Flight Crew Fatigue V: Long-Haul Air Transport Operations

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We monitored 32 flight crewmembers before, during, and after 4–9 d commercial long-haul trips crossing up to 8 time zones per 24 h. The average duty day lasted 9.8 h, and the average layover 24.8 h. Layover sleep episodes averaged 105 min shorter than pretrip sleep episodes. However, in two-thirds of layovers, crewmembers slept twice so that their total sleep per 24 h on trips averaged 49 min less than pretrip. Greater sleep loss was associated with nighttime flights than with daytime flights. The organization of layover sleep depended on prior flight direction, local time, and the circadian cycle. The circadian temperature rhythm did not synchronize to the erratic environmental time cues. Consequently, the circadian low point in alertness and performance sometimes occurred in flight. On trip days, by comparison with pretrip, crewmembers reported higher fatigue and lower activation; drank more caffeine; ate more snacks and fewer meals; and there were marked increases in reports of headaches, congested nose, and back pain. Scheduling strategies and countermeasures to improve layover sleep, cockpit alertness, and performance, are discussed.

IN THE MID-1980's, the Fatigue Countermeasures Program at NASA-Ames Research Center conducted a field study to assess fatigue in commercial long-haul flight operations. There are three factors that combine in these operations to produce unique challenges for crewmembers trying to maintain their alertness and performance on the flightdeck: a) long flights; b) non-24 h duty/rest schedules with daytime and nighttime flying; and c) rapid sequences of transmeridian flights.

Because they typically fly much longer segments than their short-haul counterparts, long-haul crews might be expected to be especially prone to the effects of time-on-task fatigue, including reduced vigilance and habituation. These decrements are particularly sensitive to sleep loss (10).They may also be exacerbated by advanced automation which tends to make the crewmember a less active participant in managing the flight, particularly during cruise (21).

Long-haul trips typically involve sequences of long duty days alternating with relatively long layovers (1–2 d) so that duty/rest cycles do not usually follow a 24-h pattern and are beyond the synchronizing limits of the circadian clock (12). This introduces two potential sources of reduced alertness and performance on the flightdeck (15). First, the low point of the circadian cycle may occur in flight. This is the time in the cycle, around the temperature minimum, when performance on laboratory tasks, in flight simulators, and in other 24-h operations is poorest (1,6,23,25,26,38) and sleepiness is greatest (4). Second, layover sleep may be compromised if the preferred part of the circadian cycle for sleep (8,9,37,42) does not coincide with the layover and local night. Restricted sleep duration and poorer quality sleep both decrease subsequent alertness and performance (5,10,30).

Long-haul crewmembers face an additional challenge because consecutive rest periods (layovers) are usually in different time zones. Thus the circadian clock is deprived of its most important 24-h time cues ("zeitgebers") from the environment–a regular pattern of work/rest and social contact, and the day/night cycle (7,40). When the clock is out of step with environmental time, the symptoms of jet-lag are commonly experienced, including sleep and digestive disturbances, reduced mental and physical performance, and mood changes (22,23,41). Jet-lag has been most extensively studied after single transmeridian flights (18,20,23,24,41). The rate of adaptation of circadian rhythms to a new time zone depends on: the rhythm being studied; the number of time zones crossed; the flight direction, with adaptation being faster after westward flights; and the strength of the geophysical and social zeitgebers experienced in the new time zone.

The effects of rapid sequences of transmeridian flights are not as well documented. Buck and co-workers (2) compared wrist activity during sleep from 30 cockpit and cabin crew before and after three scheduled trip patterns (south-north across 1 time zone: west-east polar route crossing 17 time zones; and east-west across 7 time zones). Only the 11-d polar route (Zurich via Anchorage to Tokyo, and return) resulted in more restless sleep posttrip. A similar 7-d polar route (crossing 16 time

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zones, from London via Anchorage to Tokyo, and return) was studied by Spencer and co-workers (36), who monitored subjective and objective sleep measures, subjective alertness, and the circadian temperature rhythm in 12 flight crewmembers. On the outward leg, the two successive extended days were accompanied by accumulating sleep debt, whereas tiredness by the end of the return leg was linked to circadian disruption. Throughout the trip, the temperature rhythm was of low amplitude and out of synchronization with the sleep-wake cycle and the local day/night cycle. Resynchronization of all measures was apparently completed by the sixth day back in London. This study documented major individual differences in the rate and direction of adaptation of circadian rhythms and in sleep patterns and the accumulation of sleep debt. Samel et al. (33) found an effect of layover duration in a study of subjective sleep reports from 101 flight crewmembers on 7 different polar route schedules (Frankfurt via Anchorage to Tokyo or Seoul, and return) lasting 7–11 d. The sleep debt that crews accumulated during the trip was reduced when they remained for longer periods at the destination layover. Presumably, sleep improved as the circadian clock adapted to local time. However readaptation on return to Frankfurt was also slower when crewmembers stayed longer at the destination layover. A polar route in the opposite direction (crossing 16 time zones, from Tokyo via Anchorage to London, and return) was studied by Sasaki and co-workers (35), who recorded subjective and objective sleep measures and subjective alertness from 12 crewmembers. The majority of crewmembers accumulated a significant sleep debt across the 6-d trip, despite napping and spending more time in bed during layovers than pretrip. Recovery was not completed in the 2 nights after their return home. The changes in sleep reflected the effects of prolonged wakefulness during night flights, and, particularly on the home-bound trip, the gradual drifting of the circadian clock away from home (Tokyo) time.

