626	2.902	
EEG beta1	early	3.136	3.268	2.942	2.852	1.008
(µV)	late	2.659	3.033	2.572	2.672	
Eye activity	early	391.5	330.8	347.4	316.8	78.07
(μV^2)	late	310.3	296.4	260.8	290.4	
Wrist	early	8.18	6.42	6.32	6.48	1.982
activity	late	7.77	7.72	5.95	7.17	
Head	early	160.4	129.6	147.4	134.0	32.62
movement	late	144.7	137.2	156.2	150.2	
Skin	early	135.1	90.6	91.6	129.8	56.77
resistance	late	145.0	133.5	188.0	176.7	

Table 3 Durations of sleep for individual subjects during day and nighttime flights

Subject	Day flight: Duration of sleep level (min) 0.5	1	2	1+2	Total	Night flight: Duration of sleep level (min) 0.5	1	2	1+2	Total
1	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
2	.0	.0	.0	.0	.0	1.6	3.6	7.5	11.1	12.7
3	8.9	3.2	8.6	11.8	20.7	9.0	5.7	31.4	37.1	46.1
4	2.3	.0	.0	.0	2.3	10.3	2.9	13.7	16.6	26.9
5	.0	.0	.0	.0	.0	7.7	37.6	11.1	48.7	56.4
6	4.4	14.7	29.9	44.6	49.0	19.1	16.6	54.5	71.1	90.2
7	6.2	5.7	.0	5.7	11.9	1.3	4.5	29.8	34.3	35.6
8	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0
9	.0	.0	.0	.0	.0	2.5	.0	.0	.0	2.5
10	.0	.0	.0	.0	.0	16.4	.0	.0	.0	16.4
11	.0	.0	.0	.0	.0	31.5	39.1	8.9	48.0	79.5
12	.0	.0	.0	.0	.0	–	–	–	–	–

For the night flight of subject 12, there were technical problems with recording equipment while the subject slept.

Table 4 Duration and latencies of sleep for flights where sleep occurred

Subject	*Flight*	*of recording (h)*	*Time from start level 2 (min)*	*Latency to (min)*	*Duration*
2	night	5.83	4.7	12.7	
3	day	7.41	12.1	20.7	
3	night	5.10	10.6	43.1	
4	night	4.70 (4.72)*	2.6 (2.1)*	18.6	
5	night	4.26	32.5	56.3	
6	day	6.32	2.7	46.6	
6	night	4.23 (4.33)*	7.1 (4.5)*	17.1	
6	night	5.27	2.6	66.4	
7	day	2.86	–	7.1	
7	day	3.07	–	4.4	
7	night	5.29	4.9	35.6	
11	night	4.12 (4.20)*	27.2 (23.1)	77.3	

* Where sleep was interrupted by short periods of wakefulness lasting less than 90s, the latency to level 2 from uninterrupted sleepiness is given in brackets.

No sleep level 2 occurred during the day flight for subject 7.

Table 5 Variables during wakefulness, sleepiness and sleep for each level (mean values for 9 subjects)

Variable	*Awake level 0 'A'*	*Awake level 0 'L'*	*Sleepy level 0.5*	*Sleep level 1*	*Sleep level 2*	*sd*
EEG delta (μV)	10.120	6.786	4.609 *	5.825	7.898 *	2.295
EEG theta (μV)	4.172	2.982	2.740 *	3.564	4.432 *	1.122
EEG alpha (μV)	3.079	2.481	3.312	2.741	3.143	0.906
EEG beta1 (μV)	2.783	2.169	2.179	1.995	2.141	0.566
Eye activity (μV^2)	309.4	266.5 *	104.2 *	72.7 *	69.9	46.71
Wrist activity	7.66	7.14 *	1.20 *	.52 *	.17	1.160
Head movement	57.22	38.01 *	24.24 *	14.52 *	6.73	14.77
Skin resistance	142.1 *	188.3	203.5 *	215.8 *	226.0 *	35.34

Significance level: * $p<0.05$

Awake level 0 'A': mean value for first hour of cruise (day flight)

Awake level 0 'L': mean value for awake data immediately before sleep (corresponds to awake data in Figure 8)

Comparisons are between sleep levels 0.5, 1, 2 vs awake 'L' other than for:

1 EEG delta and theta where sleep level 2 differed from level 0.5.

2 Skin resistance where sleep levels 0.5, 1 and 2 differed from awake 'A'.

Table 6 Number of periods of wrist inactivity during the first 3h of cruise for individual subjects. Times when sleepiness were observed are excluded

Subject	*Day flight*					*Night flight*				
	Duration (min)					*Duration (min)*				
	0.5–1	*1–2*	*2–5*	*>5*	*(h)**	*0.5–1*	*1–2*	*2–5*	*>5*	*(h)**
1	4	1	0	0	(3)	11	2	0	0	(3)
2	25	7	0	0	(3)	9	6	0	0	(3)
3	10	1	0	0	(3)	9	2	0	0	(3)
4	6	0	0	0	(3)	7	1	0	0	(3)
5	10	2	0	0	(3)	30	3	1	0	(2)
6	5	0	0	0	(3)	4	1	0	0	(2)
7	8	0	0	0	(2)	11	1	0	0	(3)
8	9	2	0	0	(3)	29	5	0	0	(3)
9	6	1	0	0	(3)	4	2	0	0	(3)
10	21	1	1	0	(3)	14	1	0	0	(2)
11	15	7	2	0	(3)	14	5	0	0	(1)
12	5	1	0	0	(3)	10	0	0	0	(3)

* Number of hours included for each subject (some subjects fell asleep during the first 3h of cruise).

Periods of inactivity exceeding 2 min lasted:

Subject 10 (day) : 121s
11 (day) : 123 and 124s
5 (night) : 168s

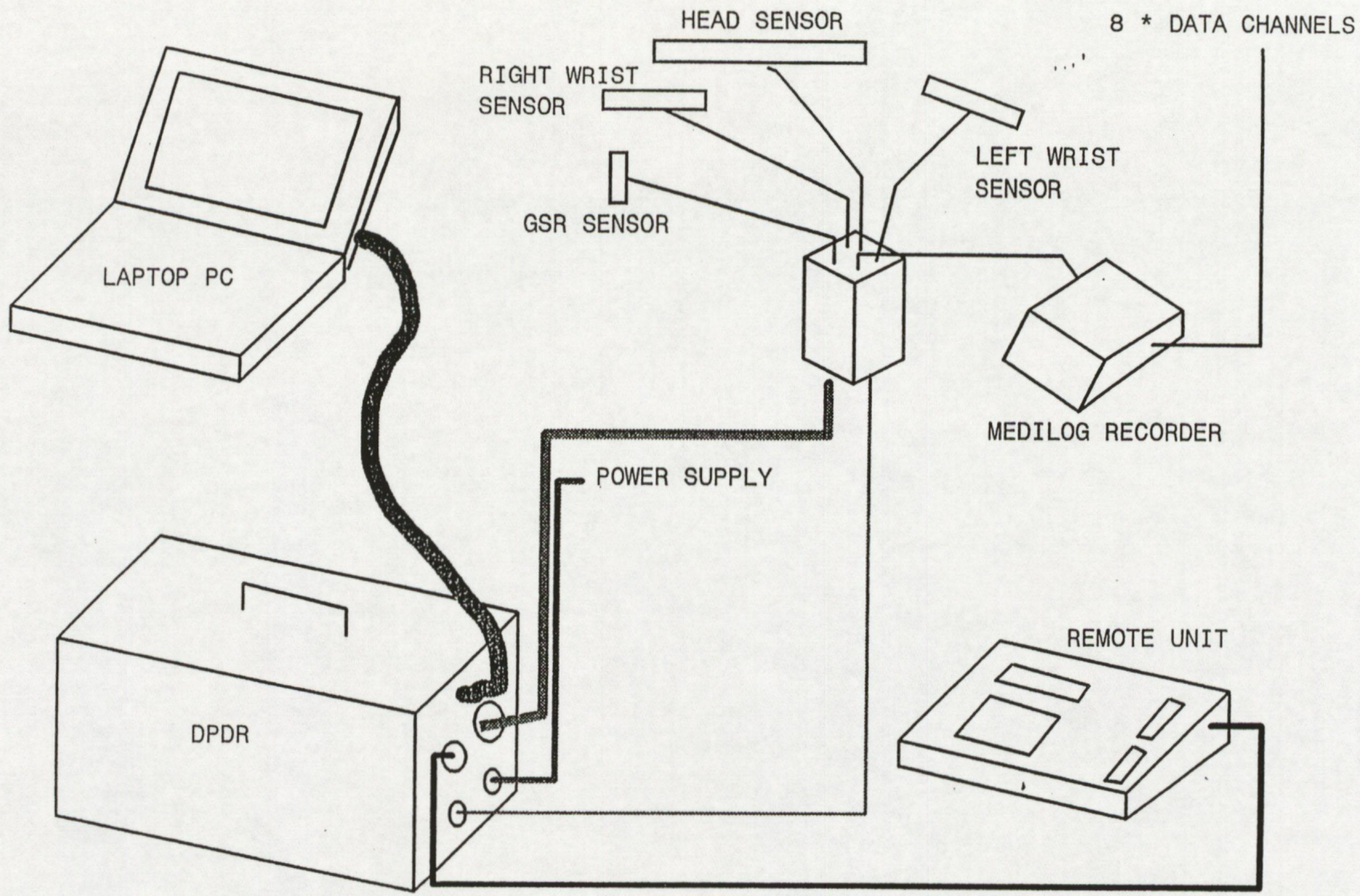
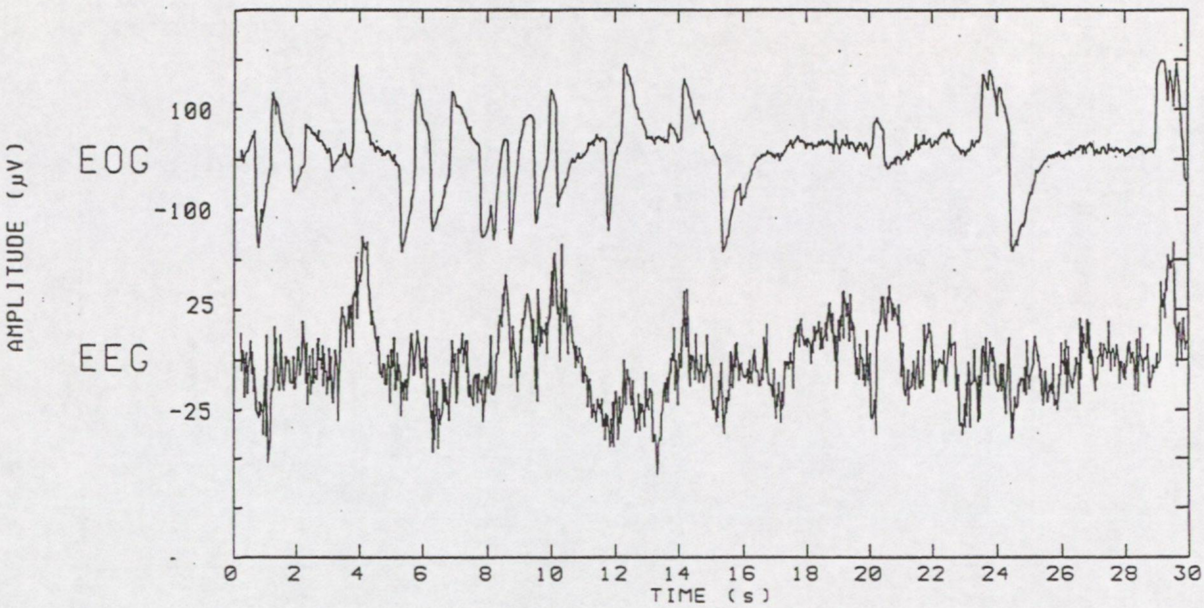
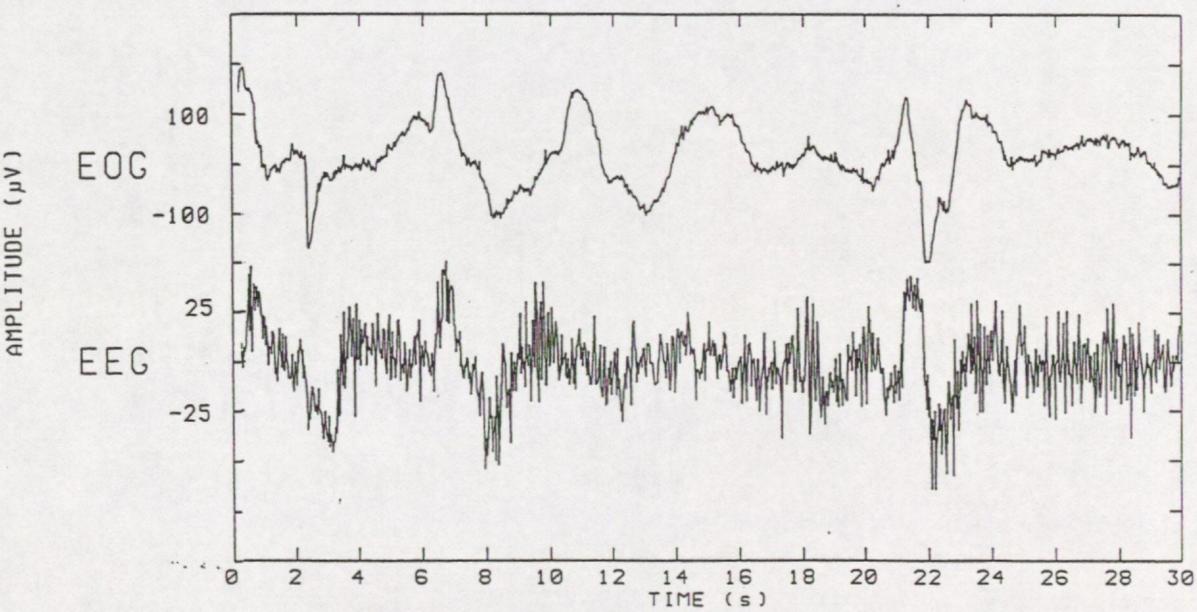


Figure 1 Schematic layout of recording devices, showing Medilog recorder, digital physiological data recorder (DPDR), remote unit for logging control inputs, physiological and physical sensor routings and PC for downloading data

