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SUMMARY

To document the psychophysiological effects of flying overnight cargo operations, 41 B-727 crew members (average age 38 yr) were monitored before, during, and after one of two typical 8-day trip patterns. During daytime layovers, the average sleep episode was 3 hr (41%) shorter than nighttime sleeps and was rated as lighter, less restorative, and poorer overall. Sleep was frequently split into several episodes and totaled 1.2 hr less per 24 hr than on pretrip days. Each trip pattern included a night off, which was an effective countermeasure against the accumulating sleep debt. The organization of sleep during daytime layovers reflected the interaction of duty timing with circadian physiology. The circadian temperature rhythm did not adapt completely to the inverted wake-rest schedule on duty days, being delayed by about 3 hr. Highest subjective fatigue and lowest activation occurred around the time of the temperature minimum. On duty days, reports of headaches increased by 400%, of congested nose by 200%, and of burning eyes by 900%. Crew members also reported eating more snacks. Compared with daytime short-haul air-transport operations, the overnight cargo trips included fewer duty and flight hours, and had longer layovers. Overnight cargo crews also averaged 5.4 yr younger than their daytime short-haul counterparts. On trips, both groups lost a comparable amount of sleep per 24 hr, but the overnight cargo crews had shorter individual sleep episodes and more broken sleep. These data clearly demonstrate that overnight cargo operations, like other night work, involve physiological disruption not found in comparable daytime operations.

1.0 OPERATIONAL OVERVIEW

This report is the seventh in a series on the physiological and psychological effects of flight operations on flight crews, and on the operational significance of these effects. This section presents a comprehensive review of the major findings and their significance. The rest of the volume contains the complete scientific description of the work.

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To document the psychophysiological effects of flying overnight cargo operations, 41 B-727 crew members were monitored before, during, and after one of two typical 8-day trip patterns. On the Destination-Layover pattern, crews stayed in layover hotels between consecutive nights of flying. After three nights on duty, they deadheaded home and had about 45 hr off duty before deadheading out to begin another three nights of flying. On the Out-and-Back pattern, crews returned home after each night of flying. After five nights on duty, they had about 45 hr off duty before flying for two additional nights. The average duty "day" on the Destination-Layover pattern was 3.5 hr longer than on the Out-and-Back pattern, with double the number of flight segments and 52 min more flight time; the average layover was 6.1 hr shorter. All flights took place in the eastern and central United States, with a maximum time zone change of 1 hr per day.

Thirty-four volunteers provided sufficient data to be included in the analyses. Their average age was 37.6 yr and they had flown for an average of 4.7 yr with the participating company. Throughout their participation in the study, they wore a portable biomedical monitor that recorded average heart rate, wrist activity, and core body temperature every 2 min. In a logbook, they rated their fatigue and mood every 2 hr while awake and kept a detailed record of their daily activities including: duty times; sleep timing, quantity, and quality; food and fluid consumption; and any occurrences of 20 different medical symptoms. They also completed a Background Questionnaire that included basic demographic information, sleep and lifestyle habits, and four personality inventories. Subjects were accompanied on all study flights by a NASA cockpit observer who kept a detailed log of operational events.

Flying at night required crews to sleep during the day. Daytime sleep episodes were about 3 hr (41%) shorter than nighttime sleep episodes and were rated as lighter, less restorative, and poorer overall. The incidence of sleeping more than once in 24 hr tripled on days with duty, compared to days without duty. Overall, crew members averaged 1.2 hr less sleep per 24 hr on duty days than on pretrip days.

The circadian temperature rhythm did not adapt completely to the inverted wake-rest schedule on duty days, being delayed by about 3 hr. As a result, the average temperature minimum occurred about an hour after coming off duty, at around 0820 local time. The time of the temperature minimum corresponds to the daily low point in alertness and in performance capabilities in the laboratory, in flight simulators, and in other 24-hour industries. Crew members were also accumulating a sleep debt across the 8 days of the trip patterns.

The way that crews organized their sleep between successive nights of flying reflected the interaction of duty timing with circadian physiology. Regardless of the time that they went to sleep after coming off duty in the morning, they tended to wake up around 1410 local time, even after as little as 4–5 hr of sleep. This clustering of wake-up times coincides with the timing of the circadian "wake-up signal" identified in laboratory studies. Anecdotal reports from crew members indicate that they often awaken spontaneously around this time but do not feel well rested. Because it is difficult to sleep past the circadian wake-up signal, getting off duty earlier enables crews to sleep longer in the morning. If late off-duty times are unavoidable due to operational constraints, then longer layovers (the present data suggest at least 19 hrs) would accommodate a second sleep episode in the evening. Layovers in which crew members slept twice ended 4–7 hr later (around 0330 local time) than layovers in which they slept only once. Because of the evening wake maintenance zone, crew members need to be aware that they risk having difficulty falling asleep if they do not go to sleep again before about 2300 local time. This is a part of the circadian cycle when it can be difficult to fall asleep, even after sleep loss.

The night off in the middle of a sequence of duty nights provided an important opportunity for recuperation. Crew members averaged 41 min more sleep per 24 hr than pretrip and 115 min more than during daytime layovers. It was effectively positioned in the sequence of night duties to offset the cumulative sleep loss imposed by the schedules. On the Destination-Layover pattern, one third of all crew members had lost more than 8 hr sleep after three nights of flying. It was clearly prudent not to add a fourth consecutive night of duty in this case. In contrast, on the Out-and-Back pattern, only one quarter of the crew members had lost more than 8 hr of sleep after five nights of flying. The amount of sleep lost varied greatly, even among crew members on the same trip pattern. It was not correlated with any of the individual attributes previously reported to predict adaptability to shift work and time zone changes (i.e., amplitude of circadian rhythms, morningness/eveningness, extraversion, and neuroticism).

When they were awake on duty at night, subjects rated their fatigue and negative affect as higher, and their activation and positive affect as lower, than when they were awake during the day pretrip. Subjective fatigue and activation appear to be influenced by both the circadian cycle and the duration of wakefulness, with minimum fatigue (peak activation) occurring 8-10 hr after awakening. Flying at night disrupted the normal relationship between these two components. The data did not permit a precise description of these changes. However, highest fatigue and lowest activation occurred around the time of the temperature minimum, as has been reported for night workers in other industries.

Crew members reported eating more snacks on duty days than on pretrip days. However, unlike the daytime short-haul air-transport crews in other NASA field studies, they did not increase their consumption of caffeine on duty days. Used appropriately, caffeine can be a convenient operational countermeasure for fatigue. Ensuring that caffeine and information about its use are readily available could help crew members maintain their alertness during night flights. However, caffeine also disturbs sleep so its use close to bedtime is not recommended. On duty days, by comparison with pretrip days, reports of headaches quadrupled, reports of congested nose doubled, and reports of burning eyes increased ninefold.

The responses of overnight cargo crew members to duty demands were compared with those of daytime short-haul air-transport flight crews for whom the same measures were available. In both cases, crews crossed no more than one time zone per 24 hr. The overnight cargo crews had shorter duty "days" (by 3 hr), with 2 hr less flight time, fewer, shorter flight segments, and longer layovers (by 2.4 hr). They were also 5.4 yr younger on average. Nevertheless, while on duty, they lost a comparable amount of sleep per 24 hr, had shorter individual sleep episodes, and had more broken sleep than their daytime short-haul counterparts. This is consistent with the finding that 62% of shift workers in other industries report sleep complaints, compared with 20% of day workers. The daytime sleep of night-shift workers is also reduced by about a third relative to a normal night of sleep at home.

Reports of headaches were more than twice as common among overnight cargo crews than among short-haul fixed-wing crews and were approaching the incidence reported by helicopter crews who flew daytime air-transport operations in cockpits in which overheating, poor ventilation, and high levels of vibration were common. Overnight cargo crews also reported that trips had a negative effect on appetite, whereas daytime short-haul fixed-wing crews reported no change.

Over the past 45 years, there has been a significant increase in scientific knowledge regarding sleep loss, circadian disruption, and their effects on performance and alertness. Laboratory studies have demonstrated that reducing sleep by 2 hr on one night is sufficient to significantly decrease subsequent alertness and performance. These studies have shown that sleep loss accumulates over time into a cumulative sleep debt. As this "debt" increases, people become increasingly sleepy. Acute sleep loss and a cumulative sleep debt, combined with poor sleep quality, all have the potential to decrease waketime alertness progressively with the number of days of reduced sleep. In laboratory studies, the combination of working through the circadian temperature minimum with a sleep debt produces the poorest performance.

Data for this study were collected between November 1987 and November 1988. Since that time, there have been a number of changes in the operations of the participating company. In domestic operations, so-called "morning" Out-and-Back patterns of the type studied here have been almost eliminated. Destination-Layover patterns are still common, but longer layovers have been introduced. "Evening" Out-and-Back patterns are also common (Clive Seal, personal communication, 1994). The maximum number of consecutive nights of flying has been extended to six, and there has also been an expansion into international cargo operations. This has resulted in some schedules which include both transmeridian and back-of-the-clock flying (David Wells, personal communication, 1994). The impact of these changes on circadian disruption and duty-related sleep loss deserves investigation. The company has also banned smoking in the cockpit. Of the 34 crew members included in the analyses in this study, only one reported being a smoker. Thus, it is unlikely that smoking in the cockpit was related to the physical symptoms reported during these trips.

Clearly, no one study can address in detail all the issues in overnight cargo operations, which are rapidly evolving and expanding in response to market demands and other forces. Schedules are varied and changeable, and logistical and cost factors limit the number of crew members who can be studied.

However, night work has some generic physiological consequences which stem from trying to override the day-active orientation dictated by the human circadian clock. The present study illustrates that overnight cargo operations, like other types of night work, can require people to work through the circadian lowpoint in alertness and performance and displace sleep to a part of the circadian cycle where its quality and quantity are reduced. Currently, there are no countermeasures, which have been shown to be safe and effective in operational settings, to overcome the incomplete adaptation of the circadian clock to night work. However, the present study indicates several approaches for minimizing sleep loss. In trip construction, particular attention can be given to the timing and duration of rest periods and to the number of consecutive nights of flying. Education and training on sleep and circadian physiology, and its operational significance, can enable crew members to develop better personal strategies for coping with the demands of overnight cargo flying. The participating company addresses fatigue issues in an ongoing way through listening to crew members and its Flight Safety Department, monitoring innovations in the industry, and as part of its recurrent training and Crew Resource Management training curriculum.

2.0 INTRODUCTION

This report is the seventh in a series on the physiological and psychological effects of flight operations on flight crews, and on the operational significance of these effects.

2.1 Overnight Cargo Operations

The overnight cargo industry represents a growing segment of commercial aviation operations worldwide (ref. 1). Five U.S. companies surveyed at the time of this study employed about 4500 flight crew members in such operations. The business community has become increasingly reliant on the next-day, door-to-door delivery service provided by this industry.

2.2 Night Work and Sleep

The daytime sleep of night workers in other industries has been shown to be reduced by at least one third compared with normal sleep at night (ref. 2). The different types of sleep are not equally affected. Deep slow-wave sleep tends to be conserved at the expense of light (Stage 2) sleep and dream (rapid eye movement [REM]) sleep (ref. 2). Sleepiness (measured subjectively or objectively) during night work is very common. Akerstedt has recently estimated that 75% of all workers experience sleepiness on every night shift and at least 20% experience sleepiness severe enough to cause the individual to fall asleep (ref. 2). This can be attributed to working during the time of maximal sleepiness (0200–0600 on a diurnal routine; ref. 6), together with the sleep loss associated with daytime sleep. A recent NASA study of planned cockpit rest in three-person long-haul flight crews showed evidence of greater sleep propensity and poorer performance (on a sustained attention, vigilance-reaction time test) during eastward nighttime transpacific flights than on westward daytime transpacific flights (ref. 7). The potential detrimental effects of night work on efficiency and safety have been highlighted in several recent publications (refs. 2, 5, 8, 9).

Flying domestic overnight cargo operations involves a combination of challenges. Like other night-shift workers (refs. 2, 3), overnight cargo flight crews must adapt to a duty-rest cycle out of synchrony with a day-oriented society and with their own diurnal physiology. They are required to work at times in the circadian cycle when they are physiologically prepared for sleep and when their performance capacity is lowest (refs. 2, 4, 5). Conversely, they may be trying to sleep when they are physiologically prepared to be awake and also at times when disturbances (noise, light, domestic or other social demands) are maximal.

2.3 Night Work and Circadian Rhythms

Across a series of night duties, there may be some adaptation of circadian rhythms to the reversed wake-rest schedule (ref. 3). The extent of this adaptation is of interest because it may be associated with improvements in sleep quality, sleepiness, and performance. In practice, however, it is very difficult to measure. The rhythm of core body temperature is the most commonly used indicator of circadian phase. However, changes in the level of physical activity, and sleep, cause shorter-term changes in temperature (so-called "masking effects") which are superimposed on the circadian variation.

Night-shift workers frequently revert, on days off, to sleeping at night and being active during the day. Continuously changing from a nocturnal to a diurnal rest-activity pattern can result in chronic desynchronization of the circadian clock from the social factors and the day-night cycle that normally stabilize it to a 24-hr day. This can produce persistent internal desynchronization between different physiological systems, a condition that has been associated with intolerance to shift work (ref. 10).

2.4 Individual Differences in Adaptation to Shift Work

Individuals with higher amplitude circadian rhythms (refs. 10, 11) and more "evening-type" (ref. 12) circadian profiles (refs. 3, 13-17) have been reported to adapt better to shift work. In a group of commercial long-haul flight crew members, Sasaki and coworkers found that evening-types showed lower levels of daytime sleepiness after an eastward flight crossing 9 time zones than did morning-types (ref. 18). It has also been reported that individuals who score high on the extraversion and neuroticism scales of the Eysenck Personality Inventory (ref. 19) may adapt more rapidly than other personality types to schedule changes (ref. 4). In a study of Norwegian Air Force pilots, more extraverted individuals showed greater adaptation of the circadian temperature rhythm 5 days after a westward flight that crossed nine time zones (refs. 20-21). Although they are statistically significant, these relationships account for only a very small amount of the variability among individuals. Thus, they are not yet useful for predicting who is most likely to experience performance decrements due to fatigue.

2.5 Flight Operations versus Other Kinds of Shift Work

Commercial flight operations within the U.S. (known as domestic operations) differ from other types of night work or shift work in several respects. These differences are important because they might be expected to influence flight crew sleep and circadian rhythms. First, the length of the work period is variable and often unpredictable. The current Federal Aviation Regulations (FARs) specify scheduled rest times according to the number of hours flown in the preceding duty day. These rest times can be reduced when unforeseen circumstances arise that are beyond the company's control (aircraft malfunctions, adverse weather, etc.). In such cases, a mandated longer rest period must begin within 16 hr after the reduced rest period.

Second, consecutive duty periods do not necessarily start and end at the same time of day. Nothing constrains the duty-rest cycle to a 24-hr period, as is typical in other shift work situations.

Third, the amount of time off between a series of working days is much more flexible in domestic commercial flight operations, including overnight cargo operations, than it is in many other types of shift work. In general, crew members bid each month for trips, which are awarded on the basis of seniority. Companies differ in the extent to which they will allow subsequent trading of trips. Many creative solutions are possible within this framework, still respecting required weekly, monthly, and annual flight time limitations.