For the NASA long-haul fatigue field study, four trip patterns lasting 4–9 d were selected from the monthly bid packages of the participating airline. They were chosen to be representative of commonly occurring patterns (i.e., westward outbound; eastward outbound; over-and-back transatlantic flights; and primarily north-south displacement, but with long flight times approximating those of the other patterns).

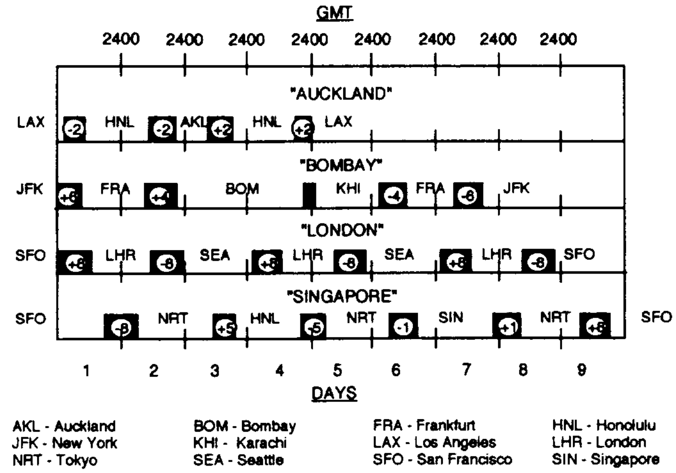

Fig. 1. Timelines of the four trips studied. Black bars indicate flights. Numbers in circles indicate the number of time zones crossed (negative values indicate westward flights; positive values indicate eastward flights).

METHODS

The 32 male flight crewmembers who volunteered to participate were flying Boeing 747–200/300 aircraft and were monitored before, during, and after one of the four trips shown in **Fig. 1**. The San Francisco-London pattern was distinctive in that crews returned to their home time zone on alternate layovers. Crews on the Singapore, London, and Auckland trips were domiciled in San Francisco, while those on the Bombay trip were domiciled in New York. Crewmembers had spent at least 4 d in the domicile time zone before entering the study. All data were collected on Greenwich Mean Time (GMT). Characteristics of the trips are summarized in **Table I**. Data for duty times and layover durations were taken from the daily logbooks kept by crewmembers. Data for flight hours, number of segments, and segment duration, were from the cockpit observer logs (14). Crewmembers flew 1–2 segments per duty day, averaging 6.8 h of flight time and 9.8 h on duty. The average layover across the duty patterns lasted 24.8 h.

To be included in the analyses, crewmembers had to have provided complete logbook data for at least one pretrip day, all trip days, and at least two posttrip days. Some 25 crewmembers (78% of the participants) provided data which met these criteria. Their distribution among the different trips and crew positions is shown in **Table II**. Their average age was 52.7 yr (SD 5.0 yr) and they had an average of 22.8 yr of airline experience (SD 7.6 yr).

Unless otherwise stated, all analyses of variance were within subjects. For t-tests, where a Levene's test revealed unequal variances, the separate t-test value was taken. Otherwise, the pooled t-test value was taken.

In addition to the logbook measures of fatigue, in this study particular attention was focused on effects of duty demands on the circadian clock. In keeping with current convention, the core temperature rhythm (measured at 2-min intervals) was used to monitor the position of the clock. To estimate the period of the clock across trip days, each crewmember's temperature data were subjected to linear-nonlinear least squares interative spectral analysis (31), which searched for significant periodicities in the range 2–40 h, at 0.25 h increments. A significant fit indicated that the fitted sinusoid had a non-zero amplitude ($p < 0.05$). There were 22 subjects (69%) who provided sufficient continuous temperature data for these analyses.

