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Crew Factors in Flight Operations: VIII. Factors Influencing Sleep Timing and Subjective Sleep Quality in Commercial Long-Haul Flight Crews

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CREW FACTORS IN FLIGHT OPERATIONS: VIII.
FACTORS INFLUENCING SLEEP TIMING AND SUBJECTIVE SLEEP QUALITY IN COMMERCIAL LONG-HAUL FLIGHT CREWS

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Summary

This report documents how flight crews organize their sleep during layovers on long-haul trips and examines environmental and physiological constraints on sleep. In the trips studied, duty periods averaging 10.3 hr alternated with layovers averaging 24.8 hr, which typically included two subject-defined sleep episodes. The relative importance of duty requirements, local time, and the circadian system in determining sleep timing and quality was different for first and second sleep episodes in a layover, and was related to specific flight schedules. The circadian system had a greater influence on the timing and duration of first-sleeps than second-sleeps. There was also a preference for sleeping during the local night. The time of falling asleep for second-sleeps was related primarily to the amount of sleep already obtained in the layover, and their duration depended on the amount of time remaining in the layover. For both first- and second-sleeps, sleep durations were longer when subjects fell asleep earlier with respect to the minimum of the circadian temperature cycle. Naps were reported during layovers and on the flight deck, and may be a useful strategy for reducing cumulative sleep loss.

The flight schedules of the trips studied forced the sleep/wake cycle to adopt a period different from that of the circadian system (measured by body temperature). However, the two systems were not completely uncoupled, as evidenced by the influence of the circadian system on the selection of sleep times and on sleep durations. The circadian system was not able to synchronize with the rapid series of time-zone shifts.

Flight and duty time regulations can be interpreted as a means of ensuring that reasonable minimum rest periods are provided. This study clearly documents that, in scheduled commercial long-haul operations, there are physiologically and environmentally determined preferred sleep times within a layover. The actual time available for sleep is thus less than the scheduled rest period.

1. Operational Overview

This report is the eighth in a series on physiological and psychological effects of flight operations on flight crews, and the operational significance of these effects. The Operational Overview is a comprehensive review of the major findings and their significance. The rest of this volume contains the complete scientific description of the work. The aim of this study was to document how flight crews organize their sleep during a variety of international trip patterns, and to elucidate how duty requirements, local time, and the circadian system (measured by the rhythm of body temperature) influence the choice of sleep times, sleep duration, and subjectively rated sleep quality. Duty requirements and local time can be viewed as environmental constraints on the time available for sleep, while the circadian system is a major physiological modulator of sleep quality and duration.

Self-reports of sleep (and nap) timing and sleep quality, and continuous records of rectal temperature were collected from 29 male flight crew members (average age 52 yr) during scheduled B-747 commercial long-haul operations. Data from four different trip patterns (figs. 2(a)-2(d)) were combined.

Sleep/wake patterns on these trips were complex. On average, duty periods lasted about 10.3 hr and were followed by layovers of about 24.8 hr during which there were typically two subject-defined sleep episodes. The average pattern of sleep and wakefulness (disregarding naps) was 19 hr wake/5.7 hr sleep/7.4 hr wake/5.8 hr sleep. The average durations of the first- and second-sleep episodes in a layover were not significantly different, despite the fact that first-sleeps followed significantly longer episodes of wakefulness. However, first-sleeps were rated as being of better quality, with less difficulty falling asleep and deeper sleep. Sleep-quality ratings

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improved as sleep duration increased, reinforcing the importance of allowing adequate time for sleep.

The circadian system appeared to have a greater influence on the timing and duration of first-sleep episodes than on second-sleep episodes in the layover, except when the level of accumulated sleep debt was high, e.g., after eastward flights crossing five or more time zones. In such cases, crew members typically went to sleep sooner after arriving at the layover destination, during the local afternoon, and woke up either about 2 hr later (if they reported a nap) or 3 hr later (if they reported a sleep episode). Otherwise, crew members tended to delay going to sleep until the local night and/or until the hours preceding the temperature minimum.

The timing of second-sleep onsets seemed to be related primarily to the amount of sleep already obtained in the layover and generally coincided with local night. The duration of second-sleeps was strongly influenced by the amount of time remaining in the layover. For both first- and second-sleeps, the circadian time of sleep onset was also a significant predictor of sleep duration. Longer sleep episodes began earlier with respect to the minimum of the circadian temperature cycle.

In summary, the relative importance of duty requirements, local time, and the circadian system in determining sleep timing and quality was different for first- and second-sleep episodes in a layover, and was related to specific flight schedules. Nevertheless, there were clearly preferred times for sleep within the layover, determined by the circadian modulation of sleep propensity and the factors driving the preference to sleep during the local night (noise, light, meal availability, etc).

Flight and duty-time regulations can be interpreted as a means of ensuring that reasonable minimum rest periods are respected. There has been a tendency on the part of regulatory authorities to view the entire time off duty as being time available for sleep, despite anecdotal evidence that the ease of falling asleep and the ability to remain asleep were not constant throughout a layover. This study clearly documents that in scheduled commercial long-haul operations, there are physiologically and environmentally determined preferred sleep times within a layover, i.e., the time available for sleep is less than the time off duty.

Evidence from this and other studies suggests that the timing and duration of the second-sleep episode in a layover is strongly linked to the amount of sleep already obtained in the layover. Particularly when the first-sleep is short, as is typical after eastward flights crossing five or more time zones, it is essential that the layover be long enough to permit an adequate second-sleep episode appropriately timed with respect to the temperature cycle and local time. The duration of any specific layover should be determined with regard to the local arrival time, and the sequence of flights preceding it in the trip pattern, which influences both the cumulative sleep loss and the phase of the circadian system.

Based on polygraphic studies of flight crew sleep after a single eastward flight crossing eight or nine time zones, Graeber et al. (ref. 1) recommended that crew members should limit sleep immediately after arrival and prolong the subsequent wake period to end around the normal local time for sleep. This is intended to improve the quality of the subsequent sleep episode, in keeping with the anecdotal report that flight crews consider it important to have a good sleep immediately before a flight. Their study looked only at sleep during the first (24 hr) layover of a trip sequence. The present study suggests that the recommended strategy may not be optimal after eastward flights later in the sequence, when crew members may have already accumulated an important sleep debt, and when the position of their circadian timing system would be much less predictable.

Naps were also reported, both during layovers and on the flight deck. Naps that represented the first-sleep episode in a layover were significantly longer (average duration 2.0 hr) than subsequent naps in the layover or flight-deck naps, and followed significantly longer episodes of wakefulness (14.7 versus 5.9 and 9.3 hr, respectively). Such first naps were not very common and were associated with the acute sleep debt imposed by overnight eastward flights crossing five or more time zones (67%) or the prolonged wakefulness associated with westward flights crossing five or more time zones (25%). Naps later in the layover tended to occur just before the next duty period and, since they reduce the duration of continuous wakefulness before the next flight, may be useful as a strategy for reducing cumulative sleep loss (ref. 2).

On the flight deck, crew members were observed to be napping at least 11% of the available time. The average duration of these naps was 46 min (range 10-130 min). Recent work from our group suggests that a preplanned 40-min time interval for napping on the flight deck can reduce subsequent reaction times (ref. 3) and the number of EEG/ECG microevents during long international flights (ref. 4). The optimal duration of such naps is an active research issue (ref. 5).

This study has significantly enhanced our understanding of how the circadian system functions in this complex operational environment. The flight schedules of the trips studied forced the sleep/wake cycle to adopt a period different from that of the underlying circadian pacemaker, although the influence of the circadian system was still seen in the selection of sleep times and in sleep durations, i.e., the two systems were not completely uncoupled. However, when the accumulated sleep debt was high, the circadian rhythm in sleep propensity could be overidden, and crew members could fall asleep at unusual times in their temperature cycles. The circadian system, in turn, effectively uncoupled from the very complex patterns of environmental synchronizing stimuli experienced by crews.

There are known to be differences between individuals in (1) the periods of their circadian pacemakers; (2) their sensitivity to environmental synchronizers; and (3) their self-selected patterns of exposure to social and sunlight cues in each time zone. At least some of these factors may be associated with certain personality profiles and probably all are age-dependent. An analysis of questionnaire data from 205 of the flight crew members in our data bases concurs with other studies suggesting that the period of the circadian pacemaker shortens with age (Gander, unpublished results). Age-related changes in sleep are also well documented, including shorter, less efficient nocturnal sleep and increased physiological sleepiness during the day (reviewed by Bliwise in ref. 6).

The timing and quality of sleep obtained by flight crews is the product of a subtle and dynamic interplay between all of these factors and cannot be captured by any simple predictive algorithm. Based on the insights gained in this and other studies, we see two particularly promising approaches to improving en route sleep for flight crews during international commercial trip patterns. The first is education, providing crew members with basic information about sleep and the functioning of the circadian system, and how their behavior can modify both. Second, expert system technology should be used to combine our understanding of the underlying physiological systems with operational knowledge acquired from flight crew members and schedulers to develop a computerized intelligent scheduling assistant.

2. Introduction

Ensuring adequate en route sleep for flight crews during international commercial trips is a complex and sensitive issue. It is considered important for operational efficiency and safety, as well as for the health and well-being of the individual flight crew member (ref. 7). The traditional approach to ensuring adequate sleep has been through flight and duty time regulations (ref. 8); however, these regulations are based largely on heuristics and have not always kept pace with the latest scientific findings about the factors controlling sleep quantity and quality. A major impediment has been the lack of field data examining the interaction of the multiple factors likely to influence sleep quantity and quality in operational situations, as opposed to the simplified environment of controlled laboratory studies. The aim of the present study was to document how flight crews organize their sleep during a variety of international commercial trips, and to try to elucidate which environmental and physiological factors influenced the choice of sleep times, sleep duration, and subjectively rated sleep quality.

Even under controlled laboratory conditions, the physiology of sleep regulation is complex (fig. 1). Sleep is not a single state. During a normal night of sleep, humans alternate repeatedly between two distinct types of sleep, in a cycle lasting about 90 min. The major part of the cycle is usually spent in non-REM (non-rapid eye movement) sleep which is classified in four stages. Stages 1-2 represent lighter sleep, and stages 3-4 are deeper "slow-wave" sleep. Non-REM sleep alternates with REM sleep, which is the state most consistently associated with dreaming (ref. 9). Sleep quality, as judged by subsequent daytime sleepiness and performance measures, is associated with sleep duration and continuity, i.e., with the number of awakenings (often not perceived or remembered by the sleeper) which occur during the sleep episode (ref. 10).

Currently, at least three interacting processes are envisaged in the physiological regulation of sleep timing and quality (refs. 11 and 12). First, several models have been proposed for the mechanism regulating the non-REM/REM cycle within a sleep episode (reviewed in ref. 12). Second, a homeostatic process is envisaged in which "sleep need" (perhaps a chemical factor) accumulates during wakefulness and dissipates (or is broken down) during sleep. The time-course of this homeostatic process is reflected in the depth of the slow-wave sleep bouts (delta spectral power density), which become progressively shallower and shorter throughout a normal night sleep, and progressively longer and deeper as the length of preceding wakefulness increases. In fact, prolonged wakefulness is not followed by proportionally longer total sleep, but rather by deeper and longer slow-wave sleep bouts. The time-course of the homeostatic sleep process can only be derived from polygraphic sleep recording of all sleep episodes. Although this is an extremely difficult procedure in the context of airline operations, it has been done in recent studies of pilots flying polar routes between Europe and Japan (ref. 13). Third, laboratory studies indicate that the phase of the daily cycle of the circadian body clock at which sleep begins influences (1) the ease of falling asleep, (2) the duration of the sleep episode, and (3) the amount of time spent in REM sleep (refs. 14-17). The phase of the circadian cycle is usually tracked by monitoring the rhythm of rectal temperature. There are two intervals during the (24-hr) day when it is relatively

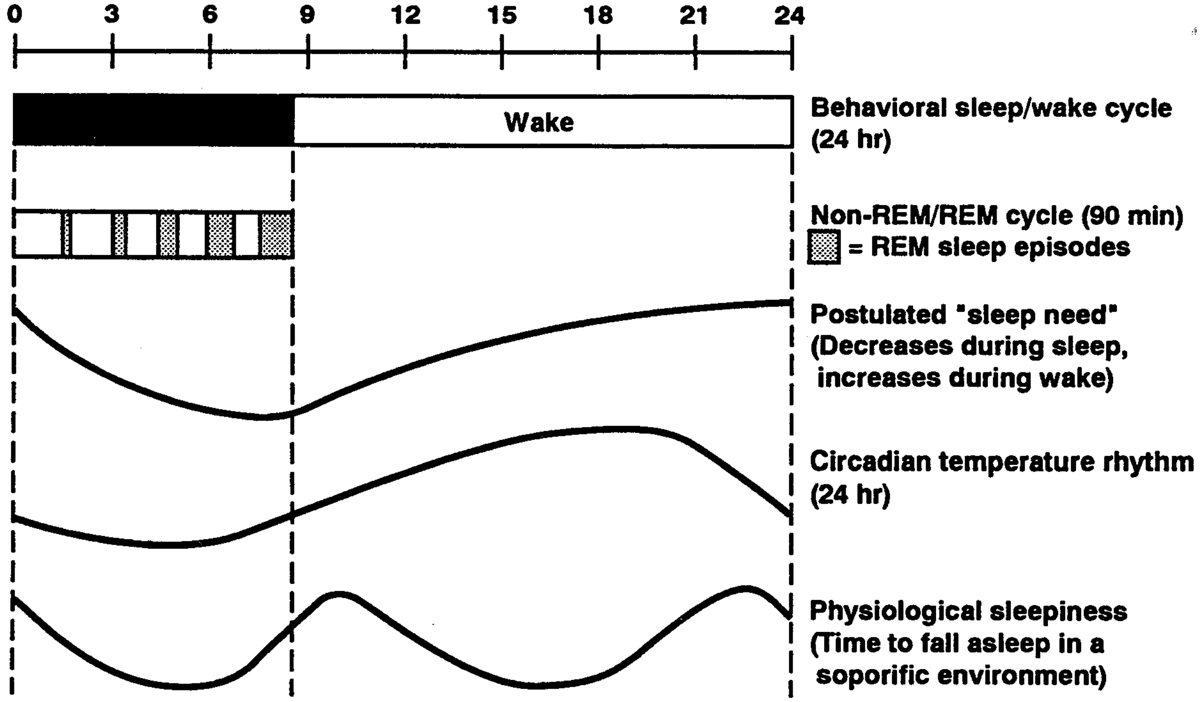


Figure 1. Physiological cycles contributing to sleep regulation. Interactions between these processes are described in the text.

easy to fall asleep: the mid-afternoon "nap window" and the early morning minimum of the temperature cycle. Sleep at night usually begins some hours before temperature gets to its daily minimum and ends as temperature rises again. The duration of the REM episodes, and the rapidity with which one enters into dream sleep, are greatest just after the time of the daily temperature minimum. A model of the interaction between the homeostatic and circadian sleep processes has been proposed (ref. 11) in which a "sleep need" factor accumulates until it reaches an upper threshold, at which time sleep begins. During sleep, the level of the sleep factor declines until it reaches a lower threshold, when wakeup occurs. The thresholds undergo daily oscillations driven by the circadian pacemaker in the hypothalamus. Under normal conditions, the circadian pacemaker is synchronized by 24-hr social and geophysical cycles (particularly sunlight), which are known collectively as "zeitgebers" (refs. 18-20). Commercial long-haul operations expose flight crews to extremely complex patterns of zeitgebers, owing to the rapid sequences of multiple time-zone crossings and irregular duty/rest schedules. Such zeitgeber shifts have been predicted to be well beyond the synchronizing capacity of the neural circadian pacemaker (ref. 21). In addition, individual crew members modify their patterns of exposure to the geophysical zeitgebers and social cues in each time zone.

A number of previous studies have examined rates of adaptation of flight crew sleep and circadian rhythms to a new time zone after a single flight across multiple time zones (refs. 1 and 22-28), or readaptation to the home time zone after a sequence of transmeridian flights (refs. 29 and 30). Sleep/wake patterns of flight crews before, during, and after sequences of transmeridian flights have been examined in several recent studies (refs. 13 and 31-33). Circadian rhythms were also recorded in two studies of pilots flying polar routes from Europe to Japan (refs. 13 and 34). These studies reveal considerable sleep and rhythm disruption with varying degrees of accumulated sleep loss and rates of recovery depending on the specifics of the particular trip patterns. They also indicate substantial variability among individuals. The changes observed in polygraphically recorded sleep quality and architecture reflect the influence of the circadian system, and also illustrate the interacting effects of the homeostatic sleep process, particularly after prolonged periods of wakefulness (ref. 13). Polar route flights, which prevent sleep during local night for several

(24-hr) days, appear to be particularly disruptive (refs. 13 and 32-34). On the other hand, regular (westward) returns to the home time zone during a sequence of repeated transatlantic flights appear to permit recovery of sleep lost during eastward overnight flights (ref. 31).

Taken together, the above studies begin to build a picture of the aspects of existing schedules which exacerbate or improve sleep duration and circadian rhythm disruption. They do not, however, directly address the issue of the factors influencing the selection of sleep times, sleep duration, and sleep quality during complex sequences of transmeridian flights. The times at which a flight crew member selects to go to sleep are constrained first and foremost by duty timing. Local time might be expected to influence both the decision to go to bed (social activities, meal availability) and the ability to fall asleep and remain asleep (light, noise). The present study begins to examine the interaction of these factors with the physiological processes involved in sleep regulation, and in particular with the circadian system. The logistics of continuous polygraphic sleep recording made it impractical to examine the homeostatic and non-REM/REM sleep regulatory mechanisms in a study of this size. We are addressing these issues in current and proposed studies. This work is part of the ongoing NASA program investigating crew factors in flight operations (refs. 7 and 35-40).

3. Methods

Trip Patterns

The data considered here were obtained from 29 male flight crew members flying one of the four trip patterns illustrated in figures 2(a)-2(d). The trips studied were selected to be representative of the different categories of commonly occurring trip patterns, i.e., outward flight westward (San Francisco-Singapore), outward flight eastward (New York-Bombay, San Francisco-London), and primarily north-south displacement but with long overnight flight times approximating those of the other patterns (Los Angeles-Auckland). Crews for the Singapore, London, and Auckland trips were domiciled in San Francisco; those for the Bombay trip were domiciled in New York. The London pattern was distinctive in that flight crews returned to their home time zone on alternate layovers. Sleep/wake behavior during this trip has been described elsewhere (refs. 31 and 41).