2.6 Field Studies of Flight Operations

The present study is one of a series of NASA field studies aimed at documenting the effects of different types of flight operations on fatigue, sleep, and circadian rhythms (refs. 7, 20-26). In all of these field studies, the same core set of physiological and subjective measurements was combined with detailed recordings of operational events. It is therefore possible to provide an initial comparison of the psychophysiological effects of predominantly night flying (commercial overnight cargo operations) versus predominantly daytime flying (commercial short-haul air-transport operations). This comparison is of interest because both types of operations are governed by the same FARs. They are also similar in that each duty period contains several relatively short flight segments with considerable time spent on the ground in between segments. Thus the discrepancy between flight hours and duty hours is often large. In addition, in the operations studied, time-zone changes were minimal (a maximum of 1 hr per day).

3.0 METHODS

3.1 Subject Recruitment

After the proposed study had been approved by airline management and by pilot representatives, a letter and brochure explaining the study and calling for volunteers were distributed at the domicile. As in most airlines, pilots bid for monthly trip schedules that were then awarded on the basis of seniority.

NASA received copies of the monthly schedules in advance and some of the trips selected for study were annotated so that the crew members knew on which trips their participation would be solicited before they decided on which trips to bid. This prior knowledge of study trips has the potential to introduce bias in the sample of crew members studied. However, the population studied did not differ on any of the personality measures from the population of volunteer pilots in the daytime short-haul fatigue field study who were not aware of which trips would be studied at the time that they bid (ref. 22). The turn-down rate in the present study was about 15%, comparable to that in the short-haul fatigue field study. Data were collected during 1987–1988, and all the trips studied involved B-727 aircraft with at least two of the three flight crew members participating. The only incentives offered for participation were the possibility to review one's own physiological data, a NASA Ames Research Center Certificate of Appreciation, and a letter of recognition. Confidentiality and anonymity of each subject's data were assured as in other NASA field studies (ref. 22).

3.2 Trip Patterns Studied

The basic pattern of overnight cargo operations involves flights into and out of a hub, where pilots wait while the incoming cargo is unloaded and sorted according to its final destination and where the new cargo is loaded for delivery to the destinations of the following outward flight segments. From discussions with pilots and flight operations personnel in the participating company, the three most common types of trip patterns were identified. Informal surveys of pilots in four other overnight cargo companies indicated that these patterns are widespread throughout the industry. The first, designated Destination-Layover (fig. 1), began from the domicile with several flight segments arriving finally at the hub. The following outward segments from the hub ended at a third location, where the crew then had a rest period (the "destination layover"). This pattern of flying between the hub and a destination layover might be repeated several times before the crew finally returned to its domicile. In the second common trip pattern, designated Out-and-Back (fig. 2), crews usually returned to their domicile for each rest period. In the third category of common trip pattern, designated Evening-Out-and-Back, duty periods began and ended earlier (around midnight) than for the usual Out-and-Back trips. They were therefore considered less challenging, in terms of their potential to disturb sleep and circadian rhythms. Since they were also a smaller proportion of the total flight schedules than the other two categories, they were not examined in the present study. Forty-one flight crew members (39 males, 2 females) from one company took part in the study. Of these, 23 were monitored before, during, and after the Destination-Layover pattern and 18 were monitored before, during, and after the Out-and-Back pattern. About half of the trips studied took place during Central daylight savings time (CDT) and half during standard time. All data were recorded on Greenwich Mean Time (GMT).

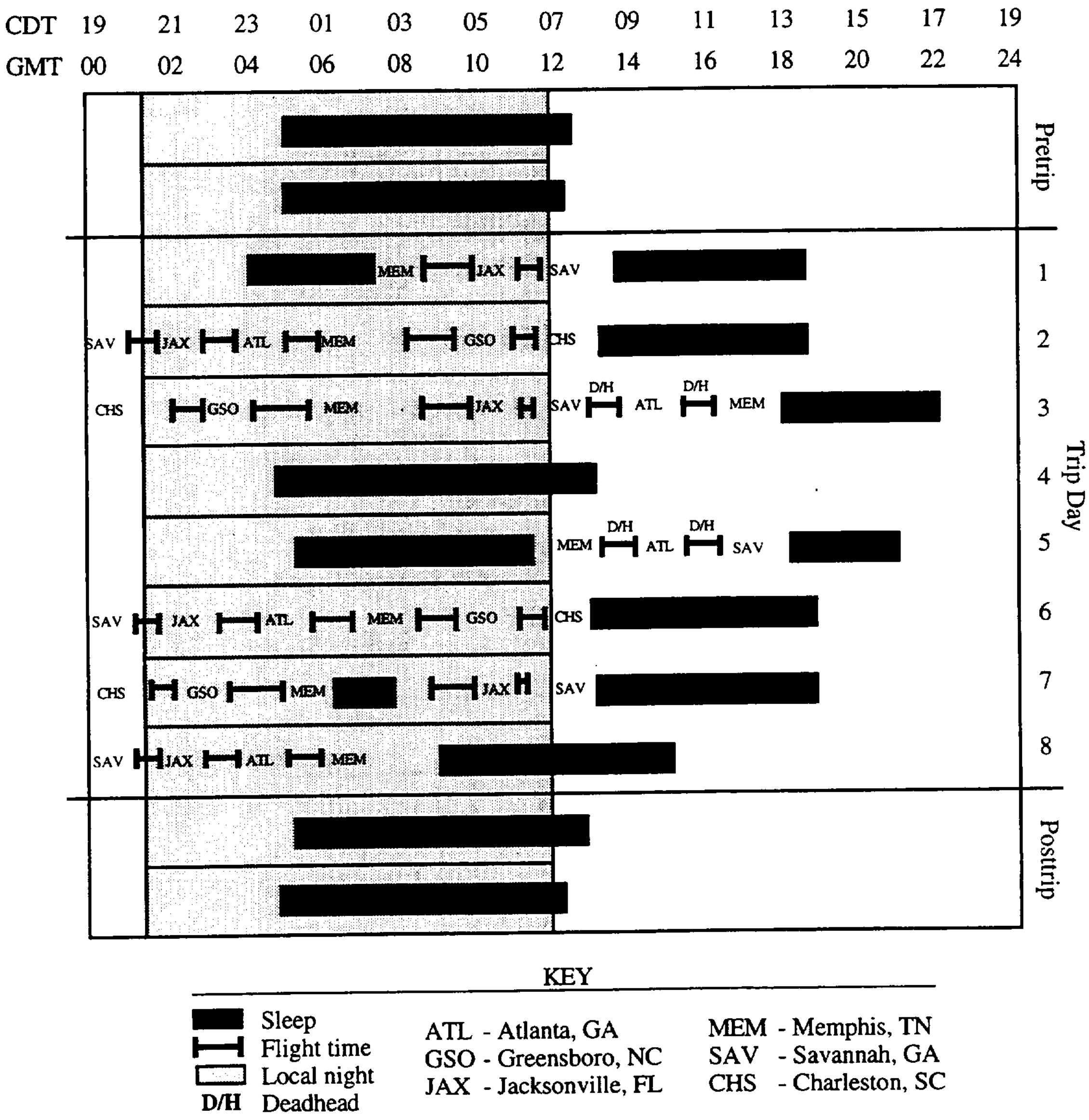

Figure 1. Average sleep and flight times for Destination-Layover trip pattern.

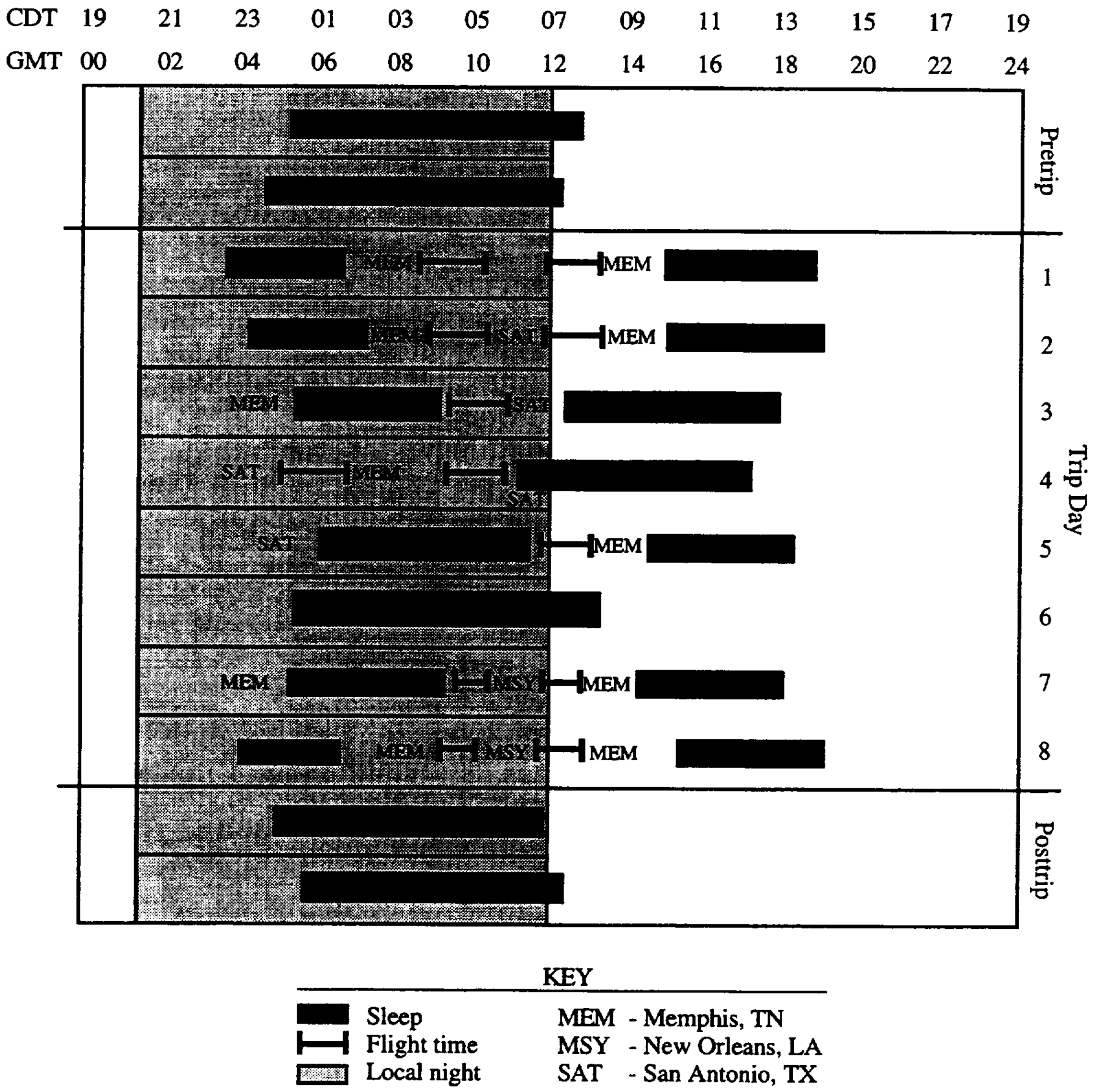

Figure 2. Average sleep and flight times for Out-and-Back trip pattern.

3.3 Data Collected

Subjects were monitored for a maximum of 3 days before the trip, throughout the trip (8 days), and for up to 4 days after the trip. They were accompanied during all flights by a NASA cockpit observer who held at least a private pilot's license and was familiar with air-transport operations. The observers instructed subjects in the use of equipment and kept a log of operationally significant events for each trip segment flown.

Each subject wore a Vitalog PMS-8 biomedical monitor (Vitalog Monitoring Inc., Redwood City, California) which recorded core body temperature, average heart rate, and average activity of the nondominant wrist every 2 min. To estimate the effects of duty demands on the circadian timing system, the temperature data were examined in two different ways. First, the temperature data for individual crew members were averaged in 20-min bins and then subjected to multiple complex demodulation (ref. 27). Second, a constant (0.28 C°) was added to the raw temperature data for each subject whenever the individual reported being asleep. This mathematical procedure was intended to help compensate for the reduction in temperature caused by inactivity and sleep, which masks the underlying circadian variation in temperature. It was based on the reported 0.28 C° difference between the temperature rhythm during sleep and wake in internally desynchronized subjects (ref. 28). The "unmasked" data for each subject were then averaged in 20-min bins and subjected to multiple complex demodulation, as before. (See the appendix for a more detailed description of the unmasking technique.) For both masked and unmasked data, the cycle-by-cycle temperature minimum was taken as the computer-selected lowest value within 12 hr in the remodulated waveform. In a few instances, this procedure identified two minima in 24 hr. When this occurred, the raw data and multiple complex demodulated waveform were superimposed on the sleep and nap times and, if there was no clear way of discriminating between the minima (circadian or masking), the data for that cycle were discarded. Missing data points in the raw data were replaced by linear interpolation, and all fitted waveforms were overlayed with the original data to check that the interpolations did not introduce spurious estimates of the minima.

Crew members also kept a daily log of: the quantity, quality, and timing of sleep; the times of naps, showers or baths, exercise, and duty periods; food, caffeine, and alcohol consumption; bowel movements and urinations; cigarettes and medication use; and medical symptoms. The logbook provided space for recording up to two sleep episodes and two naps per 24 hr. Although the durations of short sleeps and long naps may overlap, we have retained the designations given by the subjects in all the analyses. The quality of each subject-designated sleep episode was rated from 1–5 on the following four questions: Difficulty falling asleep? How deep was your sleep? Difficulty rising? How rested do you feel? Ratings were converted so that higher values indicated better sleep and were then added together to provide an overall sleep rating. Every 2 hr during the waking day, subjects completed a 26-adjective mood checklist and estimated their fatigue by placing a mark on a 10-cm line signifying a continuum from most alert to most drowsy. They also completed a Background Questionnaire compiled to obtain information on demographic and lifestyle variables, sleep and nutritional habits, and personality profiles. These measures are described in detail in ref. 22.

Every 3–4 days, the cockpit observers offered the subjects the opportunity to examine their own physiological data (during the downloading of these data onto computer diskettes) and to compare these data with their logbook entries. This feedback was intended to help maintain compliance with protocol requirements and to improve the accuracy of logbook recordings.

3.4 Data Management

Data from the Background Questionnaires, daily logs, and observer logs were coded and entered into a specially modified Relational Information Management (RIM) database on a VAX 11/750 computer. The Vitalog data were initially read out to an Apple II Plus computer and stored on diskettes. The original binary files were converted to text files and transferred to the VAX. After editing, the physiological data were entered into the same database as the questionnaire, daily log, and observer log data.

Except where noted in the respective sections of this report, all analyses of variance were within subjects. For post hoc t-tests, where Levene's test for variability was significant, the separate t-test value was taken. Otherwise, the pooled t-test value was taken.

4.0 RESULTS

4.1 Trip Statistics

Both of the trips studied included a rest day at home, interrupting a series of nights of flying in a duty pattern lasting 8 days in total. In the Destination-Layover pattern (fig. 1), crews deadheaded home (that is, flew as passengers but were on duty) after three nights of flying and had about 45 hr off duty before deadheading from their domicile to begin another three nights of flying. In the Out-and-Back pattern (fig. 2), crews arrived home after five nights of flying then had about 45 hr off duty before beginning another two nights of flying. The 8 trip days were therefore subdivided into duty and no-duty days in the analyses.

To be included in the analyses, crew members had to have provided at least one night of pretrip sleep data and two nights of posttrip sleep data. Twenty subjects (87%) on the Destination-Layover pattern and 14 subjects (78%) on the Out-and-Back pattern met these criteria. The duty variables for the trips flown by these subjects were compared by two-group t-tests (table 1).