Times of the cycle-by-cycle temperature minima were also estimated. To minimize contamination of these estimates by the short-term temperature changes caused by changes in the level of physical activity, a constant (0.28 C°) was added to the raw temperature data for each subject whenever he was asleep. This mathematical "unmasking" procedure was based on the reported 0.28°C difference between the temperature rhythm during sleep and wake in internally desynchronized people (39).

TABLE I. TRIP STATISTICS (MEAN, RANGE).

	Auckland	Bombay	London	Singapore
Daily duty duration (h)	8.2 (6.1–9.9)	9.1 (3.2–13.2)	11.7 (11.0–12.6)	10.3 (8.4–12.1)
Layover duration (h)	20.2 (11.9–24.4)	29.0 (18.4–48.2)	23.8 (20.0–29.1)	26.1 (23.3–28.8)
Flight hours/duty day	6.5 (4.4–8.4)	5.4 (1.4–8.2)	9.3 (8.5–10.7)	5.8 (2.8–10.2)
Segments/duty day	1.0	1.2 (1–2)	1.0	1.3 (1–2)
Time zones/duty day	2.0	3.6 (0–6)	8.0	4.0 (1–8)
Segments/trip	4.0	6.0	6.0	8.0
Time zones/trip	8.0	18.0	48.0	28.0

Masked and unmasked temperature data for each crewmember were averaged in 20-min bins and subjected to multiple complex demodulation (27). The cycle-by-cycle temperature minimum was taken as the computer-selected lowest value within 12 h in the remodulated waveform. If this procedure identified two minima in 24 h, then the data and the remodulated waveform were superimposed on the sleep and nap times. If there was no clear way of discriminating between the minima (circadian or masking), then the data for that cycle were discarded. Missing points in the raw data were replaced by linear interpolation, and all the fitted waveforms were overlaid with the original data to check that the interpolation did not introduce spurious estimates of minima. A detailed description of the effects of the unmasking procedure on the estimation of circadian parameters is contained in reference 17.

RESULTS

Sleep on Pretrip, Trip, and Posttrip Days

In the daily logbooks it was possible to record up to two sleep episodes and two naps per 24 h, and sleep patterns on layovers were complex and varied. As a first comparison, **Table III** presents the duration and quality of individual sleep episodes on pretrip, trip, and posttrip days*. The probabilities in Table III indicate values for the pretrip/trip/posttrip comparisons in one-way analyses of variance (ANOVA) with subjects treated as random variable. Where ANOVA revealed significant differences, post hoc t-tests were used to compare pretrip, trip, and posttrip values. All the comparisons discussed were significant at least at the 0.05 level.

TABLE II. CREWMEMBERS STUDIED ON EACH TRIP PATTERN.

Trip Pattern	Captains	First Officers	Flight Engineers	Total
Auckland	2	1	1	4
Bombay	2	1	1	4
London	3	3	3	9
Singapore	3	2	3	8
Total	10	7	8	25

* Sleep latency was calculated as the difference between the reported times of going to bed and falling asleep. Scores on the four sleep quality questions (rated from 1-least to 5-most) were converted so that higher values indicated better sleep, and combined to give the overall sleep rating. Heart rate and activity data during each sleep episode were trimmed to include values from 20 min after the reported sleep onset time until 10 min before the reported wakeup time (14).

Sleep episodes during layovers were shorter than those either pretrip or posttrip. Sleep episodes on posttrip days were shorter than those on pretrip days, and tended to be deeper ($t = 1.80$, $p = 0.08$). Overall, crewmembers reported significantly less sleep per 24 h during trips than either pretrip or postrip. Consequently, they accumulated a sleep debt across the days of the trip.

This is illustrated in **Fig. 2**. For each subject, daily sleep loss (or gain) was calculated by subtracting the total sleep per 24 h (including naps) from his average total sleep per 24 h on pretrip days. The sleep loss (or gain) on consecutive trip days was added to produce the cumulative sleep loss curve. Curves for all the subjects on each trip pattern were then averaged together. The zigzag patterns in the sleep loss curves for the London and Singapore trips are the result of sleep loss after night flights (sharp rises) vs. recuperation (flattening or decline) after daytime flights. Usually the night flights were eastward flights across four or more time zones. However, on the Singapore pattern, the increase in sleep loss on day 6 followed a flight from Nerita (Japan), via Hong Kong, to Singapore, crossing one time zone west and arriving in the middle of the local night. There was considerable variability in sleep loss between crewmembers, and between the trip patterns. This is examined further in **Table IV**.

Considering the total sleep loss per 24 h is somewhat misleading in these operations, because duty days were associated with extended periods of wakefulness (mean 20.6 h, maximum 35.8 h), whereas layovers often included two sleep episodes and a much shorter period of wakefulness. Recall that the average cycle of one-duty-period-plus-one-rest-period was about 35 h (Table I).