After the trip patterns to be studied had been selected, crews who won the monthly bid for those patterns were invited to participate in the study. The problem of volunteer bias is thus minimized. To ensure confidentiality, each subject's data were tagged by a five-digit code which he alone could identify. Table 1 shows a breakdown of the subjects from each trip whose data were used in the present analyses.

The average age of the volunteers was 52.1 (S.D. 4.5) years, and they had, on average, 18,484 (S.D. 3,922) hr of flight experience.

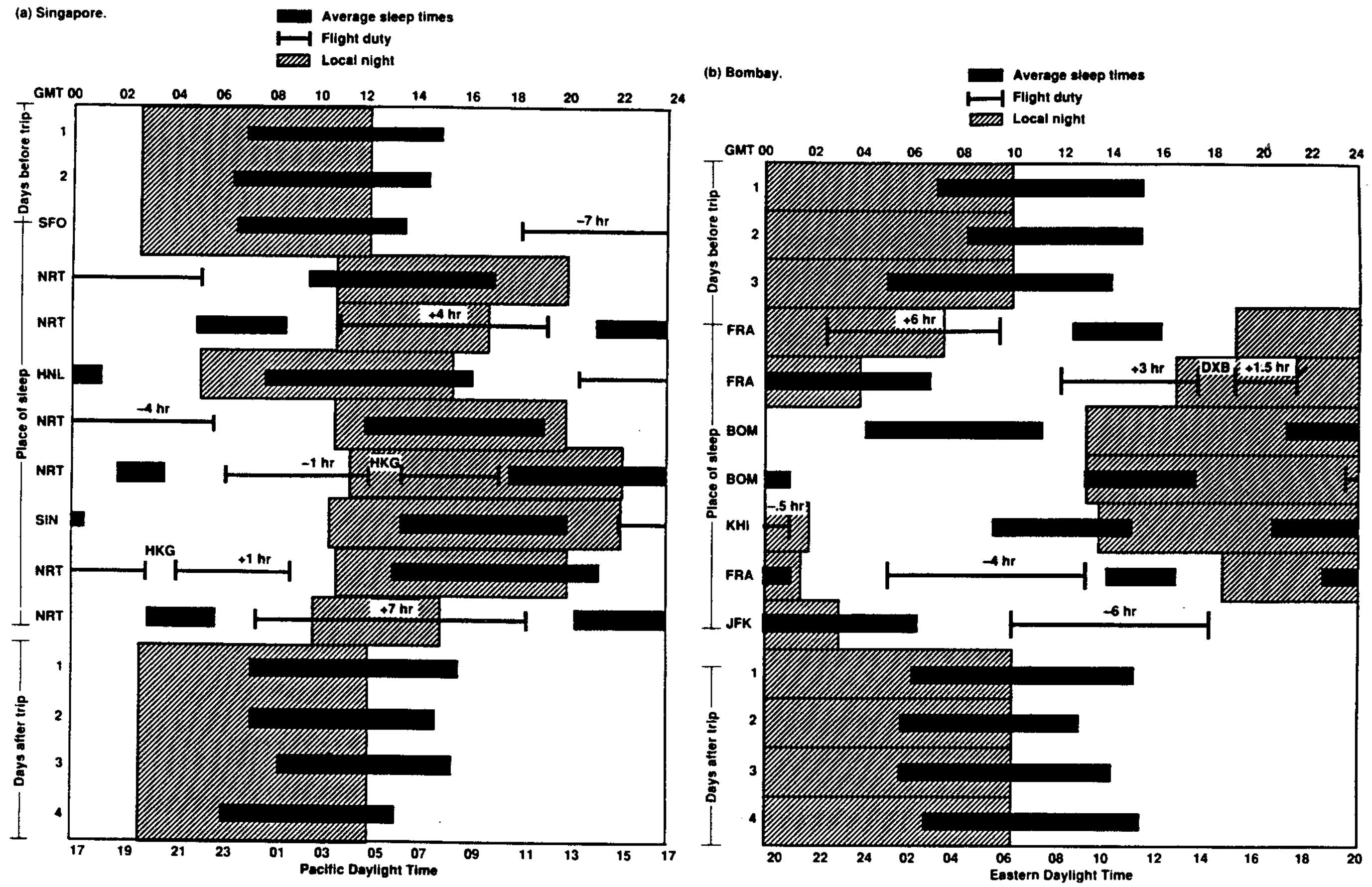
Data collection began a maximum of 3 days before the trip pattern and continued throughout the pattern (in the presence of a NASA cockpit observer) and for up to 5 days after the pattern was finished. Since the aim of the present analyses was to examine the factors controlling sleep timing and quality during trips, the pre- and post-trip data are not discussed here. Ideally, crew members should have been adequately rested and fully adapted to the local time zone before departure. In reality, crews do not always have enough time off between trips to ensure that these criteria are met. In order to have a sufficient number of eligible subjects, we settled on the compromise that subjects had to have at least 4 days off before beginning the study trip.

Sleep/Wake Cycle Data

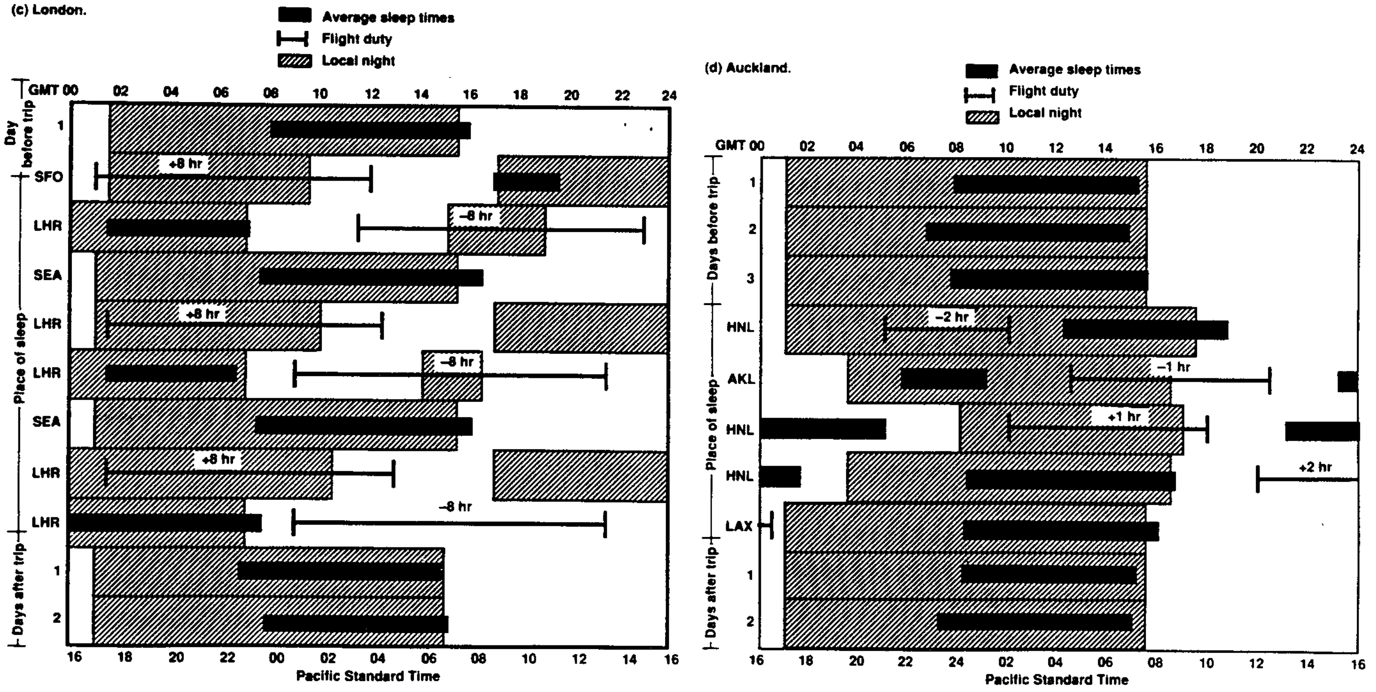
Subjects kept a detailed log of daily activities (ref. 37). The logbook format was modified from that used in previous studies, to provide space for two sleep and two nap entries in one 24-hr period. The maximum number of entries observed was three. For sleeps, the following times were recorded: going to bed, falling asleep, awakenings during sleep (up to three), waking up, and getting up. Estimated sleep duration (minus time spent in bed but awake) was also noted. In international flight crews, these subjective estimates of sleep duration have been found to be significantly correlated with total sleep times measured polygraphically (ref. 23). Four questions concerning sleep quality were rated on a scale from 1 to 5: (1) Difficulty falling asleep?; (2) How deep was your sleep?; (3) Difficulty rising?; and (4) How rested do you feel? These questions were subsequently converted so that a high number indicated good sleep, and the ratings were then summed to give an overall sleep-quality rating on a scale from 4 to 20.

Naps were noted only by the times of going to sleep and waking up. Nap durations were calculated subsequently, from time asleep to time awake. The durations of subject-defined sleeps and naps were significantly different (mean for sleeps = 5.64 hr; mean for naps = 1.05 hr; 1-way ANOVA $F = 285$, $p < 0.0001$). The designation by the subjects was therefore retained in the analysis, rather than introducing an arbitrary definition *post hoc.*

There are two possible ways of defining wake durations in these data: from the end of any sleep or nap to the


(a) Singapore.

(b) Bombay.


(c) London.

(d) Auckland.

Figure 2. Average sleep and flight times for four trips studied. Horizontal axis represents 24 hr period (GMT 0000 to GMT 2400) and successive days are plotted vertically beneath each other. Numbers over flight times indicate number and direction (+ eastward) of time zones crossed. (SFO-San Francisco; NRT-Narita (Tokyo); HNL-Honolulu; SIN-Singapore; FRA-Frankfurt; BOM-Bombay; KHI-Karachi; JFK-New York; LHR-London Heathrow; SEA-Seattle; AUK-Auckland; LAX-Los Angeles.)

Table 1. Composition of the population studied

Trip pattern	Captains	First officers	Flight engineers	Total
Auckland	2	2	2	6
Bombay	2	1	2	5
London	2	3	2	7
Singapore	3	4	4	11
Total	9	10	10	29

beginning of the next sleep or nap (denoted hereafter as sleep/ nap (s/n) cycles); or from the end of one sleep to the beginning of the next sleep (sleep/sleep (s/s) cycles, i.e., disregarding any intervening naps). All analyses were carried out for both definitions of wake duration.

Definition of Duty Cycles

Duty times were defined according to the company regulations; i.e., crew members went on duty 1 hr before scheduled departure from the gate and finished duty 0.5 hr after actual arrival at the gate. This information was available from the cockpit observer logs (ref. 37). The following relationships between the timing of sleep episodes and duty cycles were calculated: (1) time from off-duty to asleep; (2) time from asleep to next on-duty; and (3) time from awake to next on-duty.

These relationships are summarized in figure 3. Only values less than 24 hr were retained, on the assumption that sleep onsets and wakeups occurring more than 24 hr from a duty episode were probably not greatly influenced by that duty. This criterion eliminated the data from the Bombay layover on the Bombay trip (fig. 2(b)). All other layovers included a maximum of two sleep episodes (excluding naps). Thus all the sleep episodes considered here were either first- or second-sleeps within a layover. There are five sleeps that were preceded by a nap since coming off duty, and were therefore defined as second-sleeps in s/n cycles but as first-sleeps in s/s cycles (fig. 4). The analyses include these 5 sleeps plus 67 unambiguous first-sleeps and 54 unambiguous second-sleeps. The local times of the layovers during which these sleep episodes occurred are shown in figure 5.

Circadian Rhythm Data

Rectal temperature, heart rate, and activity of the non-dominant wrist were recorded every 2 min using portable

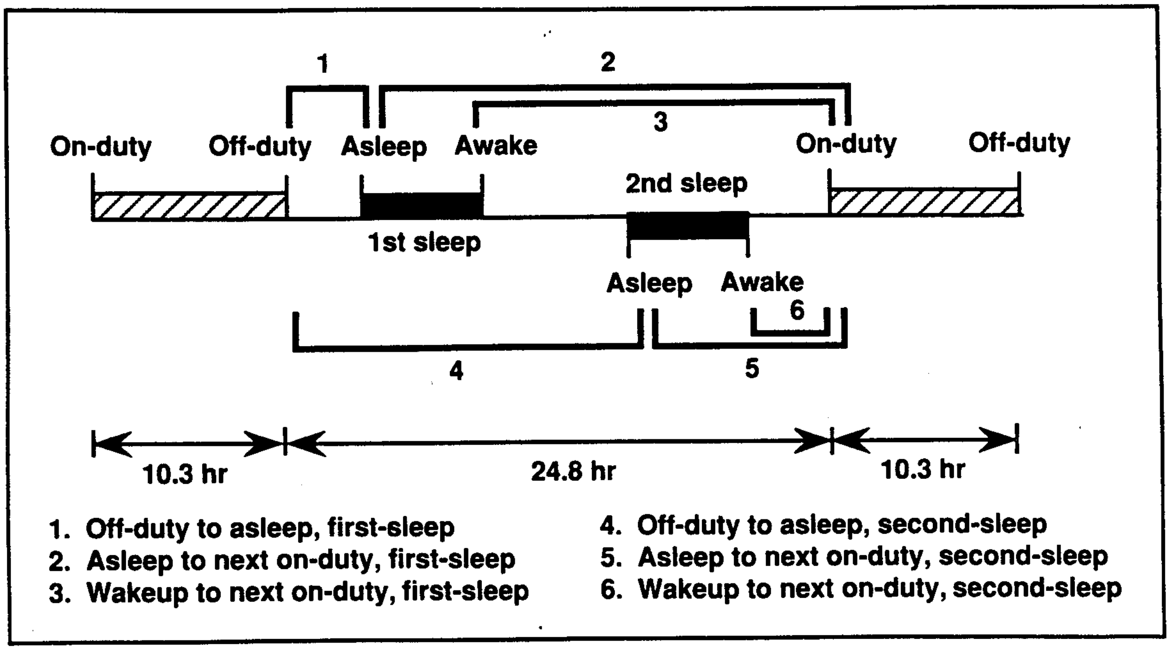


Figure 3. Calculated relationships between duty times and sleep times. Average duty period was 10.3 hr; average layover was 24.8 hr.

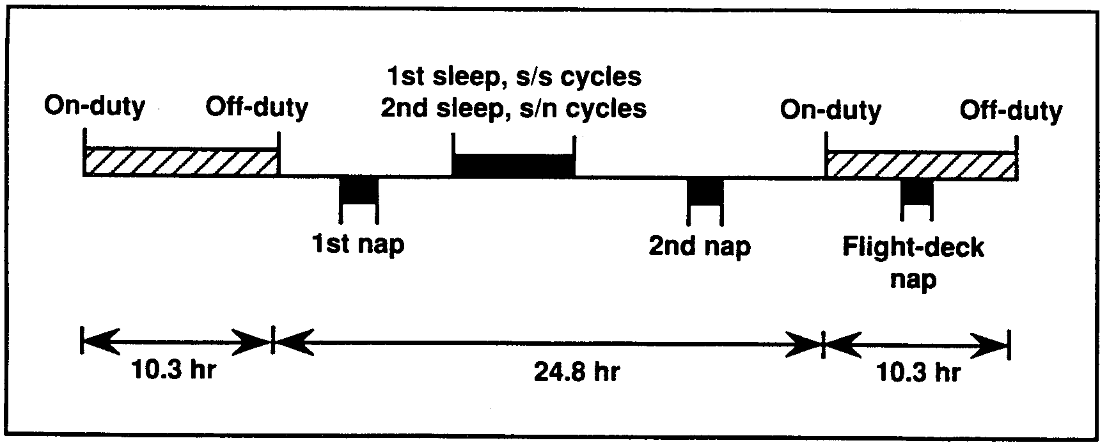


Figure 4. Ambiguity in definition of first- and second-sleeps, and definition of three categories of naps. Average duty period was 10.3 hr; average layover was 24.8 hr.

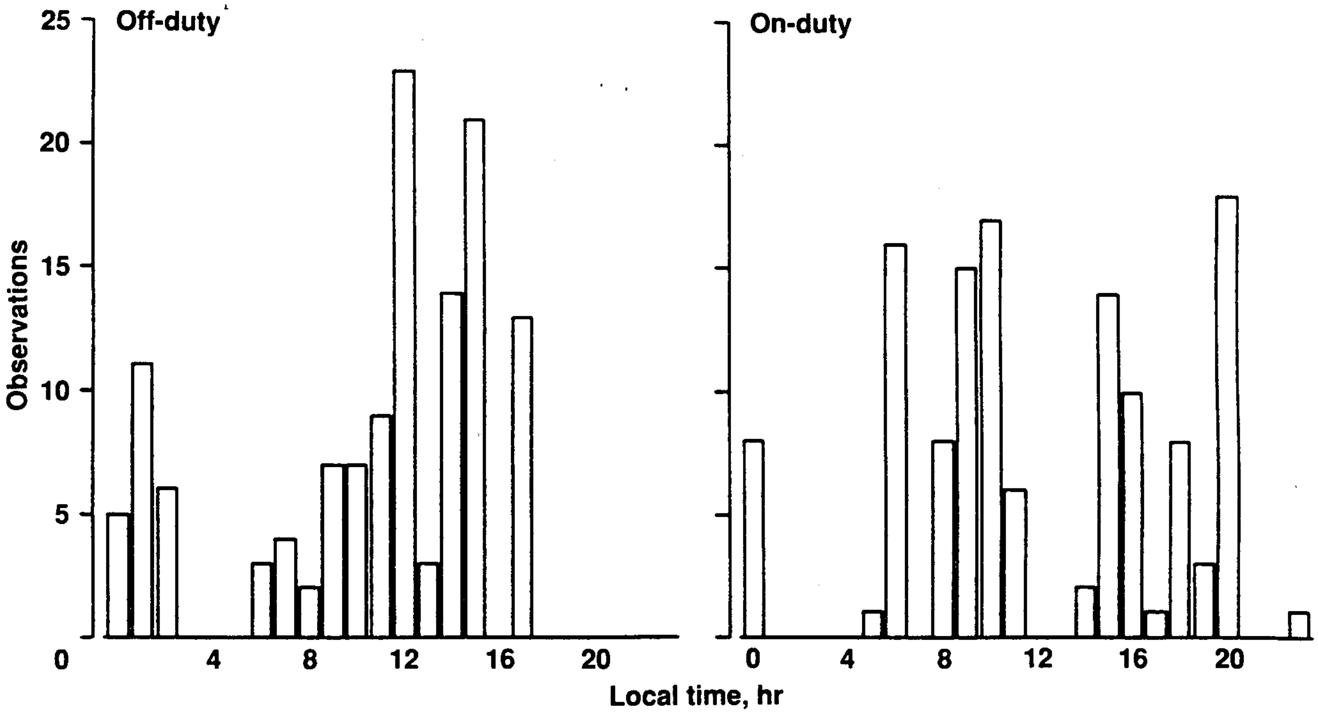


Figure 5. Frequency distributions of local times of coming off duty and going on duty for layovers whose sleep episodes contributed to the analyses (see sec. 3).

biomedical monitors (Vitalog Corporation PMS-8, Redwood City, Calif.). In keeping with current convention, the rectal temperature rhythm was used as a marker of the underlying circadian time-keeping system. Despite this convention, it is recognized that the temperature rhythm is not necessarily an accurate marker, since temperature is elevated by physical activity and lowered during sleep. The sleep/wake cycle is thus said to produce "masking" of the temperature rhythm (refs. 42 and 43).