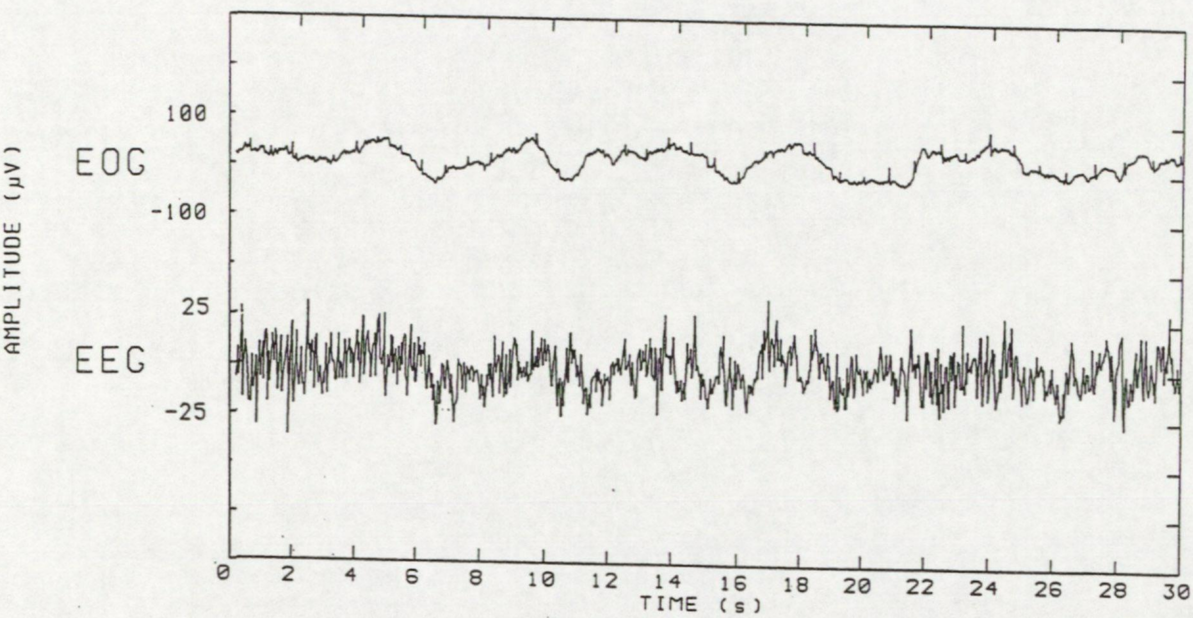


(a) alert wakefulness (level 0)

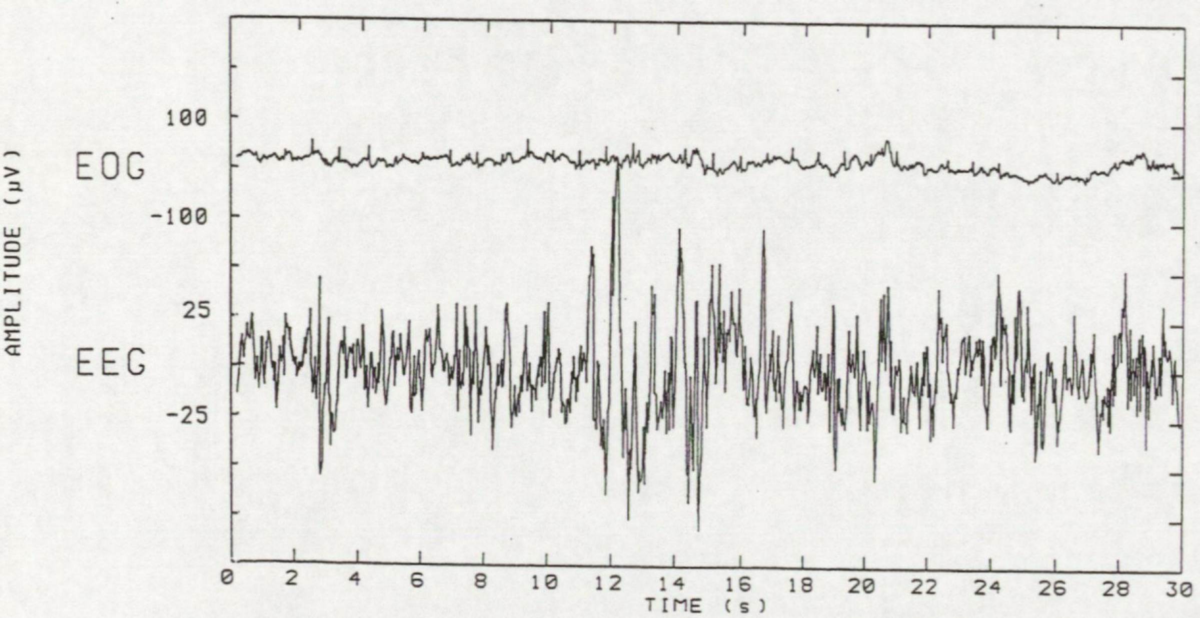


(b) sleepiness (level 0.5)

Figure 2 EOG and EEG waveforms for wakefulness levels



(c) drowsy sleep (level 1)



(d) sleep (level 2)

Figure 2 (continued)

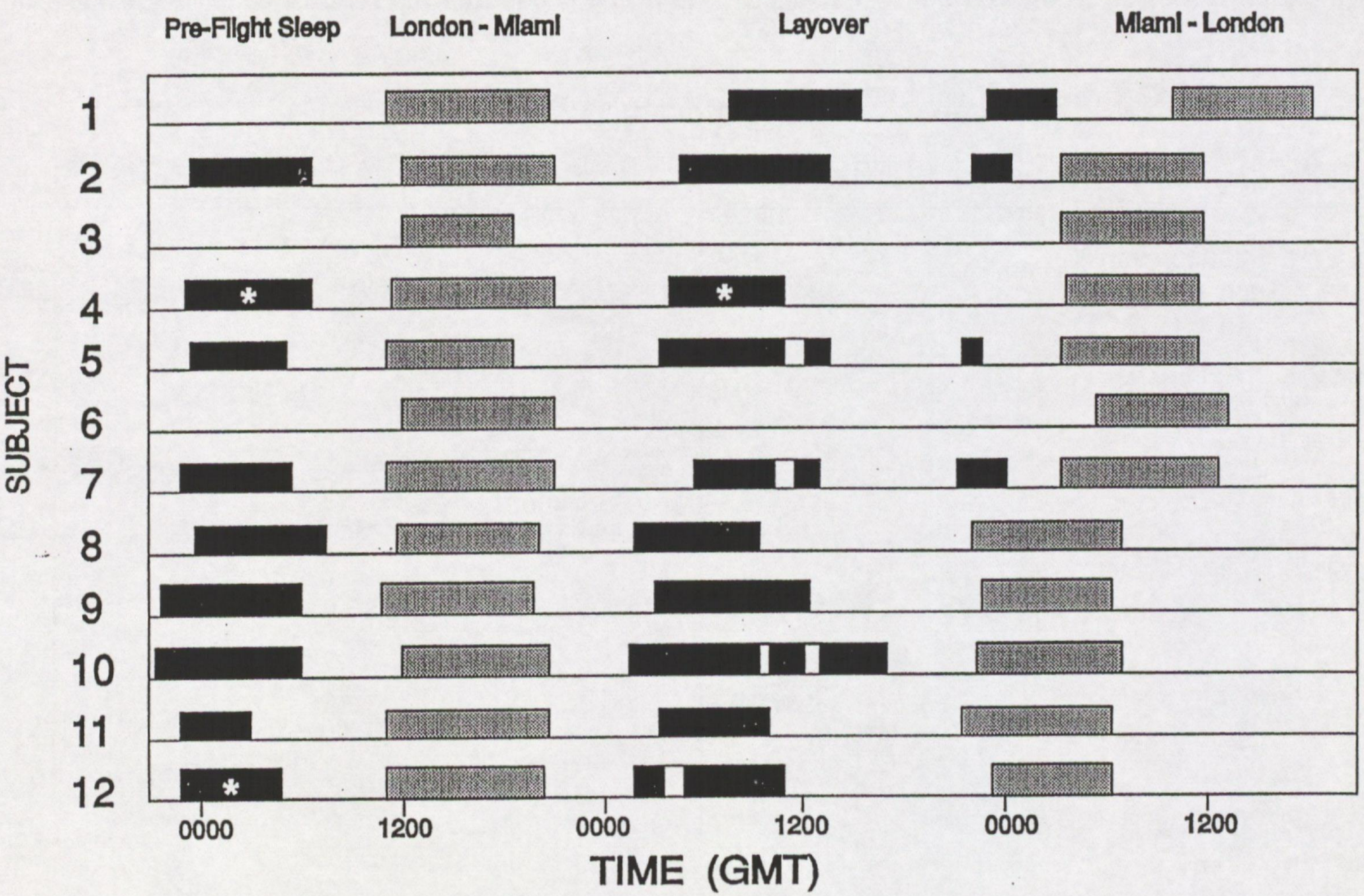


Figure 3 Preflight and layover sleeps, naps and flight times for individual subjects. Sleeps and naps are shown in black, with a '*' indicating subjectively reported poor quality of sleep; intervals of white within sleeps represent periods of wakefulness. Flights are shown in grey

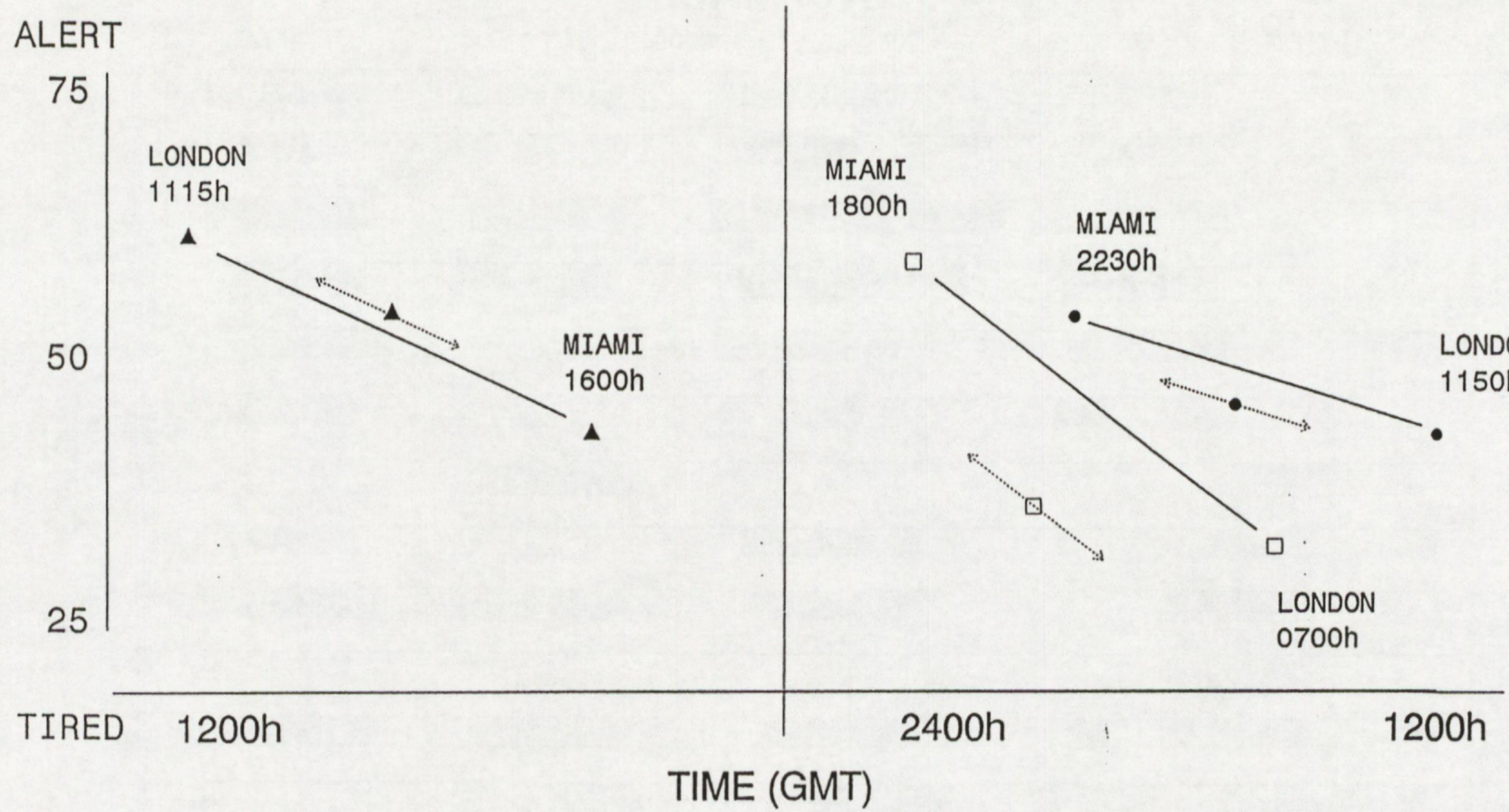


Figure 4 **Subjectively assessed alertness at the start and end of flights, meaned over subjects. Retrospective estimates of alertness during flight are shown as points with extended arrows**

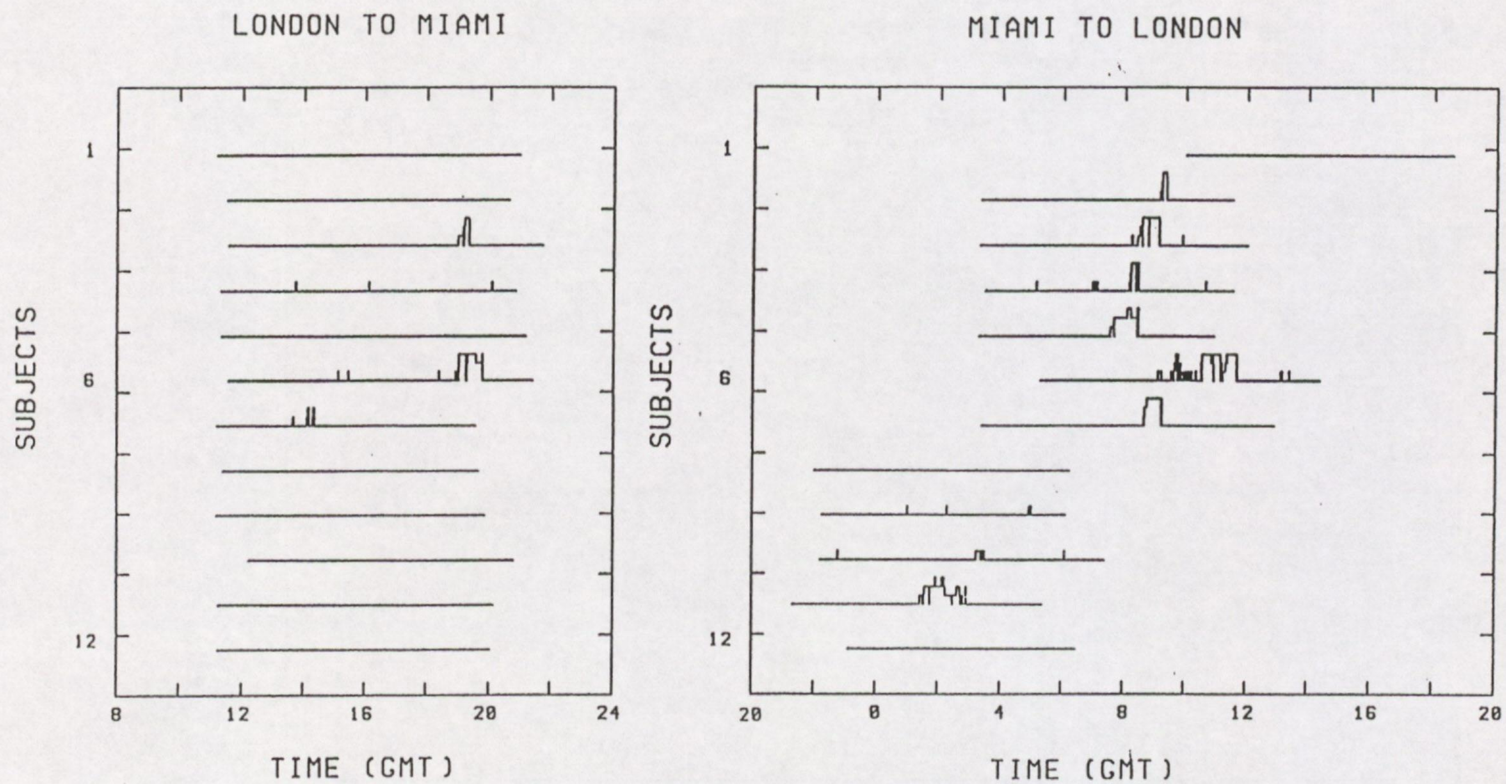


Figure 5 **Sleepiness profiles during flight for individual subjects. Each line has 4 levels corresponding to awake (0), sleepiness (0.5), drowsy sleep (1) and sleep (2)**