Crew members flying the Destination-Layover pattern went on duty about 3.4 hr earlier and consequently had duty days about 3.5 hr longer than did crew members flying the Out-and-Back pattern. The Destination-Layover pattern averaged double the number of flight segments and 52 min more flight time per night. Layovers between duty nights were also more than 6 hr shorter on the Destination-Layover pattern. Destination-Layover crews flew in and out of the hub four times during the 8-day pattern, whereas Out-and-Back crews had only one hub turn.

Table 1. Comparison of Trip Pattern Characteristics

	Destination-Layover, n=20 Mean (s.d.)	Out-and-Back, n=14 Mean (s.d.)	t
On-duty time (hr)	0317 (4.34)	0643 (2.23)	7.83***
Off-duty time (hr)	1152 (3.42)	1150 (1.99)	0.09
Duty duration (hr)	8.57 (3.96)	5.11 (1.96)	8.72***
Layover duration (hr)†	12.36 (2.34)	18.49 (2.13)	17.03***
Home day duration (hr)	44.82 (1.90)	45.13 (2.99)	0.29
Number of segments per night	3.65 (1.16)	1.84 (0.60)	10.64***
Segment duration (hr)	0.80 (0.41)	1.13 (0.35)	9.18***
Flight hr per 24 hr	2.93 (1.04)	2.07 (0.72)	7.17***
Number of segments per trip	21.90 (2.23)	12.63 (0.92)	10.98***
Number of hub turns	4	1	

† Layovers between successive nights of flying; does not include the "no-duty" day

*** $p < 0.001$

4.2 Pilot Statistics

The characteristics of the crew members on the two trip patterns were compared by two-group t-tests (table 2). These data are from the Background Questionnaires and include information on: demographics; personality style (Eysenck Personality Inventory); morningness/eveningness; personal attributes; and orientation to work and family. The number of years of experience was taken as the largest value from among the following categories: years with the present airline; years of military experience; years of airline experience; years of general aviation experience; and other. The Destination-Layover crew members had been with the participating airline slightly longer on average (5.1 yr) than had the Out-and-Back crew members (4.3 yr). There were no other significant ($p < 0.05$) differences between the crew members on the two trip patterns.

Table 2. Comparison of Subject Populations for the Two Trip Patterns

	Destination-Layover Mean (s.d.)	Out-and-Back Mean (s.d.)	t
Age (yr)	37.8 (4.8)	37.4 (4.9)	0.19
Experience (yr)	12.8 (4.4)	12.8 (3.3)	0.01
Height (inches)	70.0 (3.0)	70.5 (2.6)	0.50
Weight (lbs)	181.2 (27.8)	174.4 (29.5)	0.68
Eysenck Personality Inventory			
Neuroticism	4.5 (4.2)	5.2 (3.7)	0.51
Extraversion	11.2 (4.0)	10.7 (3.9)	0.35
Morning/Eveningness Questionnaire			
	55.0 (6.9)	53.7 (9.3)	0.45
Personal Attributes Questionnaire			
Instrumentality	25.3 (3.8)	23.4 (4.1)	1.43
Expressivity	23.5 (3.8)	22.2 (4.0)	0.92
I+E	3.3 (0.9)	3.0 (1.1)	0.86
Work and Family Orientation			
Mastery	21.5 (3.9)	21.0 (3.3)	0.41
Competitiveness	13.4 (4.4)	12.9 (3.8)	0.34
Work	18.5 (1.3)	17.9 (2.0)	1.13

4.3 Trip Effects of Trips on Physiological and Psychological Variables

4.3.1 Sleep

Being on duty at night required subjects to sleep during the day. As a first comparison, the characteristics of individual daytime sleep episodes were compared with nighttime sleep episodes on pretrip, no-duty, and posttrip days (table 3). For each subject, mean heart rate, temperature, and activity levels during each sleep episode were calculated from 20 min after the reported sleep onset time until 10 min before the reported wake-up time. This trimming minimized contamination of the estimates of mean heart rate, temperature, and activity levels during sleep by the comparatively high values that occur immediately before and after sleep (ref. 22). Variability in heart rate and activity during sleep was estimated as the standard deviation of the raw scores for each sleep episode for each subject. The sleep ratings in table 3 have been converted so that higher values indicate better sleep. To test if sleep differed significantly among pretrip, duty, no-duty, and posttrip days, one-way ANOVAs (analysis of variance) were performed, with subjects treated as a random variable. These analyses are the source of the F ratios and the significance levels indicated in table 3. Where the ANOVA revealed significant pretrip/duty/no-duty/posttrip differences, the values for pretrip, duty, no-duty, and posttrip sleeps were compared by post hoc t-tests. As expected, sleep episodes occurred significantly later on duty days than on pretrip days (for sleep onset, $t = 12.93$, $p < 0.0001$; for wake-up, $t = 4.37$, $p < 0.0001$), or on the no-duty day (for sleep onset, $t = 11.45$ $p < 0.0001$; for wake-up, $t = 2.87$, $0.01 > p > 0.001$), or on posttrip days (for sleep onset, $t = 12.39$, $p < 0.0001$; for wake-up, $t = 4.99$, $p < 0.0001$). These differences in sleep timing are emphasized in the distributions in figs. 3 and 4.

Table 3. Comparisons of Sleep Measures Before, During, and After Trips

	Pretrip	Duty	No-Duty	Post	F
Sleep onset, local time	0033	0543	0041	0034	92.90***
Wake-up, local time	0813	1017	0850	0756	15.74***
Sleep latency, min	14.11	17.81	25.04	21.89	1.99
Sleep duration, hr	7.46	4.56	8.09	7.21	40.90***
Total sleep per 24 hr	7.54	6.31	8.23	.65	10.62***
Difficulty falling asleep?	4.21	4.12	4.23	4.04	0.35
How deep was your sleep?	3.65	3.39	4.06	3.76	5.54**
Difficulty rising?	3.48	3.31	3.38	3.69	1.60
How rested do you feel?	3.27	2.66	3.28	3.40	5.40**
Sleep rating	14.60	13.43	14.97	14.88	3.84*
Number of awakenings	1.68	0.81	1.15	1.13	10.98**
Mean heart rate, beats per min	62.78	63.23	60.98	61.56	1.81
Heart rate, s.d.	6.89	6.55	6.41	6.88	0.56
Mean activity, counts per min	2.77	2.62	1.31	1.70	1.19
Activity, s.d.	7.06	6.11	5.18	6.31	0.81
Mean temperature, C°	36.74	36.81	36.66	36.72	3.92*
Temperature, s.d.	0.12	0.11	0.14	0.14	1.75

* $0.05 > p > 0.01$; **$0.01 > p > 0.001$; ***$p < 0.001$

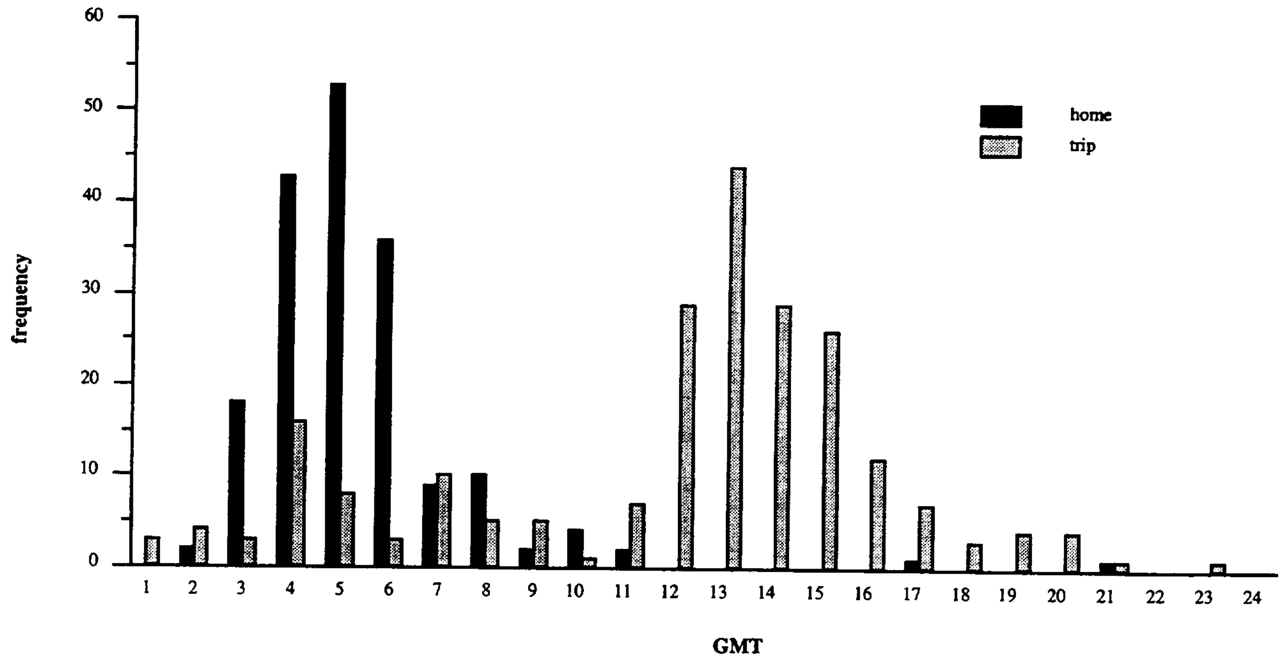

Figure 3. Distributions of times of falling asleep at home (i.e., combining pretrip, no-duty, and posttrip days) and on trip days.

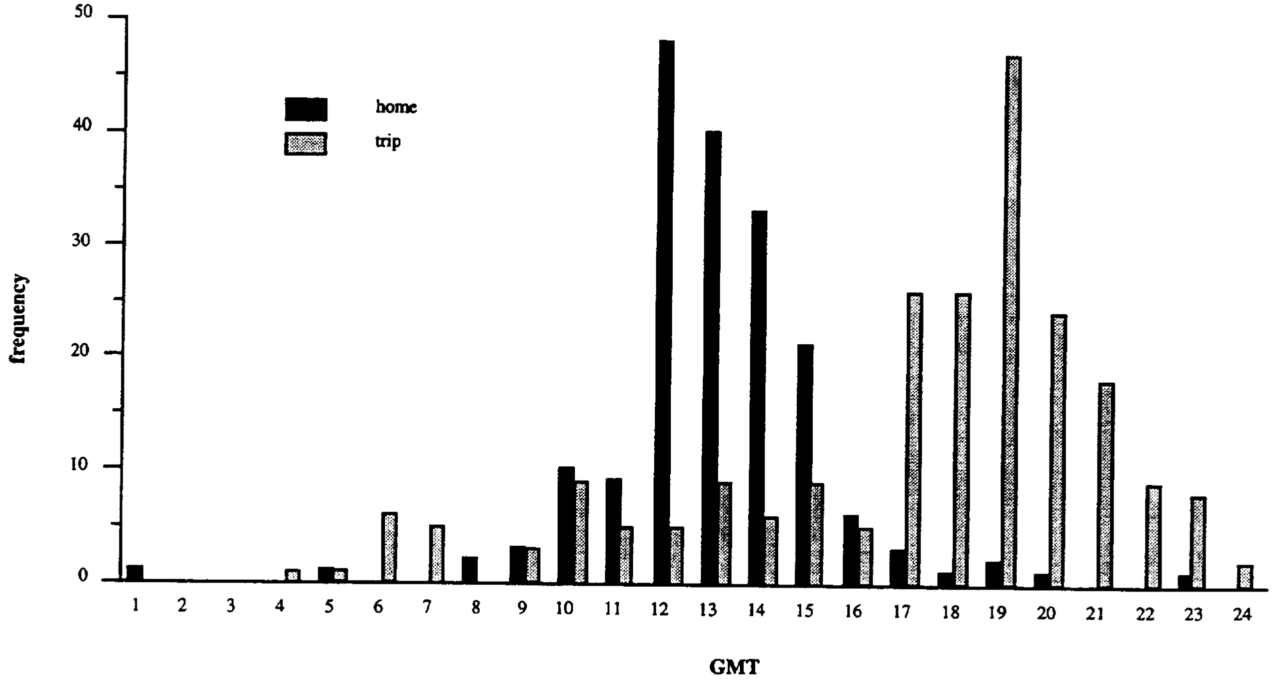

Figure 4. Distributions of times of waking up at home (i.e., combining pretrip, no-duty, and posttrip days) and on trip days.

Individual sleep episodes on duty days were significantly shorter than sleep episodes pretrip ($t = 10.17$, $p < 0.0001$), or on the no-duty day ($t = 10.76$, $p < 0.0001$), or on posttrip days ($t = 8.77$, $p < 0.0001$). The total sleep per 24 hr was significantly shorter on duty days than on pretrip days ($t = 4.22$, $p < 0.0001$), or on the no-duty day ($t = 5.65$, $p < 0.0001$), or on posttrip days ($t = 5.09$, $p < 0.0001$). Sleep episodes on duty days were rated as less deep than those on the no-duty day ($t = 3.80$, $0.001 > p > 0.0001$), or on posttrip days ($t = 2.06$, $p < 0.05$). Pretrip sleep episodes were also rated as less deep than those on the no-duty day ($t = 2.11$, $0.05 > p > 0.01$). Subjects reported feeling less rested after sleep on duty days than after pretrip sleep ($t = 3.20$, $0.01 > p > 0.001$), or after sleep on the no-duty day ($t = 3.02$, $0.01 > p > 0.001$) or after posttrip sleeps ($t = 4.16$, $p < 0.0001$). Overall, sleep episodes on duty days were rated as significantly worse than those on either pretrip days ($t = 2.57$, $0.05 > p > 0.01$), or on the no-duty day ($t = 2.55$, $0.05 > p > 0.01$) or on posttrip days ($t = 2.73$, $0.01 > p > 0.001$). Subjects reported significantly more awakenings during pretrip sleep episodes than during sleep episodes on either duty days ($t = 6.63$, $p < 0.0001$), or on the no-duty day ($t = 2.61$, $0.05 > p > 0.01$), or on posttrip days ($t = 3.13$, $0.01 > p > 0.001$). They also reported fewer awakenings during sleep episodes on duty days than during those on posttrip days ($t = 2.25$, $0.05 > p > 0.01$). However, sleep episodes on trip days were about 40% (3.1 hr) shorter than sleep episodes at other times (i.e., combining pretrip, no-duty, and posttrip). If the number of awakenings per hour of sleep is considered, the difference between trip sleep and posttrip sleep disappears. The average numbers of awakenings per hour of sleep were: 0.23 for pretrip sleep; 0.18 for trip sleep; 0.14 for sleep on the no-duty day; and 0.17 for posttrip sleep. The average temperature during sleep was higher for duty sleep episodes than for no-duty sleep episodes ($t = 2.26$, $0.05 > p > 0.01$).

Although individual daytime sleep episodes were 3.1 hr shorter than average nighttime sleep episodes, the total sleep per 24 hr on duty days averaged only 1.2 hr less than on pretrip days and 1.5 hr less than on all days without duty (combining pretrip, no-duty, and posttrip days; see table 3). This was because, on average, 53% of the subjects reported multiple sleep episodes or naps on days containing duty (fig. 5), whereas only 17% reported multiple sleep episodes or naps on days without duty. The incidence of multiple sleep episodes or naps per 24 hr varied markedly among duty days and between the two trip patterns. This observation prompted further analyses of the relationships between duty factors and sleep patterns during layovers. Note that in fig. 5, the first and fifth days on the Destination-Layover pattern followed an off-duty period (fig.1) and included one sleep episode before going back on duty and one after the night of flying. The analyses in tables 4-6 considered only those sleep episodes which occurred during layovers between consecutive nights of flying. Within these layovers, only subject-designated sleep episodes were considered, not subject-designated naps, since the latter accounted for only 2.6% of the total sleep time on the Destination-Layover pattern and 3.5% on the Out-and-Back pattern.