Influence of Prior Flight Direction on Layover Sleep

Examination of the sleep/wake records of individual crewmembers revealed that three basic sleep patterns together accounted for 97% of layovers (excluding the 48 h layover on the Bombay trip and the 12 h layover on the Auckland trip). Crewmembers either: slept once (29% of layovers); or had a longer sleep episode followed by a shorter sleep episode (26% of layovers); or had a shorter sleep episode followed by a longer sleep episode (42% of layovers). These sleep patterns are related to prior flight direction in **Fig. 3**, which includes data from 122 layovers. After westward flights crossing four or more time zones, the first sleep episode was usually long (83% of cases), and was followed in 50% of cases by a second shorter sleep episode toward the end of the layover. Conversely, after eastward flights crossing four or more time zones, in nearly 70% of cases crewmembers

TABLE III. COMPARISONS OF INDIVIDUAL SLEEP EPISODES BEFORE, DURING, AND AFTER TRIPS (MEANS).

	Pretrip	Trip	Posttrip	p(F)
Sleep onset (GMT)	7.30	12.69	10.76	***
Wakeup (GMT)	14.74	13.05	13.70	***
Sleep latency (min)	31.73	33.88	37.39	
Sleep duration (h)	7.08	5.33	6.00	***
Total sleep/24 h	7.29	6.48	8.01	***
Difficulty falling asleep?	3.79	4.07	4.06	
How deep was your sleep?	3.15	3.51	3.52	*
Difficulty rising?	3.67	3.45	3.53	
How rested do you feel?	3.26	2.90	3.11	
Sleep rating	13.87	13.93	14.13	
# Awakenings	1.02	0.71	1.07	
Heart rate during sleep	62.75	64.64	63.56	
Variability in heart rate during sleep	6.10	6.23	6.41	
Activity during sleep	1.91	3.21	3.20	
Variability in activity during sleep	6.89	7.03	7.83	
Temperature during sleep	36.34	36.35	36.28	
Variability in temperature during sleep	0.16	0.13	0.13	

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

took a short sleep soon after arrival at the layover, followed by a longer sleep later in the layover. After flights crossing fewer than four time zones, the three sleep patterns occurred with approximately equal frequency.

To test whether the total amount of sleep obtained in a layover was dependent on prior flight direction, between subjects one-way ANOVAs were carried out **(Table V)**. There were no significant differences in either the total number of hours of sleep that crewmembers were able to obtain, or in the percentage of the layover time that they spent asleep, after flights crossing four or more time zones west vs. east vs. flights crossing fewer than four time zones.

Within subjects one-way ANOVAs were also carried out separately for the Bombay, Singapore, and London trips. These confirmed that prior flight direction did not have any consistent effect on the total amount of sleep that crewmembers were able to obtain in a layover. (On the Auckland trip, all layovers followed flights crossing fewer than four time zones.) Taken together, these analyses suggest that preceding flight direction influenced how crewmembers organized their layover sleep, but not how much sleep they were able to obtain.

To test whether the duration of continuous wakefulness was different for different flight directions, a one-way between-subjects ANOVA was performed (Table V).

Tukey post hoc tests with Bonferroni correction revealed that duty days which included flights crossing fewer than 4 time zones involved significantly ($p < 0.01$) shorter wake durations than duty days including flights crossing 4 or more time zones, either westward or eastward.

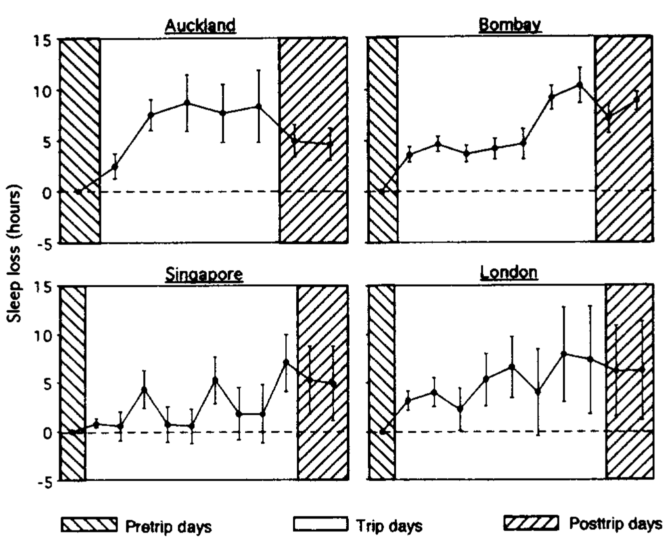

Fig. 2. Average day-by-day cumulative sleep loss with respect to baseline sleep, on each of the trip patterns. For each subject, his total sleep per 24 h on each trip day was subtracted from his average total sleep per 24 h on pretrip days, to give a daily measure of sleep loss. Average daily sleep loss was then calculated, and the values added across the consecutive trip days and posttrip days.Vertical bars indicate standard errors.