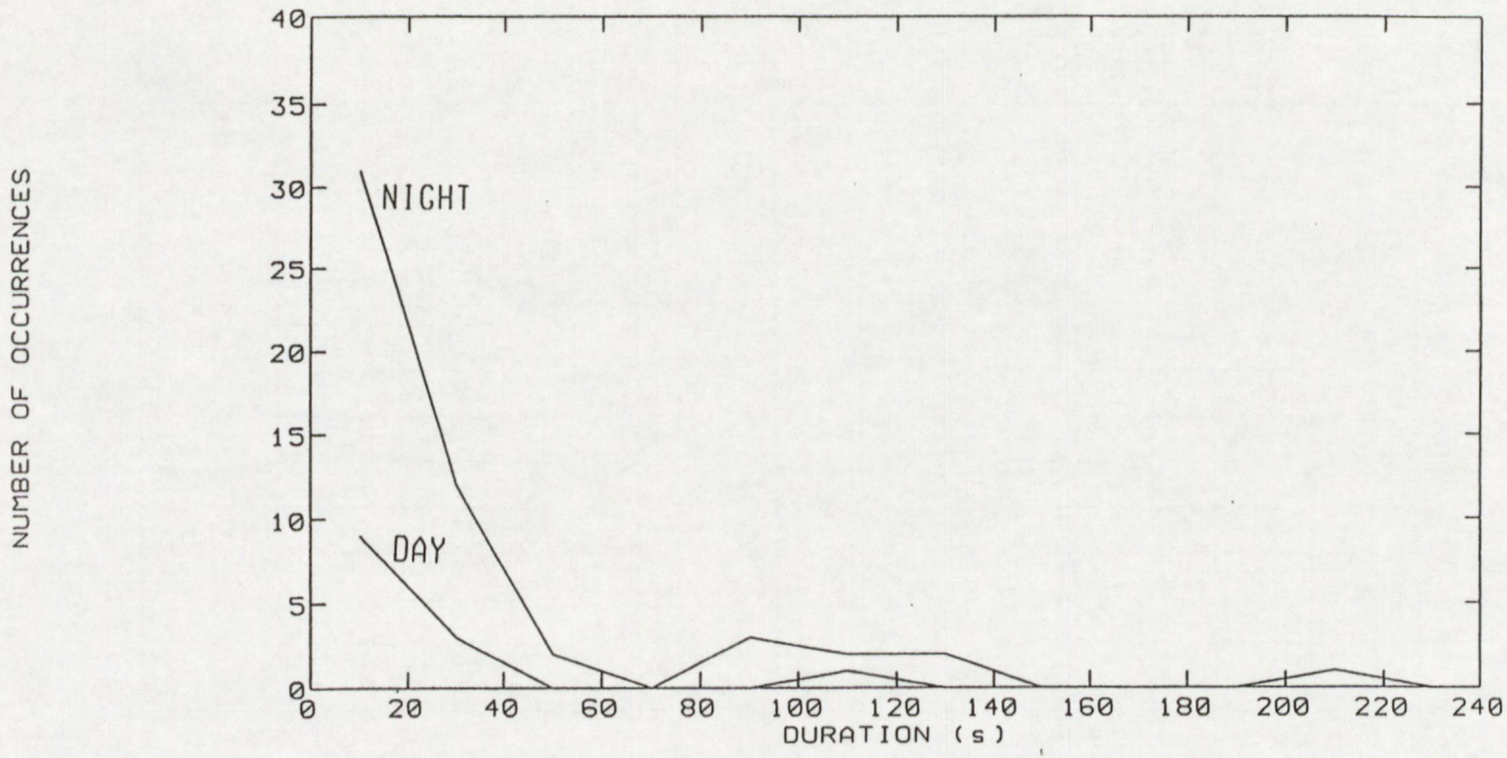


Figure 6 Distribution of durations of periods classified as sleepiness (level 0.5) for all subjects, excluding those that were immediately before or part of a period of sleep

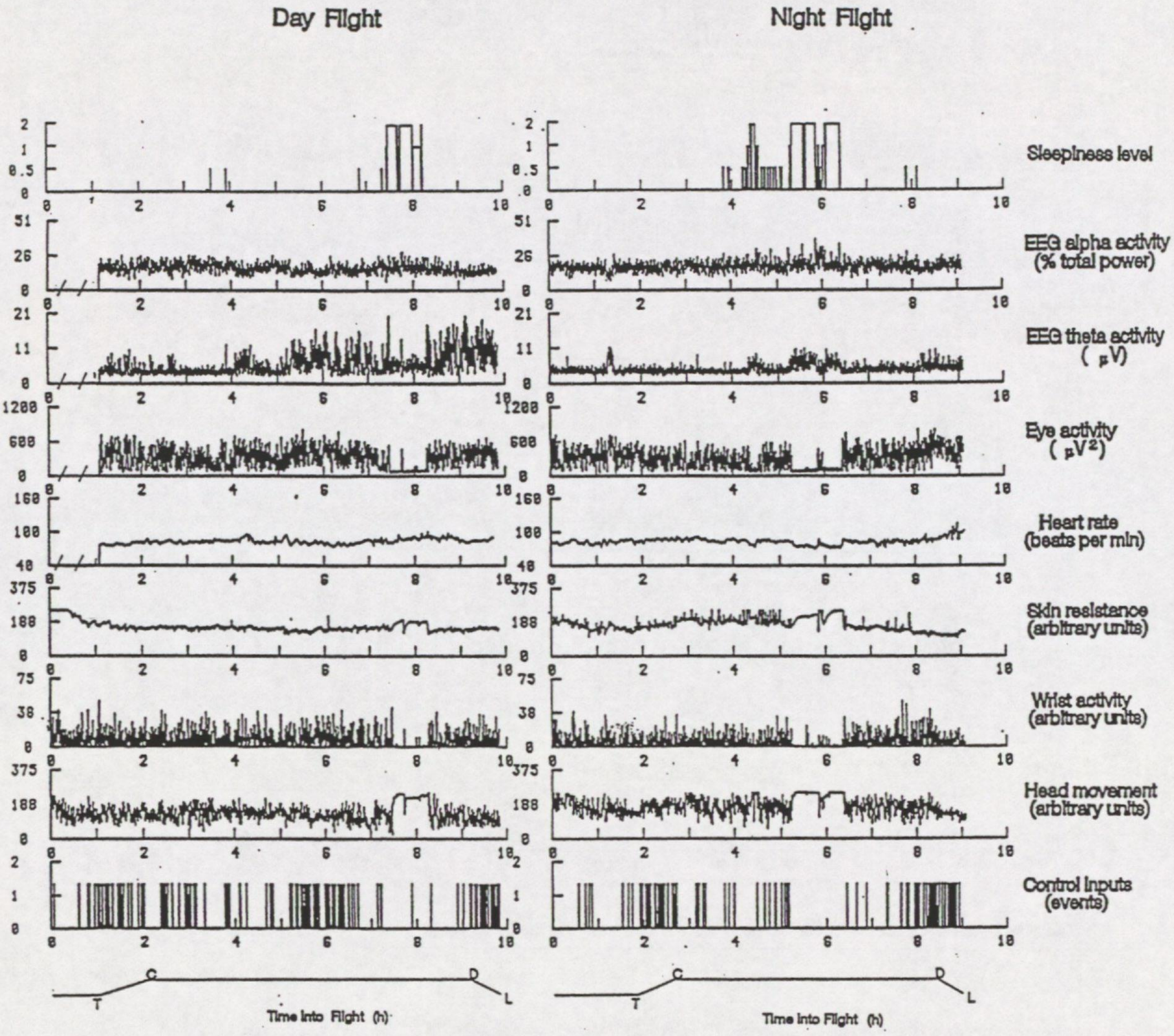
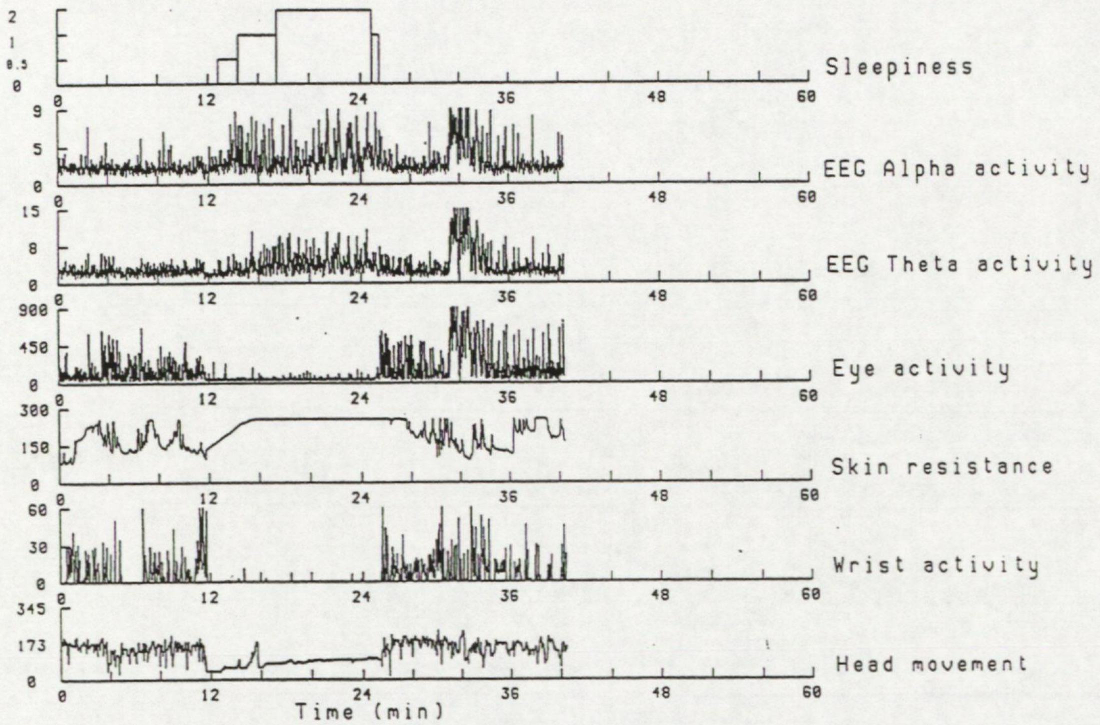
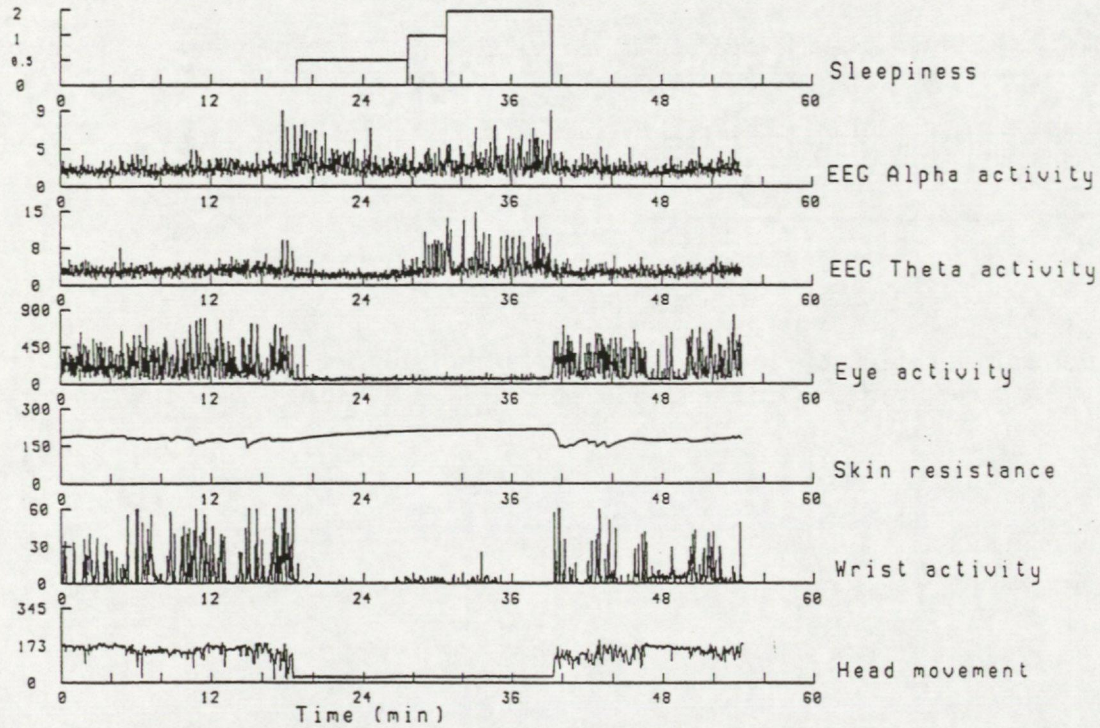


Figure 7 **Data for subject 6, for the day and overnight flights, showing each variable as a time series, with the sleepiness profile at the top**