To estimate the circadian phase, the cycle-by-cycle minima of the temperature rhythm were taken as the computer-selected lowest values within 12 hr of the multiple complex demodulated wave form (ref. 44) fitted to consecutive 20-min bins of data. In a few cases, this algorithm resulted in more than one minimum per 24 hr. In such cases, the raw data and multiple complex demodulated wave form were superimposed on the sleep and nap times and, if there was no clear way of discriminating between the minima (circadian or masking due to sleep), all the data for that cycle were discarded.

The circadian times (CT) of sleep onset and wakeup were calculated as follows:

CT asleep = asleep (GMT) – temperature minimum (GMT)

CT awake = awake (GMT) – temperature minimum (GMT)

For a sleep onset or wakeup to be attributed unequivocally to a given temperature minimum, it had to occur within 12 hr of that minimum, i.e., $-12 < CT < 12$. Sleeps and naps with CT values outside this range were discarded.

To address in more detail the issue of masking of the temperature rhythm by the sleep/wake cycle, an initial exploratory investigation compared four different circadian phase-estimating techniques. A subset of the data (the Singapore trip pattern) was "unmasked" by adding 0.28 °C to the raw temperature data whenever the subjects were asleep, based on the reported 0.28 °C difference between the temperature rhythm during sleep and wake in internally desynchronized subjects (ref. 45). To locate the temperature minima, the original and unmasked data sets were then subjected to multiple complex demodulation (ref. 44) and robust, locally weighted regression smoothing (ref. 46). Paired t-tests showed no significant differences between the techniques for estimates of circadian sleep onset and wakeup times for designated sleeps. For designated naps, however, multiple complex demodulation of the original data gave significantly earlier estimates than either unmasked multiple complex demodulation or unmasked Cleveland smooth (table 2).

The technique of adding a constant to the temperature data while the subject is asleep is a simplistic way of unmasking the circadian component, because the effects of sleep or activity masking are probably circadian phase-dependent. It is not possible to model this phase-dependence in the present data because the initial problem is estimating phase, i.e., the arguments become circular. For these reasons, and for convenience, multiple complex demodulation of the original data was chosen as the standard phase-estimating technique for these studies, acknowledging the caveat that it may give earlier estimates of the circadian phase of naps (but not designated sleep episodes) as a result of the masking influence of sleep. An example of the actual and fitted temperature wave forms for one subject, together with sleep, nap, and duty times, is shown in figure 6. These automated techniques for determining circadian time (CT) were designed to be conservative; i.e., some data may have been excluded unnecessarily. On the other hand, manual cycle-by-cycle checking of each sleep episode with adjacent temperature minima was considered too vulnerable to observer bias, as well as being very time-consuming.

Table 2. Circadian times of nap onsets and wakeups for different phase-estimating techniques[a]

	Asleep			Awake		
	t	p	Δ mean, hr	t	p	Δ mean, hr
cdm vs unmasked cdm	–2.11	0.05	1.29	–2.09	0.05	1.50
cdm vs unmasked smo	–2.12	0.05	0.89	–2.34	0.03	1.78

[a]cdm = multiple complex demodulation (ref. 44); smo = Cleveland "smooth" (ref. 46).

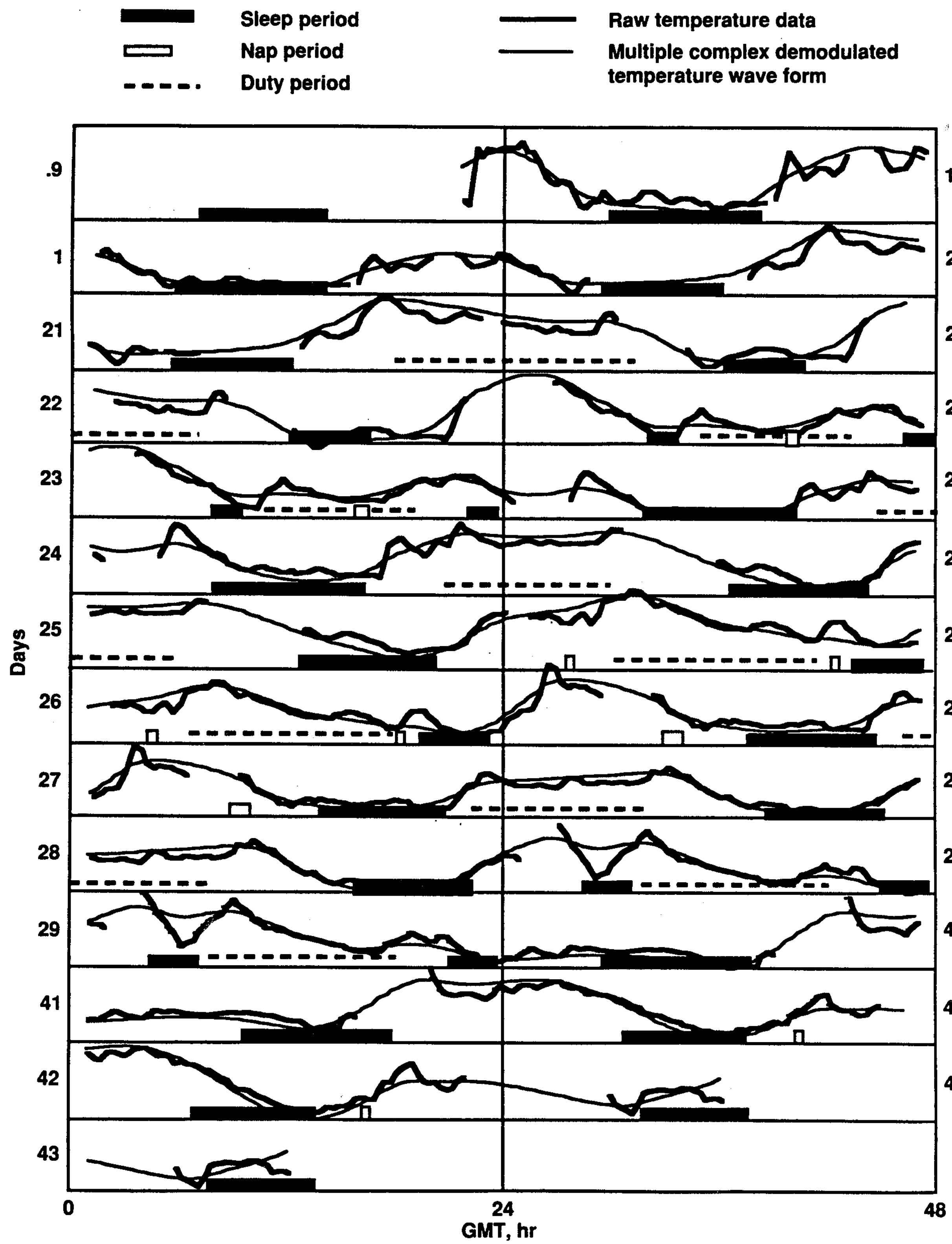


Figure 6. Sleep and temperature records for subject 21221. Data for each 24-hr segment on left-hand side have been duplicated and replotted on right-hand side next to preceding 24-hr segment so that, e.g., days 21 and 22 are plotted above days 22 and 23. Days 0.9 and 1.0 are pretrip baseline, days 21-29 are trip days, days 41-43 are post-trip recovery. Thick curves represent the raw temperature data, thin curves the multiple complex demodulated wave form used to estimate phases of successive circadian minima. Black bars indicate sleep episodes and naps; horizontal lines indicate duty periods.

The period of the temperature rhythm for each subject was estimated across all trip days using linear-nonlinear, least-squares, iterative multiple regression (ref. 47). Periods in the range of 2-40 hr were tested, at 0.25-hr period intervals. A significant fit indicates that the fitted sinusoid had an amplitude significantly different ($p < 0.05$) from zero.

Background Questionnaire

Subjects also completed a background questionnaire which included general demographic and life-style information, sleep and nutritional habits, and personality profiles (ref. 37). The latter included the Personal Attributes Questionnaire (ref. 48); the Work and Family Orientation Questionnaire (refs. 49 and 50); the Eysenck Personality Inventory (ref. 51); and the Morningness/Eveningness Questionnaire (ref. 52).

Analytical Approach

Because the present data come from an observational field study, they have the advantage of operational authenticity at the expense of control over the experimental variables. There was no study design to test specific hypotheses and no experimental manipulations were performed. However, the average layover duration was just over 24 hr (mean 24.75 hr, S.D. 6.31 hr) and crew members potentially had the opportunity to sleep at any hour of the local day and night (fig. 5). The time zone changes and irregular hours of work and rest also ensured that sleep opportunities occurred at all phases of the circadian cycle. These fortuitous facts, together with the precise information on duty timing, make the data amenable to a multivariate examination of the effects of (1) duty requirements, (2) local time, and (3) the circadian timing system, in determining sleep timing and subjective sleep quality. Consequently, for subject-defined sleeps, different sets of variables were identified (table 3) which were expected *a priori* to influence (a) the duration of wakefulness; (b) the duration of sleep; and (c) sleep-quality ratings.

These variables were compared for the first- and second-sleep episodes within layovers, and in s/s versus s/n cycles, by two-way ANOVA. Their relative contributions to the variance in the respective independent variables (wake duration, sleep duration, sleep-quality ratings) was compared by stepwise multiple regression and by all-possible-subsets regression. These multiple regression techniques assume linear relationships between the dependent and independent variables. In several instances, there was *a priori* evidence that the relationships were probably quadratic, and these are discussed in detail in the various analyses.

The timing of sleep onset and wakeup was also examined with respect to duty timing, local time, and circadian time, i.e., with respect to the timing of the daily minimum in core temperature. Circadian regulation of sleep has been studied most extensively in subjects living in time-free environments whose sleep/wake and core-temperature rhythms simultaneously exhibit different periods (desynchronized free-run; refs. 14-16). From these data, a number of generalizations can be drawn (ref. 53).

1. The circadian phase of sleep onset predicts sleep duration; however, the relationship is not linear.

2. The circadian phase of sleep onset predicts the duration of prior wakefulness. This relationship is also not linear.

3. As a result of (1) and (2), the circadian phase of sleep onset predicts the period of the overall wake/sleep cycle.

4. The longer the subjects stay awake, the shorter their subsequent sleep; i.e., there is a negative correlation between wake duration and subsequent sleep duration. This conserves the circadian period of the wake/sleep cycle. Sleep duration and the following wake duration are uncorrelated.

Table 3. Dependent variables potentially influencing wake duration, sleep duration, and subjective sleep quality ratings

Wake duration	Sleep duration	Sleep quality ratings
Duty duration	Prior wake duration	Prior wake duration
Off-duty to asleep	Prior duty duration	Prior duty duration
Asleep to next on-duty	Awake to next on-duty	Off-duty to asleep
Local time of sleep onset	Local time of wakeup	Awake to next on-duty
Circadian time of sleep onset	Circadian time of sleep onset	Local time of sleep onset
	Circadian time of wakeup	Local time of wakeup
		Circadian time of sleep onset
		Circadian time of wakeup

5. The circadian distribution of wakeup times is unimodal, with almost all wakeups occurring while the rectal temperature is rising.

6. The circadian distribution of sleep onsets is bimodal. The peak time of sleep onsets occurs near the temperature minimum, with a secondary peak, labeled the "nap phase," occurring about 9 hr later.

The extent to which the present data conform to these generalizations was examined to determine the importance of the circadian system in the control of sleep timing in a much more complex real-world environment.

Subject-defined naps could not be analyzed in the same manner for the following reasons. First, local time is not a meaningful reference for flight-deck naps. Second, whereas layover naps can be referenced to duty timing in the same way as sleep periods, naps occurring during duty periods must be considered differently. Third, naps often produced complex temperature rhythm wave forms, and an adjacent circadian minimum could only be identified unambiguously for 40 of the 96 naps available for analysis. Fourth, the quality of sleep was not rated for naps. Thus, prior wake durations and nap durations were compared for the three types of naps (flight-deck naps, and first and second naps within a layover; fig. 7). In addition, the timing of layover naps was examined with respect to local time and time within the layover, while flight-deck naps were examined for their timing within the duty period. The circadian timing of naps was also examined for the subset (42%) of naps for which this information was available.

The relationships between the durations of successive wake and sleep episodes can provide important information on the mechanisms controlling sleep timing. Even when subjects are left to wake up spontaneously, prolonged wake episodes are not generally followed by proportionally longer sleep periods, but rather by deeper sleep (ref. 11). Indeed, in the absence of any environmental timing information or constraints, longer wake episodes are followed by proportionally shorter sleep episodes, so that the overall period of the circadian wake/sleep cycle is maintained (refs. 53 and 54). Correlations between sleep duration and prior and subsequent wake durations were therefore examined to look at the factors controlling the relative durations of wake and sleep.

The temperature rhythm wave forms recorded during these trip patterns were very complex, with masking from the combination of long (first-sleep) and short (second-sleep) wake/sleep cycles and naps, as well as the rapid sequence of zeitgeber shifts. In view of the findings from our previous simulation study (ref. 36), the temperature rhythms were subjected to linear-nonlinear, least-squares, interactive spectral analysis to test the hypothesis that a free-running or near free-running circadian component might still be present.

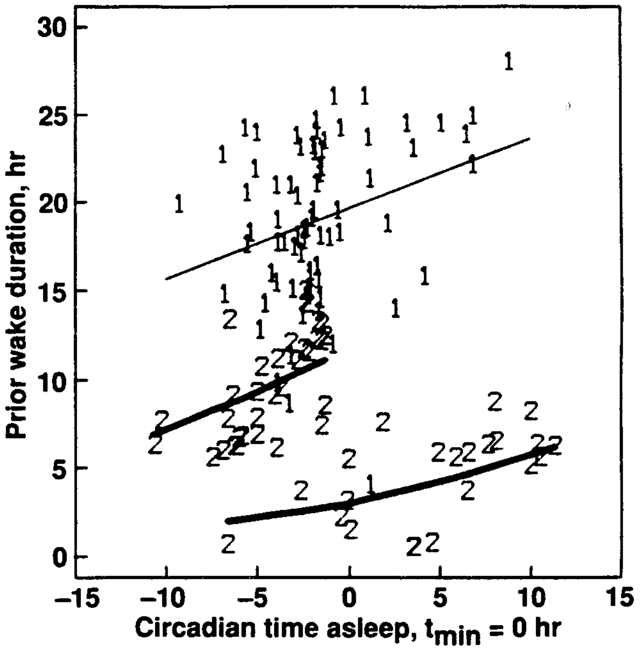


Figure 7. Relationship between duration of prior wakefulness and the circadian time of falling asleep, for subject-defined sleeps in s/s cycles. First-sleeps are denoted "1," second-sleeps "2." Circadian time (CT) zero is time of temperature minimum. There is significant positive correlation for first-sleeps (fine line). On the other hand, the relationship for second-sleeps is evidently nonlinear. Equivalent data from desynchronized subjects in time-isolation are best fitted by a quadratic function. Thick lines here represent best-fitted quadratic to second-sleep data with overlap between phases CT-7 and CT-2 such that wake durations less than 5 hr contributed to lower curve. (Lower curve represents a displacement of beginning of upper curve by 24 hr.)

All data were entered into a modified Relational Information (RIM) data base on a VAX 11/750 computer. Data manipulation and graphics were carried out using the "S" language and environment (Bell Laboratories). Paired t-tests, two-way analyses of variance of repeated measures, stepwise multiple regression, and all-possible-subsets regression were carried out using BMDP statistical software (ref. 55).

4. Results

Designated Sleeps

Duration of wake episodes preceding designated sleeps– Means for the dependent variables tested for their contribution to the variability in wake duration (table 3) are listed in table 4. Two-way ANOVA revealed that first-sleeps followed significantly longer periods of wakefulness than did second-sleeps.

The multiple regression analyses of the variables expected to contribute to the variability in wake duration are summarized in table 5. First- and second-sleeps were considered separately for two reasons. First, they have significantly different values for the independent variable (prior wake duration). Second, it was hypothesized that the duration of prior wake might be determined by different combinations of the dependent variables for the two types of sleep, since wake episodes preceding first-sleeps included duty periods, whereas wake episodes preceding second-sleeps occurred during layovers.

The variance in the duration of wake episodes preceding first-sleeps is partially (40%) explained by the above dependent variables for s/s cycles, but not at all for s/n cycles. For s/s cycles, duty-related variables (time from off-duty to asleep, from asleep to next on-duty, and duration of the preceding duty) contribute most to the duration of wake. The circadian phase of sleep onset also contributes significantly.

For wake episodes preceding second-sleeps, the results are very similar for either cycle definition, with the most important contribution to the variance coming from the time from off-duty to asleep, and a lesser contribution from local sleep onset time.