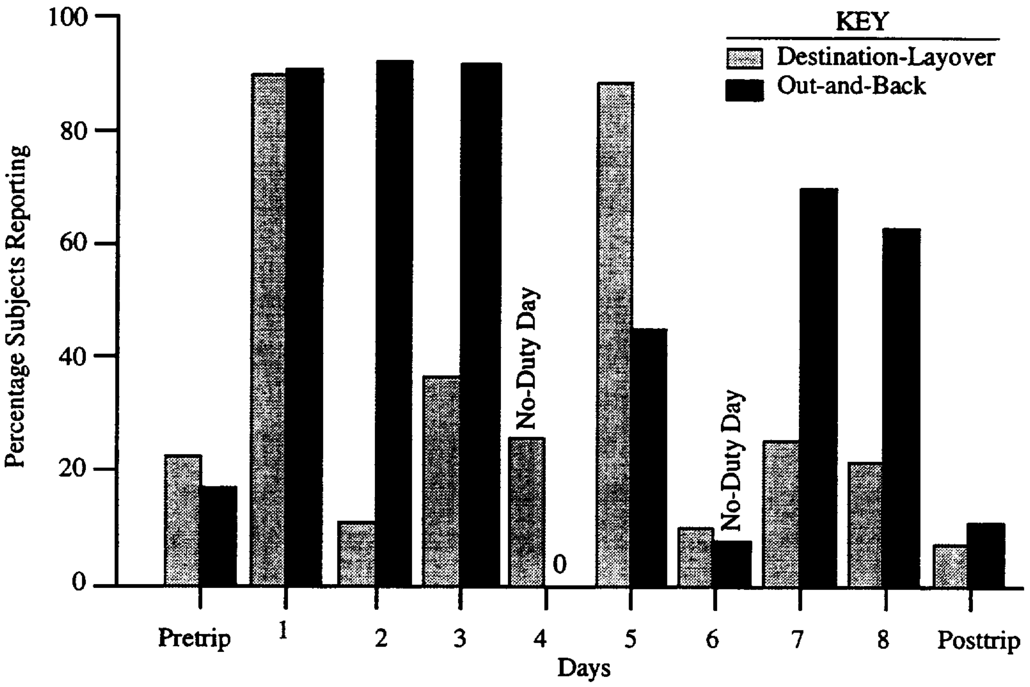

Figure 5. Subjects reporting more than one sleep or nap episode per 24 hr on different days of the study.

Examination of individual sleep-wake records revealed three basic patterns of sleep on the days between night duties. Subjects slept either: 1) twice in the layover; 2) once in the layover, going to sleep in the morning; or 3) once in the evening. The frequency of occurrence of these different sleep patterns is summarized in table 4. On the Destination-Layover trip pattern, crew members normally slept only once in the morning (96% of all layovers). In contrast, on the Out-and Back pattern crew members were frequently able to sleep a second time (58% of all layovers) before going back on duty in the evening.

Table 4. Basic Sleep Patterns during Daytime Layovers

	Destination-Layover % of Layovers[a]	Out-and-Back % of Layovers[b]
Two sleeps per layover	4	58
One morning sleep	96	37
One evening sleep	-	5

[a] n = 84 layovers

[b] n = 78 layovers

One-way ANOVAs were performed to test whether the timing and duration of the sleep episodes in these categories differed significantly among the categories or between the two trip patterns (table 5). For these analyses, sleep episodes were sorted into seven categories (three types of sleep episode on the Destination-Layover pattern and four types of sleep episode on the Out-and-Back pattern).

Table 5. Comparison of Different Categories of Sleep Episode

	Destination-Layover				Out-and-Back				
	1st of 2	2nd of 2	AM Single	PM Single	1st of 2	2nd of 2	AM Single	PM Single	F(df1, df2)
Asleep (local)	0722	0450	0911	-	0944	2249	0806	2146	299.09(6, 12)***
Wake-up (local)	1226	0717	1443	-	1356	0205	1401	0143	333.77(6, 12)***
Sleep duration (hr)	4.91	2.33	5.44	-	4.30	3.29	5.79	4.02	14.06(6, 202)***

***$p < 0.001$
df1 = degrees of freedom of numerator
df2 = degrees of freedom of denominator

Post hoc Tukey tests with Bonferroni correction were used to compare each sleep category with every other category. Rather than describing all the comparisons, the following discussion is restricted to comparisons among the major categories (excluding paired sleep episodes on the Destination-Layover pattern and late single sleep episodes on the Out-and-Back pattern; see table 4). The major sleep categories are summarized in fig. 6. Single morning sleep episodes on the two patterns were indistinguishable in timing and duration. They were significantly longer than either of the sleep episodes of a pair. On the Out-and-Back pattern, single morning sleep episodes also began earlier than first sleep episodes of a pair. Wake-up times were indistinguishable for single morning sleep episodes and first sleep episodes of a pair on both trip patterns, i.e., when crew members went to sleep in the morning they tended to wake up around the same time (combined average, 1413 local time).

To test whether the timing and duration of the layover had a consistent effect on the way crew members organized their sleep, one-way ANOVAs were performed comparing layovers containing two sleep episodes with layovers containing one morning sleep episode or one evening sleep episode (table 6). For these analyses, layovers were sorted into the five categories (two types of layover on the Destination-Layover pattern and three types of layover on the Out-and-Back pattern).

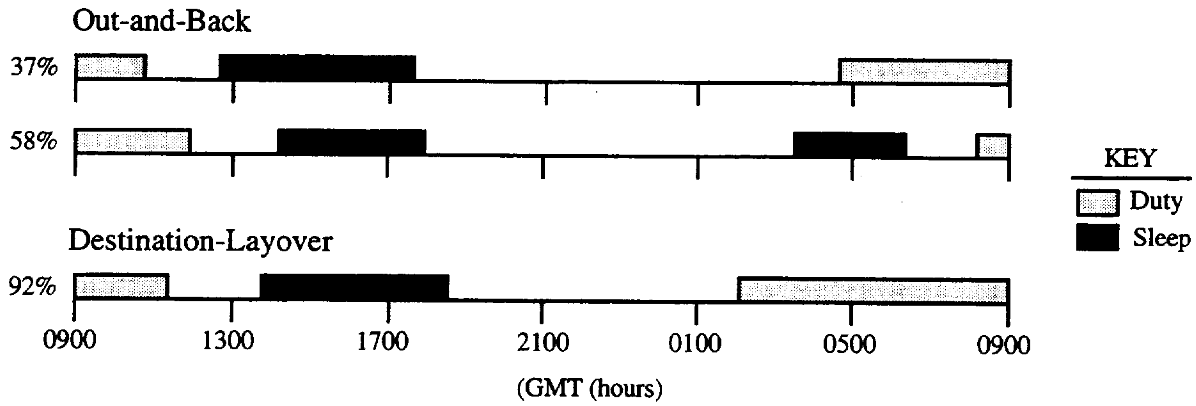

Figure 6. Average layover and sleep timing on two trip patterns. Percentages indicate layovers in each trip pattern during which early single or split sleep episodes occurred.

Table 6. Comparison of One- and Two-Sleep Layovers

	Destination-Layover			Out-and-Back			
	2 Sleeps	Early Single	Late Single	2 Sleeps	Early Single	Late Single	F(df1, df2)
Off-duty (local)	0616	0725	-	0759	0628	0816	14.11(4, 152)***
On-duty (local)	0116	2017	-	0328	2315	0308	377.13(4, 9)***
Layover duration (hr)	18.99	12.86	-	19.48	16.78	18.88	164.07(4, 9)***

***$p < 0.001$
df1 = degrees of freedom of numerator
df2 = degrees of freedom of denominator

Again, post hoc Tukey tests with Bonferroni correction were used to compare each layover category with every other category. As before, only the comparisons among the major categories are discussed here. For both trip patterns, layovers in which crew members slept once in the morning began earlier, finished earlier, and were shorter than layovers in which crew members slept twice. Destination-Layover layovers in which crew members slept once in the morning (96% of all layovers between consecutive nights of flying on this pattern) were shorter than all other categories of layovers. These analyses indicate that the decision to sleep once or twice in a layover was largely determined by the timing and duration of the layover.

To test whether the total sleep per 24 hr was comparable on the two trip patterns, a two-way ANOVA was performed (table 7) comparing them across pretrip, duty, no-duty, and posttrip days. The two trip patterns did not differ significantly in the amount of sleep subjects were able to obtain per 24 hr, either on days with duty or on days without duty. For both trip patterns, crew members slept significantly less on duty days.

Table 7. Total Sleep per 24 hr on the Two Trip Patterns

	Trip Pattern F	Pre/Duty/No-Duty/Post F	Interaction F
Total daily sleep	0.47	17.43***	1.95

***p < 0.001

Each subject's total sleep per 24 hr (including naps) was subtracted from the individual's mean total baseline sleep per 24 hr (including naps), giving a daily measure of sleep loss (fig. 7). As expected, from table 7, the total cumulative sleep loss by the end of the two trip patterns (compared to pretrip baseline) was not significantly different (9.8 hr for the Destination-Layover pattern, 9.9 hr for the Out-and-Back pattern; two-group t-test, t = 0.49, p = 0.62).

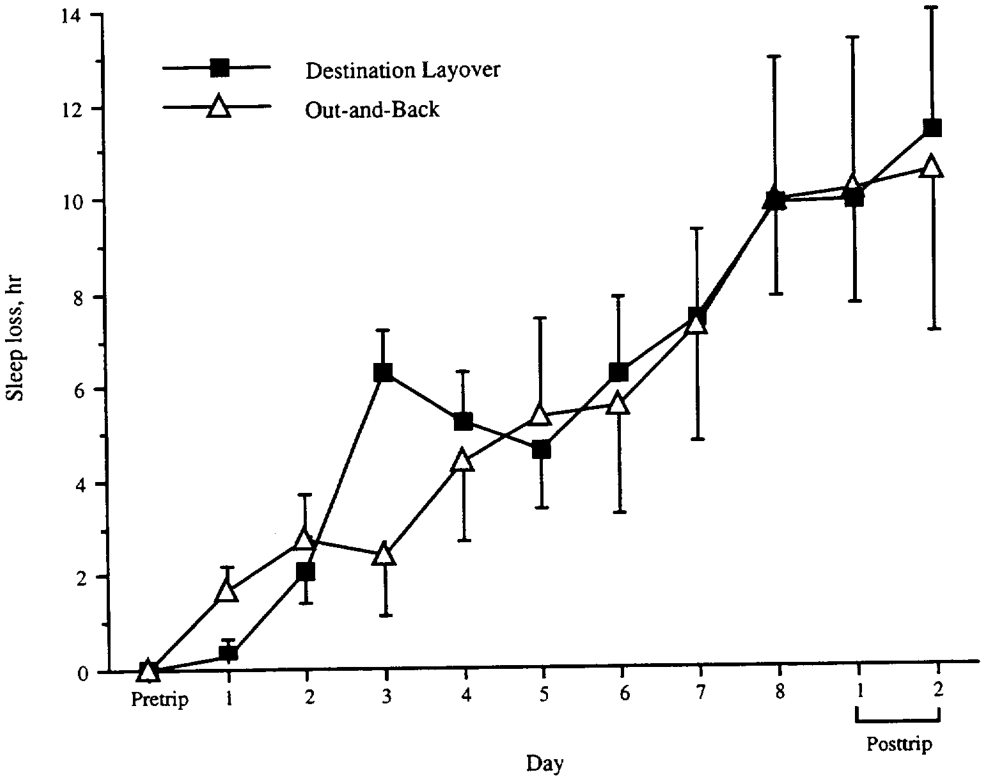

Figure 7. Average daily sleep loss across the two trip patterns. Vertical bars indicate standard errors. Since sleep loss is calculated with respect to the pretrip sleep duration, the average pretrip sleep loss is zero.

4.3.2 Sleep loss and individual attributes

Each subject's daily sleep loss was expressed as a percentage of total sleep per 24 hr pretrip and then an average daily percentage sleep loss was calculated for all trip days. Average daily percentage sleep loss on trip days has previously been shown to increase with age among long-haul flight crew members (ref. 29). In the present study, correlation analyses were performed to see if this measure was related to any of the individual attributes reported to predict adaptation to shift work in other industries (see Section 1.0). The amplitude of the temperature rhythm was calculated as the difference between the minimum and maximum of the multiple complex demodulated waveform fitted to the pretrip baseline temperature data (see Section 3.0). The correlations in table 8 include data from the 25 crew members who gave at least one cycle of baseline temperature data. None of these relationships was significant at the 0.05 level.

Table 8. Individual Differences in Mean Daily Percentage Sleep Loss

Attribute	Correlation Coefficient
Temperature amplitude (masked)	-0.00
Temperature amplitude (unmasked)	-0.16
Neuroticism	-0.04
Extraversion	0.08
Morningness/eveningness	0.27

4.3.3 Circadian phase

The average times of the daily temperature minima for crew members on the Destination-Layover trip pattern are shown in fig. 8a (n = 10, i.e. 44% of subjects) and for crew members on the Out-and-Back trip pattern in fig. 8b (n = 4, i.e., 22% of subjects). In general, the effect of flying at night was to move the subsequent temperature minimum several hours later, with the exception of the second trip day on the Out-and-Back pattern (fig. 8b). For both patterns, on the no-duty day (trip day 4 for Destination-Layover crews, trip day 6 for Out-and-Back crews) the time of the temperature minimum returned towards its earlier pretrip position.

To test whether the unmasking technique (adding 0.28 C° to the raw temperature data for each subject when asleep) altered the estimated times of the temperature minima, a two-way within subjects ANOVA was performed for each trip pattern (table 9). This compared masked and unmasked minima estimates across the days of the study.