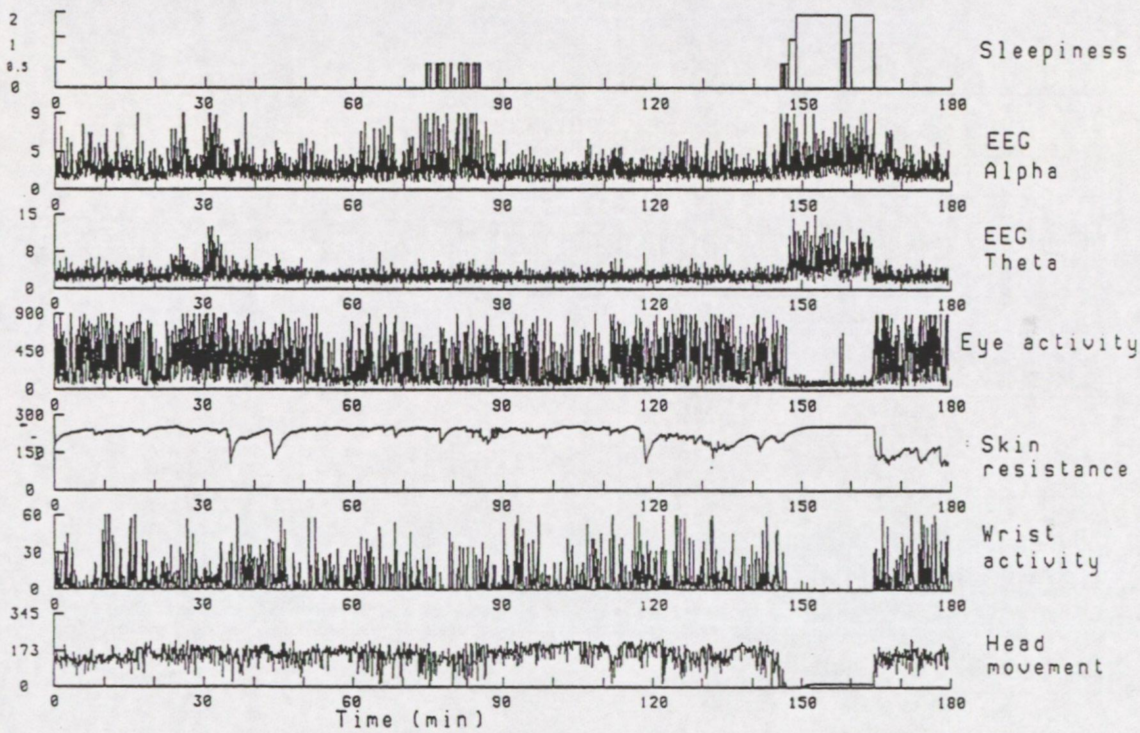


(a) Subject 2 Night Flight (from 5.6h into flight)

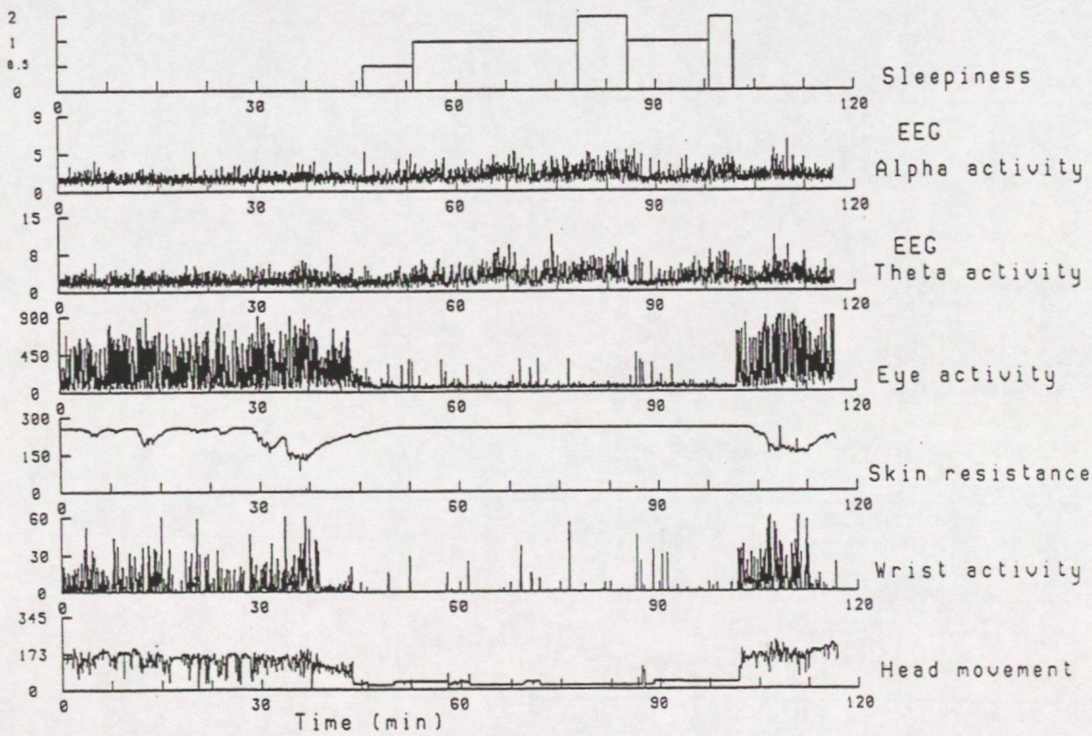


(b) Subject 3 Day Flight (from 6.5h into sector)

Figure 8(a)–(i) Time series data for all subjects who slept for any significant amount of time, starting from a period of wakefulness before the episode of sleep and followed by subsequent wakefulness lasting a similar period. Time into sector of the start of the data segment is indicated as a subheading

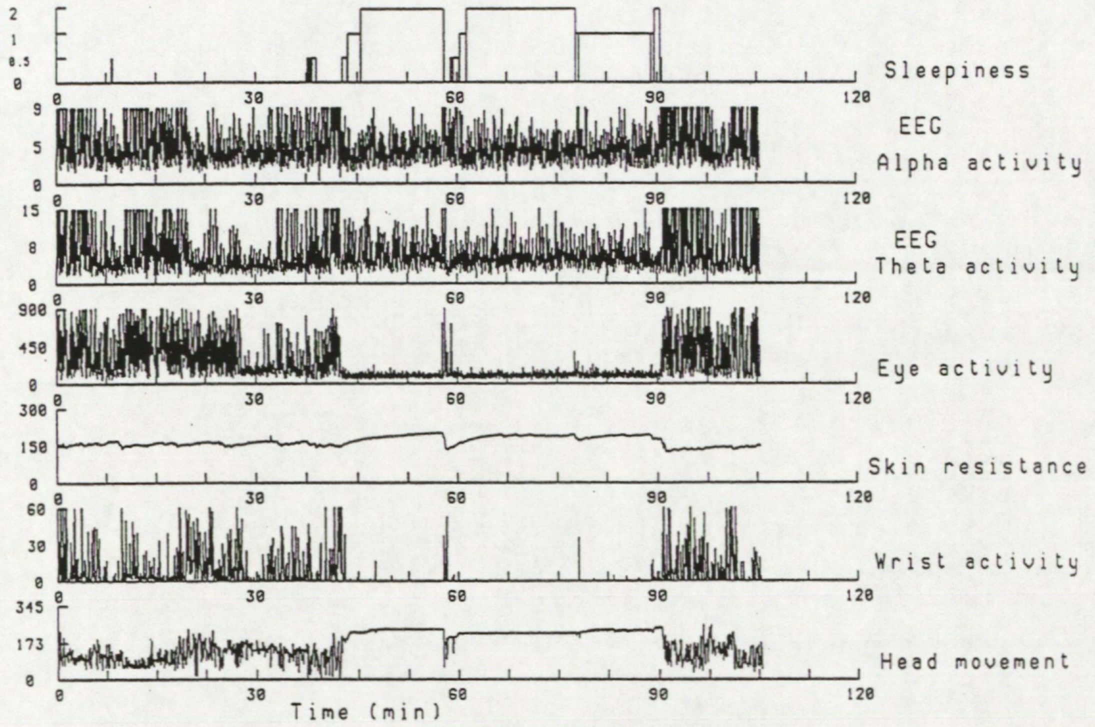


(c) Subject 4 Night Flight (from 2.5h into sector)

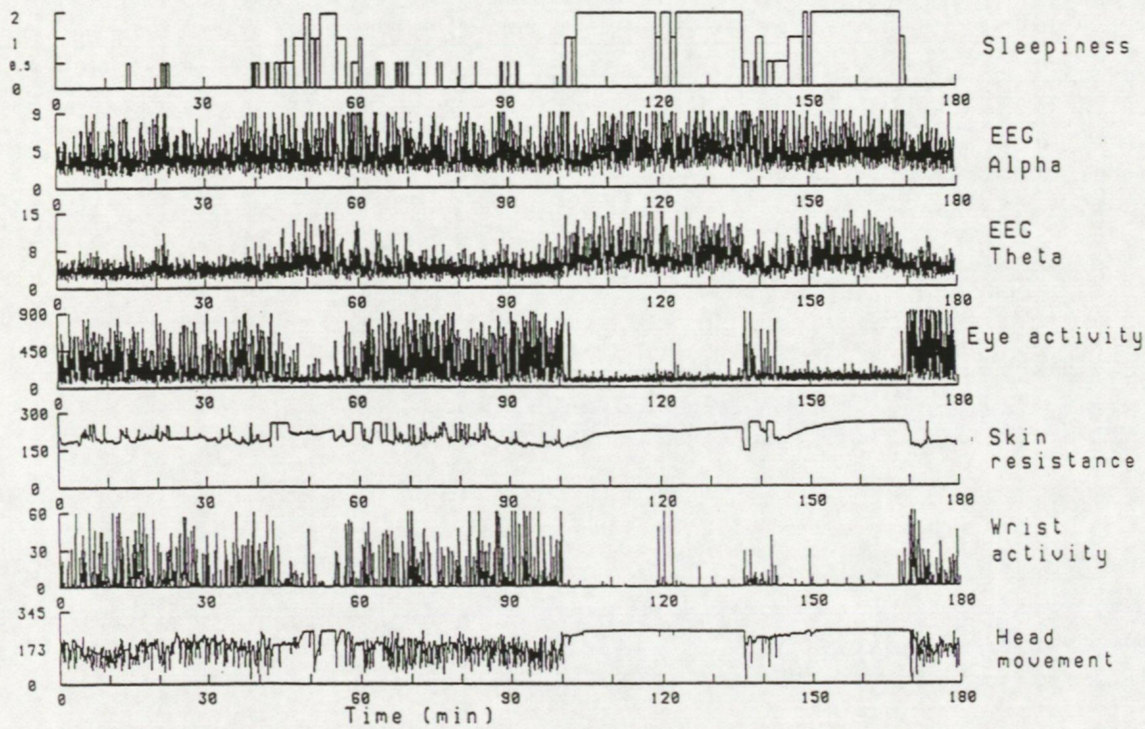


(d) Subject 5 Night Flight (from 3.2h into sector)

Figure 8(a)–(i) (continued)

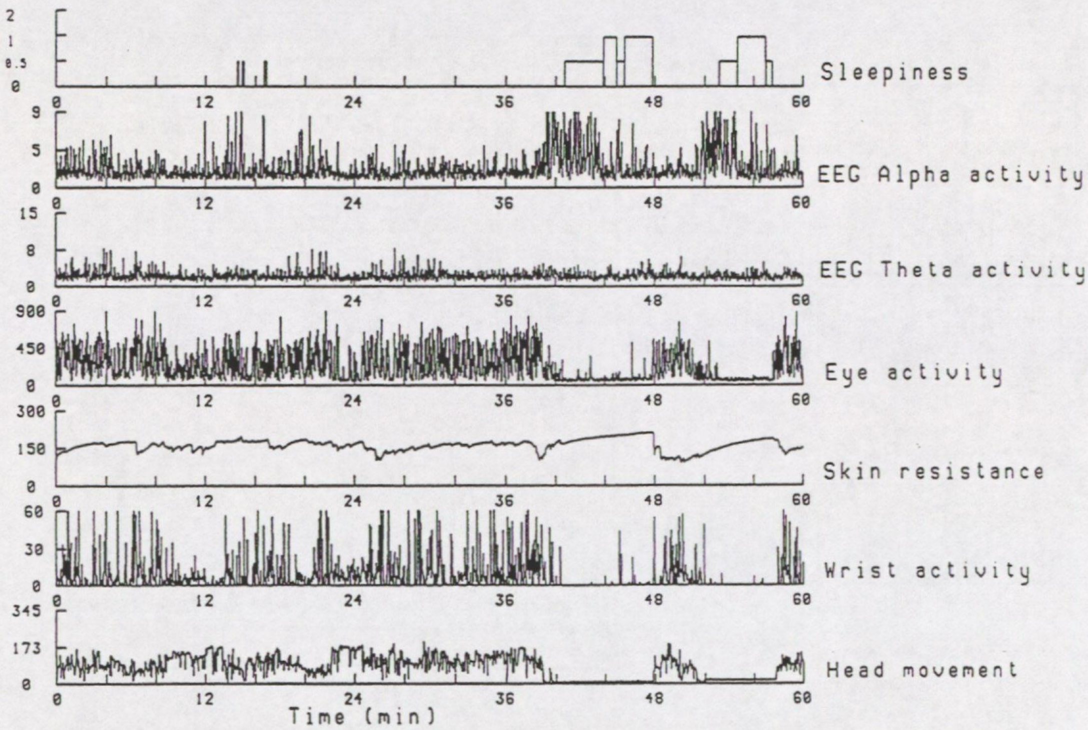


(e) Subject 6 Day Flight (from 6.7h into sector)

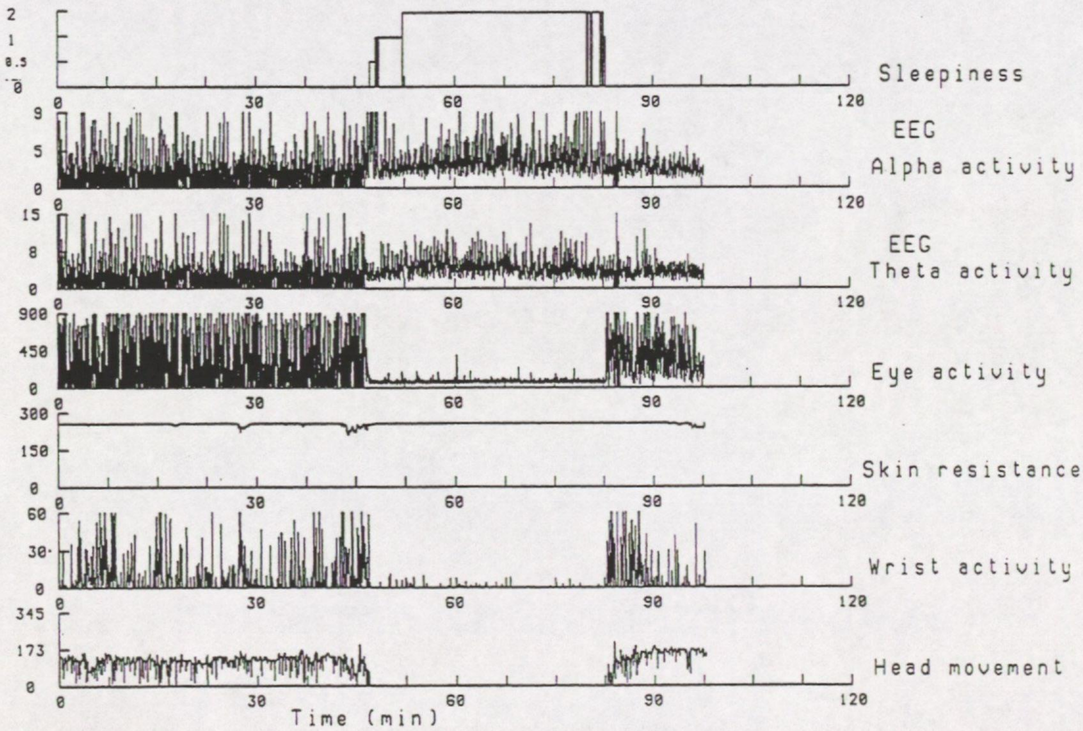


(f) Subject 6 Night Flight (from 3.6h into sector)