In subjects living in time-free environments, the relationship between the circadian phase of sleep onset and the duration of the preceding wake episode is not linear. The average curve (best-fitted quadratic) is an ascending ramp, with a region of overlap 5 to 6 hr before the temperature minimum. Sleeps beginning in this region follow either very long or very short prior wake episodes. A similar relationship might be interpreted for the wake episodes preceding second-sleeps (fig. 7), but not for first sleeps. In addition, the longest wake episodes preceding second-sleeps are about 15 hr, which is about the duration of the shortest prior wake episodes in the data from desynchronized free-run. Although the assumption of linearity between the circadian phase of sleep onset and the duration of prior wake is reasonable for first-sleeps, it is clearly violated for second-sleeps. The observation that the circadian phase of sleep onset does not appear as a significant contributor to the variance in wake durations preceding second-sleeps (table 5) may therefore be misleading.

Timing of sleep onset for designated sleeps– The distributions of sleep onsets with respect to duty timing, local time, and circadian time are shown in figures 8-10. As expected, first-sleep onsets were concentrated in the hours immediately after coming off duty. On the other hand, second-sleep onsets were broadly distributed later in the

Table 4. Comparison of wake duration and sleep-onset variables for first- and second-sleeps

	Mean, hr			
	Sleep/sleep cycles		Sleep/nap cycles	
	1st sleeps	2nd sleeps	1st sleeps	2nd sleeps
Prior wake duration	18.97	7.39	16.90	6.44
Time from off-duty to asleep	3.97	15.00	3.64	14.42
Time from asleep to next on-duty	20.09	10.55	20.23	11.20
Prior duty duration	10.28	10.15	10.27	10.17
Local time of sleep onset	15.48	14.98	15.56	14.93
Circadian time of sleep onset	–3.37	–5.79	–3.46	–5.57
Significant differences (two-way ANOVA: cycle type by sleep type)				
Prior wake duration	s/s vs s/n cycles[a]	F = 7.99	p = 0.005	
	1st vs 2nd Sleeps	F = 424.35	p = 0.000	
Off-duty to asleep	1st vs 2nd Sleeps	F = 527.81	p = 0.000	
Asleep to next on-duty	1st vs 2nd Sleeps	F = 277.41	p = 0.000	

[a] s/s = sleep/sleep; s/n = sleep/nap.

Table 5. Contributions to the variance in wake duration

Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Wake episodes preceding first-sleeps				
Sleep/sleep cycles				
Off-duty to asleep	1.001	0.605	0.000	0.250
Circadian time asleep	0.385	0.290	0.005	0.077
Asleep to on-duty	0.361	0.314	0.009	0.068
Prior duty length	0.699	0.269	0.019	0.053
Local time asleep	–0.142	–0.217	0.066	0.033
For best subset: $r^2 = 0.404$, F = 8.68, p = 0.0000				
Sleep/nap cycles				
Off-duty to asleep	0.542	0.228	0.065	0.052
For best subset: $r^2 = 0.052$, F = 3.53, p = 0.0650				
Wake episodes preceding second-sleeps				
Sleep/sleep cycles				
Off-duty to asleep	0.506	0.630	0.000	0.390
Local time asleep	0.125	0.301	0.007	0.089
For best subset: $r^2 = 0.439$, F = 19.54, p = 0.0000				
Sleep/nap cycles				
Off-duty to asleep	0.429	0.571	0.000	0.316
Local time asleep	0.076	0.194	0.093	0.037
For best subset: $r^2 = 0.324$, F = 12.96, p = 0.0000				

layover (fig. 8). Very few sleep episodes began during the local morning hours or in the late-afternoon to early-evening. Rather, pilots tended to fall asleep around the local "nap" time (early afternoon), or during the local night (fig. 9). The distributions are not significantly different for first- and second-sleeps, although a larger proportion of first-sleeps began in the local afternoon. Figure 10 suggests that particularly for first-sleeps, the circadian system also influences the timing of sleep onsets, which occurred most frequently just before the temperature minimum (CT0). The difference between the circadian distributions of first- and second-sleep onsets is not significant at the 0.05 level (1-way ANOVA, F = 3.08, p = 0.081); however, second-sleeps appear to have a more dispersed distribution, with a second peak of sleep onsets about 8 hr before the temperature minimum and a greater number of second-sleeps beginning while temperature is rising. The distribution for first-sleeps in figure 10 is similar to that described for desynchronized free-run (fig. 4-1d in ref. 53), except that the distribution in figure 10 peaks several hours earlier.

To avoid misinterpreting these distributions, it is necessary to identify any possible causal relationships between them. For example, because a large proportion of first-sleeps began shortly after coming off duty and shortly before the temperature minimum, the issue arises whether the observed temperature minimum, and therefore the distribution in figure 10, might be a masking artifact, i.e., tired crew members went to sleep soon after coming off duty and this lowered their body temperature. In this case,

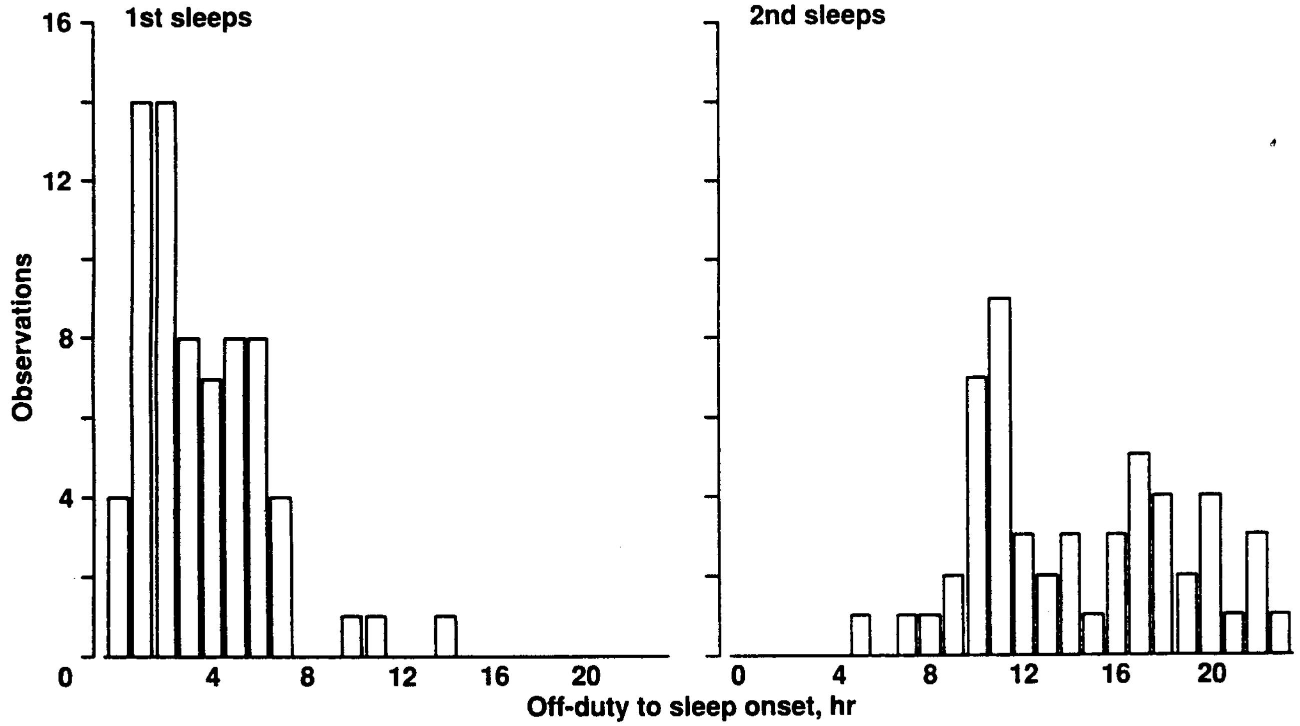


Figure 8. *Frequency distributions of occurrence of sleep onsets with respect to time elapsed since coming off duty.*

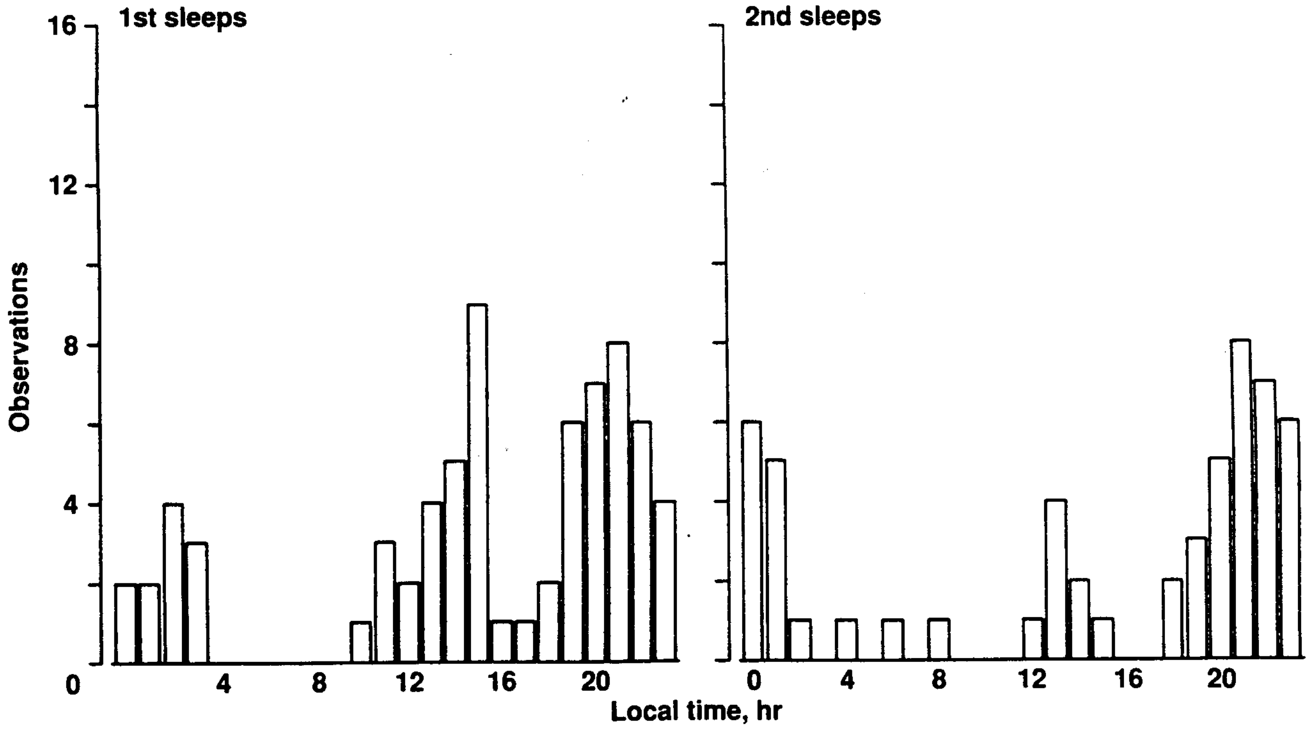


Figure 9. *Frequency distributions of occurrence of sleep onsets with respect to local time.*

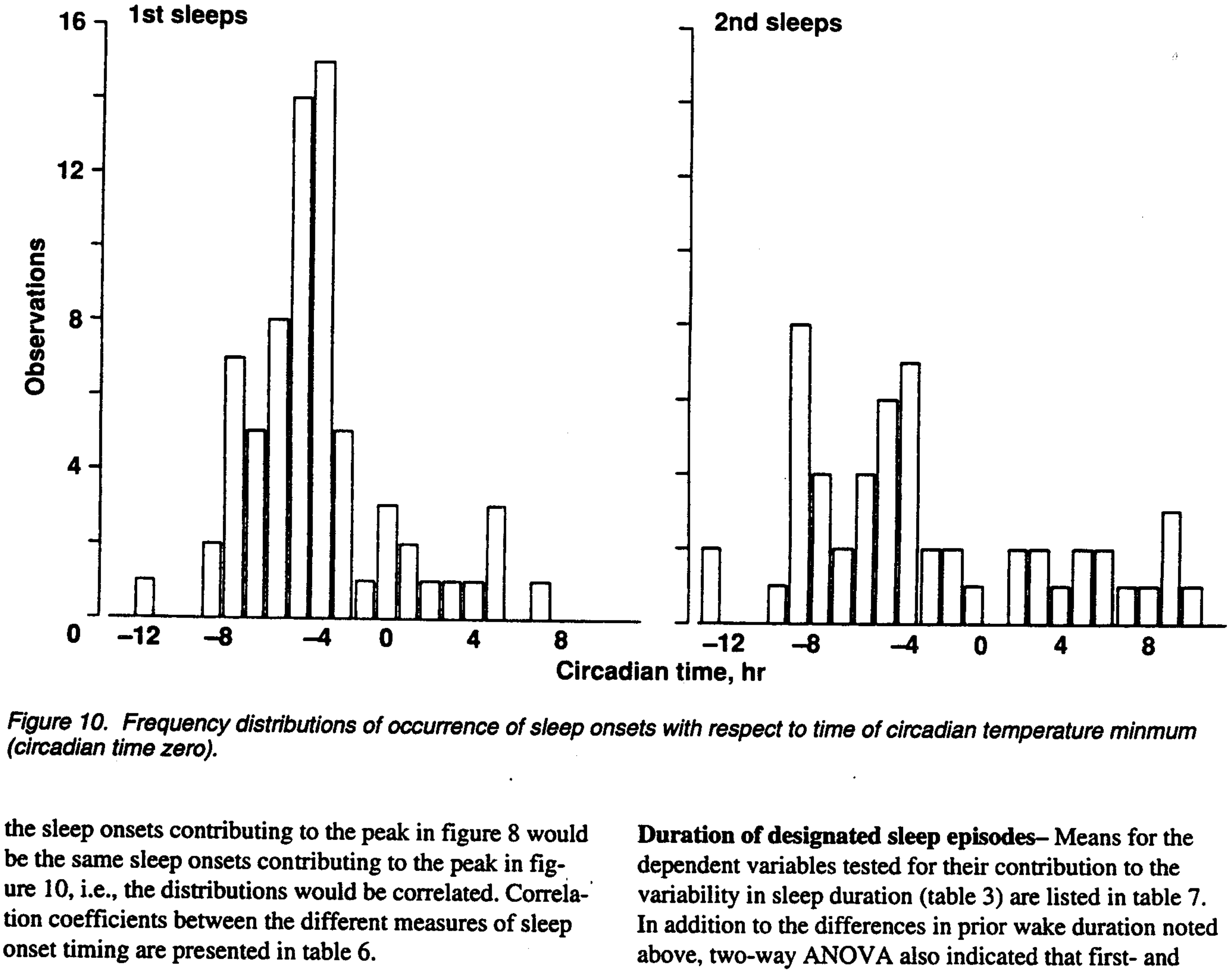


Figure 10. Frequency distributions of occurrence of sleep onsets with respect to time of circadian temperature minmum (circadian time zero).

the sleep onsets contributing to the peak in figure 8 would be the same sleep onsets contributing to the peak in figure 10, i.e., the distributions would be correlated. Correlation coefficients between the different measures of sleep onset timing are presented in table 6.

These analyses indicate that the shapes of the circadian distributions of sleep onsets for first- and second-sleeps are not an artifact of either of the other distributions. The correlation between time-since-coming-off-duty and local-time suggests that first-sleep episodes beginning in the local afternoon, which normally followed nighttime flights, began sooner after coming off duty than first sleep episodes beginning during the local night, i.e., after daytime flights. This probably reflects greater sleep loss associated with nighttime flights (ref. 32).

Duration of designated sleep episodes– Means for the dependent variables tested for their contribution to the variability in sleep duration (table 3) are listed in table 7. In addition to the differences in prior wake duration noted above, two-way ANOVA also indicated that first- and second-sleeps in a layover differed significantly in their local and circadian times of wakeup. These findings are examined in more detail in the following subsection.

The multiple regression analyses of the variables expected to contribute to the variability in sleep duration are summarized in table 8. First- and second-sleeps were considered separately, because it was hypothesized that their durations, although not significantly different, might be controlled by different combinations of the dependent variables.

Table 6. Correlation coefficients for measures of sleep-onset timing

	1st Sleeps		2nd Sleeps	
	Local time	Circadian time	Local time	Circadian time
Time since off-duty	0.42^{***}	−0.06	−0.13	−0.24
Local time		−0.04	0.01	

Note: $^{***}p < 0.001$.

Table 7. Comparison of sleep duration and wakeup variables for first- and second-sleeps

	Mean, hr			
	Sleep/sleep cycles		Sleep/nap cycles	
	1st sleeps	2nd sleeps	1st sleeps	2nd sleeps
Sleep duration	5.68	5.84	5.62	5.90
Prior wake duration	18.97	7.39	16.90	6.44
Prior duty duration	10.28	10.15	10.27	10.17
Time from wakeup to next on-duty	14.14	4.87	14.34	5.43
Local time of wakeup	10.86	8.34	11.16	8.22
Circadian time of sleep onset	–3.37	–5.79	–3.46	–5.57
Circadian wakeup time	3.51	1.33	3.39	1.65
Significant differences (two-way ANOVA: cycle type by sleep type)				
Prior wake duration	s/s vs s/n cycles[a]		F = 7.99	p = 0.005
	1st vs 2nd sleeps		F = 424.35	p = 0.000
Time from wakeup to next on-duty	1st vs 2nd sleeps		F = 200.26	p = 0.000
Local wakeup time	1st vs 2nd sleeps		F = 12.53	p = 0.001
Circadian wakeup time	1st vs 2nd sleeps		F = 9.70	p = 0.002

[a] s/s = sleep/sleep; s/n = sleep/nap.

The considerable agreement between s/s and s/n cycles in table 8 is not surprising, since sleep duration is independent of cycle definition. However, since there are five sleep episodes that change their definition (first or second) according to the cycle definition (fig. 4), both sets of analyses were carried out for completeness.

Table 8 indicates that for first-sleeps, the duration of sleep is determined largely by factors relating to wakeup. Neither prior wake duration nor duty duration are significant determinants of sleep duration. The local time of wakeup contributes most to the variance, followed by the time from wakeup to the next on-duty, and the circadian phase of wakeup. The circadian phase of sleep onset also makes a small but significant contribution to the variance in sleep duration.