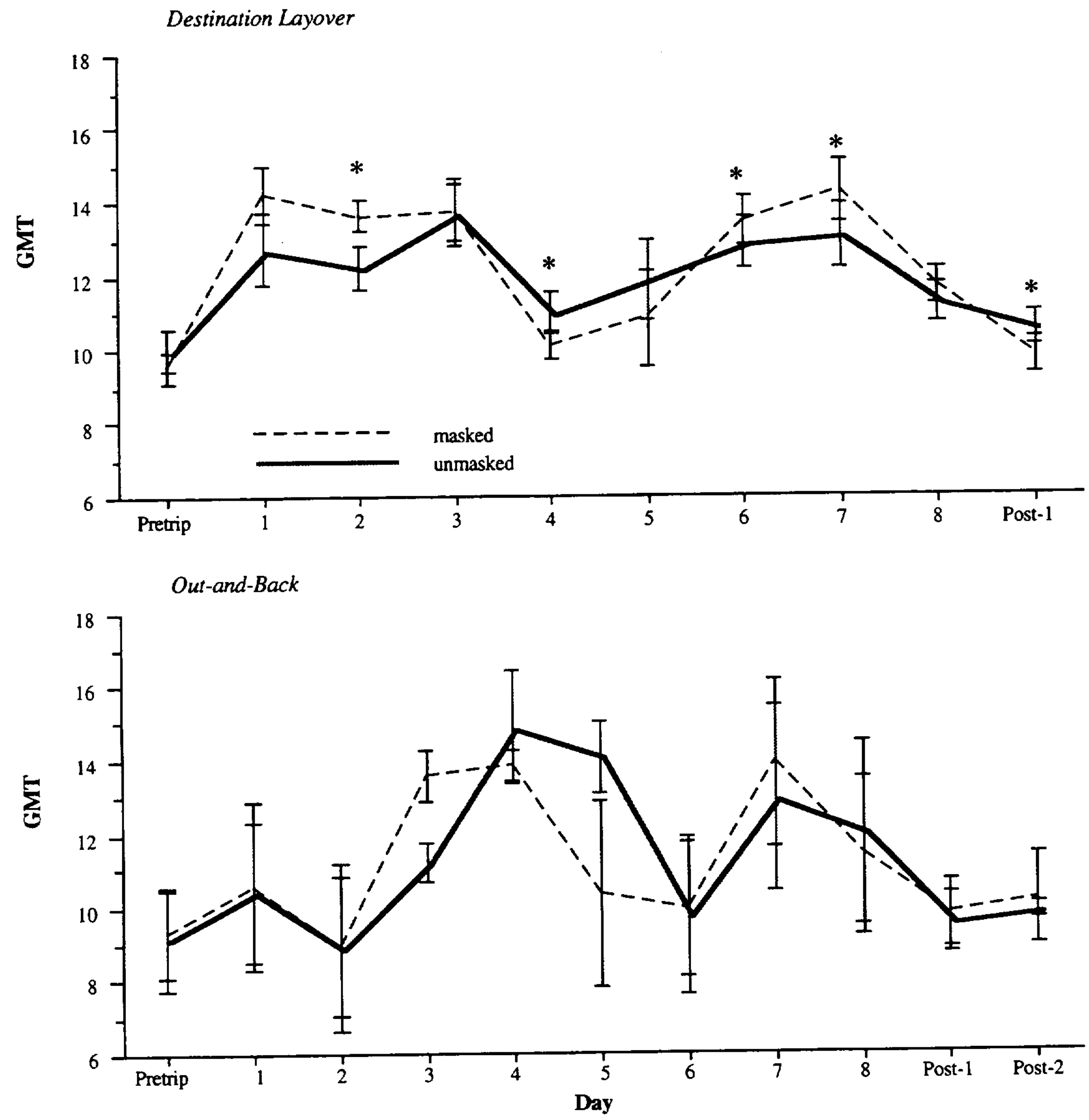

Figure 8. Average times of the daily temperature minima across the two trip patterns. Vertical bars indicate standard errors. Asterisks indicate days on which masked estimate was significantly different from unmasked estimate.

Table 9. Masked versus Unmasked Estimates of Cycle-by-Cycle Temperature Minima

Trip pattern	Days F	Masked/Unmasked F	Interaction F
Destination-Layover	7.98***	1.57	3.90***
Out-and-Back	2.23*	0.08	1.41

* 0.05 > p > 0.01; ***p < 0.001

Overall, the masked and unmasked estimates of the timing of the daily temperature minima were not significantly different. However, the significant interaction for the Destination-Layover trip pattern suggests that the masked and unmasked estimates did not change in a similar way across the days of the study. Significant differences (post hoc t-tests) between the masked and unmasked estimates on a given day are indicated by asterisks in fig. 8a. In general, when subjects flew at night, the masked estimate of the time of the temperature minimum was later than the unmasked estimate. Conversely, when they slept at night, the masked estimate was earlier than the unmasked estimate. This pattern was not seen in the Out-and-Back data (fig. 8b). However, it may have been obscured by the small sample size ($n = 4$). A significant progressive adaptation of the temperature rhythm across successive nights of flying was not observed in either trip pattern. Therefore, the data were grouped into pretrip, duty, no-duty, and posttrip days.

To test whether the timing of the daily temperature minimum was affected differently by the two trip patterns, for both masked and unmasked estimates a two-way ANOVA was performed comparing the trip patterns across pretrip, duty, no-duty, and posttrip days (table 10). Two additional subjects from each trip pattern were included in these analyses (for a total of 12 subjects [52%] on the Destination-Layover pattern and 6 subjects [33%] on the Out-and-Back pattern). Each of these subjects had one trip day on which it was not possible to identify a clear temperature minimum and they were therefore not included in fig. 8 or in the analyses in table 9.

Table 10. Comparison of Times of Daily Temperature Minima on the Two Trip Patterns

Temperature Minima	Trip Type F	Pre/Duty/No-Duty/Post F	Interaction F
Masked	1.03	30.34***	0.49
Unmasked	1.36	11.29***	0.36

***$p < 0.001$

These analyses suggest that, overall, the two trip patterns did not have different effects on the timing of the daily temperature minimum. However, for both masked and unmasked estimates, the timing of the temperature minimum varied significantly across pretrip, duty, no-duty, and posttrip days. These differences were further evaluated by post hoc t-tests. The significant differences are summarized in table 11.

For both masked and unmasked estimates, the temperature minimum occurred later on duty days than at any other time (fig. 9). For both types of estimates, the timing of the temperature minimum was not significantly different among pretrip, no-duty, and posttrip days. The average times of the daily temperature minima across pretrip, duty, no-duty, and posttrip days are summarized in table 12. The masked estimates suggest that the temperature minimum was delayed by 3.5 hr on duty days relative to pretrip; the unmasked estimates suggest that the delay was 2.8 hr. However, these two measurements of the shift in the temperature minimum were not significantly different (paired t-test, t = 0.62, p = 0.54).

Table 11. Significant Post Hoc t-tests for ANOVAs in Table 9

	Duty vs. Pretrip t	Duty vs. No-Duty t	Duty vs. Posttrip t
Masked	6.23****	4.91****	4.77****
Unmasked	4.53****	2.89**	3.28**

**0.01 > p > 0.001; ****p < 0.0001

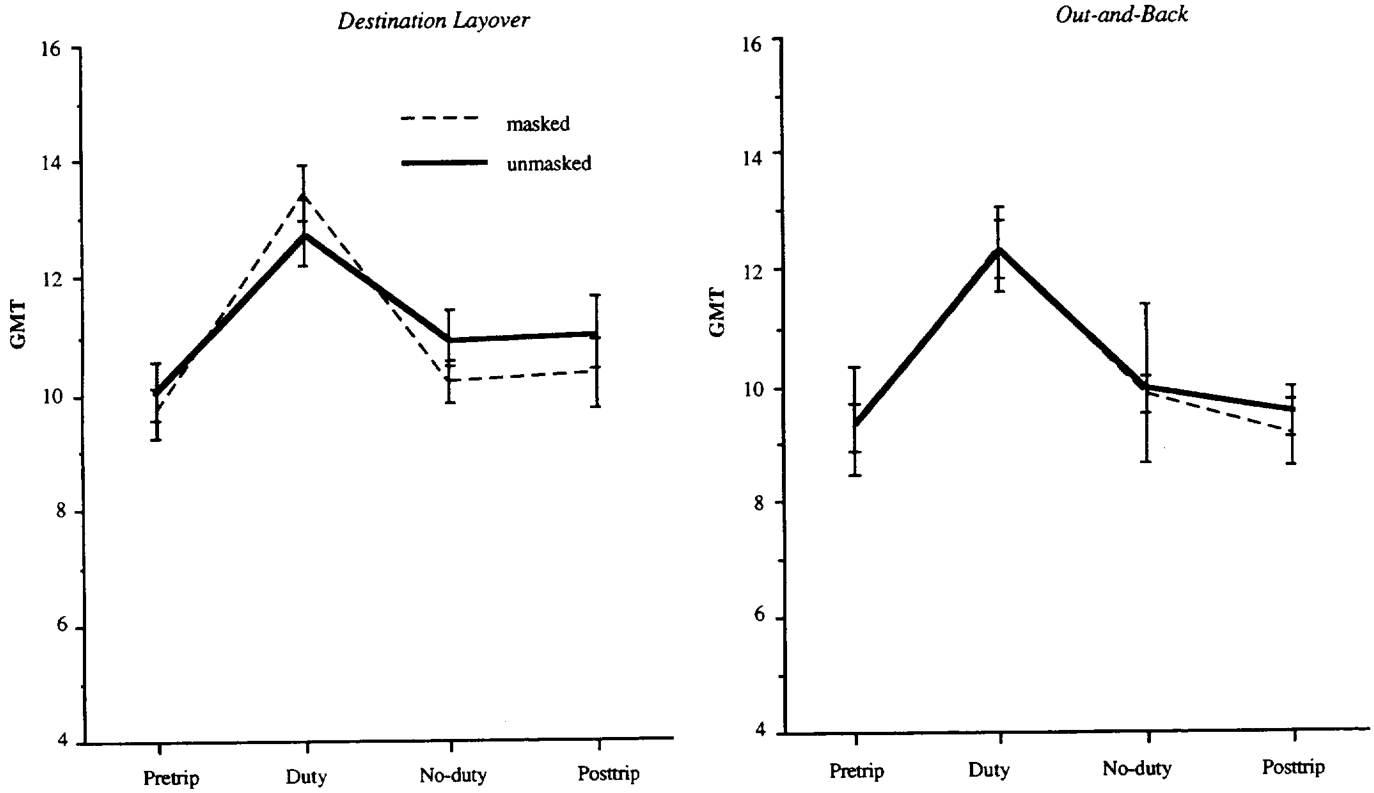

Figure 9. Average times of temperature minima on pretrip, duty, no-duty, and posttrip days, for two trip patterns. Vertical bars indicate standard errors.

Table 12. Mean Local Times of Daily Temperature Minimum

	Pretrip	Duty	No-Duty	Posttrip
Masked	0504	0834	0540	0526
Unmasked	0520	0808	0608	0603

4.3.4 Subjective fatigue and mood

Every 2 hr while they were awake, subjects rated their fatigue level on a 10-cm line ranging from "drowsy" to "alert." They also rated their current mood from 1 (not at all) to 4 (extremely) on 26 adjectives that have been shown to load on three orthogonal factors designated positive affect, negative affect, and activation (ref. 22). There are three issues that complicate the analysis of these fatigue and mood data. First, in other NASA field studies these measures have been found to differ significantly between individuals and to exhibit marked time-of-day variation (refs. 22, 25). In the present study, when they were on duty, crew members gave ratings during the night and slept during the day. Conversely, when they were off duty (pretrip, the no-duty day, and posttrip) they gave ratings during the day and slept at night. As a result, the data sampled different times of day. Second, the temperature data suggest that the circadian clock shifted about 3 hr when crew members were flying at night, relative to pretrip. Even with this shift, ratings made during different stages of the study (pretrip, duty, no-duty, posttrip) sampled different parts of the circadian cycle. Third, most subjects did not provide complete data for the times that they were awake.

To obtain a first indication of whether duty demands altered the time-of-day variation in fatigue and mood, the pretrip, duty, no-duty, and posttrip data were analyzed separately by one-way ANOVAs (time-of-day) with subjects treated as a random variable (table 13; fig. 10). Only two subjects provided data for 20 hr/day across pretrip, duty, no-duty, and posttrip days. Only four subjects provided data for 16 hr/day across pretrip, duty, no-duty, and posttrip days. Thus, for the analyses in table 13, each subject included for each study stage provided data for all (4-hr) time bins but different groups of subjects and times of day were included in the analysis for each study stage.

Table 13. Time-of-Day Variations in Fatigue and Mood Ratings

Rating	Pretrip F(df1, df2)	Duty F(df1, df2)	No-Duty F(df1, df2)	Posttrip F(df1, df2)
Fatigue	7.57(4, 40)***	13.01(5, 175)***	2.05(4, 20)	6.97(4, 28)***
Positive affect	1.54(4, 44)	11.46(5, 180)***	1.22(4, 28)	3.15(4, 28)*
Negative affect	1.62(4, 44)	19.57(5, 180)***	3.25(4, 28)*	5.36(4, 28)**
Activation	7.90(4, 44)***	12.28(5, 180)***	2.26(4, 28)	4.80(4, 28)**

*0.05 > p > 0.01; **0.01 > p > 0.001; ***p < 0.001
df1 = degrees of freedom of numerator
df2 = degrees of freedom of denominator

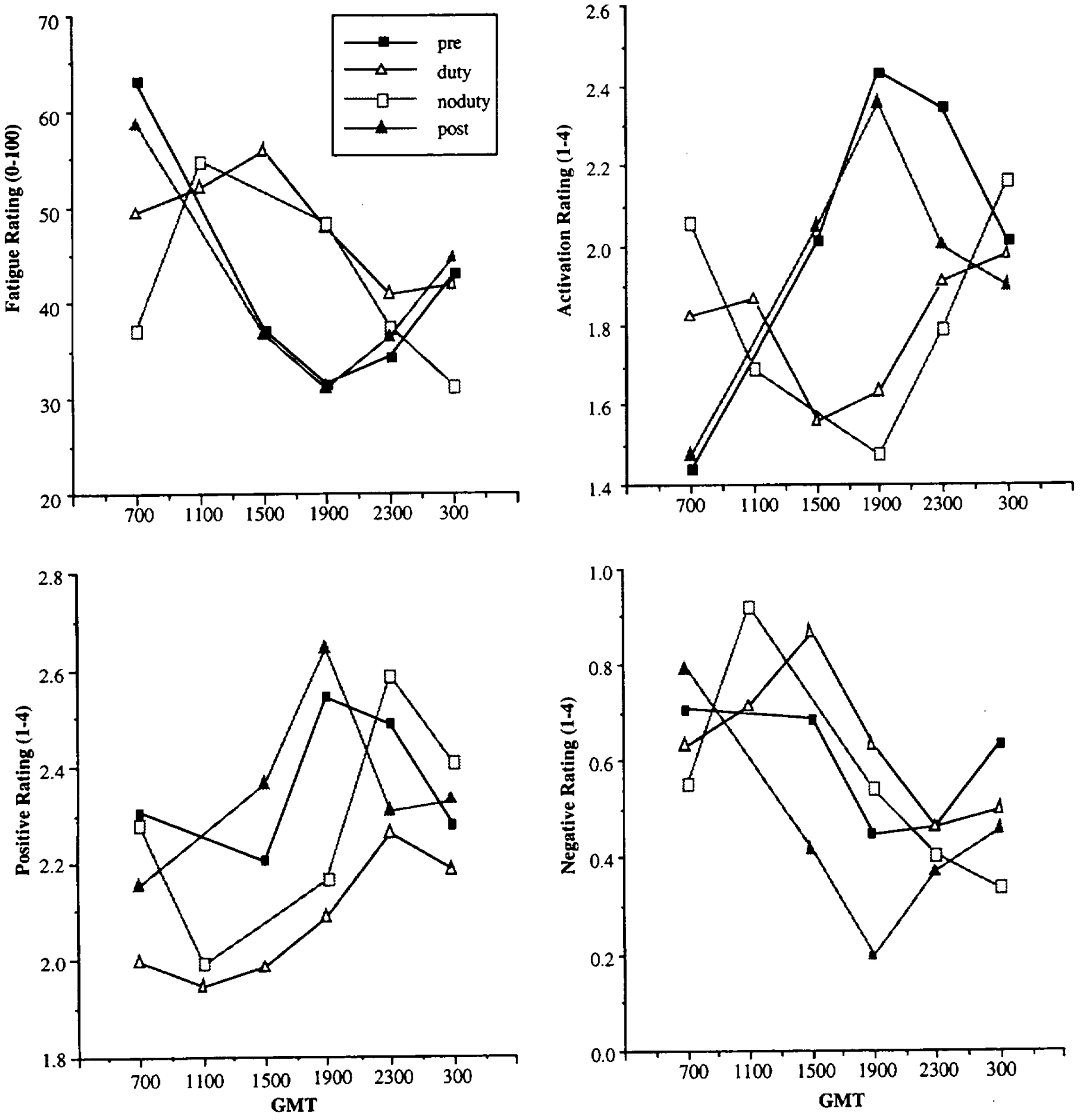

Figure 10. Average fatigue and mood ratings at different times of day on pretrip, duty, no-duty and posttrip days. GMT times represent midpoints of 4-hr data bins. Higher values indicate more fatigue, greater activation, higher positive mood ratings, and higher negative mood ratings.