Influence of Local Time on Layover Sleep

In the Background Questionnaire (14) crewmembers were asked to describe their strategy after multiple time zone crossings on a scale from 1 (stick to home time) to 5 (shift to local time), and to rate how successful they thought their strategy was on a scale from 1 (very effective) to 5 (not at all effective). The distributions of their responses are shown in **Fig. 4**. Responses on the two questions were not significantly correlated. The majority of crewmembers tended to try to adapt to local time. Overall they felt that their strategies were only moderately successful (average 2.5).

Fig. 5 shows the distributions of layover sleep episodes with respect to local time. There was a clear preference for sleeping during local night, with a secondary preferred sleep time in the local afternoon. The majority of afternoon sleep episodes were short and followed eastward night flights crossing four or more time zones (12). They also appear as the secondary late-afternoon peak in the distribution of wakeups with respect to local time in the lower half of Fig. 5.

Circadian Adaptation

Of the 22 subjects providing continuous temperature data, 18 (82%) showed significant circadian variation

TABLE IV. PERCENTAGES OF SUBJECTS GAINING AND LOSING SLEEP ON THE FOUR TRIP PATTERNS.

	Auckland	Bombay	London	Singapore
% subjects gaining sleep	0	0	33	11
% subjects >1 h loss/24 h	60	80	33	22
% subjects >2 h loss/24 h	20	20	33	11
	n = 5	n = 5	n = 9	n = 9

Note: Three additional crewmembers were included in these analyses (c.f. Table II). They provided pretrip and trip sleep data, but no posttrip sleep data.

across trip days, with an average period of 25.7 h (SD 1.27 h). One subject from each of the four trip patterns showed no significant circadian periodicity in core temperature across trip days. One consequence of the failure of the circadian clock to synchronize to the duty/rest cycle was that the temperature minimum sometimes occurred in flight. This is shown for the Auckland, London, and Singapore trips in **Fig. 6**. (Only one subject gave complete data on temperature minima during the Bombay trip).

The circadian times of layover sleep episodes were calculated on a cycle-by-cycle basis by subtracting the GMT time of the nearest temperature minimum from the GMT times of sleep onset and wakeup. This was done for both masked and unmasked estimates of the times of the temperature minima. **Fig. 7** shows the distributions of layover sleeps with respect to the circadian cycle. For the unmasked data, the average sleep onset time was 2 min after the temperature minimum, and the average wakeup time was 6.4 h after the temperature minimum. This is comparable to the circadian distributions of sleep onset and wakeup when people living in time-free environments adopt subjective "days" that are different from the period of the circadian temperature rhythm (37). There were 13 sleep episodes (10%) that ended as the masked temperature was falling, or around the time of the unmasked temperature minimum. These sleep episodes, which were short and occurred right at the end of layovers, were probably terminated because crewmembers had to get up to go on duty, rather than in response to physiological factors (12).

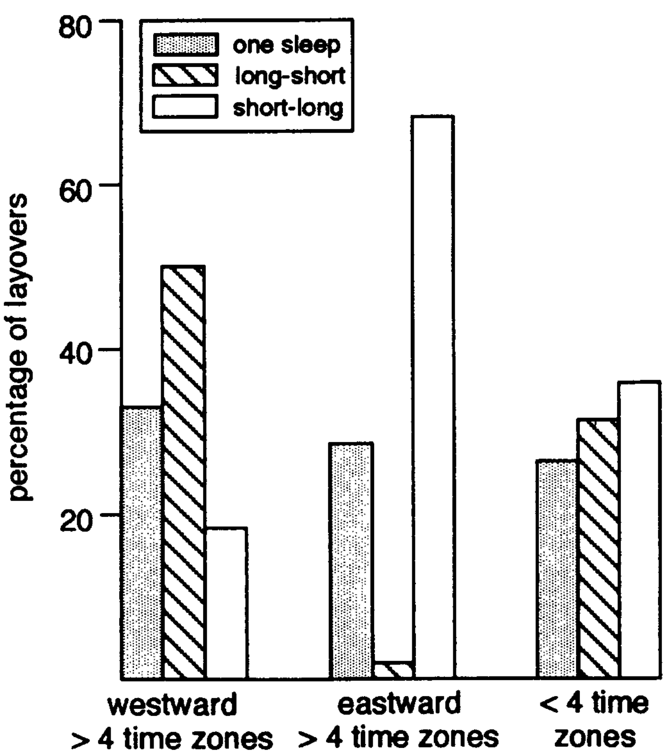

Fig. 3. Layover sleep patterns vs. prior flight direction. Flights crossing less than four time zones in either direction have been grouped together. Long-short indicates layovers in which the first sleep episode was long and the second short. Short-long indicates layovers in which the first sleep episode was short and the second long.