For second-sleeps, duty-related variables—the time from coming off duty to falling asleep (fig. 11), and the time from awakening to next on-duty (fig. 12)—appear to be the most important contributors to the variance in sleep duration. However, figure 11 suggests that, for second-sleeps beginning in the first 12 hr after coming off duty, sleep duration may be largely independent of the time from off-duty to asleep, whereas for sleeps beginning later in the layover, there is a negative correlation, i.e., the relationship between these two variables shows a bifurcation. Similarly, in figure 12, for second-sleeps ending within 5 hr before the next duty period, sleep duration appears to be largely independent of the time remaining until on-duty, whereas for sleeps ending earlier in the layover there is evidence of a negative correlation. Thus, neither of these duty-related variables shows a strictly linear relationship to sleep duration, and the analyses in table 8 may represent an oversimplification. The circadian phases of sleep onset and wakeup also make small but significant contributions to the variance in the duration of second-sleeps.

In internally desynchronized subjects living in time-free environments, the relationship between the circadian phase of sleep onset and sleep duration is not linear. The average curve (best-fitted quadratic) is a descending ramp with a region of overlap 8 to 9 hr after the temperature minimum (ref. 53). Sleeps beginning in this region are either very long or very short. A similar relationship appears to exist for sleep durations in the present study (fig. 13). Since the durations of first- and second-sleeps were not significantly different (table 7), they were considered together. The heavy curve in figure 13 is the best-fitted quadratic to these data, and the fine curve is the equivalent section of the best-fitted quadratic to data from subjects in desynchronized free-run (fig. 4-1a in ref. 53). The most important difference between the curves is that in the present data the sleep durations at each circadian phase are several hours shorter. This is probably because of the occurrence of naps and multiple sleeps in a 24-hr period in our data. There are also no very long sleeps (>15 hr) comparable to those in the region of overlap 8-9 hr after the temperature minimum in desynchronized free-running subjects. Duty constraints and the average period of the circadian system (see Period of Temperature Rhythm at end of this section) would be expected to preclude such long sleeps in our data. Thus the relationship between the circadian phase of sleep onset and sleep duration is probably not linear, and therefore its importance may be underestimated in table 8, for both first- and second-sleeps.

Table 8. Contributions to the variance in sleep duration

First-sleeps in a layover

Sleep/sleep cycles

Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Local time asleep	–0.164	–0.442	0.000	0.184
Asleep to on-duty	–0.160	–0.338	0.000	0.099
Circadian time awake	0.194	0.310	0.000	0.087
Circadian time asleep	–0.169	–0.235	0.004	0.050

For best subset: $r^2 = 0.627$, F = 28.10, p = 0.0000

Sleep/nap cycles

Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Local time asleep	–0.169	–0.456	0.000	0.197
Asleep to on-duty	–0.167	–0.336	0.000	0.099
Circadian time awake	0.198	0.318	0.000	0.094
Circadian time asleep	–0.156	–0.219	0.010	0.043

For best subset: $r^2 = 0.626$, F = 25.99, p = 0.0000

Second-sleeps in a layover

Sleep/sleep cycles

Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Off-duty asleep	–0.423	–0.715	0.000	0.276
Awake to on-duty	–0.248	–0.451	0.000	0.143
Circadian time asleep	–0.143	–0.309	0.007	0.076
Circadian time awake	0.095	0.217	0.051	0.038
Local time awake	–0.102	–0.210	0.060	0.035
Prior wake length	0.140	0.194	0.131	0.022

For best subset: $r^2 = 0.553$, F = 9.69, p = 0.0000

Sleep/nap cycles

Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Off-duty asleep	–0.397	–0.746	0.000	0.285
Awake to on-duty	–0.269	–0.551	0.000	0.191
Circadian time asleep	–0.140	–0.300	0.005	0.075
Circadian time awake	–0.109	–0.222	0.036	0.040
Local time awake	0.095	0.217	0.038	0.039
Prior wake length	0.155	0.214	0.073	0.029

For best subset: $r^2 = 0.551$, F = 10.62, p = 0.0000

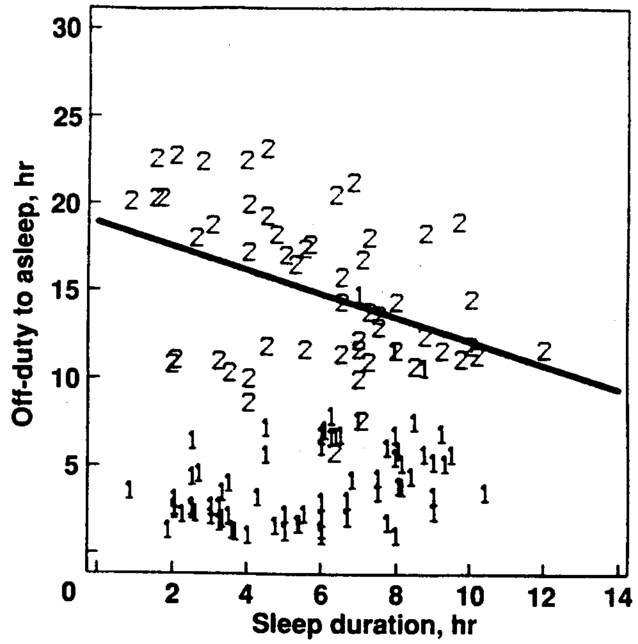


Figure 11. Relationship between sleep duration and time elapsing from coming off duty to falling asleep, for subject-defined sleeps in s/s cycles. For all second-sleep episodes combined, there is a significant negative correlation (thick line). However, figure suggests that durations of second-sleep episodes beginning in the first 12 hr of layover are independent of time since coming off duty.

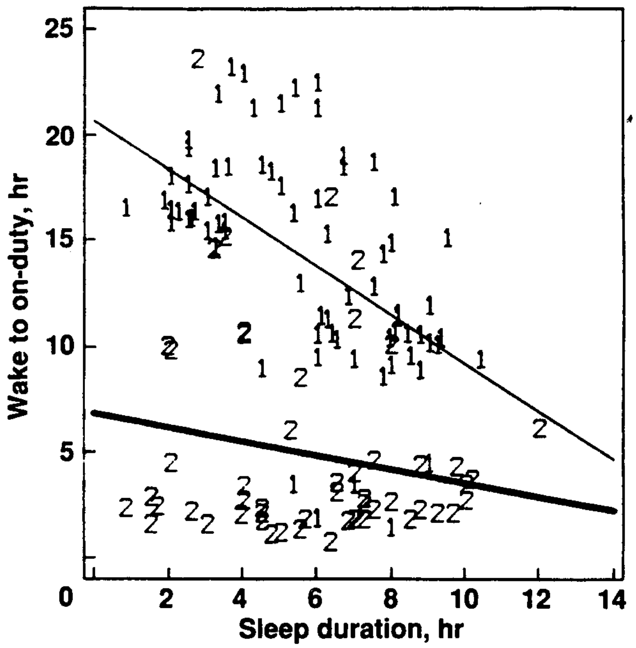


Figure 12. Relationship between sleep duration and time remaining at wakeup until next duty period. Correlations are significant for both first- (fine line) and second-sleeps (thick line). However, figure suggests that durations of second-sleeps ending within 5 hr of next duty period are independent of time remaining to duty onset.

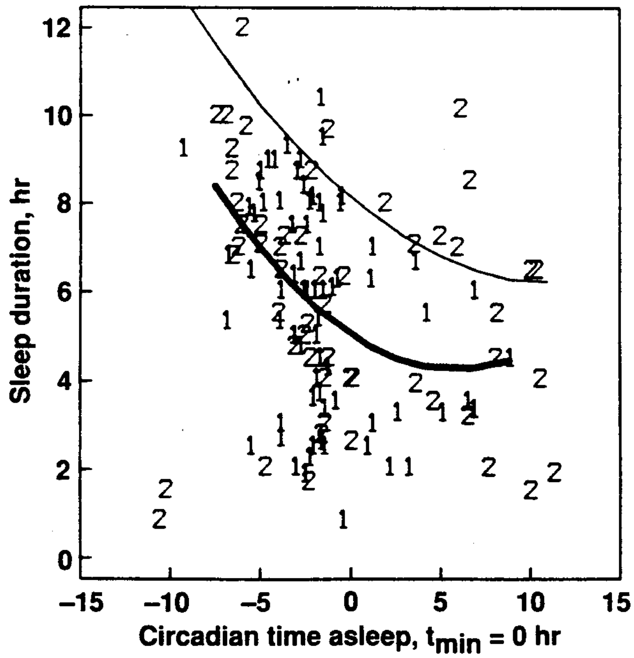


Figure 13. Relationship between sleep duration and circadian time of falling asleep, for subject-defined sleeps in s/s cycles. Circadian time (CT) zero is time of temperature minimum. Thick line represents best-fitted quadratic to first- and second-sleep data combined. Fine line represents the equivalent section of best-fitted quadratic to data from desynchronized subjects in time-isolation (from fig. 4-1a in ref. 53).

Timing of wakeup for designated sleeps– The distributions of wakeups with respect to duty timing, local time, and the temperature minimum are shown in figures 14-16. As expected, wakeups from first-sleeps are broadly distributed early in the layover, whereas 67% of second-sleeps finish within 4 hr of the next duty period.

First- and second-sleeps differ significantly in their distributions of local wakeup times (fig. 15). This difference is due primarily to a group of first-sleeps for which wakeup occurs between 1600 and 2000 hr. Twenty-two such sleeps are identified in s/n cycles, and 21 in s/s cycles. These are further examined in table 9.

In summary, these are very short sleeps begun during the early afternoon (local nap time) and shortly after coming off duty. They begin and end across a broad range of circadian times (for sleep onset, CT –6.66 to CT 6.83; for wakeup CT –5.66 to CT 10.16). Wakeup occurs, on average, about 15 hr before the next on-duty, i.e., circadian and duty factors do not appear to be controlling the timing of wakeup and the duration of these sleeps. Two thirds of these sleep episodes occurred after eastward flights crossing more than five time zones, whereas the remaining third followed flights crossing fewer than five time zones. None followed westward flights crossing five or more time zones. This represents 88% of all first sleeps after eastward flights crossing five or more time zones.

First- and second-sleeps also differ significantly in their timing of wakeup with respect to the temperature rhythm. Figure 16 suggests that this is primarily because of a group of 11 second-sleeps for which wakeup occurs between CT –12 and CT –6. The same 11 sleeps are identified in both s/s and s/n cycles. They are further characterized in table 10.

These are shorter than average sleeps begun on the rising phase of the temperature rhythm (9/11) or just after the temperature maximum (2/11). They begin after a short period of wakefulness and occur across a broad range of ocal times. Wakeup occurs very soon before going on duty. (By comparison, the average time from wakeup to next on-duty for second sleeps is: s/n cycles is 5.43 hr, s/s cycles 4.87 hr.) Thus, these appear to be short second-sleeps whose timing and duration are determined primarily by the start of the next duty period. In general, wakeup occurs as temperature is rising, and the distributions in figure 16, particularly for first-sleeps, are similar to that described for desynchronized free-run (figs. 4 and 5 in ref. 53), except that they peak several hours earlier.

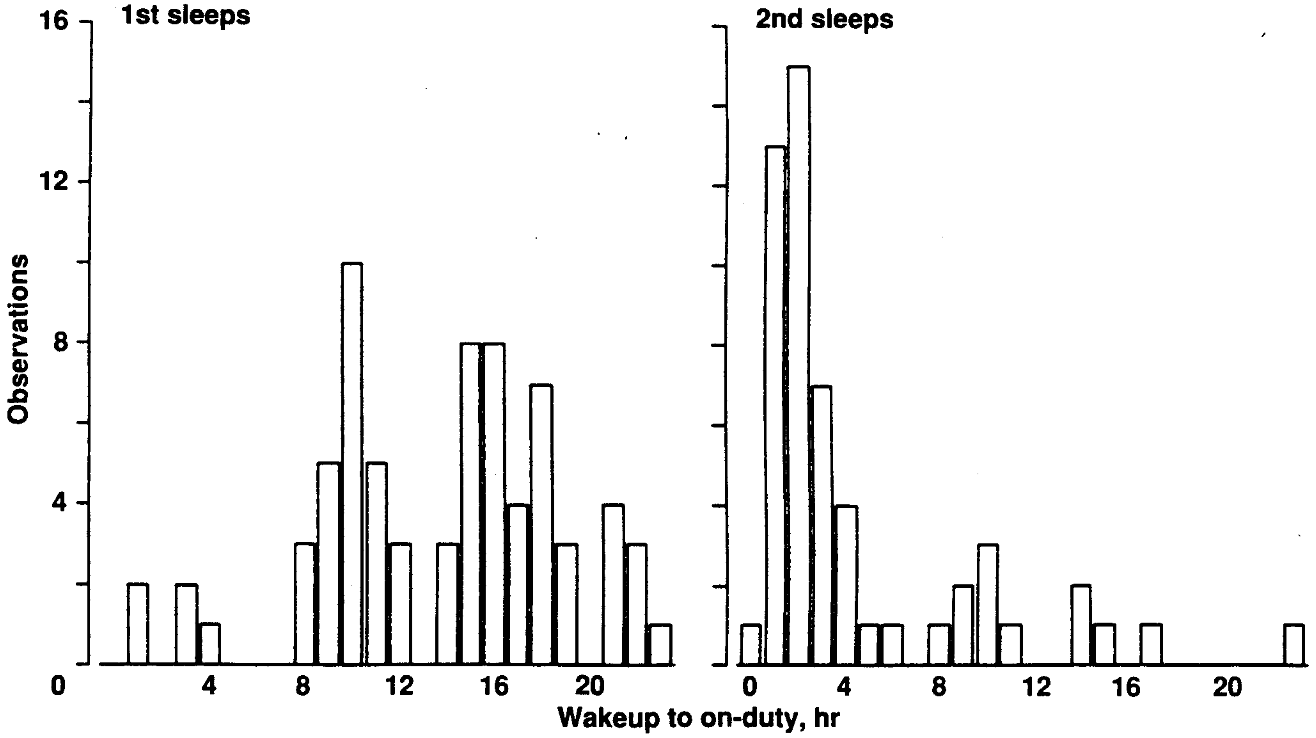


Figure 14. Frequency distributions of occurrence of wakeups with respect to time remaining until next duty period.

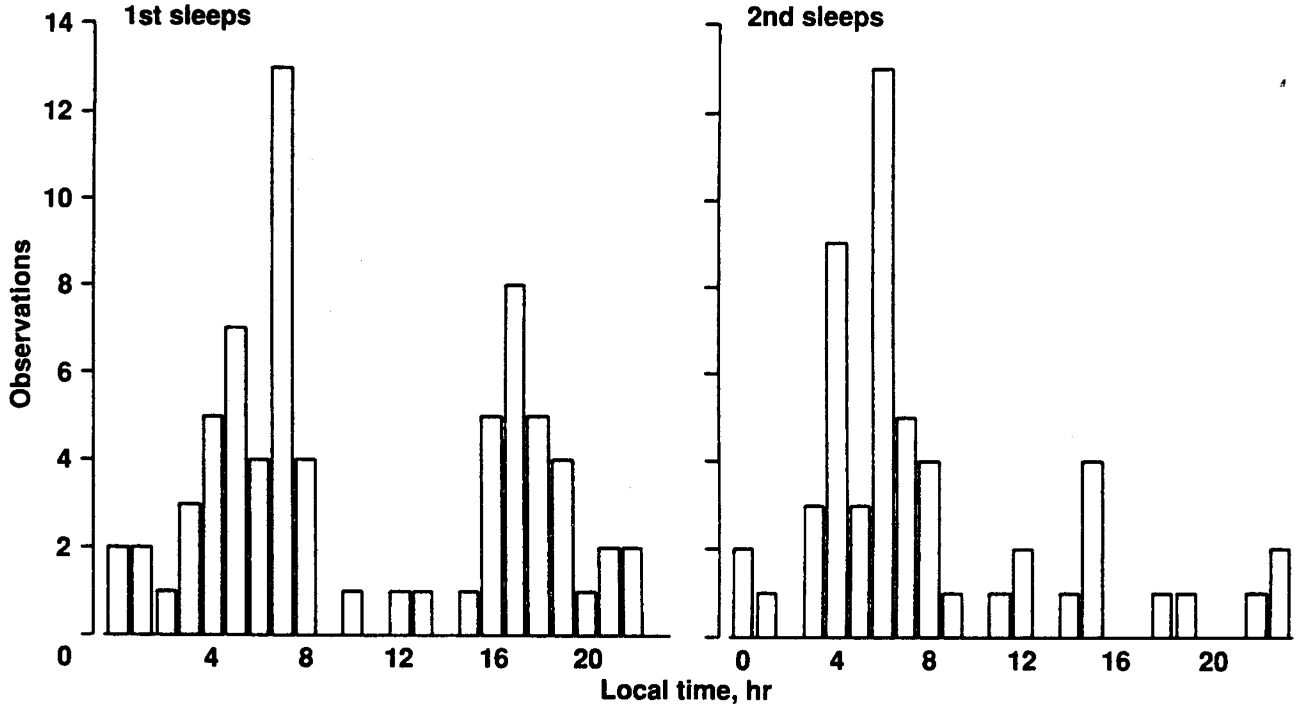


Figure 15. Frequency distributions of occurrence of wakeups with respect to local time.