Figure 8(a)–(i) (continued)

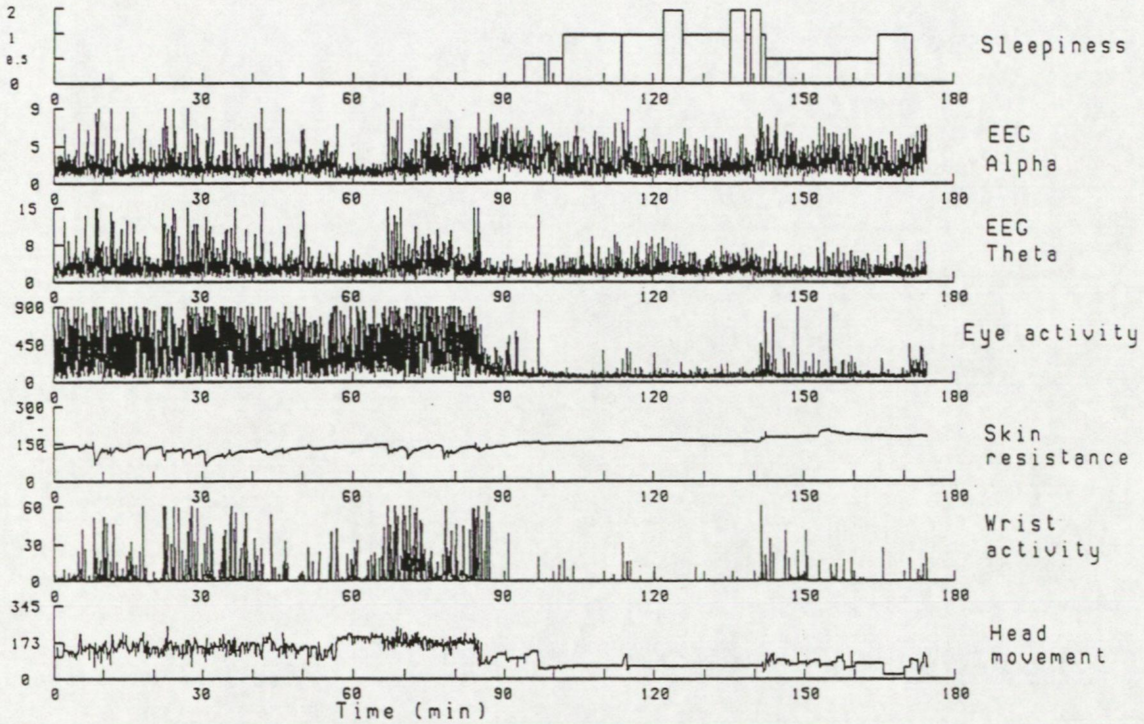


(g) Subject 7 Day Flight (from 2.2h into sector)



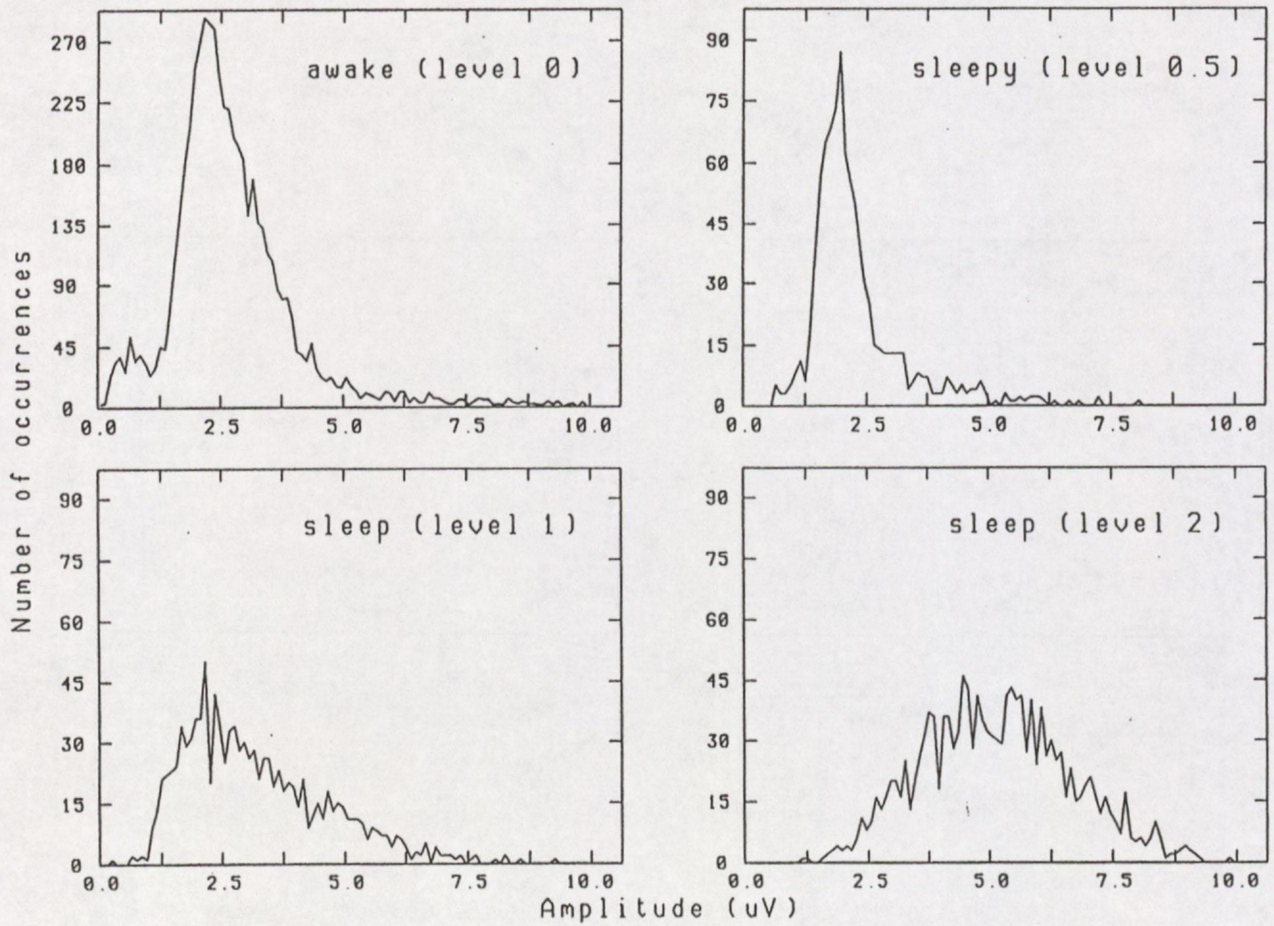
(h) Subject 7 Night Flight (from 5.1h into flight)

Figure 8(a)–(i) (continued)



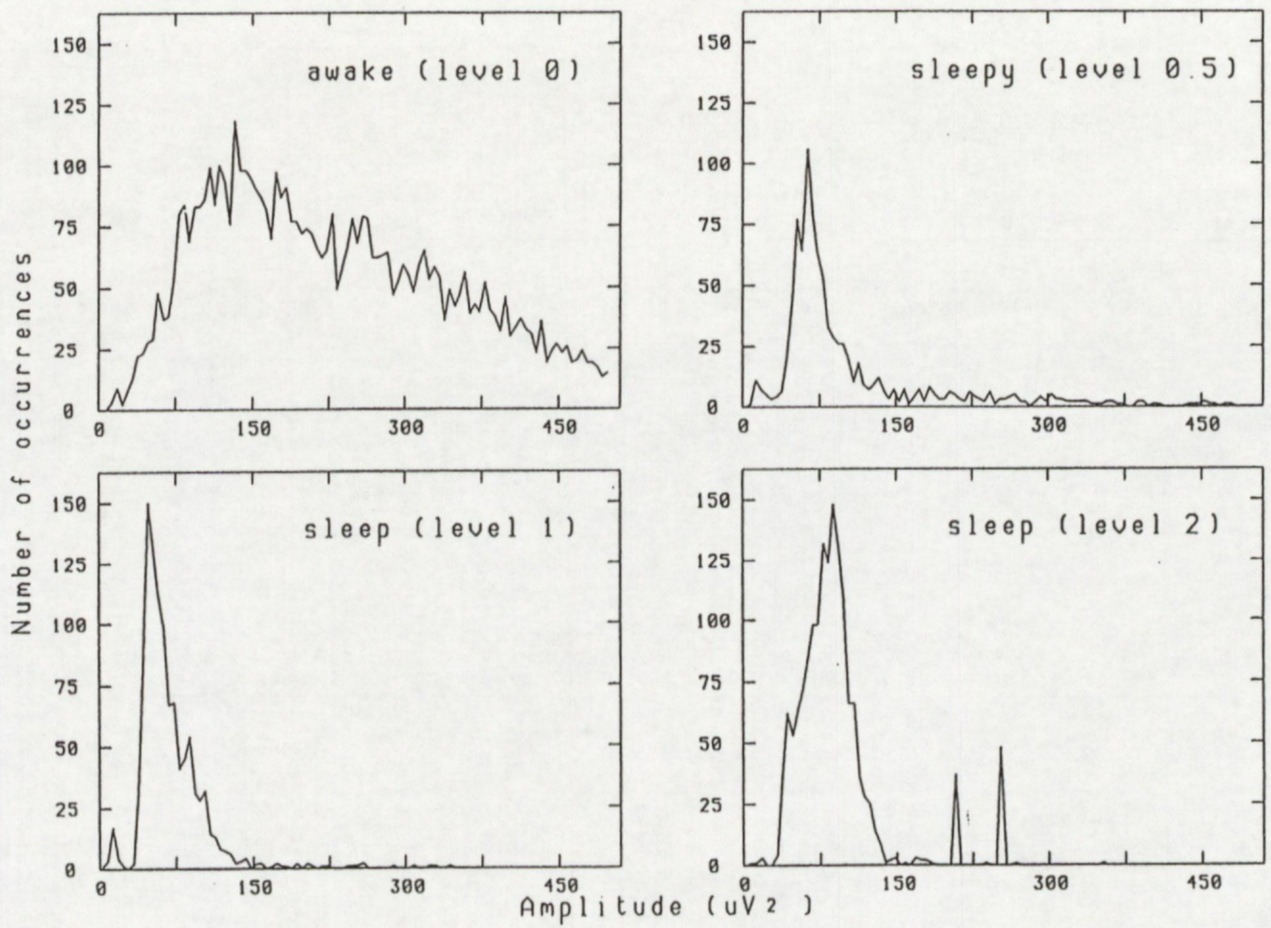
(i) Subject 11 Night Flight (from 2.25h into flight)

Figure 8(a)–(i) (continued)