On pretrip and posttrip days, fatigue was rated highest at 0700 GMT (0230 local time) and lowest at 1900 GMT (1430 local time). This replicates the pretrip pattern seen in helicopter pilots (ref. 25). When they were on duty, overnight cargo crew members reported feeling most fatigued at 1500 GMT (1030 local time). Conversely, they felt least fatigued at 2300 GMT (1830 local time). Because of the reduction of the data into 4-hr time-bins, it is impossible to establish with precision the amount of shift in the fatigue rhythm from pretrip to trip days.

Positive affect did not show a significant time-of-day variation pretrip, which is consistent with comparable data from helicopter and short-haul fixed-wing pilots (refs. 22, 25). On duty days, it was lowest in the early hours of the morning (0700 to 1500 GMT, 0230 to 1030 local time) and highest at 2300 GMT (1830 local time), that is, when fatigue was lowest. Negative affect did not show a significant time-of-day variation pretrip, in contrast to other studies (refs. 22, 25). On duty days, it was highest when fatigue was highest (1030 local time) and lowest when fatigue was lowest (1830 local time). Activation showed a pattern of variation that was the mirror image of fatigue, as it did in other studies (refs. 22, 25). The timing of the pretrip maxima at 1900 GMT (1430 local time) and minima at 0700 GMT (0230 local time) replicates that seen in other studies (ref. 25).

To examine the combined effects of duty demands and the reversed activity-rest schedule on subjective fatigue and mood, one-way ANOVAs were performed, with subjects treated as a random variable (table 14). Ratings made pretrip during daytime wakefulness (1400–2200 GMT) were compared with ratings made while on duty at night (0600–1200 GMT). Thirty-six subjects provided sufficient data to be included in these analyses. During duty nights, fatigue and negative affect were higher and positive affect and activation were lower than during pretrip days.

Table 14. Fatigue and Mood during Daytime versus Nighttime Wakefulness

Rating	Pretrip Mean	Duty Mean	F
Fatigue	33.46	51.05	53.28***
Positive affect	2.35	1.98	30.65***
Negative affect	0.49	0.68	13.26***
Activation	2.34	1.85	49.13***

***$p < 0.001$

4.3.5 Caffeine consumption

Although there was no cabin crew, every flight was provided with a large cooler of drinks (bottled water, fruit juices, soda, etc.) and flight crews often obtained a thermos of coffee from operations. Coffee and snack foods were available at most en route airports and a full cafeteria service was available at the hub. Some crew members, particularly on the Out-and-Back pattern, brought their own food and beverages on duty with them. The number of cups of caffeinated beverages and the time of day at which caffeine was consumed were recorded in the daily logbook. All of the 34 subjects included in the sleep analyses consumed caffeine at some time during the study. To test whether caffeine consumption was different across pretrip, duty, no-duty, and posttrip days, a one-way ANOVA was performed with subjects treated as a random variable.

Caffeine consumption was highest on duty days (average 2.4 cups per day); however, this was not significantly different ($F = 2.55$, $p = 0.06$) from consumption on the no-duty day (2.21), pretrip days (2.06), or posttrip days (1.75).

4.3.6 Meals and Snacks

The time of eating and the general content of meals (breakfast, lunch, dinner) and snacks were recorded in the daily logbook. To test whether consumption of meals and snacks was different across pretrip, duty, no-duty, and posttrip days, one-way ANOVAs were performed with subjects treated as a random variable. Subjects reported significant variation in the reporting of meals ($F= 9.02$, $p < .001$) and snacks ($F= 10.17$, $p < .001$) across pretrip, duty, no-duty, and posttrip days. Subjects reported fewer meals on posttrip days (mean = 2.01) than on pretrip days (mean = 2.67, $t = 3.67$, $0.001 > p > 0.0001$), duty days (mean = 2.48, $t = 2.22$, $0.05 > p > 0.01$), or on the no-duty day (mean = 2.76, $t = 3.34$, $0.01 > p > 0.001$). More snacks were reported during duty days (mean 1.36 per day) than on pretrip days (mean = 0.78, $t = 3.46$, $p = 0.001$), the no-duty day (mean = 0.94, $t = 2.03$, $0.05 > p > 0.01$), or posttrip days (mean = 0.61, $t = 4.68$, $p < 0.0001$). The low consumption of caffeine, meals, and snacks reported posttrip probably reflects incomplete reporting.

4.3.7 Symptoms

Subjects also noted when they experienced any of the 20 symptoms that were included in the table in the logbook (ref. 22). Twenty-eight of the 34 subjects included in the sleep analyses (82%) reported symptoms at some time during the study. The three most common symptoms were headaches (42% of all reports, reported by 59% of subjects at some time during the study), congested nose (19% of all reports, reported by 26% of subjects at some time during the study), and burning eyes (9% of all reports, reported by 18% of subjects at some time during the study). The percentage of these reports that occurred on pretrip, trip, and posttrip days is shown in table 15.

The incidence of headaches quadrupled on duty days, by comparison with pretrip, while the incidence of congested nose doubled and the incidence of burning eyes increased ninefold.

Table 15. Reports of Common Symptoms

Symptom	Pretrip % of Reports	Duty % of Reports	No-Duty % of Reports	Posttrip % of Reports
Headache	16.67	72.2	1.9	9.3
Congested nose	16.0	32.0	8.0	44.0
Burning eyes	8.3	75.0	16.7	0.0

4.4 Comparison with Daytime Short-Haul Air-Transport Operations

4.4.1 Comparison of duty demands

Table 16 compares (two-group t-tests) the average duty characteristics of the overnight cargo trips studied with those of the daytime short-haul trips flown by the 44 subjects included in the sleep analyses reported in ref. 22. The information for table 16 came from the daily logbooks kept by the crew members and from the cockpit observer logs. As expected, the timing of the duty periods was inverted between the two types of operations. The overnight cargo crew members had duty "days" that were about 3.5 hr shorter and layovers that were about 2.4 hr longer than those of the short-haul crew members. The overnight cargo duty periods averaged 2.0 hr less flight time, with fewer flight segments (2.3) and shorter flight segments (by 10 min).

Table 16. Comparison of Duty Characteristics

Duty Characteristic	Overnight Cargo Mean (s.d.)	Short-Haul Mean (s.d.)	t
Local time on duty, hr	2343 (3.53)	0844 (2.96)	27.11***
Local time off duty, hr	0652 (3.01)	1922 (2.94)	40.54***
Daily duty duration, hr	7.14 (3.69)	10.64 (2.19)	11.67***
Layover duration, hr	14.87 (3.79)	12.52 (2.52)	6.31***
Flight hr per day	2.55 (1.00)	4.50 (1.39)	14.93***
Flight segments per day	2.78 (1.30)	5.12 (1.34)	14.34***
Segment duration, hr	0.90 (0.42)	1.07 (0.47)	7.26***

***$p < 0.001$

4.4.2 Comparison of subject populations

Demographic and personality measures for the crew members included in the overnight cargo and daytime short-haul analyses are compared by two-group t-tests in table 17. This information came from the Background Questionnaires.

The number for years of experience was taken as the largest value from among the following categories: years with the present airline; years of military experience; years of airline experience; years of general aviation experience; and other. The overnight cargo crew members were 5.4 yr younger on average and had 9.4 yr less experience in their present airline than the short-haul crew members. There were no significant differences between the two groups in their height or weight nor in their scores on the personality inventories.

Table 17. Comparison of Crew Member Characteristics

Crew Member Characteristic	Overnight Cargo Mean (s.d.)	Short-Haul Mean (s.d.)	t
Age, yr	37.62 (4.76)	43.02 (7.65)	3.82***
Experience, yr	12.79 (4.35)	17.07 (6.56)	3.57***
Present airline, yr	4.74 (4.17)	14.41 (8.49)	6.60***
Height, in	70.21 (2.82)	70.59 (1.86)	0.73
Weight, lbs	178.40 (28.29)	174.84 (16.84)	0.69
Eysenck Personality Inventory			
Neuroticism	5.09 (3.91)	6.58 (4.51)	1.49
Extraversion	11.00 (3.89)	10.91 (3.46)	0.11
Morning/Eveningness Questionnaire	54.44 (7.86)	57.64 (8.67)	1.68
Personal Attributes Questionnaire			
Instrumentality	24.50 (3.96)	23.27 (3.94)	1.36
Expressivity	22.94 (3.85)	22.34 (4.40)	0.63
I+E	3.18 (0.99)	2.84 (1.01)	1.46
Work and Family Orientation			
Mastery	21.30 (3.64)	19.95 (4.10)	1.50
Competitiveness	13.15 (4.08)	12.57 (3.49)	0.67
Work	18.24 (1.63)	17.66 (2.09)	1.32

***$p < 0.001$

4.4.3 Comparison of the responses to trips

To compare the sleep loss during overnight cargo and daytime short-haul fixed-wing operations, the average daily percentage sleep loss for crew members during each type of operation was compared (by two-group t-test on the z scores calculated with respect to the combined mean). This comparison included data from 33 pilots from each type of operation (total 66 pilots); it did not reveal a significant difference between the two groups ($t = 0.24$, $p = 0.81$).

The average daily percentage sleep loss tends to underestimate the sleep disruption resulting from duty demands because it considers only the total sleep per 24 hr, that is, it ignores the breaking up of sleep into several shorter episodes which is characteristic of daytime sleep. In fig. 11, the percentage of subjects reporting more than one sleep episode (including naps) per 24 hr is compared for overnight cargo operations versus two daytime short-haul operations that were studied using the same measures (refs. 22, 25). Multiple sleep episodes were 17 times more common during overnight cargo operations than during daytime short-haul fixed-wing operations and 2.5 times more common than during daytime short-haul helicopter operations. The incidence of multiple sleep episodes per 24 hr was particularly low during short-haul fixed-wing operations because long duty days and short layovers seldom allowed sufficient time for a second sleep episode or naps. Another way to examine sleep disruption is to look at the percentage of the total sleep per 24 hr that comes from sleep episodes other than the longest (fig. 12). By this measure, overnight cargo crews gained 9.5 times more sleep from secondary sleep episodes than did short-haul fixed-wing crews and 5.0 times more than helicopter crews.

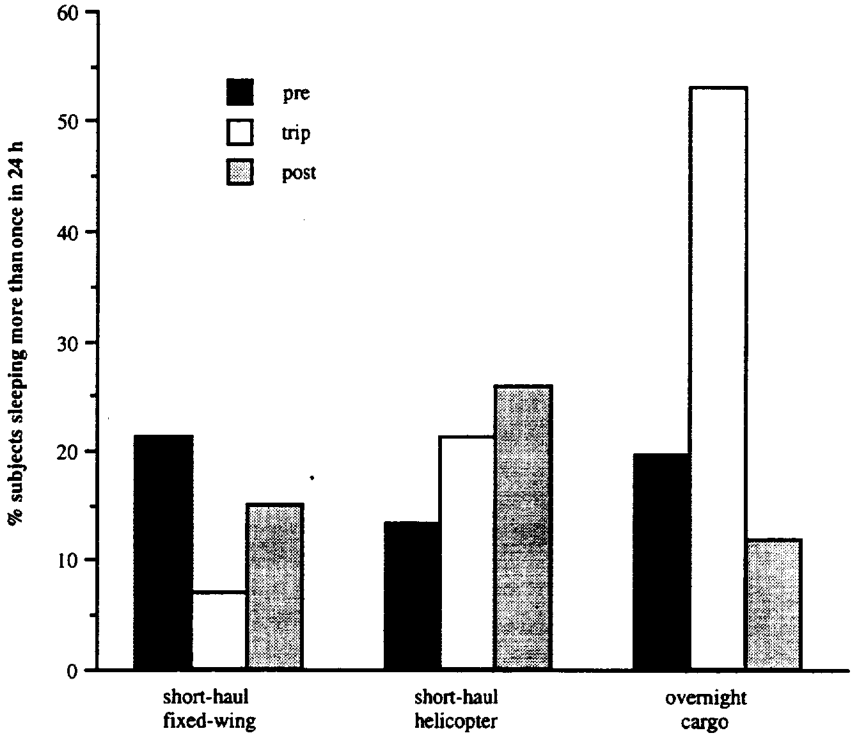

Figure 11. Subjects reporting more than one sleep or nap episode per 24 hr on pretrip, trip, and posttrip days, comparing daytime and nighttime operations.

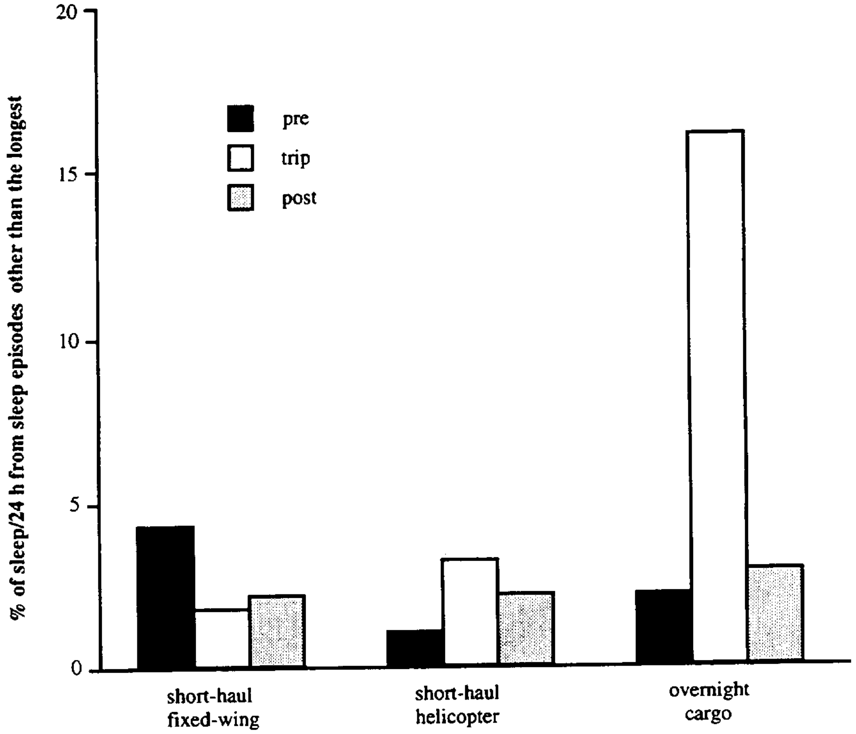

Figure 12. Daily sleep coming from sleep episodes other than the longest, on pretrip, trip, and posttrip days, comparing daytime and nighttime operations.