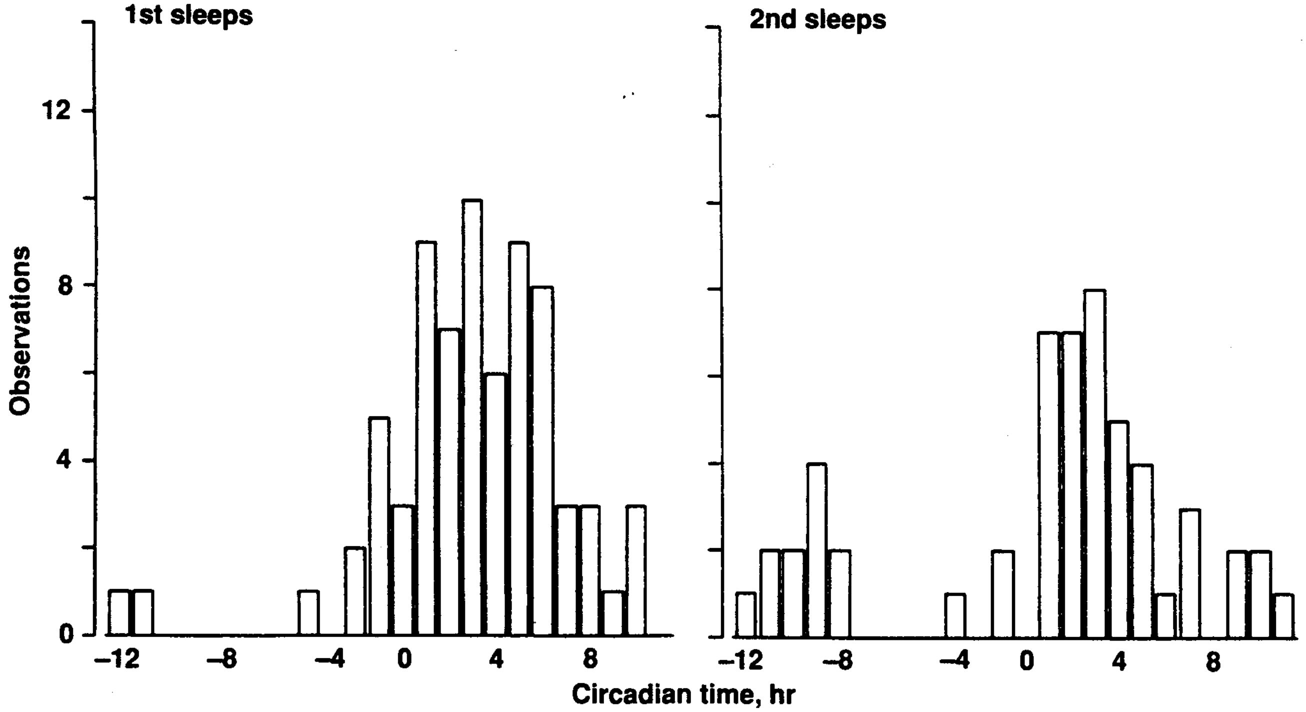


Figure 16. Frequency distributions of occurence of wakeups with respect to time of circadian temperature minimum (circadian time zero).

Table 9. Mean values for first-sleeps with wakeups between 1600 and 2000 hr local time

	Sleep/nap cycles	Sleep/sleep cycles
Local time of sleep onset	14.37	14.24
Local time of wakeup	17.62	17.60
Time from off-duty to sleep onset	2.28	2.28
Time from wakeup to on-duty	15.57	15.30
Circadian time of sleep onset	–0.85 (S.D. 3.81)	–0.58 (S.D. 3.67)
Circadian time of wakeup	2.40 (S.D. 3.93)	2.78 (S.D. 3.58)
Sleep duration	3.22	3.33
Prior wake duration	14.28	17.29

Table 10. Mean values for second-sleeps with wakeups between CT –12 and CT –6

Local time of sleep onset	3.17 (S.D. 5.67)	
Local time of wakeup	8.08 (S.D. 4.11)	
Time from wakeup to on-duty	3.62	
Circadian time of sleep onset	9.32	
Circadian time of wakeup	13.73	
Sleep duration	4.91	
Prior wake duration	s/n 6.06	s/s 6.54

Correlations between the different measures of wakeup timing are summarized in table 11. First-sleeps ending later in the temperature cycle also ended closer to the next duty period. However, since 93% of first-sleeps ended more than 8 hr before the next duty period, this correlation is not particularly interesting. Second-sleeps ending later in the local day also ended closer to the next duty period. This may have been a result of crew members trying to sleep as long as possible before beginning a duty period overlapping local night.

Sleep-Quality Ratings for Designated Sleeps

The sleep-quality ratings for first- and second-sleeps are compared in table 12. The range of possible values for the four individual questions was 1-5, and the means in table 12 have been converted so that higher values indicate better sleep. The overall sleep rating has a range of possible values from 4 to 20, and is the sum of the (converted) individual questions. First-sleeps were rated as being better overall, with less difficulty falling asleep and deeper sleep.

Multiple regression analyses of the variables expected to contribute to the overall sleep rating (table 3) are summarized in table 13. Comparable analyses for the individual sleep questions sometimes gave incompatible results between the two techniques (stepwise versus all-possible-subsets regression), suggesting that the limited range of possible values of the individual sleep questions (1-5) was insufficient for these analyses.

For first-sleeps, the most important contributions to the variance in subjective sleep ratings come from sleep duration, prior duty length, and prior wake duration. For second-sleeps, sleep duration is the most important predictor.

Designated Naps

Naps fall into two initial categories: those occurring on the ground, and those occurring in flight. Since none of the flights studied involved augmented crews, all in-flight naps occurred on the flight deck. Naps occurring during layovers can be further subdivided into naps which represent the first-sleep episode in a layover and those which are preceded by other sleeps or naps in the layover, designated second naps (fig. 4). One-way ANOVA indicated that first-naps in a layover were significantly longer than either second-naps or flight-deck naps. They also followed significantly longer episodes of wakefulness than flight-deck naps, which followed significantly longer episodes of wakefulness than second naps in a layover (table 14). Eight of the twelve first layover naps followed eastward flights crossing five or more time zones, and three followed westward flights crossing five or more time zones.

Table 11. Correlation coefficients for measures of wakeup timing

	1st sleeps		2nd sleeps	
	Local time	Circadian time	Local time	Circadian time
Time to next duty	0.18	–0.25*	–0.29*	0.26
Local time		–0.01	–0.13	

*p < 0.05.

Table 12. Comparison of sleep-quality ratings for first- and second-sleeps

	Mean			
	Sleep/sleep cycles		Sleep/nap cycles	
	1st sleeps	2nd sleeps	1st sleeps	2nd sleeps
Difficulty falling asleep?	4.37	3.80	4.37	3.85
How deep was your sleep?	3.69	3.37	3.67	3.42
Difficulty rising?	3.66	3.43	3.63	3.47
How rested do you feel?	3.00	3.02	2.98	3.04
Overall sleep rating	14.72	13.61	14.65	13.77
Significant differences (two-way ANOVA: cycle type by sleep type)				
Difficulty falling asleep?	1st vs 2nd sleeps		F = 13.84	p = 0.000
How deep was your sleep?	1st vs 2nd sleeps		F = 4.13	p = 0.043
Overall sleep rating	1st vs 2nd sleeps		F = 6.76	p = 0.010

The timing of layover nap onsets with respect to duty time and local time is shown in figures 17-20. The onsets of first-naps were tightly clustered at the beginning of layovers, whereas 67% of second-naps ended within 4 hr of the next duty period. Naps tended to be taken in the local afternoon. It should be noted, however, that local time was not the only factor contributing to the subjective definition of whether a sleep episode constituted a sleep or a nap, since nearly a third of all first-sleeps began in the local afternoon, and naps and sleeps have significantly different durations. The limited number of layover naps (12 first-naps and 33 second-naps) precluded multiple regression analyses of the relative contributions of different factors to nap timing. In addition, unambiguous temperature data were available for only 23 layover naps. The distributions of nap onset times with respect to the temperature minimum are not significantly different for first versus second layover naps or flight-deck naps (1-way ANOVA F = 1.13, p = 0.333). Figure 21 suggests that layover nap onsets are fairly equally distributed across the temperature cycle; however, the small number of naps contributing to this figure must be taken into account. The distribution of nap wakeups with respect to the temperature cycle appears to be an artifact of the nap onset distribution ($r^2 = 0.99$, $p << 0.01$).

The timing of flight-deck naps within the duty period is shown in figure 22. Recall that duty was defined as starting 1 hr before scheduled departure from the gate and ending 0.5 hr after actual arrival at the gate. The limited number of flight-deck naps recorded (36, for 17 of which there are unambiguous temperature data) precluded multiple regression analyses of the relative contributions of different possible factors to nap timing. The circadian distribution of flight-deck nap onsets does suggest a peak just before the temperature minimum (fig. 21). However, as noted above, the distributions for the three types of naps are not significantly different.

Cycles

In the present analyses, we have considered two definitions of wake duration, i.e., including naps as sleep episodes, or disregarding naps. In addition, two types of sleeps (first- and second-sleep episodes in a layover) have been identified which have significantly different prior wake durations. Two-way analyses of variance (table 15) confirm that cycle lengths are significantly longer for s/s cycles than for s/n cycles, and significantly longer for first-sleeps than for second-sleeps.

Table 13. Contributions to the variance in subjective sleep quality ratings

Ratings for first sleeps				
	Sleep/sleep cycles			
Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Prior duty length	0.450	0.320	0.010	0.090
Prior wake length	–0.148	–0.268	0.041	0.056
Sleep duration	0.257	0.239	0.060	0.047
Off-duty asleep	0.208	0.224	0.096	0.037
For best subset: $r^2 = 0.204$, F = 3.99, p = 0.0061				
	Sleep/nap cycles			
Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Sleep duration	0.486	0.453	0.001	0.163
Prior duty length	0.447	0.316	0.011	0.091
Prior wake length	–0.142	–0.280	0.030	0.066
Circadian time awake	–0.152	–0.246	0.063	0.048
For best subset: $r^2 = 0.227$, F = 4.25, p = 0.0044				

Ratings for second sleeps				
	Sleep/sleep cycles			
Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Sleep duration	0.692	0.541	0.000	0.277
Circadian time asleep	0.159	0.264	0.040	0.067
Local time asleep	–0.078	–0.204	0.107	0.041
For best subset: $r^2 = 0.320$ F = 7.06, p = 0.0005				
	Sleep/nap cycles			
Variable	Unstandardized reg. coeff.	Standardized reg. coeff.	p	Contribution to r^2
Sleep duration	0.574	0.444	0.002	0.156
Local time asleep	–0.075	–0.207	0.089	0.042
Circadian time asleep	0.128	0.209	0.096	0.040
Local time awake	–0.121	–0.201	0.128	0.033
For best subset: $r^2 = 0.338$, F = 6.13, p = 0.0005				

Table 14. Durations of naps and wake episodes preceding naps

	Mean hours		
	Flight-deck naps	1st naps	2nd naps
Nap duration	0.77	1.99	1.02
Prior wake duration	9.31	14.65	5.87
Significant differences (Tukey and Bonferroni)			
Nap duration	1st vs 2nd naps		p < 0.01
	1st vs flight-deck naps		p < 0.01
Prior wake duration	1st vs 2nd naps		p < 0.01
	1st vs flight-deck naps		p < 0.01
	Flight-deck vs 2nd naps		p < 0.01

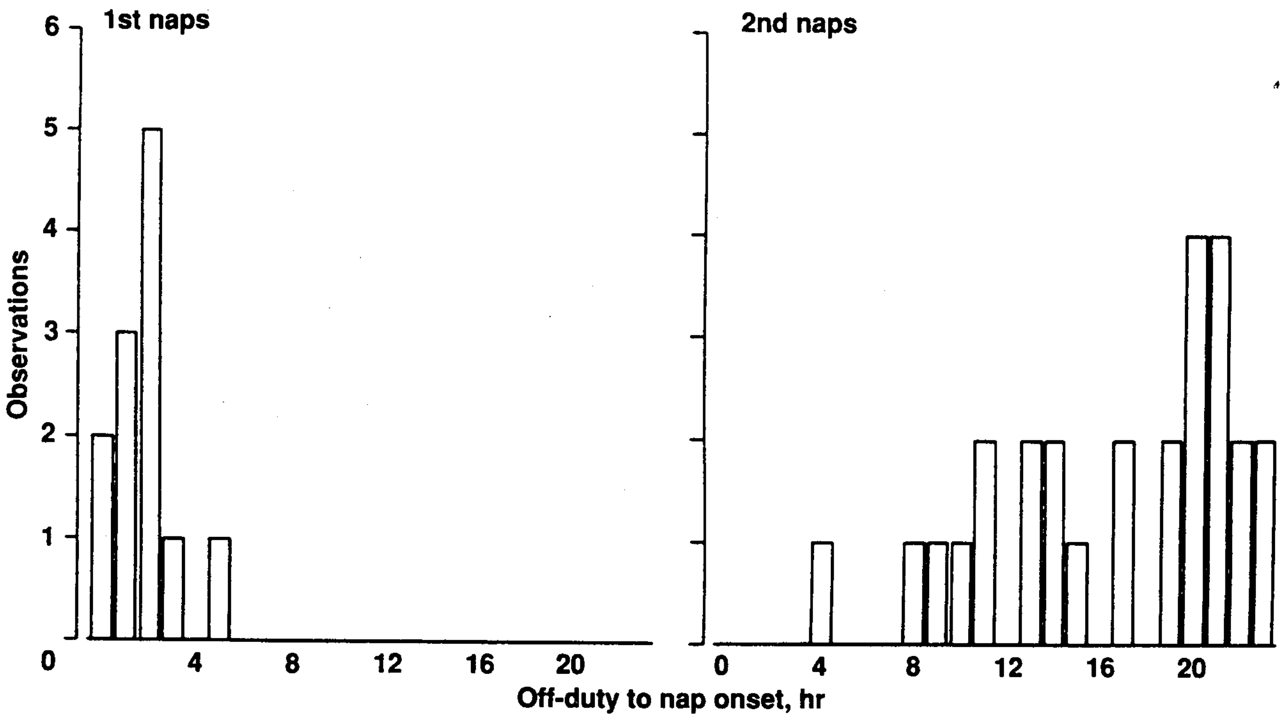


Figure 17. *Frequency distributions of occurrence of layover nap onsets with respect to time elapsed since coming off duty.*

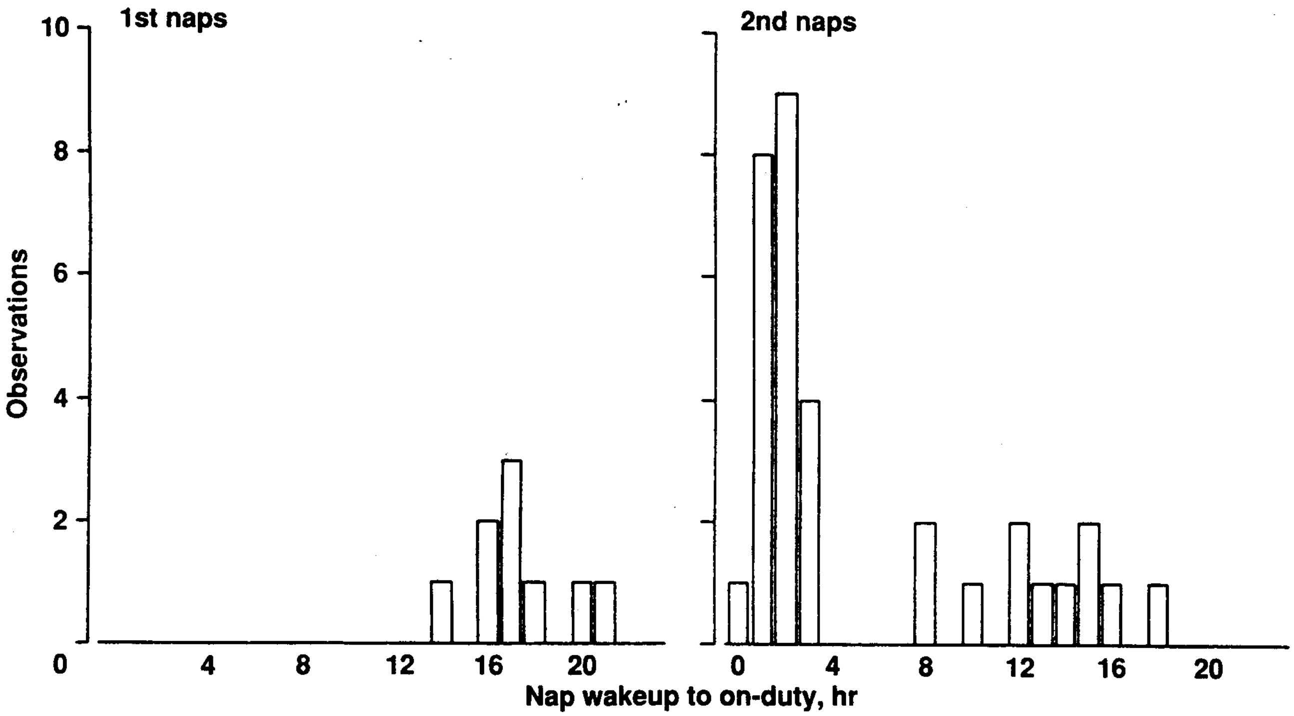


Figure 18. *Frequency distributions of occurrence of layover nap wakeups with respect to time remaining until next duty period.*

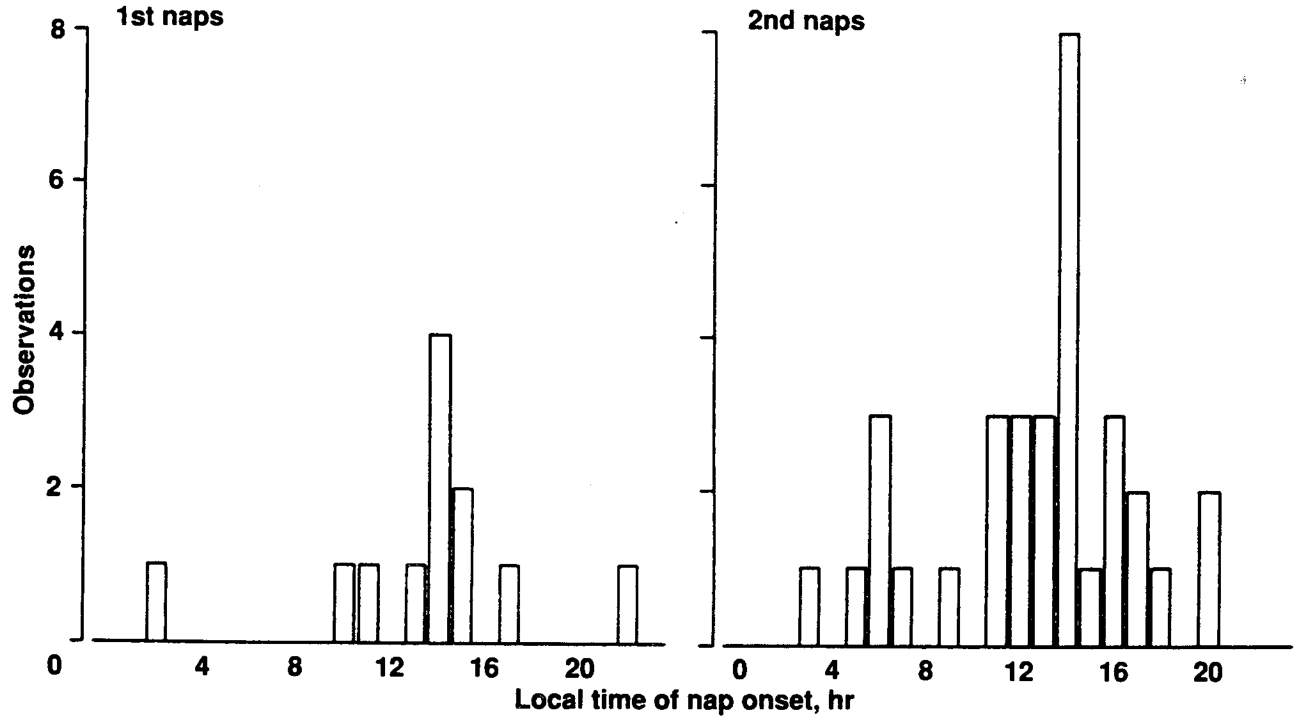


Figure 19. Frequency distributions of occurrence of layover nap onsets with respect to local time.