Fatigue and Mood Ratings

Every 2 h while they were awake, subjects rated their fatigue levels on a 10 cm line from "most alert" to "most drowsy" and rated their current mood from 0 (not at all) to 4 (extremely) on 26 adjectives. These adjectives have previously found to load on three orthogonal factors, designated "positive affect," "negative affect," and "activation" (13). One-way ANOVAs, with subjects treated as a random variable, were carried out to see if the ratings varied significantly on pretrip days **(Table VI)**. There were 20 subjects who provided sufficient data, which were converted to local time for these analyses.

On pretrip days, ratings of fatigue, negative affect, and activation showed significant time-of-day variation similar to that observed pretrip in other studies (11,15,16). Positive affect did not show significant time-of-day variation pretrip.

Because the duty-rest schedule did not follow a 24 h pattern, and the circadian clock was drifting with respect to environmental time during trips, crewmembers were rating themselves at different times during the circadian cycle on trips vs. pretrip. It is thus impossible to separate out the effects of duty from the effects of sampling a different part of the circadian cycle. To obtain an overall comparison, fatigue and mood ratings made on trips were compared with those pretrip. Data were available for 18 subjects. One-way ANOVAs, with subjects treated as a random variable, indicated that fatigue on trips was significantly higher ($F = 12.67$, $p < 0.01$) and activation was significantly lower ($F = 5.03$, $p < 0.05$). Positive and negative affect did not change significantly on trips by comparison with pretrip.

Caffeine, Meals, and Snacks

Caffeine was available in-flight as well as on the ground. In their daily logbooks, crewmembers recorded the number of cups of caffeinated beverages that they

TABLE V. TOTAL SLEEP AND DURATION OF CONTINUOUS WAKEFULNESS (MEAN ± SD) AS A FUNCTION OF FLIGHT DIRECTION.

	West > 3	East > 3	<4	F
# of hours asleep	9.43 (2.63)	9.14 (2.98)	8.96 (2.78)	0.24
% of layover asleep	35.78 (8.04)	40.51 (11.49)	38.95 (8.27)	2.14
	n = 31	n = 36	n = 36	
Wake duration (h)	21.32 (3.79)	22.74 (6.75)	17.59 (3.81)	17.56****

**** $p < 0.0001$.

drank and the time of day (GMT) at which they drank them. Caffeine was consumed by 92% of subjects at some time during the study. To test if duty demands had an effect on caffeine consumption, a one-way ANOVA was performed, with subjects treated as a random variable **(Table VII)**.

Crewmembers drank significantly more caffeine per 24 h on trips than either pretrip ($t = -2.63$, $0.05 > p > 0.01$) or posttrip ($t = 2.24$, $0.05 > p > 0.01$).

They also recorded the times that they ate and the classification of meals (breakfast, lunch, dinner, snack) in the daily logbook. To test whether duty demands had an effect on the number of meals or snacks eaten per 24 h, one-way ANOVAs were performed, with subjects treated as a random variable (Table VII). These analyses include data for 24 subjects. Crewmembers ate significantly fewer meals per 24 h on trips than pretrip ($t = 2.28$, $0.5 > p > 0.01$) and they ate more snacks per 24 h on trips than either pretrip ($t = 3.03$, $p < 0.01$) or posttrip ($t = 4.37$, $p < 0.0001$).

Physical Symptoms

The logbook contained a table for each day noting physical symptoms (14). Some 80% of crewmembers indicated that they had experienced at least one of the 20 symptoms at some time during the study. The three most common symptoms were: headaches (reported by 56% of subjects at some time during the study); congested nose (reported by 28% of subjects at some time during the study); and back pain (reported by 20% of subjects at some time during the study). The frequency of reports of each of these symptoms on pretrip, trip, and posttrip days is shown in **Table VIII**.

The incidence of reports of headaches increased 2.7-fold on trips by comparison with pretrip, while the incidence of congested nose increased 17.2-fold, and the incidence of back pain increased 7.5-fold.