Table 18 compares the incidences of the three most commonly reported symptoms among crew members flying overnight cargo, daytime short-haul fixed-wing, and daytime helicopter operations.

Table 18. Subjects Reporting Three Most Common Symptoms

Operation	1st Symptom	2nd Symptom	3rd Symptom
Overnight cargo	headache (59%)	congested nose (26%)	burning eyes (8%)
Short-haul	headache (27%)	congested nose (20%)	back pain (11%)
Helicopter	headache (73%)	back pain (32%)	burning eyes (18%)

Shift workers are often considered to have higher levels of domestic stress, and higher incidences of gastrointestinal complaints, than day workers (ref. 9). Several items in the Background Questionnaire addressed these issues, for example: marital status, general health, experience with stomach or intestinal problems during a trip, appetite on trips, and diet on trips. Two other questions address issues of fatigue and performance: extent fatigue affects performance and how often does fatigue affect performance on a trip. Responses to these questions were compared for 41 overnight cargo crew members and 90 daytime fixed-wing short-haul crew members.

Because responses to these questions might change systematically with age, the groups were compared by two-way ANOVAs (operation by age) with 5-yr age bins from 30–50 and over-50-year-olds. These results are summarized in table 19.

Table 19. Comparison of Responses by Overnight Cargo and Daytime Short-Haul Flight Crews

Questionnaire Item	Operation Type F	Age F	Interaction F
Marital status	0.91	1.57	0.13
General health	2.13	1.76	0.73
Stomach/intestinal problems	0.89	0.92	1.22
Appetite on trips	5.84*	0.57	0.51
Diet on trips	2.23	0.80	1.41
Extent of fatigue effects	0.50	0.60	1.42
How often fatigue affects performance	0.05	1.88	1.09

* 0.05 > p > 0.01

The only significant difference between the two groups was that overnight cargo crews reported that their appetite decreased slightly on trips (average 2.4 on a scale from 1 to 5) whereas short-haul crews reported no change (average 3.0 on a scale from 1 to 5).

5.0 DISCUSSION

The data gathering procedures used in this study were designed to cause minimum disruption to the normal flow of scheduled overnight cargo operations. The investigators' objective was to observe situations without influencing them. This naturalistic approach has important face validity for the operational community. On the other hand, it lacks the rigor of laboratory-based scientific experimentation in which some variables are controlled while others are systematically manipulated in an attempt to reveal causal links. To exploit both approaches—observational and experimental—findings from laboratory experiments were used to guide data analysis and interpretation; for example, in determining the effects of sleep loss and the circadian control of sleep.

5.1 Effects of Trips on Sleep

It should be noted that all of the sleep data used in the present study are from subjective reports, which are known to be more variable than physiological sleep measures obtained from polygraphic recordings. Within-subjects designs were used in the ANOVAs to compensate for the large inter-individual variability in these measures. The changes in sleep timing and duration after night duty were sufficiently large that the greater variability of the subjective data would not be expected to alter the major findings. The consistent relationships between sleep timing and layover timing also support the validity of the measures used.

Flying at night required crews to try to sleep during the day. Daytime sleep episodes were about 3 hr shorter than nighttime sleep episodes and were rated as lighter, less restorative, and of poorer quality overall. Core body temperature was also higher during daytime sleep episodes as a result of the incomplete circadian adaptation to night work, i.e., daytime sleep and nighttime sleep occurred during different parts of the circadian temperature cycle.

When duty schedules permitted (see below), crew members often slept more than once during a daytime layover. The incidence of multiple sleep episodes or naps per 24 hr tripled on duty days compared to days without duty (53% versus 17%). Even with these additional sleep episodes, crew members lost an average of 1.2 hr of sleep per 24 hr on duty days, relative to their total daily sleep pretrip. In the laboratory, reducing nighttime sleep by this amount results in daytime sleepiness which increases progressively with the number of days of reduced sleep (refs. 30, 31). However, restriction of nighttime sleep in the laboratory also results in shorter sleep latencies and deeper sleep with fewer awakenings. In contrast, crew members rated their daytime sleep as lighter, less restorative, and of poorer quality overall than nighttime sleep. If, as these subjective ratings suggest, the quality of daytime sleep was compromised, then this would be expected to have an adverse effect on subsequent alertness and performance in addition to the effects of sleep loss.

The loss of 1.2 hr of sleep per 24 hr represents a reduction in total sleep duration on duty days of about 16% compared to pretrip baseline. Individual daytime sleep episodes were 41% shorter than pretrip nighttime sleep episodes. Night-shift workers in other industries report reductions in sleep duration of a least one third for daytime sleep episodes compared to nighttime sleep (ref. 2). The work-rest schedules of the overnight cargo crews were also much more variable on a day-to-day basis than those of other night workers and daily sleep loss varied greatly depending on the timing and duration of the layovers (fig. 6).

The night off in the middle of the sequence of duty nights clearly provided an important opportunity for recuperation. Crews averaged 41 min more sleep per 24 hr than pretrip and 115 min more than during daytime layovers. On the Destination-Layover pattern, this opportunity occurred after three nights of flying, by which time a third of the crew members had already lost the equivalent of a full night of sleep (8 hr). On the Out-and-Back pattern, the night off occurred after five nights of flying, by which time a quarter of the crew members had lost more than 8 hr of sleep. The average duty "day" on the Destination-Layover pattern was 3.5 hr longer, with double the number of flight segments and 52 min more flight time, and the average layover was 6.1 hr shorter. Nevertheless, the average sleep debt accumulated by the end of the two 8-day patterns was not significantly different (about 10 hr). There was considerable variability in sleep loss among individuals within each of the trip patterns. This variability was not correlated with any of the individual attributes reported by others (refs. 3, 4, 10-21) to predict adaptability to shift work and time-zone changes, that is, amplitude of circadian rhythms, morningness/eveningness, extraversion, and neuroticism.

Layover timing and duration had a major influence on the sleep that crew members were able to obtain between consecutive nights of flying. Layovers containing one morning sleep episode (96% of Destination-Layover layovers, 37% of Out-and-Back layovers) began earlier and were shorter than layovers containing two shorter sleep episodes (4% of Destination-Layover layovers, 58% of Out-and-Back layovers). A third sleep pattern, sleeping once late in the layover, was observed in only 5% of Out-and-Back layovers.

There was a remarkable coincidence of wake-up times for single morning sleep episodes and first sleep episodes of a pair in layovers between consecutive nights of flying. On the Out-and-Back pattern, single morning sleep episodes ended, on average, at 1401 local time and first sleep episodes of a pair ended at 1356 local time. On the Destination-Layover pattern, the average wake-up time for single morning sleeps was 1443 local time. This is about 6.0 hr after the average temperature minimum on duty days (0834 for the masked estimate, 0808 for the unmasked estimate). When isolated subjects in time-free environments have a sleep-wake cycle that does not match the period of the circadian temperature rhythm, they wake up spontaneously, most often, about 6 hr after the temperature minimum (ref. 32). This observation has given rise to the notion of a circadian "wake-up signal." The present data suggest that crew members had difficulty sleeping past the circadian wake-up signal, even though they had slept considerably less than on baseline nights (7.5 hr). On the Out-and-Back pattern, single morning sleep episodes averaged 5.8 hr, while first sleep episodes of a pair averaged 4.3 hr. On the Destination-Layover pattern, single morning sleep episodes averaged 5.4 hr.

Studies of sleep in a variety of experimental protocols have revealed the existence of a "wake-maintenance zone" of several hours duration and centered about 8 hr before the circadian temperature minimum in a time-free environment, or shortly before the habitual bedtime (ref. 32). While traversing this zone, subjects have difficulty falling asleep even when they are suffering from sleep loss. In the present data, 8 hr before the average temperature minimum is around 0030 on duty days. The average time of sleep onset on pretrip days was also about 0030. On the Out-and-Back pattern, the average sleep onset time for second sleep episodes in a layover was around 2250, i.e., just before the predicted evening wake-maintenance zone. Layovers containing two sleep episodes ended 4–7 hr later (0328) than layovers in which crew members slept only once.

5.2 Effects of Trips on Circadian Phase

The analyses suggest that the daily temperature minimum occurred about 3 hr later when crews flew at night than during the pretrip baseline period when they slept at night. This would suggest incomplete circadian adaptation to the reversed work-rest schedule, comparable with findings from studies of night workers in other industries (for example, refs. 3, 9–10). To compensate for the masking of the circadian variation in temperature by changes in the level of physical activity, 0.28 C° was added to the raw temperature data for each subject when asleep. Overall, this mathematical "unmasking" did not significantly change the magnitude of the delay associated with night duty (3.5 hr in the masked data, 2.8 hr in the unmasked data). However, on the Destination-Layover pattern, the masked and unmasked estimates of the temperature minima were significantly different on certain days. In general, when the subjects flew at night, the masked estimate of the time of the temperature minimum tended to be later than the unmasked estimate. Conversely, when they slept at night, the masked estimate tended to be earlier than the unmasked estimate. A more detailed discussion of the unmasking technique can be found in the appendix.

5.3 Effects of Trips on Subjective Fatigue and Mood

On pretrip days, fatigue was lowest, and activation highest, several hours after wake-up. Conversely, fatigue was highest, and activation lowest, in the last rating before nighttime sleep. This is in accord with the pretrip time-of-day variation observed in North Sea helicopter crews (ref. 25) and with the time-of-day variation in similar variables in the laboratory (ref. 33). Rhythms in subjective fatigue and activation do not always parallel the objective variations in physiological sleepiness measured by the multiple sleep latency test (refs. 18, 33).

Several experimental protocols have demonstrated that subjective fatigue (or alertness) and activation are influenced by two components: (1) a circadian variation which parallels the circadian temperature cycle; and (2) a component associated with the sleep-wake cycle, with minimum fatigue (peak activation) occurring 8–10 hr after waking (ref. 33). For crews in the present study, flying at night delayed the circadian temperature rhythm about 3 hr and altered the sleep-wake pattern, that is, it disrupted the normal relationship between these two components. As expected, it also altered the time-of-day variation in subjective fatigue and activation (fig. 10). However, because of the reduction of the data into 4-hr time-bins, it is not possible to establish with precision the amount of shift in these rhythms from pretrip to duty days. Studies of night workers in other industries have found lowest subjective alertness coinciding with the minimum in body temperature (ref. 33). In the present study, when crew members were flying at night, highest fatigue and lowest activation were observed in the time bin from 0830 to 1230 local time, that is, just after the time of the temperature minimum (about 0820). Because of the variability in layover sleep patterns, it is difficult to make generalizations about the relationship between the sleep-wake cycle on duty days, and fatigue and activation ratings.

Positive and negative affect did not show significant time-of-day variations pretrip. This contrasts with the significant pretrip time-of-day variation in negative affect shown by the helicopter crews (ref. 25). In general, in normal healthy subjects, measures of affect show weak circadian variation at most (ref. 33). On the other hand, in the present study, positive and negative affect showed significant time-of-day variation on duty days, when they varied as mirror images. Positive affect was highest, and negative affect lowest, when fatigue was lowest, that is, in the time-bin from 1630 to 2030 local time. Both affect variables continued to show significant time-of-day variation posttrip, maintaining the same relationship to the subjective fatigue rhythm as was observed on duty days.

Average fatigue and mood ratings during nighttime wakefulness while on duty were compared with average ratings during pretrip daytime wakefulness. During duty, fatigue and negative affect were higher, and activation and positive affect were lower, than during pretrip days.

5.4 Effects of Trips on Caffeine and Food Consumption

In contrast to crew members flying daytime short-haul operations (refs. 22, 25), overnight cargo crew members did not significantly increase their caffeine consumption on duty days. Snacking increased significantly on trips, although the number of meals consumed daily did not change. The meals eaten on duty days may have been less filling or snacking may have been used as a countermeasure to help stay awake.

5.5 Effects of Trips on Symptoms

Fifty-nine per cent of the subjects reported headaches at some time during the study, 26% reported congested nose, and 18% reported burning eyes. The incidence of headaches quadrupled on duty days, by comparison with pretrip, the incidence of congested nose doubled, and the incidence of burning eyes increased ninefold. These changes cannot be attributed to smoking in the cockpit (now banned by the participating company) because only two of the 41 participants reported smoking. Of the 34 crew members included in the analyses in this study, only one reported being a smoker.

5.6 Day versus Night Flying

By comparison with the daytime short-haul fixed-wing operations studied, the overnight cargo operations had shorter duty days (by an average of 3 hr), with 2 hr less flight time and fewer, shorter flight segments and had layovers between duty "days" that averaged 2.4 hr longer. The overnight cargo crews were, on average, 5.4 yr younger than their daytime short-haul counterparts. This may confer some advantage in terms of adaptability to shift work (ref. 29). However, overnight cargo crews were also less experienced overall and averaged 9.4 yr less experience with their present airline. This represents a minimum estimate of how long they had been flying overnight cargo operations (an average of 4.7 yr).

The average daily percentage sleep loss was not significantly different for the two groups, despite the difference in layover duration. Multiple sleep episodes per 24 hr were 17 times more common on overnight cargo trips than on daytime short-haul fixed-wing trips. The long duty days and short nighttime layovers in the latter operations resulted in a particularly low incidence of multiple sleep episodes on trip days. On the other hand, daytime short-haul helicopter crews had layovers that averaged 2.1 hr longer than those of the overnight cargo crews (ref. 25) but reported multiple sleep episodes 2.5 times less often during trips. On trips, overnight cargo crews gained 9.5 times more sleep from secondary sleep episodes than did short-haul fixed-wing crews and 5.0 times more than did helicopter crews. (Secondary sleep episodes were defined as those sleep episodes other than the longest in each GMT day.)

Though overnight cargo crews were not losing more sleep per 24 hr than their daytime short-haul counterparts, it is clear that they confront different physiological challenges. First, the circadian cycle does not adapt completely to the inverted duty-rest schedule and therefore overnight cargo crews are working about the time of peak physiological sleepiness (about 0200–0600 for people sleeping at night, or about the time of the circadian temperature minimum). Thus, even without sleep loss, it would be expected that the nighttime circadian factor would create more sleepiness compared to daytime short-haul operations.

Second, performance on a number of laboratory tasks (e.g., signal detection, reaction time, simple arithmetic; ref. 34) and the performance of experienced fighter pilots in an F-104G simulator (ref. 35) parallels the circadian temperature rhythm and is at its worst about the time of the daily temperature minimum. In other 24-hr operations, performance is consistently lowest on the night shift (refs. 9, 36). Thus, even without sleep loss, overnight cargo crews would be expected to be more vulnerable to lower performance than their day-flying short-haul counterparts.

Third, there are several observations that suggest the quality of the daytime sleep obtained by overnight cargo crew members is not comparable to that obtained by short-haul crew members sleeping at night. The daytime sleep of overnight cargo crews was often split into several episodes across the 24-hr day. The daytime sleep of overnight cargo crews was also displaced in the circadian cycle, relative to a normal night of sleep and it is well established that sleep quantity and quality vary across the circadian cycle.

Headaches were reported more than twice as often among overnight cargo crews as they were among short-haul fixed-wing crews and were approaching the incidence reported by helicopter crew members who flew in cockpits where overheating, poor ventilation, and high levels of vibration were common (ref. 25). Overnight cargo crews more frequently reported congested nose than short-haul fixed-wing crews and reported an incidence of burning eyes that was comparable to that of helicopter crews. Overnight cargo crews also reported a more negative effect of trips on appetite than did daytime short-haul fixed-wing crews. This may have been related, at least in part, to duty hours coinciding with the part of the circadian cycle not normally associated with eating (late evening through early morning).