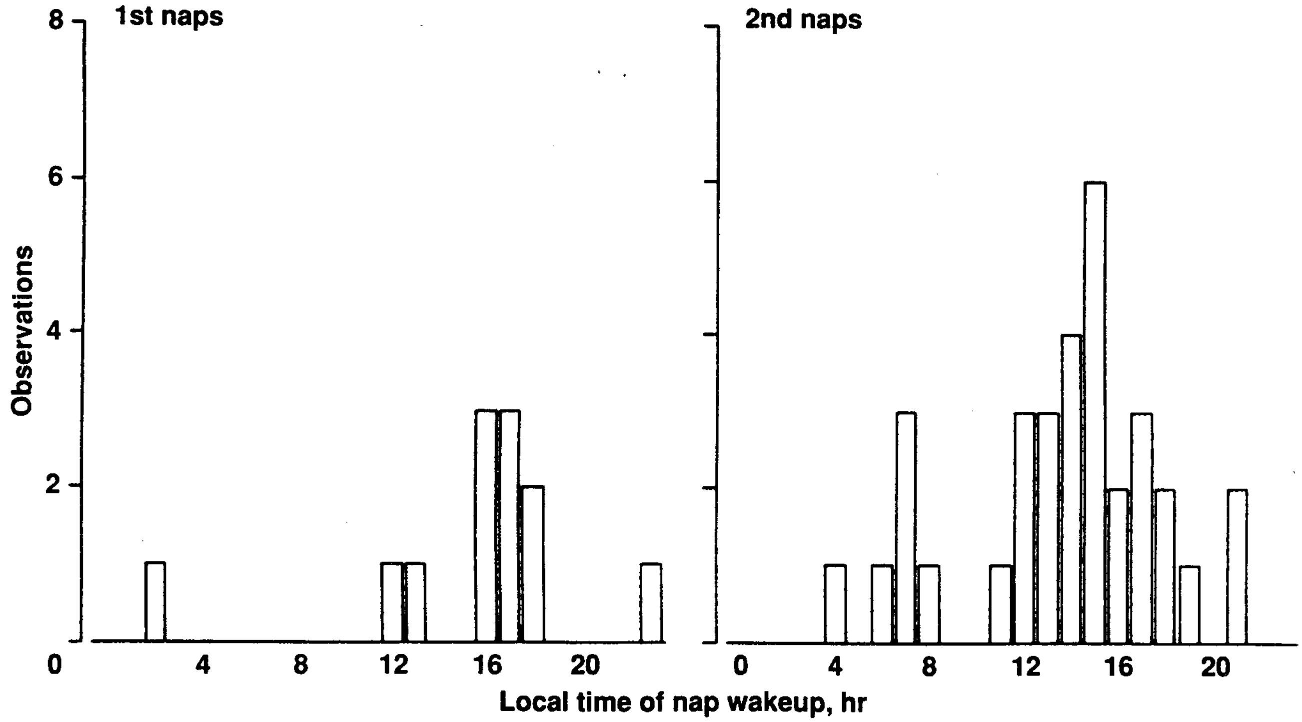


Figure 20. Frequency distributions of occurrence of layover nap wakeups with respect to local time.

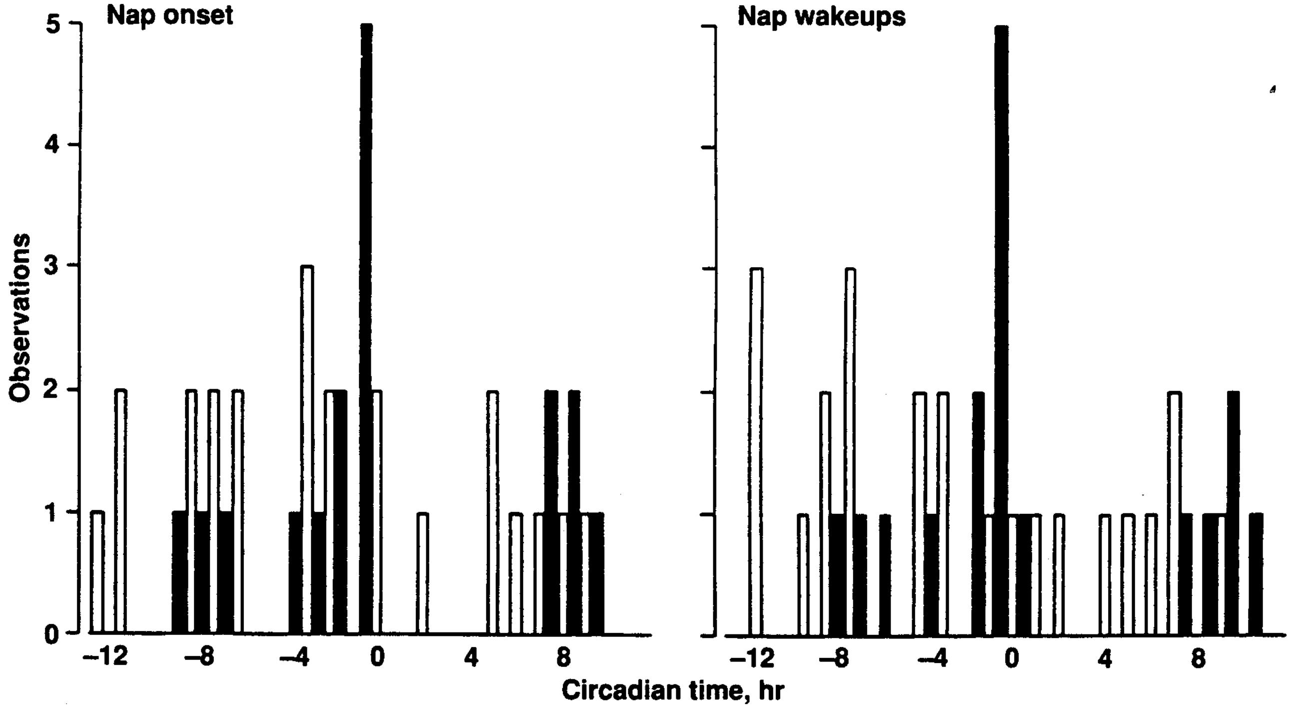


Figure 21. Frequency distributions of occurrence of nap onsets with respect to circadian temperature minimum (circadian time zero). Open bars indicate layover naps, solid bars flight-deck naps.

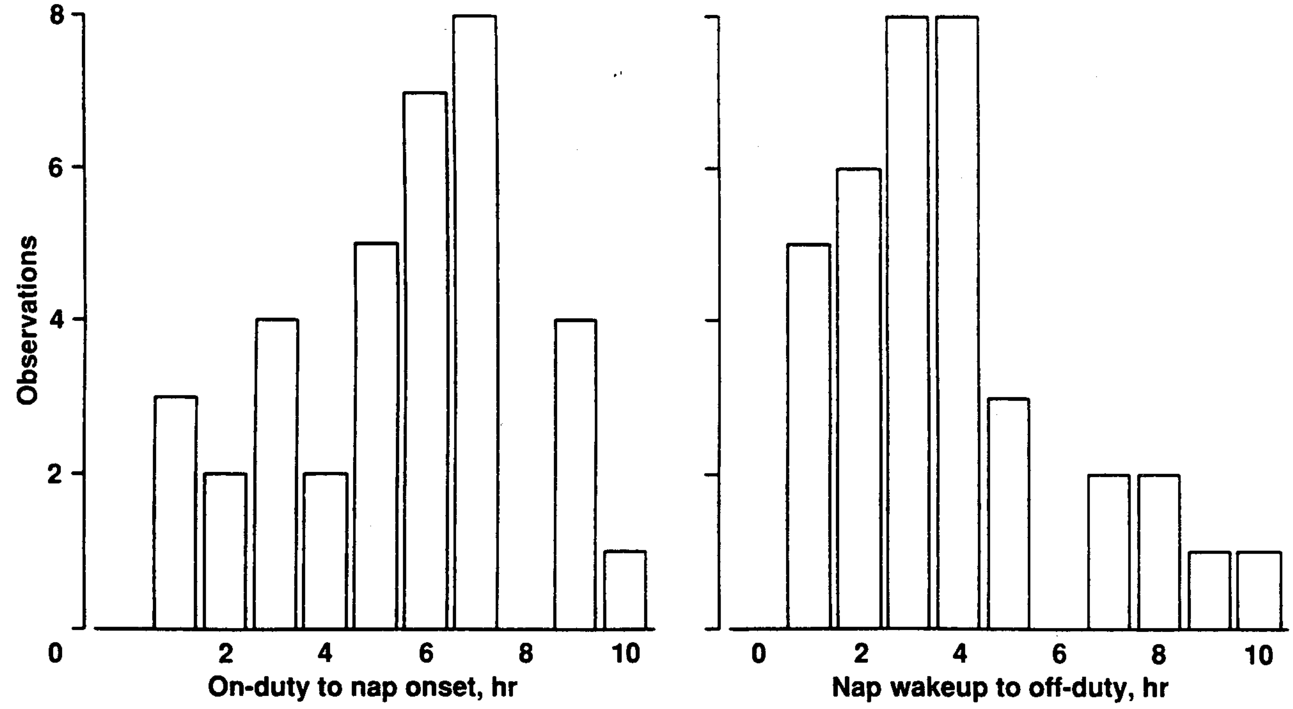


Figure 22. Frequency distributions of occurrence of flight-deck nap onsets with respect to time since coming on duty, and of flight-deck nap wakeups with respect to time remaining until going off duty.

Correlations between successive sleep and wake episodes are shown in table 16. Neither first- nor second-sleep durations showed significant negative correlations with preceding wake durations. In other words, no evidence was found for conservation of the circadian wake/sleep cycle length. Indeed, both first- and second-sleeps showed significant positive correlation with following wake durations, although this relationship was significant for second-sleeps only in s/n cycles.

Period of the Temperature Rhythm

Of the 29 subjects, 22 had rectal temperature records with no major gaps in the data. Of these 22, 18 (82%) had significant periods in the range of 24-27 hr, with a mean of 25.68 hr (S.D. 1.27 hr). One subject from each of the four trip patterns showed no significant circadian periodicity. One-way analyses of variance were performed to test whether these four subjects were in any way different from subjects who showed significant rhythms, or from subjects who provided incomplete temperature data. The variables examined were years of airline experience, height, weight, age, and scores on the following: the Eysenck Personality Inventory (ref. 51); Morningness/Eveningness Questionnaire (ref. 52); Personal Attributes Questionnaire (ref. 48); and Work and Family Orientation Questionnaire (ref. 49). Subjects who did not show significant circadian temperature rhythms tended to be less extroverted ($F = 2.68$, $p = 0.086$) on the Eysenck "extroversion" scale, and were more expressive ($F = 4.41$, $p = 0.021$) on the Personal Attributes Questionnaire "expressivity" scale.

5. Discussion

The aim of this study was to document how flight crews organize their sleep during a variety of international trip patterns, and to elucidate how duty requirements, local time, and the circadian system (measured by the rhythm of rectal temperature) influenced the choice of sleep times, sleep duration, and subjectively rated sleep quality. Duty requirements and local time can be viewed as environmental constraints on the time available for sleep, whereas the circadian system is a major physiological modulator of sleep quality and duration.

Sleep/wake patterns on these trips were complex. On average, duty periods lasted about 10.3 hr and were followed by layovers of about 24.8 hr during which there were typically two sleep episodes. The average pattern of sleep and wakefulness (disregarding naps) was 19 hr wake/5.7 hr sleep/7.4 hr wake/5.8 hr sleep. However, napping was also common, both on the flight deck and during layovers. In addition, local time was different at successive layover destinations, and there was a clear preference for sleeping during the local night.

This study provides an extraordinary wealth of information on the functioning of the circadian system in this complex operational environment. There is, however, a

Table 15. Comparison of cycle lengths

	Mean hours			
	Sleep/sleep cycles		Sleep/nap cycles	
	1st Sleeps	2nd Sleeps	1st Sleeps	2nd Sleeps
Wake/sleep cycles	24.62	13.26	22.47	12.36
Sleep/wake cycles	23.51	17.42	20.36	14.22
Significant differences (two-way ANOVA: cycle type by sleep type)				
Wake/sleep cycles	1st vs 2nd sleeps	$F = 273.50$	$p = 0.000$	
	s/s vs s/n cycles	$F = 5.53$	$p = 0.020$	
Sleep/wake cycles	1st vs 2nd sleeps	$F = 37.83$	$p = 0.000$	
	s/s vs s/n cycles	$F = 10.22$	$p = 0.002$	

Table 16. Squared correlation coefficients for sleep and wake durations

	First sleeps		Second sleeps	
	Sleep/sleep cycles	Sleep/nap cycles	Sleep/sleep cycles	Sleep/nap cycles
Prior wake	0.0009	0.020	0.0001	0.005
Following wake	0.142^{**}	0.099^{**}	0.017	0.070^{*}

$^{*}0.05 > p > 0.01$; $^{**}0.01 > p > 0.001$.

major methodological issue which must be addressed in interpreting these data, i.e., the problem of the reliability of the rectal temperature rhythm as a marker of the underlying circadian pacemaker, particularly because of the complex masking effects introduced by the unusual sleep/wake patterns. There are several lines of evidence which persuade us that the phase marker we used (daily minimum of the multiple complex demodulated wave form) is a valid measure of circadian phase and not predominantly a measure of masking influences.

1. Applying a simple model to the original temperature data to compensate for sleep/wake masking (adding 0.28 °C while the subject was asleep) did not significantly change the estimates of circadian times of designated sleep episodes (onset and wakeup), although it did delay the estimates for naps by a little more than an hour. Sleep times estimated with respect to the multiple complex demodulated wave-form minima (original data or unmasked) were not significantly different from those estimated with respect to temperature minima located by locally weighted regression smoothing (original data or unmasked). For naps, however, multiple complex demodulation of the original data gave earlier estimates of nap times than did locally weighted regression smoothing of the unmasked data. These analyses suggest that minima associated with naps may be more contaminated by masking influences than minima associated with sleep episodes. This, together with the limited number of naps for which data were available, necessitate that information on the circadian timing of naps be interpreted with caution.

2. Although designated sleep onsets, particularly for first-sleep episodes in a layover, tended to be clustered in the hours before the temperature minimum, some sleep onsets occurred after the temperature minimum. This is inconsistent with the interpretation that the estimated minima are primarily a result of decreases in temperature resulting from inactivity during sleep. Indeed, a group of second-sleep episodes in a layover was identified which occurred across the temperature maximum. The timing of these sleeps was shown to be driven by duty constraints.

3. Most of the wakeups from designated sleeps occurred some hours after the estimated temperature minimum; i.e., the rise in temperature was not simply a passive response to increased activity associated with wakefulness. In addition, the times of wakeup with respect to the estimated temperature minimum were significantly different for first- and second-sleep episodes in a layover.

4. The distributions of designated sleep onsets and wakeups, particularly for first-sleeps, closely resemble those derived from desynchronized subjects in time-free environments, although they peak several hours earlier. These distributions are not artifacts of the distributions of sleep timing with respect to local time or duty timing. Designated sleep durations also show a dependence on the circadian phase of sleep onset comparable to that observed in desynchronized free-run, except that sleep durations at each phase were shorter than in time isolation. We thus argue that our technique of estimating circadian phase from the daily minimum of the multiple complex demodulated wave form is at least as valid as the techniques used to estimate circadian phase from the temperature rhythm recorded in laboratory studies in time-isolation.

The sequences of zeitgeber shifts experienced in the trips studied here appeared to be beyond the synchronizing capacity of the circadian system. Eighty-two percent of flight crew members showed a significant non-entrained circadian period (average 25.7 hr) in their temperature rhythm, despite the complex masking effects superimposed by the unusual sleep/wake cycle. In effect, these schedules forced the sleep/wake cycle to adopt a period different from that of the circadian temperature rhythm, a phenomenon which has been produced with artificial zeitgeber cycles in laboratory studies (e.g., ref. 56) and which can occur spontaneously in isolated subjects living in time-free environments (reviewed in ref. 53). However, both in the laboratory and in our data, the circadian system still modulated the timing of sleep onset and sleep duration, i.e., the sleep/wake cycle was not uncoupled completely from the circadian timing system.

Different combinations of factors influenced the timing and quality of first- and second-sleep episodes in a layover, and of naps. Each of these categories of sleep episode will therefore be discussed separately.

Duty "Days" and First-Sleeps in a Layover

Wake episodes (disregarding naps) that included a duty period were significantly longer (average 19.0 hr) than those occurring during layovers (average duration 7.4 hr). However, the duration of the duty period (average 10.3 hr) accounted for only a small fraction of the variability in the duration of duty days. In fact, the most variable part of the duty day was the time elapsing from coming off duty to falling asleep. In other words, simply being off duty was not a sufficient condition for crew members to be able to fall asleep. Ninety-six percent of the first-sleep episodes began within 8 hr after coming off duty (fig. 8); however, figures 9 and 10 strongly suggest that crew members tended to delay sleep onset until the early afternoon or local night, and until the hours immediately preceding the daily temperature minimum. The latter interpretation is supported by the finding that the circadian phase of sleep onset contributed significantly to the variability in the duration of duty days, with longer wake durations being associated with later phases of sleep onset. The time from sleep onset to the next on-duty also contributed significantly to the variance in the duration of duty days. This replicates findings from a similar study of pilots flying commercial short-haul operations (ref. 57) and suggests that crew members tried to schedule their sleep with respect to the duration of the layover: the shorter the layover, the sooner the first-sleep episode began. The variables tested as possible factors affecting the duration of duty days (disregarding naps) accounted for a total of 40% of the variance.