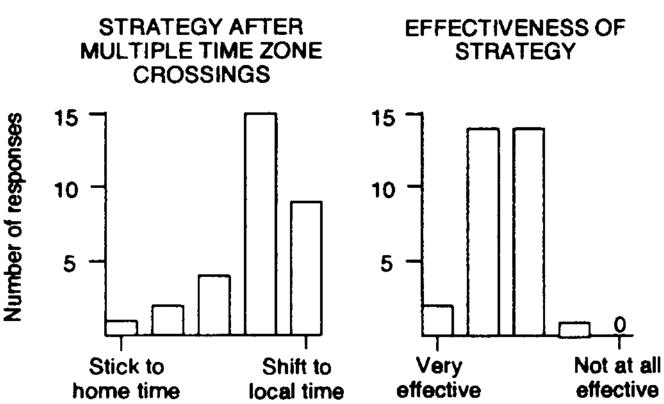

Fig. 4. Distributions of responses to two questions on crewmember strategies after time zone shifts.

Comparisons With Daytime Short-Haul Fixed-Wing Operations

Table IX compares (by 2-group *t*-tests) the duty characteristics of the long-haul operations with those of the daytime short-haul fixed-wing operations described in the second paper of this series (16). The short-haul statistics are for the subset of trips flown by the 44 subjects included in the sleep analyses in (16).

The two groups had duty days of comparable length, however the long-haul crewmembers usually flew only one segment which was longer, on average, than the total daily flight time of the short-haul crews who flew up to

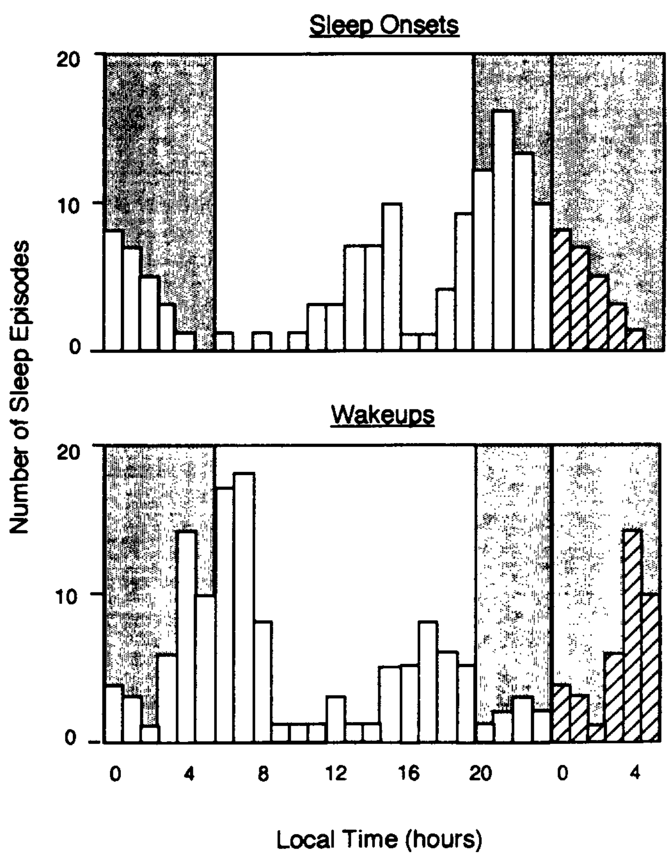

Fig. 5. Distributions of layover sleep onsets and wakeups with respect to local time. Shading indicates approximate times of local night. The first 6 h of data are repeated (cross-hatched columns), to emphasize the cyclic nature of the pattern.