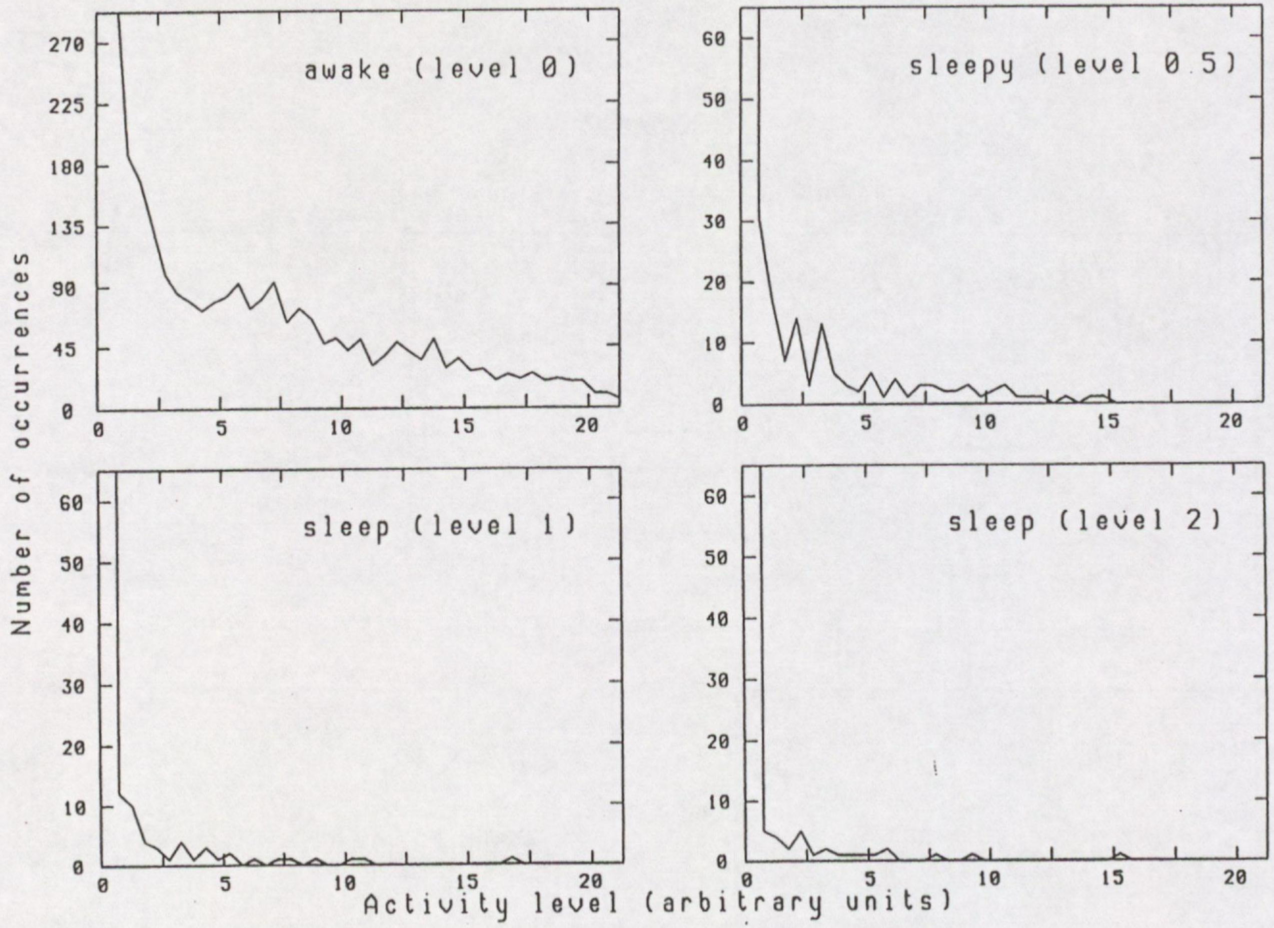
(a) for EEG theta

Figure 9 Amplitude distributions for wakefulness and sleep levels 0.5, 1 and 2



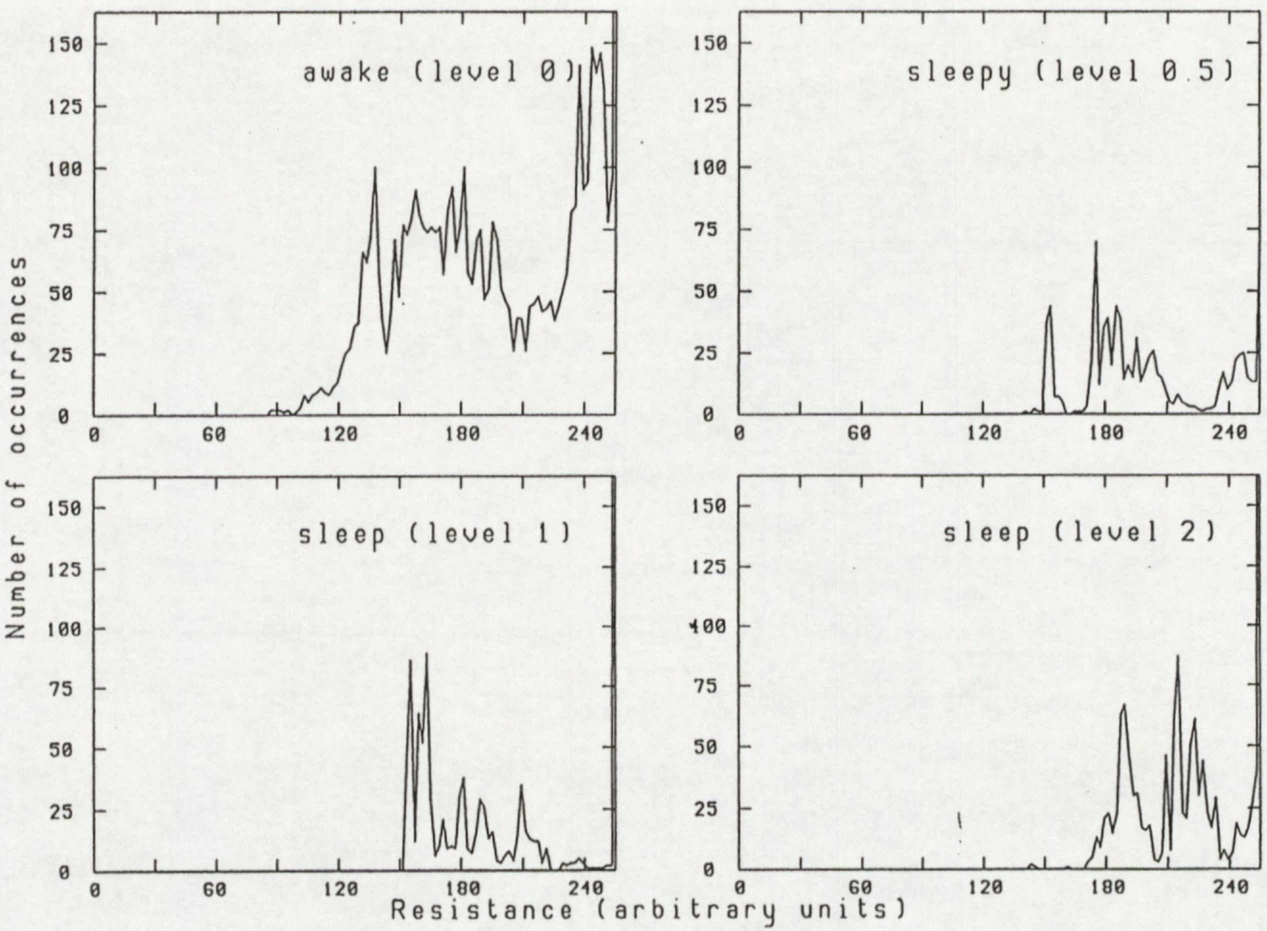
(b) for eye activity

Figure 9 (continued)



(c) wrist activity

Figure 9 (continued)



(d) skin resistance

Figure 9 (continued)

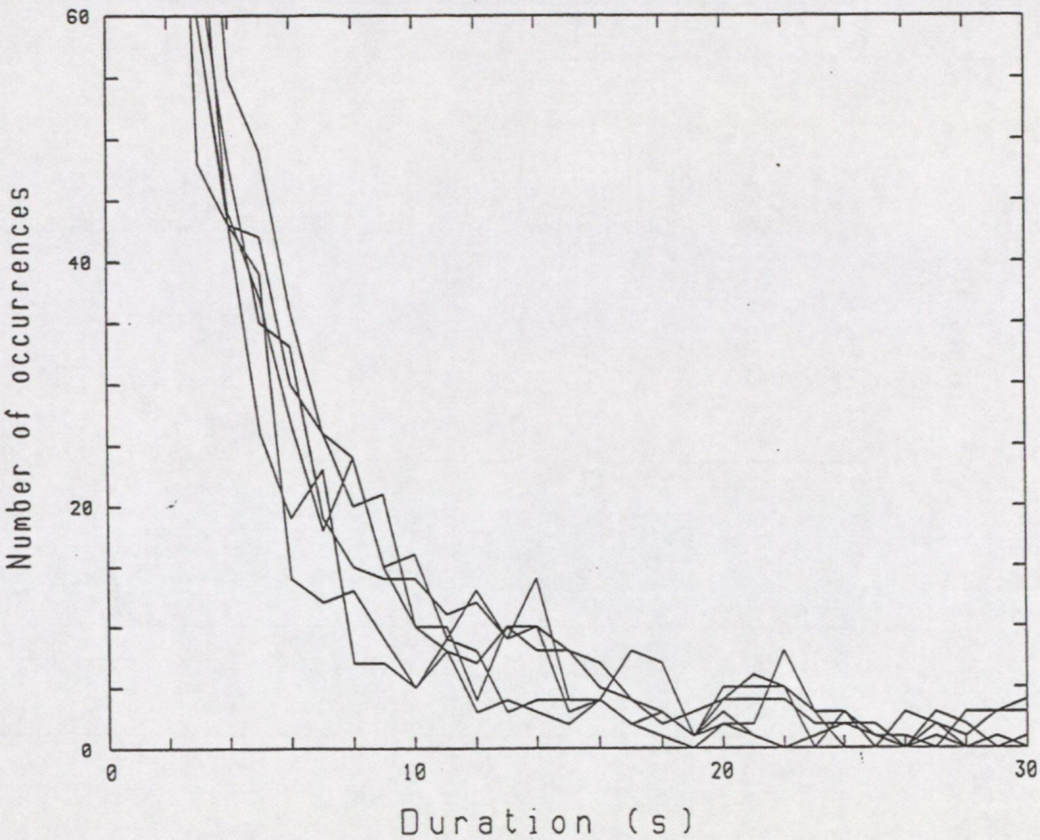


Figure 10 Distribution of periods of wrist inactivity for 6 subjects, typical of the group of 12

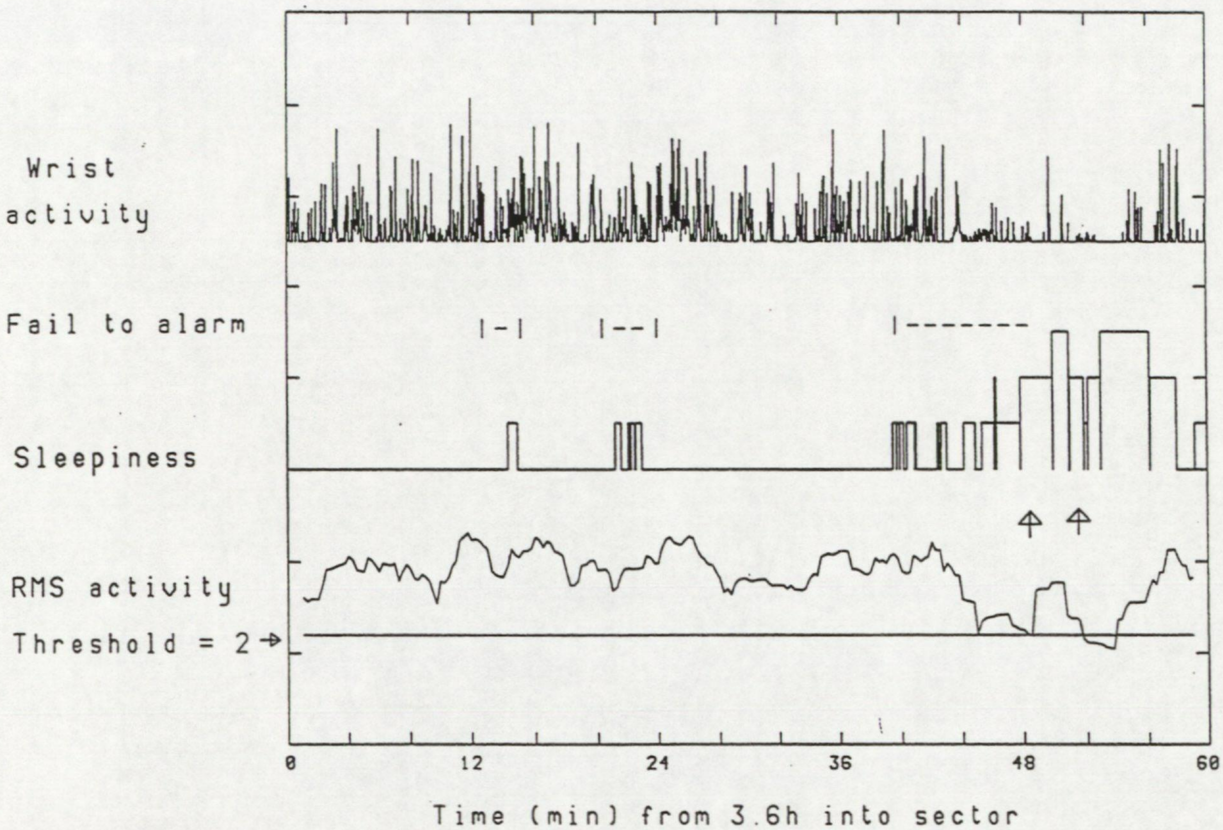


Figure 11 An example of an alarm system based on wrist activity for a segment of data from subject 6 when he was falling asleep. The time series are:

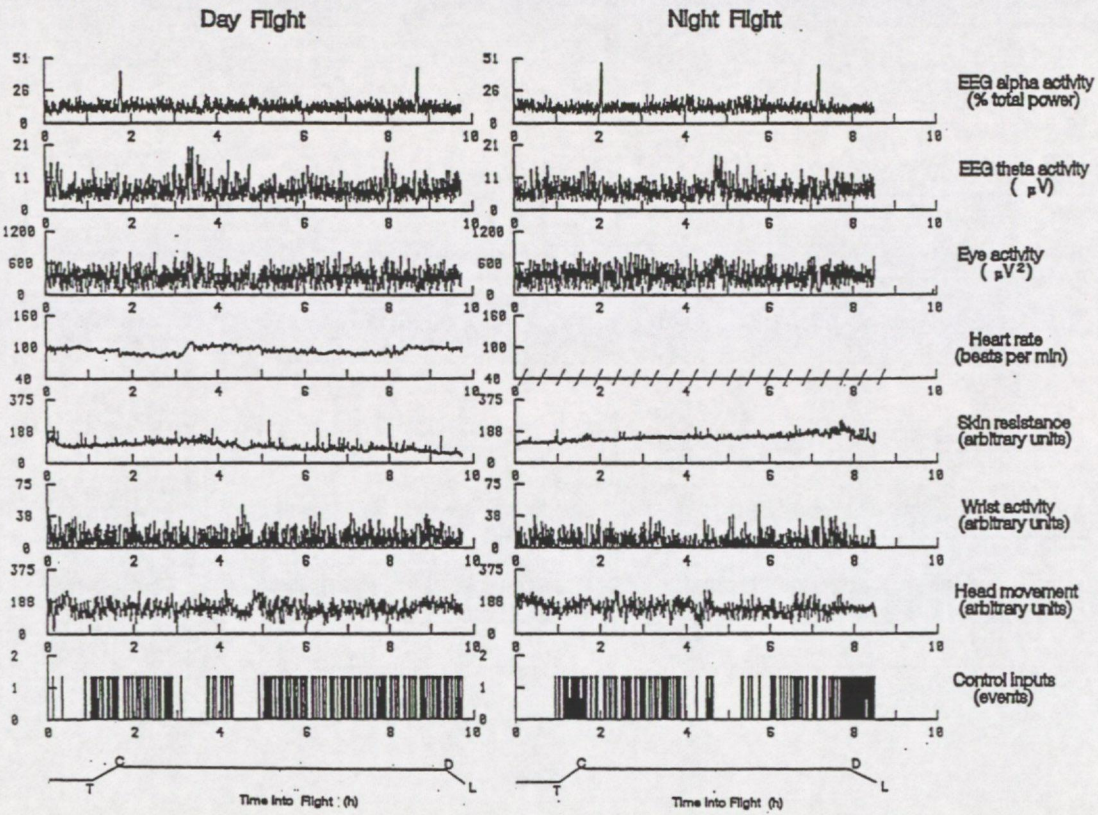
- **wrist activity (1s time resolution)**
- **incidence of false negative alarms indicated by '|---|' symbols**
- **the sleepiness profile**
- **RMS wrist activity, with an alarm threshold level superimposed.**

The parameters of the alarm were:

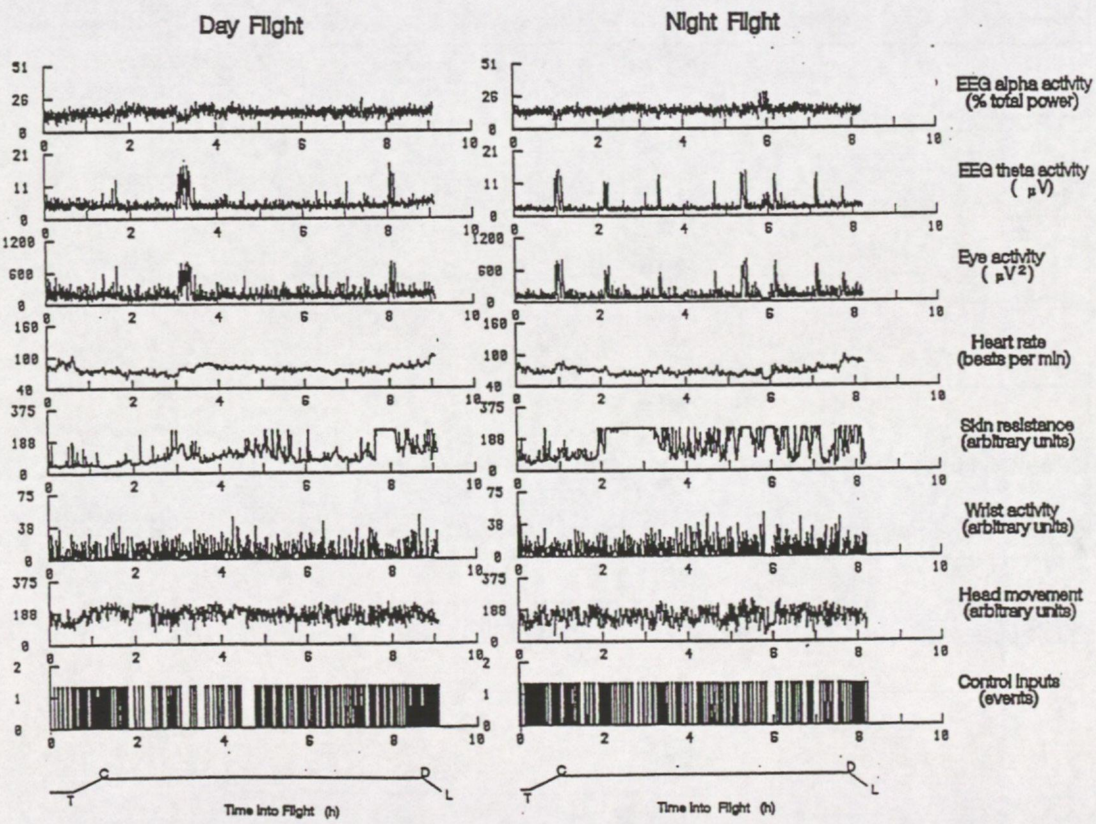
- **integration interval 120s**
- **update rate 15s**
- **threshold level 2.0.**

Activation of the alarm is shown by an upwards arrow below the sleepiness profile

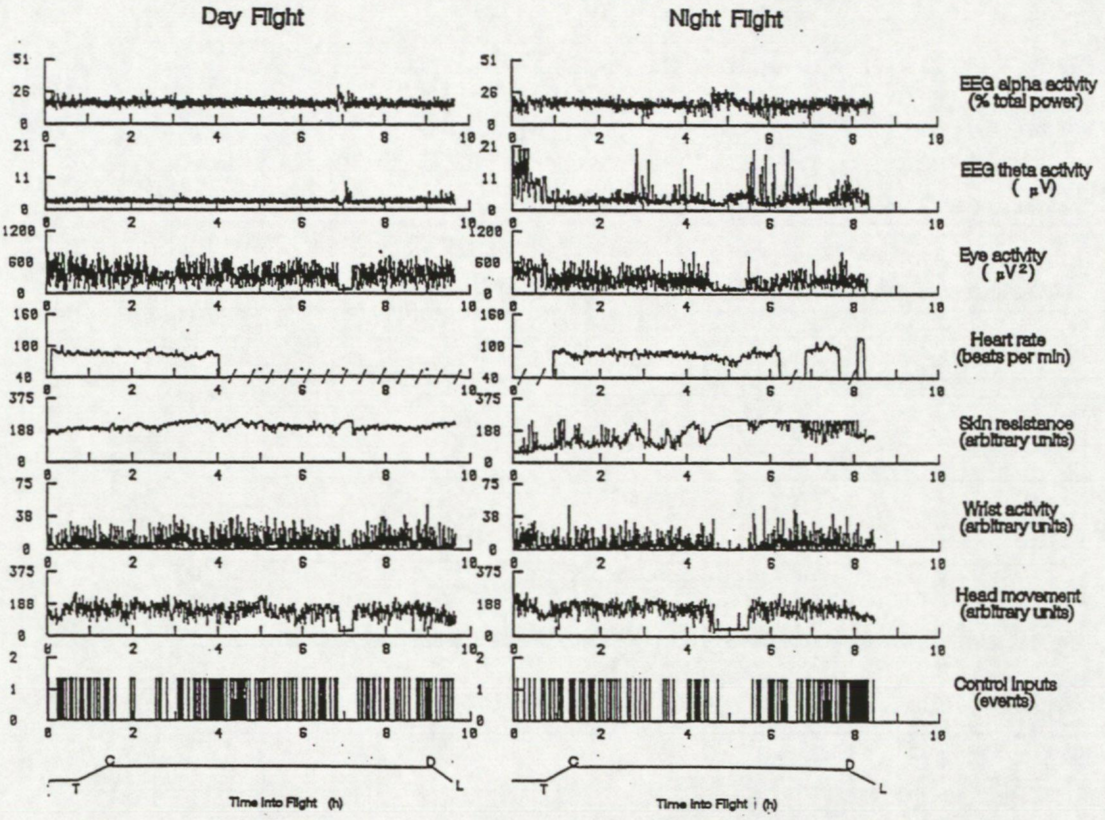
Appendix Data for Subject Nos 1–5 and 7–12



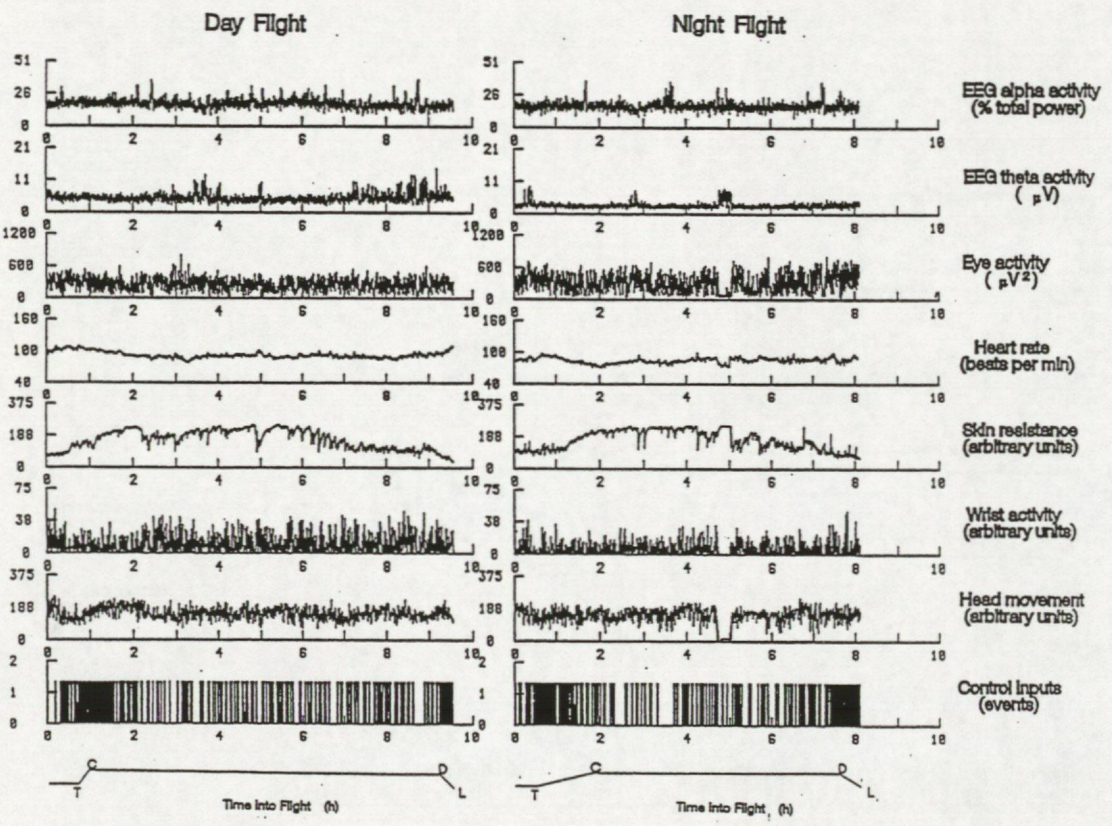
Subject 1



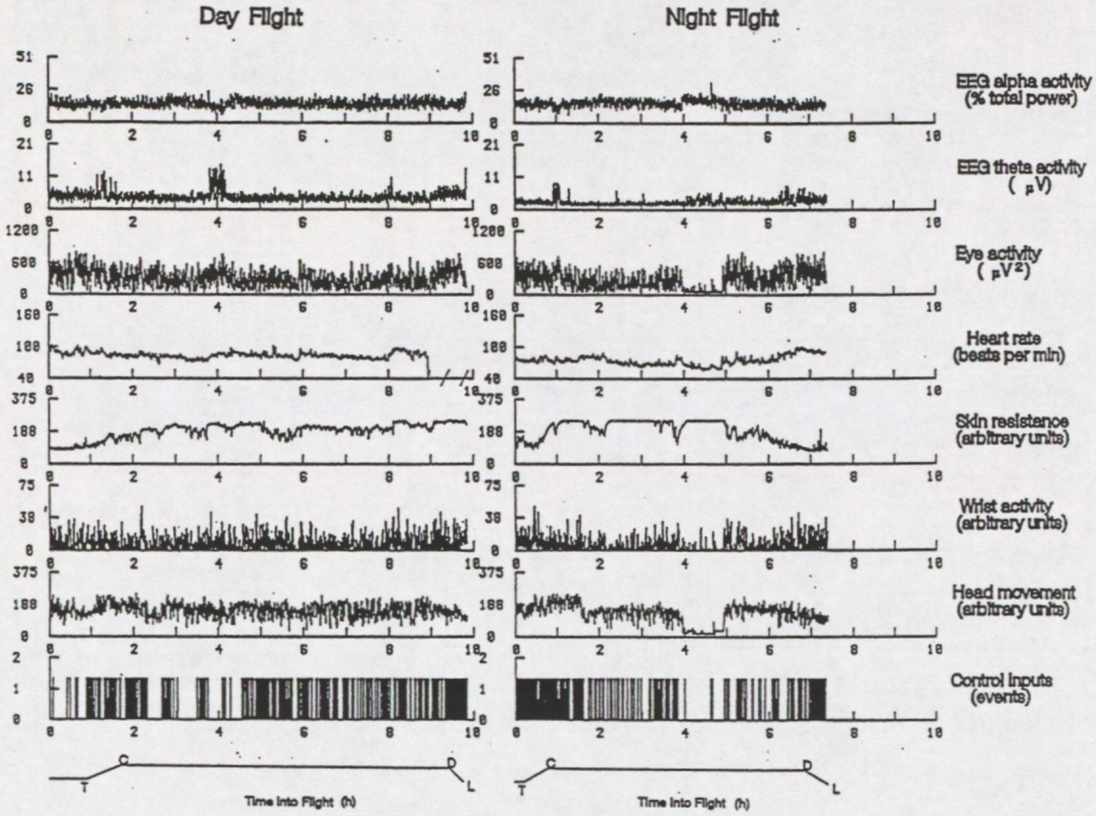
Subject 2



Subject 3



Subject 4



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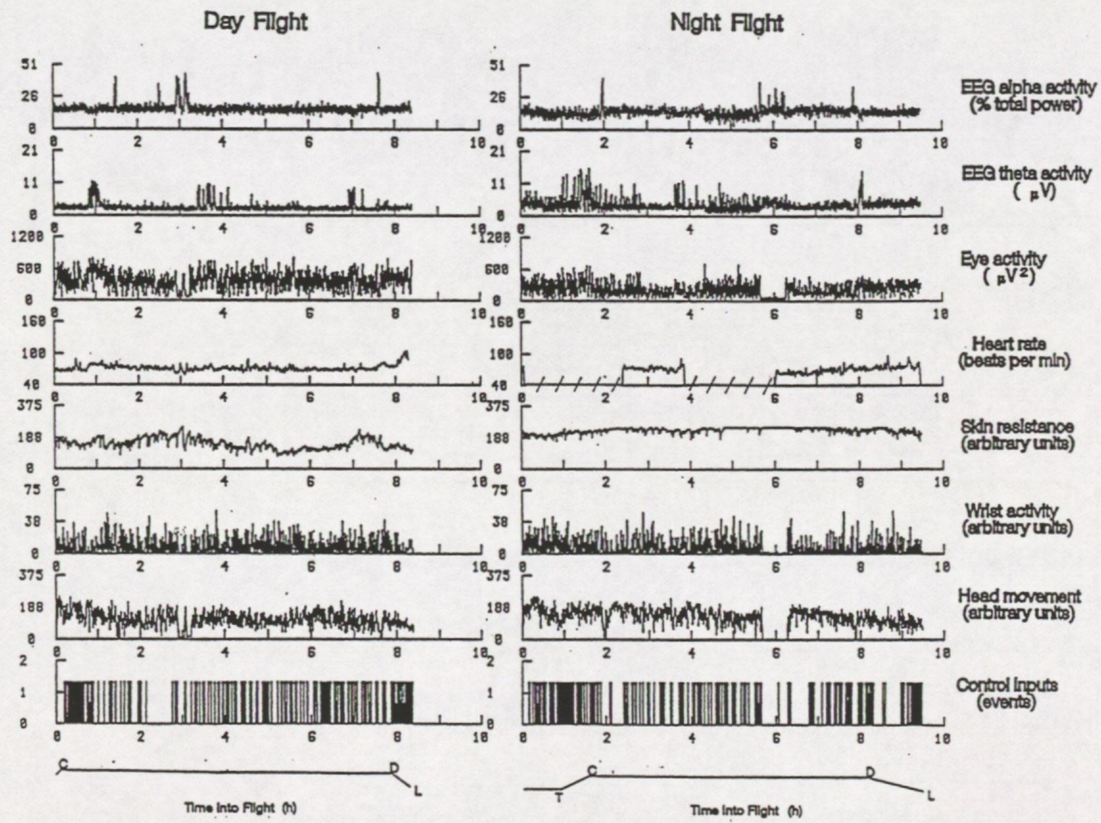