The most important contributor to the variability in the duration of first-sleep episodes was the local time of wakeup. This is primarily attributable to the fact that 30% of first-sleeps began in the local afternoon and ended about 3 hr later (table 9), while first-sleeps begun during the local night were significantly longer. The scenario suggested by table 9 is that of a tired crew member going to sleep soon after arriving at the layover, sleeping about 3 hr, and then getting up for dinner. This is typical for first-sleep episodes after eastward flights crossing five or more time zones. These short afternoon sleeps were broadly distributed with respect to the temperature rhythm and began soon after arrival at the layover, i.e., these sleeps appeared to be a response to the high sleep debt typically accumulated during long overnight flights. Such short sleeps, apparently terminated in response to local social constraints, would not be expected to be sufficient for the crew member to feel well-rested. Based on polygraphic studies of flight crew sleep after a single eastward flight crossing eight or nine time zones, Graeber et al. (refs. 1 and 24) recommended that crew members should limit sleep immediately after arrival and prolong the subsequent wake period to end around the normal local time for sleep. This is intended to improve the quality of the subsequent sleep episode, in keeping with the anecdotal report that flight crews consider it important to have a good sleep immediately before a flight. Their study looked only at sleep during the first (24 hr) layover of a trip sequence. The present study suggests that the recommended strategy may not be optimal after eastward flights later in the sequence, when crew members may have already accumulated an important sleep debt and when the position of their circadian system would be much less predictable. In any case, it is important that layovers after eastward flights crossing multiple time zones be long enough to permit an adequate second-sleep episode appropriately timed with respect to the temperature cycle and local time.

The time from wakeup to the next on-duty also contributes significantly to the variability in first-sleep durations. The relationship is such that shorter sleeps end earlier with respect to the next-on duty, i.e., there is no evidence that first-sleeps are being truncated by the next duty period. The later in the temperature cycle that a first-sleep began, the shorter its duration, and this relationship explains a small but significant amount of the variability in sleep duration. However, the data from desynchronized free-running subjects suggests that this relationship is not linear but is better approximated by a quadratic function, i.e., its importance may be underestimated in the present analyses. First-sleeps ending later in the temperature cycle were longer than first-sleeps ending earlier in the temperature cycle, and this relationship also contributed significantly to the variability in first-sleep durations. This reflects the tight clustering of first-sleep onsets just before the temperature minimum. The variables tested as possible factors affecting the duration of the first sleep episodes in layovers accounted for a total of 63% of the variance.

Layover "Days" and Second-Sleeps in a Layover

As noted above, the wake episodes preceding second-sleeps in a layover were short (average 7.4 hr, excluding naps). The most important contribution to the variance in the duration of layover wake episodes was the time elapsing from coming off duty to the onset of the second-sleep episode. This time since off-duty can be decomposed into three components: off-duty to first-sleep onset, first-sleep duration, and the wake episode from first-sleep wakeup to second-sleep onset. First-sleep durations were positively correlated with following wake durations, i.e., the shorter the first-sleep episode, the sooner crew members fell asleep again. Thus, the timing of second-sleep onsets appeared to be determined, at least in part, by the accumulated sleep debt. However, the contribution of the circadian time of second-sleep onset to the variance in layover wake duration is not accurately assessed by the present methods because the relationship between the two variables is not linear. The distribution of second-sleep onsets with respect to the temperature rhythm is relatively broad, which suggests that the circadian system may be less important in controlling the timing of sleep onset for second-sleeps than it is for first-sleeps, although the distributions are not significantly different (1-way ANOVA $F = 3.08$, $p = 0.081$). The only other significant contributor to the variance in layover wake durations (disregarding naps) was the local time of sleep onset for second-sleeps, with afternoon sleeps following shorter wake episodes than sleeps begun during the local night. A smaller proportion of second-sleeps began during the local afternoon, by comparison with first-sleeps, i.e., the preference for sleeping during the local night was clearer for second-sleeps. This may have been because crew members had already slept during the layover and were thus more able to defer sleep until this preferred time. The amount of time remaining in the layover was apparently not an important factor determining the timing of sleep onset for second-sleeps, although it clearly influenced their duration (see below). The variables tested as possible factors affecting the duration of layover wake episodes (disregarding naps) accounted for a total of 44% of the variance.

Although they followed significantly shorter periods of wakefulness, second-sleep episodes in a layover were not significantly different in length from first-sleep episodes. The most important contributor to the variance in second-sleep durations was the time from coming off duty to falling asleep. In general, the later a second-sleep episode began in the layover, the shorter its duration. This may, however, be an oversimplification because there is evidence that the durations of second-sleep episodes beginning in the first 12 hr of the layover (39% of all second-sleep episodes) were largely independent of the time since coming off duty. The time remaining in the layover at wakeup also contributed significantly to the variance in second-sleep durations. In general, the longer the sleep episode, the closer wakeup occurred to the next on-duty. This relationship may be misleading, however, since it is attributable to the 26% of second-sleep episodes ending more than 5 hr before the next duty period. For the remaining 74% of second-sleep episodes, sleep duration was independent of the time remaining in the layover at wakeup ($r^2 = 0.05$, $F = 2.13$, $p > 0.05$). These findings, though complex, are consistent with the interpretation that most second-sleep episodes ended within 5 hr of the next duty period and that their duration was determined primarily by how early they began in the layover.

The circadian time of falling asleep also made a significant contribution to the variability in the duration of second-sleep episodes. As noted for first-sleeps, its actual importance may be underestimated in the present analyses. The later a sleep episode began with respect to the temperature minimum, the shorter its duration. Conversely, the later in the temperature cycle that wakeup occurred, the longer the sleep episode; this relationship also made a small but significant contribution to the variability in second-sleep durations.

The circadian distribution of wakeups for second-sleeps differs significantly from that for first-sleeps, due to 11 second-sleeps for which wakeup occurs just after the temperature maximum (fig. 19). The scenario suggested by these 11 sleeps (table 10) is that of a flight crew member who, nearing the end of the layover, feels inadequately rested and/or wants to "stock up" on sleep because he anticipates significant sleep loss during the next duty period. In the limited time remaining, he attempts to sleep irrespective of his physiological readiness to sleep (circadian phase) and the local time, both of which may compromise the quality and quantity of sleep he is able to obtain.

The local time of wakeup also made a small contribution to the variance in the duration of second-sleep episodes. Second-sleep episodes ending in the local morning hours were longer than those ending later in the day, reflecting the trend that night-sleep episodes were longer than afternoon sleep episodes. The variables tested as possible factors affecting the duration of the second-sleep episodes in layovers accounted for a total of 55% of the variance.

Sleep Quality Ratings

First-sleep episodes in a layover were rated better overall than second-sleep episodes, with less difficulty falling asleep and deeper sleep (table 12). First-sleeps were rated as better the longer their duration, the longer the preceding duty period, and the shorter the preceding wake episode. This latter relationship may have been due to subjects feeling inadequately rested following very long prior wake durations (up to 28 hr). The variables tested as possible factors affecting sleep-quality ratings for first-sleep episodes in layovers accounted for a total of 20-23% of the variance.

Second-sleep episodes in a layover were rated as better the longer their duration. Second-sleep episodes beginning later with respect to the daily temperature minimum were also rated as being of better quality. The variables tested as possible factors affecting sleep-quality ratings for second-sleep episodes in layovers accounted for a total of 32-34% of the variance.

These findings reinforce confidence in the sleep-quality ratings used. For example, first-sleep episodes in a layover followed much longer wake episodes that also included a duty period. It is thus consistent that wake duration and duty duration appear as significant contributors to the variance in sleep-quality ratings for first-sleeps but not for second-sleeps. Similarly, the times of sleep onset with respect to the temperature minimum appear to be more broadly distributed for second-sleeps than for first-sleeps. It is therefore reasonable that the circadian time of sleep onset should contribute significantly to the variance in sleep-quality ratings for second-sleeps but not for first-sleeps.

For both first- and second-sleep episodes, sleep quality is most consistently related to sleep duration. This reinforces the importance of ensuring that adequate time is available for sleep.

Naps

Napping can be an important strategy to reduce accumulated sleep debt, and it has recently been demonstrated that planned times (40 min) for napping on the flight deck can reduce reaction times and the number of EEG/ECG microevents in three-person crews during international long-haul operations (refs. 3-5).

In the present study, three types of naps were identified: naps that represented the first-sleep episode in a layover; naps that followed other sleep episodes in a layover; and flight-deck naps. Although the number of naps in each category is small, there is evidence suggesting that the factors controlling their timing and duration were different. First-layover naps were longer (average 2.0 hr) than either of the other types of nap, and followed longer periods of wakefulness (average 14.7 hr). Two thirds of these first naps followed eastward flights crossing five or more time zones. As with the short first-sleep episodes following eastward flights over five or more time zones, they were probably a response to the acute sleep loss imposed by the overnight flight and were terminated because crew members awoke for local dinner time. One quarter of first-layover naps followed westward flights crossing more than five time zones and could be interpreted as being driven by the extended period of wakefulness or sleep debt accrued since the beginning of the trip. In contrast, second naps in a layover were shorter (average 1.0 hr) and followed short wake episodes (average 5.9 hr). They tended to be taken just before the next duty period, either in response to accumulated sleep need or in anticipation of significant sleep loss during the next duty period. Such naps serve to reduce the duration of continuous wakefulness prior to the next flight, which has been suggested as a possible strategy for reducing cumulative sleep loss during commercial long-haul operations (ref. 2). The number of layover naps for which circadian-phase data could be obtained was small, and there was no indication of preferred timing with respect to the temperature minimum.

Flight-deck naps are currently receiving much attention from researchers and regulators as a result of the preplanned napping study mentioned above (refs. 3-5). In the present study, crews were given no instructions about napping and the analyses considered only the naps noted by crew members in their daily logbooks. However, flight-deck observers accompanying these crews also noted a number of naps that were not reported in the logbooks. The combined observer and logbook data suggest that, on average, 11% of flight crew members were taking the opportunity to nap when conditions permitted, although these data probably still underestimate the incidence of flight-deck napping for reasons detailed by Graeber (refs. 7 and 40). The average duration of the flight-deck naps analyzed here was 46 min (range 10-130 min). A number of factors might be expected to contribute to the timing of flight-deck naps. First, the cockpit observers reported different strategies among crews for the allocation of available nap time; for example, some captains dictate who will nap when, other crews decide on the basis of who feels most sleepy, and some do not discuss it. Naps taken early in the flight might be expected to be a response to an accumulated sleep debt and/or the twice-daily peaks in physiological sleepiness, i.e., the tendency to fall asleep just before the body temperature minimum or about 9 hr later (ref. 53). The soporific environment and increasing duration of wakefulness would be expected to be increasingly important later in the flight. The limited number of naps precluded multivariate analyses of the relative importance of these factors in the present data set. There is some suggestion that the incidence of flight-deck nap onsets was greatest just before the temperature minimum; however, this needs to be tested with additional data.

Cycles

In the present data set, there were no significant correlations between sleep duration and prior wake duration. This is consistent with the generalization that prolonged wakefulness is compensated by deeper, rather than correspondingly longer, subsequent sleep (ref. 11). However, it contrasts with the observation that, in time-free environments, longer wake episodes are followed by shorter sleep episodes, in order to conserve the overall period of the circadian wake/sleep cycle (refs. 53 and 54). In desynchronized free-run, the circadian phase of sleep onset predicts both the duration of prior wake and sleep duration, and thus the duration of the wake/sleep cycle (ref. 53). In the present data, the circadian phase of sleep onset contributes significantly to the variance in prior wake for first-sleeps only when naps are ignored in measurement of wake duration (s/s cycles), and not at all for second-sleeps (table 5). Only first-sleep s/s cycles have an average period in the normal circadian range (24.62 hr). In contrast, the circadian phase of sleep onset contributes significantly to the variance in sleep duration for both cycle types and for both sleep types (table 8). This reinforces the interpretation that the circadian system plays an important role in the timing and duration of sleep, but a minimal role in determining the duration of wake in this complex operational environment.

An interesting finding in this study was that sleep duration was positively correlated with following wake duration (table 16)—subjects fell asleep again sooner after shorter sleeps. This relationship was significant at $p < 0.01$ for first-sleeps regardless of the definition of following wake duration, and significant at $p < 0.05$ for second-sleeps and following wake episodes in sleep/nap cycles. This suggests that subjects were inadequately rested after shorter first-sleeps, e.g., those first-sleeps that were terminated for social considerations (table 9). In such cases, the homeostatic sleep mechanism (accumulated sleep debt) may have played a more important role than the circadian system in determining the duration of wakefulness between the first- and second-sleeps in a layover. This interpretation is also consistent with the finding (ref. 2) that the durations of first and second layover sleep episodes were negatively correlated in 21 B-747 crew members during a sequence of transpacific flights. Crew members in the present study also napped or slept sooner after shorter second-sleeps, e.g., those truncated by the next duty period (table 10).

In spite of the complex wake/sleep patterns in the present data, 21 of the 25 subjects for whom adequate data were available exhibited significant circadian or near-circadian periods in their temperature records. The remaining four subjects tended to be less extroverted than either the subjects who showed significant rhythms or the subjects for whom there were incomplete temperature data. This is consistent with findings from several other studies which suggest that extroverts may adjust more rapidly to time-zone and schedule changes (refs. 28 and 58). There are studies, however, which failed to find this relationship (ref. 59). On the other hand, these four subjects also scored higher in expressiveness, i.e., they were more group-oriented, sensitive to the feelings of others, warm in interpersonal relationships, and communicative. Expressiveness has been found to be positively related to check-airman ratings of flight crew performance (ref. 60).

6. Conclusions

These analyses represent a very global approach to the issue of ensuring adequate en route sleep for flight crews during scheduled commercial long-haul operations. We were interested in trying to develop a general understanding of the interactions between duty requirements, local time, and the circadian system, rather than entering into detailed analyses of specific flight schedules, which is a necessary complement to our approach. Flight and duty time regulations can be interpreted as a means of ensuring that reasonable minimum rest periods are respected. However, the perspective highlighted by this study is that the time available for sleep is less than the scheduled time off duty. There were clearly preferred times for sleep within the layover, determined by the circadian modulation of sleep propensity and the factors driving the preference to sleep during the local night (noise, light, meal availability, etc.).

This study has significantly enhanced our understanding of how the circadian system functions in this complex operational setting. Overall, the circadian system appeared to have a greater influence on the timing and duration of first-sleep episodes than on second-sleep episodes in the layover, except when the level of accumulated sleep debt was high, e.g., after eastward flights crossing five or more time zones. In such cases, crew members typically went to sleep sooner after arriving at the layover, during the local afternoon, and woke up either about 2 hr later (if they reported a nap) or 3 hr later (if they reported a sleep episode). Otherwise, crew members tended to delay going to sleep until the local night and/or until the hours preceding the temperature minimum. The timing of second-sleep onsets seemed to be related primarily to the amount of sleep already obtained in the layover and generally coincided with local night. The duration of second-sleeps was strongly influenced by the amount of time remaining in the layover. However, for both first- and second-sleeps, the circadian time of sleep onset was also a significant predictor of sleep duration.

The flight schedules of the trips studied forced the sleep/wake cycle to adopt a period different from that of the underlying circadian pacemaker, although the influence of the circadian system was still seen in the selection of sleep times and in sleep durations; i.e., the two systems were not completely uncoupled. The homeostatic sleep mechanism evidently had an overriding influence in some instances when the accumulated sleep debt could be assumed to be high. The circadian system, in turn, effectively uncoupled from the very complex patterns of environmental synchronizing stimuli experienced by crews. There are known to be differences between individuals in (1) the periods of their circadian pacemakers, (2) their sensitivity to environmental synchronizers, and (3) their self-selected patterns of exposure to social and sunlight cues in each time zone. At least some of these factors may be associated with certain personality profiles and probably all are age-dependent. An analysis of questionnaire data from 205 of the flight crew members in our data bases concurs with other studies suggesting that the period of the circadian pacemaker shortens with age, and we are currently looking to confirm this in the corresponding physiological data (Gander, unpublished observations). Age-related changes in sleep are also well documented, including shorter, less efficient nocturnal sleep and increased physiological sleepiness during the day (ref. 6).

The timing and quality of sleep obtained by flight crews is the product of a subtle and dynamic interplay between all of these factors and cannot be captured by any simple predictive algorithm. The insights gained in this and other studies suggest to us two profitable directions for improving en route sleep for flight crews during international commercial trip patterns. First, crew members need to have basic information about sleep and the functioning of the circadian system, and about how their behavior can modify both. Second, current expert-system technology permits the development of systems that reason on the basis of heuristics. Flight crews and schedulers have a great wealth of heuristic information on this problem which needs to be collected and structured using appropriate knowledge acquisition techniques. This operational knowledge, combined with our understanding of the underlying physiological systems, should be integrated to provide a computerized intelligent scheduling assistant (ref. 61).

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13. ABSTRACT *(Maximum 200 words)*

This report documents how flight crews organize their sleep during layovers on long-haul trips and examines environmental and physiological constraints on sleep. In the trips studied, duty periods averaging 10.3 hr alternated with layovers averaging 24.8 hr, which typically included two subject-defined sleep episodes. The circadian system had a greater influence on the timing and duration of first-sleeps than second-sleeps. There was also a preference for sleeping during the local night. The time of falling asleep for second-sleeps was related primarily to the amount of sleep already obtained in the layover, and their duration depended on the amount of time remaining in the layover. For both first- and second-sleeps, sleep durations were longer when subjects fell asleep earlier with respect to the minimum of the circadian temperature cycle. Naps reported during layovers and on the flight deck may be a useful strategy for reducing cumulative sleep loss.

The circadian system was not able to synchronize with the rapid series of time-zone shifts. The sleep/wake cycle was forced to adopt a period different from that of the circadian system.

Flight and duty time regulations are a means of ensuring that reasonable minimum rest periods are provided. This study clearly documents that there are physiologically and environmentally determined preferred sleep times within a layover. The actual time available for sleep is thus less than the scheduled rest period.

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