5.7 Conclusions

Flying at night imposes a number of physiological challenges that are not present in comparable daytime operations. As this study demonstrates, circadian adaptation to night duty is incomplete. On average, crew members came off duty around 0720 local time, which is about an hour before the average time of the temperature minimum after a night of flying. The time of the temperature minimum corresponds to the daily low point in alertness and in performance capabilities in the laboratory, in flight simulators, and in other 24-hour industries (refs. 34-36). The daytime sleep of crew members was truncated in many instances by the circadian wake-up signal. Depending on the duration of the layover, they were often unable to sleep again before going back on duty. In addition, their daytime sleep was reported as being lighter and less restorative than nighttime sleep. Thus crew members were working around the circadian low point with an accumulating sleep debt. In laboratory studies, this combination produces lowest performance (ref. 34). Field data from other 24-hr shift work operations and accident rates in other modes of transport also consistently indicate worse performance at night (refs. 2, 9, 36). It is important to note that no performance measures were collected in this study and there were no incidents or accidents on any of the study flights.

There are many checks and balances in the system which serve to reduce the potential for human error in the cockpit, from design and automation strategies to company scheduling policies and federal regulations. However, in most cases these approaches do not currently recognize that human circadian physiology creates a window of vulnerability for performance decrement around the time of the circadian temperature minimum, which is exacerbated when combined with sleep loss. Addressing this increased vulnerability explicitly is a way of further reducing the potential for error. The data from this study suggest several approaches that may be useful in managing fatigue during overnight cargo operations.

1. The timing and duration of layovers had consistent effects on sleep. Getting off duty earlier permitted a longer sleep episode before the circadian wake-up signal. Going back on duty later allowed a second sleep episode closer to duty time, thus reducing the duration of wakefulness for the next duty period. The balance of these two effects should be considered when determining the timing and duration of layovers. For example, crew members finishing duty after 0700 local time are unlikely to obtain 7 hr of sleep before the circadian wake-up signal (about 1420 local time after a night of flying). In such cases, it would be desirable to allow sufficient layover time (the present data suggest around 19 h) for a second sleep episode. Crew members need to be aware that they risk having difficulty falling asleep if they do not go to sleep again before about 2300 local time, because of the evening wake-maintenance zone.

2. The night off presents an important opportunity for recuperation. The present data indicate that it can be positioned strategically in the sequence of night duties to offset the cumulative sleep loss imposed by the schedules. On the Destination-Layover pattern, for example, it was clearly prudent to avoid a fourth consecutive night of flying when one third of the crew members had already lost more than 8 hr of sleep after three nights of flying. In contrast, on the Out-and-Back pattern, only a quarter of crew members had lost more than 8 hr sleep after five nights of flying. The use of naps as a fatigue countermeasure in overnight cargo operations deserves further attention (ref. 37).

3. Gastrointestinal problems frequently accompany incomplete circadian adaptation to a work schedule or to a new time zone. The Background Questionnaire did not identify major differences between the effects of daytime and nighttime flying, except that overnight cargo crews reported a decrease in appetite on trips, whereas daytime short-haul crews reported no change. However, it would be premature to conclude on this basis that there are no differences over a long period of time. Both groups reported more snacking on trips. Education about the effects of shift work on digestion, and attention to the quality of the food available on trips, could be beneficial. In contrast to daytime short-haul fixed-wing crews, overnight cargo crews did not increase their caffeine consumption on trips. Used appropriately, caffeine can be a convenient operational countermeasure for acute fatigue (ref. 37). Ensuring that caffeine, and information about its use, are readily available could help crew members maintain their alertness during night flights. However, caffeine also disrupts sleep, so that its use close to bedtime is not recommended.

4. These data, collected during scheduled flight operations, support the conclusion that nighttime flying imposes different physiological challenges than daytime flying. Wherever possible, these differences should be taken into account in trip construction, with particular attention being given to the timing and duration of rest periods and to the number of consecutive nights of flying. Crew members may also be able to improve their flightdeck alertness and performance through education and training on the physiological causes of fatigue, its potential operational consequences, and personal countermeasure strategies to minimize its effects.

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Appendix

Circadian Phase Estimation

In this study, the extent to which the circadian clock adapted to a series of night duties was estimated from the shift in the time of the daily temperature minimum from pretrip days to duty days. The validity of this approach needs to be considered in detail, because of the problem of the changes in temperature produced by physical activity (masking) that are superimposed on the circadian variation in temperature.

The mathematical "unmasking" technique used here (adding 0.28 C° to the raw temperature data for each subject when asleep) is clearly very simplistic. However, its effect on the estimated times of the cycle-by-cycle temperature minima is not so straightforward as it might seem at first glance. Some smoothing also occurs in the fitting of the multiple complex demodulated waveform. When the midpoint of the sleep episode occurs close to the masked temperature minimum, the unmasking technique (adding a constant during sleep) has minimal effect on the estimated time of the temperature minimum. When the midpoint of the sleep episode is displaced from the masked temperature minimum, the unmasking technique alters the estimated time of the temperature minimum, but in a complex way.

This relationship is illustrated in fig. A-1. The displacement of the midpoint of sleep from the masked temperature minimum is plotted on the x-axis and the difference between the masked and unmasked estimates of the time of the temperature minimum is plotted on the y-axis. When the midpoint of sleep occurs up to about 4 hr before the masked temperature minimum ($-4 < x < 0$ in fig. A-1), then the unmasking technique gives a later estimate of the time of the temperature minimum. Conversely, when the midpoint of sleep occurs up to about 4 hr after the masked temperature minimum ($0 < x < 4$ in fig. A-1), then the unmasking technique gives an earlier estimate of the time of the temperature minimum. Across this relative phase range ($-4 < x < 4$ in fig. A-1), there is a significant linear correlation between the displacement of the midpoint of sleep from the masked temperature minimum, and the difference between the masked and unmasked estimates of the temperature minimum ($r = .63$, $p < 0.01$). Although there are fewer data points, it also appears that the unmasking technique affects the estimated time of the temperature minimum even when the midpoint of the sleep episode is close to the temperature maximum. When the midpoint of sleep occurs in the hours after the temperature maximum ($-12 < x < -8$ in fig. A-1), then the unmasking technique gives an earlier estimate of the time of the temperature minimum. Conversely, when the midpoint of sleep occurs in the hours before the temperature maximum (8 < x < 12 in fig. A-1), then the unmasking technique gives a later estimate of the time of the temperature minimum. In summary, the effect of the unmasking technique on the estimated time of the temperature minimum is dependent on when in the temperature cycle sleep occurs.

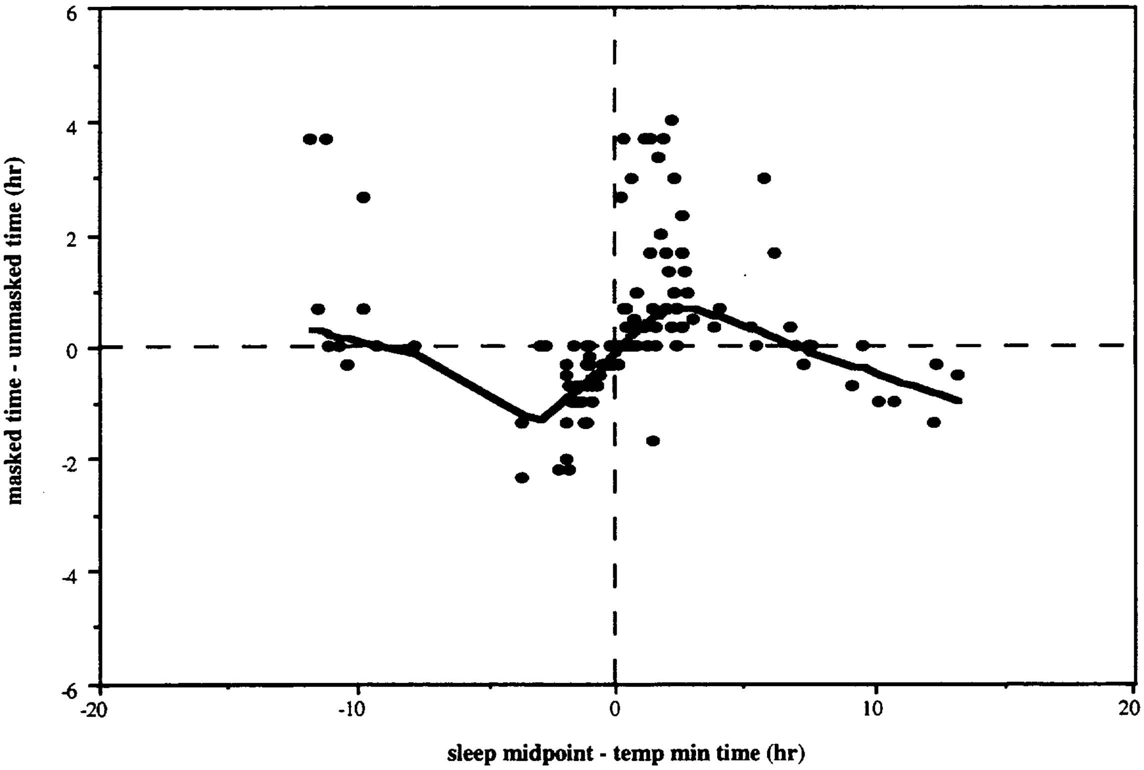

Figure A-1. Effect of unmasking technique on estimated time of temperature minimum. Fitted curve is a robust locally weighted regression smooth, with f = 0.67 (ref. 38).

When crew members went to sleep in the morning after a night of flying, they were sleeping later in the temperature cycle than when they slept at night. A two-way ANOVA was performed (table A-1) to compare the masked and unmasked estimates of the temperature minima across the phases of the study (pretrip/duty/no-duty/posttrip). This analysis included data from 18 subjects.

Table A-1. Effects of Unmasking Technique on Estimated Time of Temperature Minimum

	Mask/Unmask F	Pre/Duty/No-duty/Post F	Interaction F
Estimated time of temperature minimum	3.57	21.63***	4.62**

**0.01 > p > 0.001; ***p < 0.001

Overall, the masked and unmasked estimates were not significantly different (p = 0.08). However, the significant interaction indicates that the masked and unmasked estimates did not change similarly across all phases of the study. This is illustrated in fig. A-2. Post hoc tests indicated that the masked estimates were significantly earlier than the unmasked estimates on the no-duty day (F = 7.33, p = 0.015) and on posttrip days (F = 6.62, p = 0.020). Sleep onset and wake-up times were not significantly different among pretrip, no-duty, and posttrip days. Thus, the significant differences between the masked and unmasked estimates of the time of the temperature minimum on no-duty and posttrip days suggests that the circadian system had shifted relative to pretrip. The extent of this small shift cannot be measured with great precision because these data are from a real-world setting which does not permit fine control of all the potential contaminating variables. On the other hand, it is clear that the circadian system did not invert to match the reversed rest-activity cycle on duty days. This is the most relevant point from an operational perspective because it indicates that crew members were being required to work around the circadian times of lowest alertness and performance.

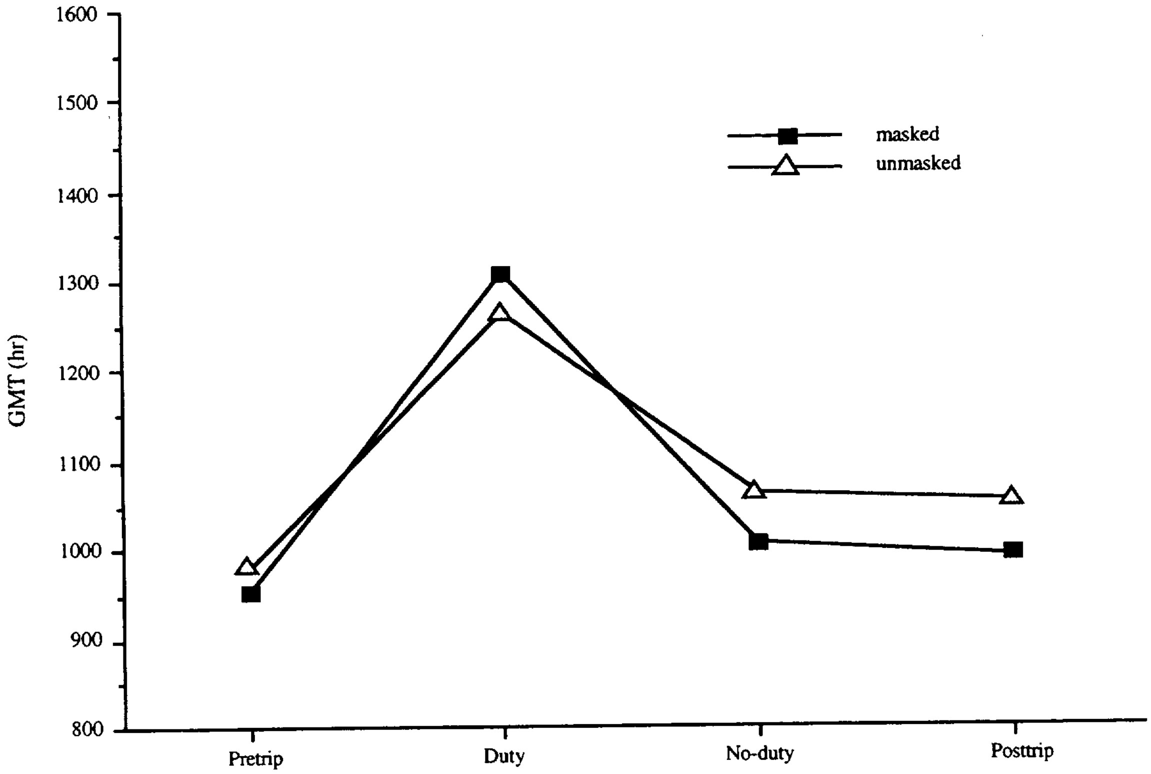

Figure A-2. Comparison of masked and unmasked estimates of times of the temperature minima on pretrip, duty, no-duty, and posttrip days.

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To document the psychophysiological effects of flying overnight cargo operations, 41 B-727 crew members (average age 38 yr) were monitored before, during, and after one of two typical 8-day trip patterns. During daytime layovers, the average sleep episode was 3 hr (41%) shorter than nighttime sleeps and was rated as lighter, less restorative, and poorer overall. Sleep was frequently split into several episodes and totaled 1.2 hr less per 24 hr than on pretrip days. Each trip pattern included a night off, which was an effective countermeasure against the accumulating sleep debt. The organization of sleep during daytime layovers reflected the interaction of duty timing with circadian physiology. The circadian temperature rhythm did not adapt completely to the inverted wake-rest schedule on duty days, being delayed by about 3 hr. Highest subjective fatigue and lowest activation occurred around the time of the temperature minimum. On duty days, reports of headaches increased by 400%, of congested nose by 200%, and of burning eyes by 900%. Crew members also reported eating more snacks. Compared with daytime short-haul air-transport operations, the overnight cargo trips included fewer duty and flight hours, and had longer layovers. Overnight cargo crews also averaged 5.4 yr younger than their daytime short-haul counterparts. On trips, both groups lost a comparable amount of sleep per 24 hr, but the overnight cargo crews had shorter individual sleep episodes and more broken sleep. These data clearly demonstrate that overnight cargo operations, like other night work, involve physiological disruption not found in comparable daytime operations.

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