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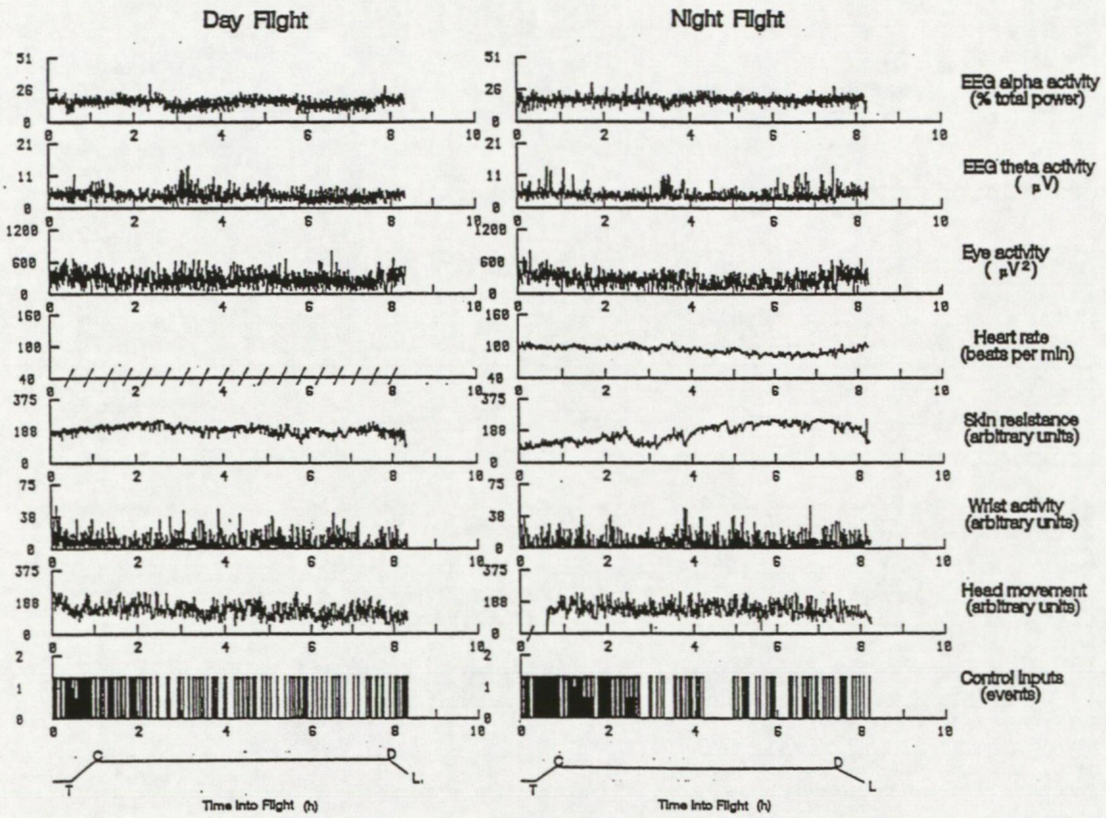

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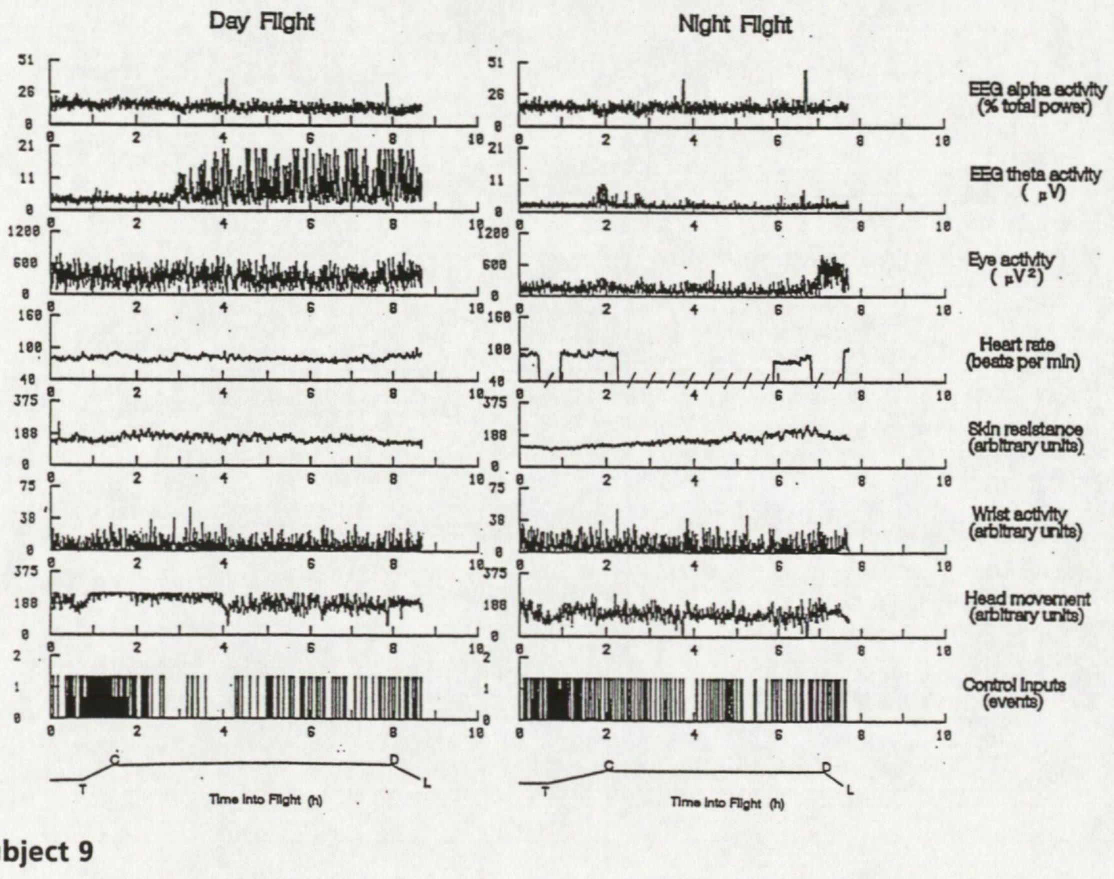
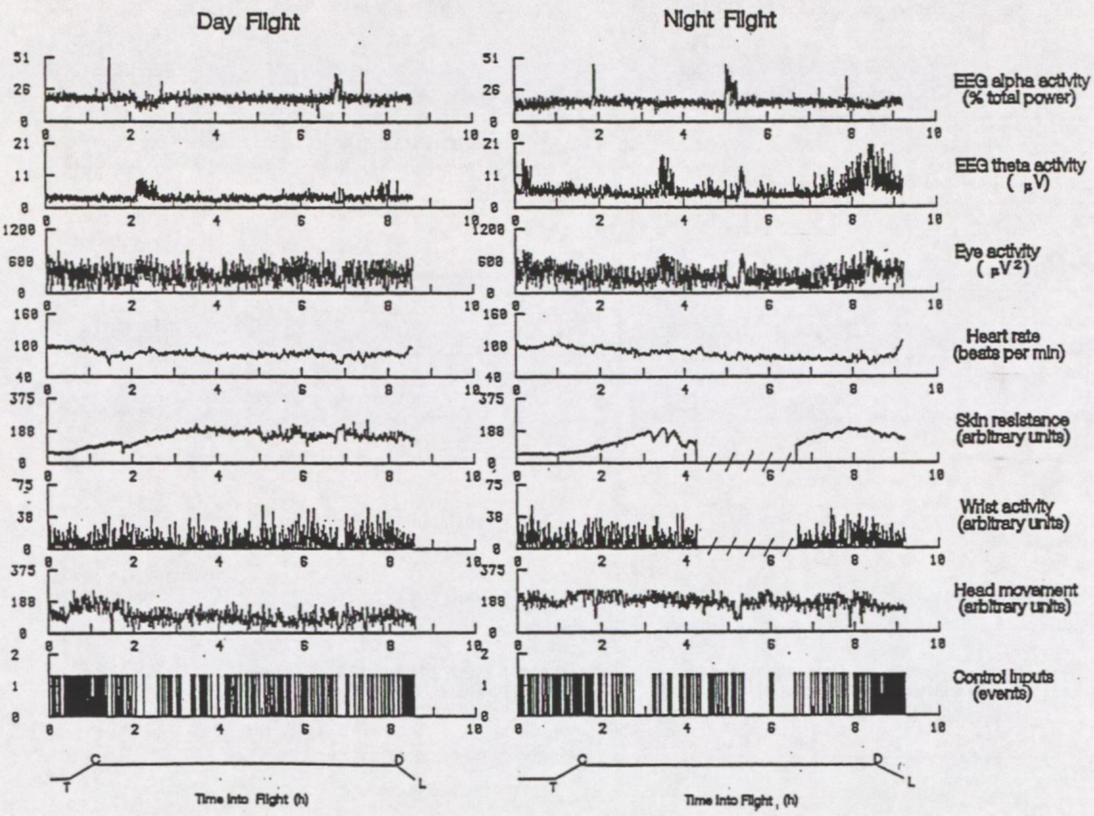
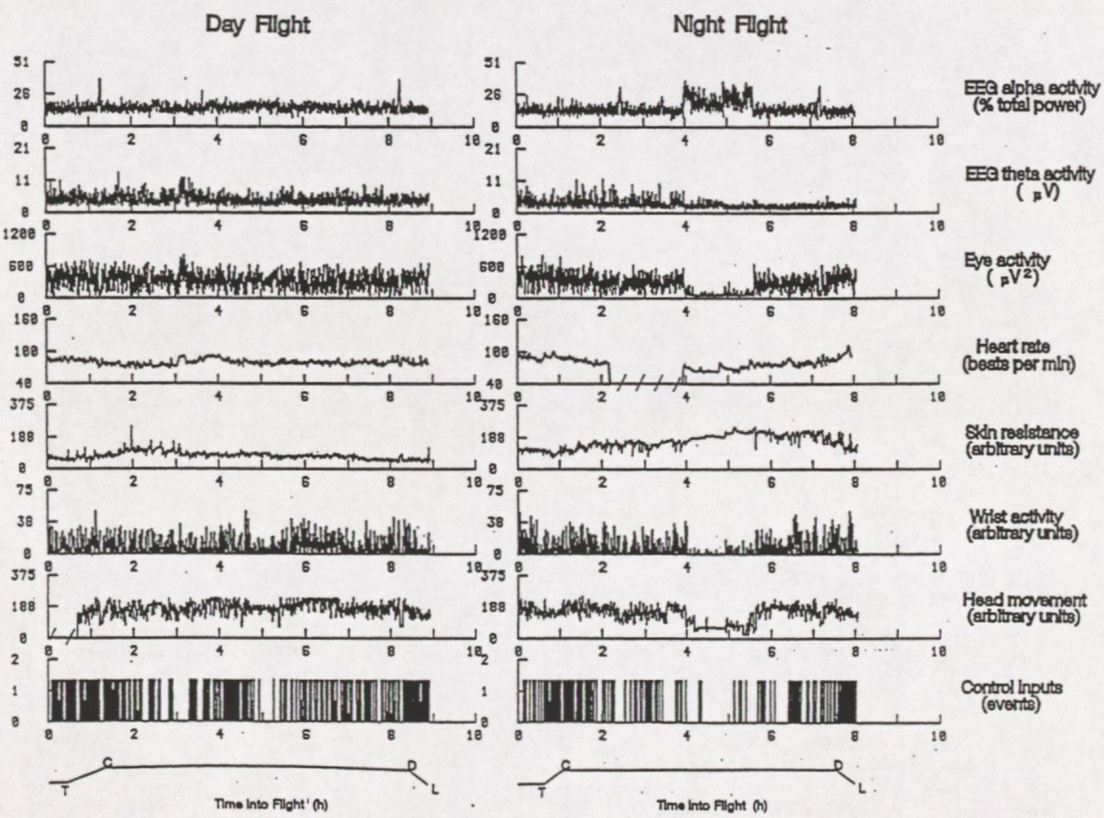


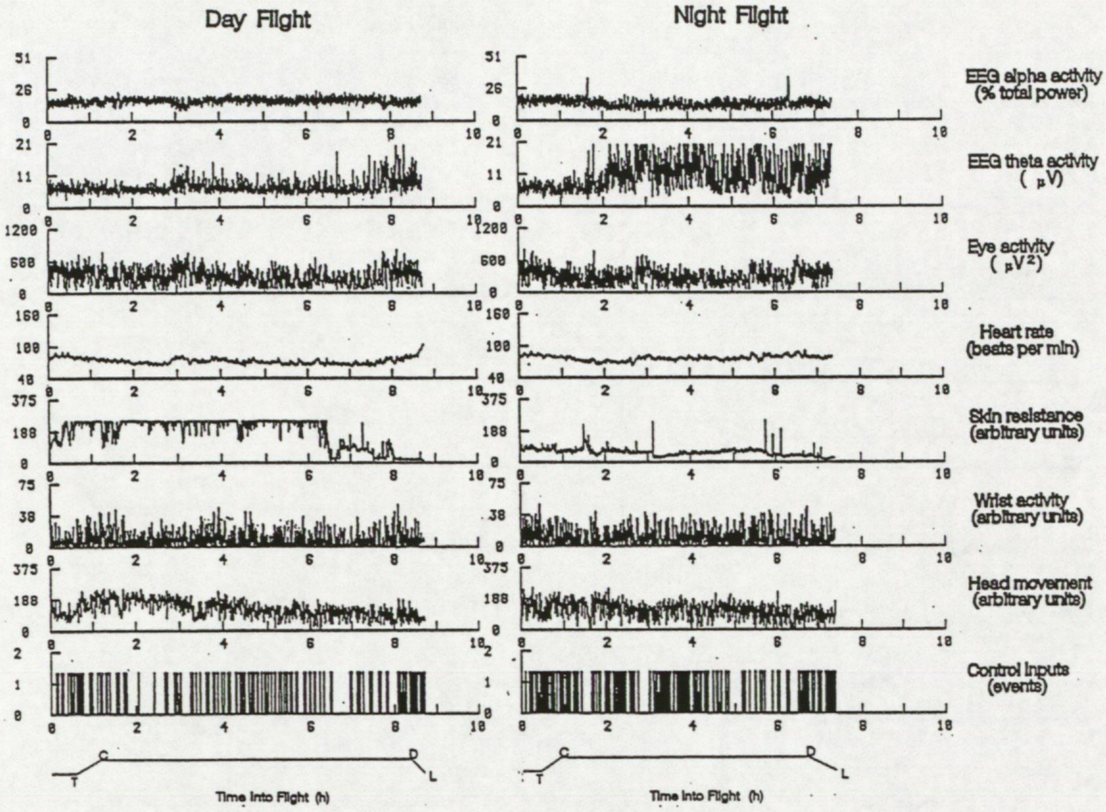
Subject 9



Subject 10



Subject 11


Day Flight
Night Flight
EEG alpha activity (% total power)
EEG theta activity (μV)
Eye activity (μV²)
Heart rate (beats per min)
Skin resistance (arbitrary units)
Wrist activity (arbitrary units)
Head movement (arbitrary units)
Control inputs (events)
Time into Flight (h)
Time into Flight (h)

Subject 12