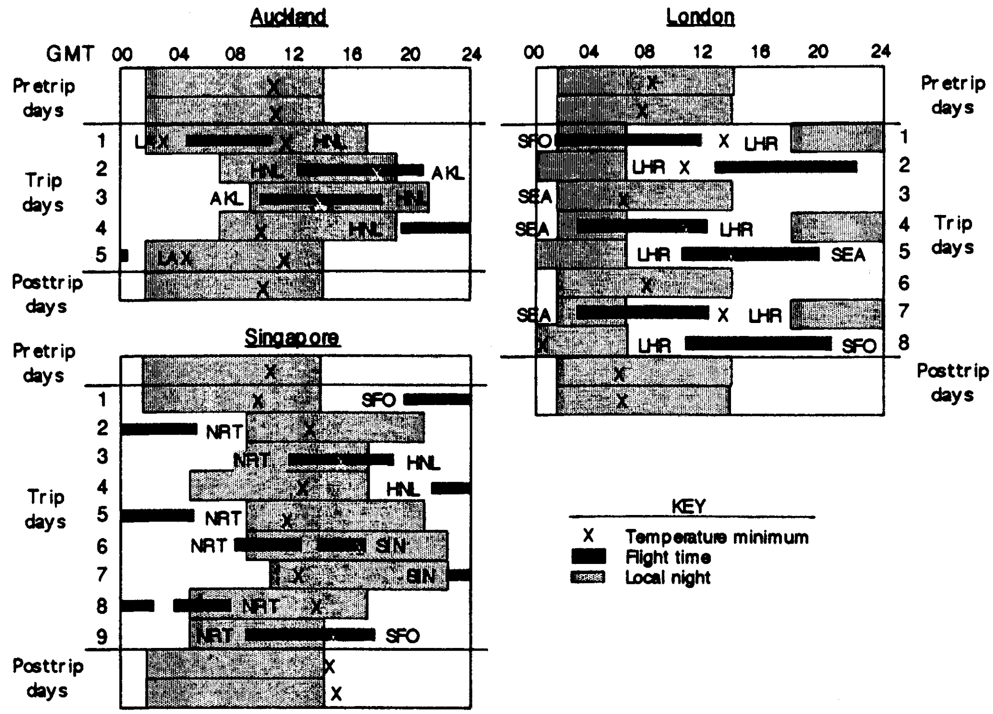

Fig. 6. Average times of the unmasked daily temperature minima on the Auckland trip pattern (average of three subjects per day), the London trip pattern (average of four subjects per day), and the Singapore trip pattern (average of six subjects per day).

8 segments per day. Long-haul layovers were twice as long. Long-haul operations also included both daytime and nighttime flying, and crossed up to 8 time zones per 24 h, whereas the short-haul operations included primarily daytime flying and crossed no more than one time zone per 24 h.

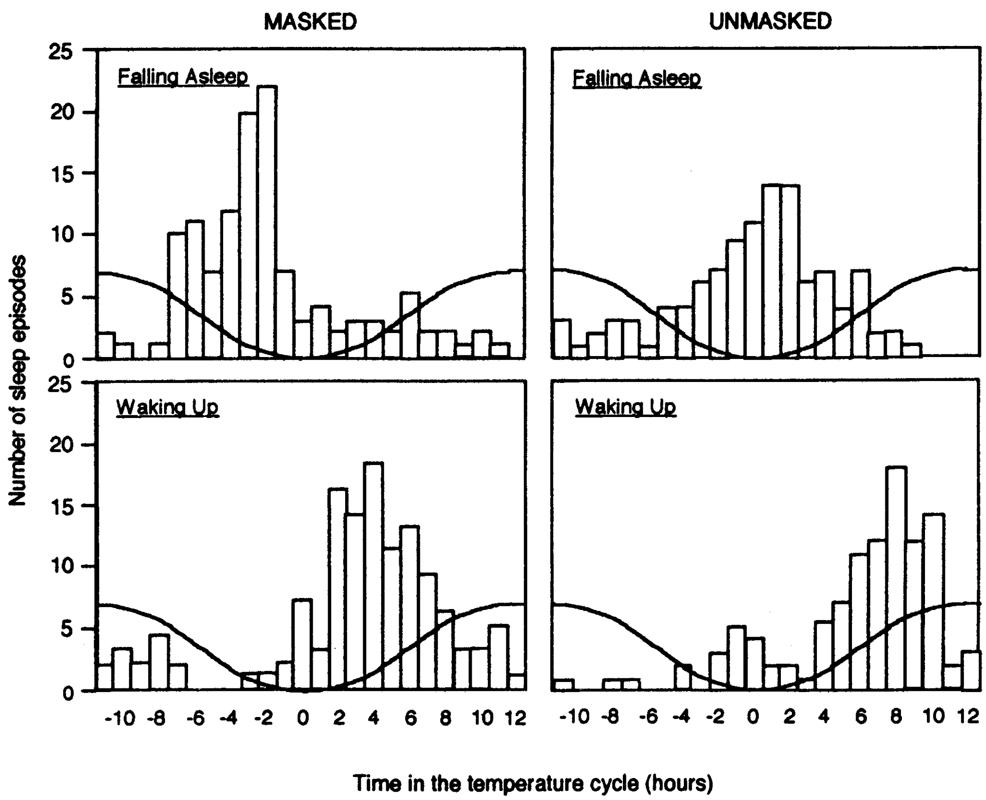

Fig. 7. Distributions of layover sleep onsets and wakeups plotted with respect to the temperature rhythm (shown schematically), for both masked and unmasked estimates. The temperature minimum has been designated circadian time zero.

TABLE VI. TIME-OF-DAY VARIATION IN PRETRIP FATIGUE AND MOOD RATINGS.

	Mean, 0800–1200 Hours	Mean, 1200–1600 Hours	Mean, 1600–2000 Hours	Mean, 2000–2400 Hours	F
Fatigue	31.12	32.84	41.65	55.28	12.60***
Positive affect	2.45	2.41	2.55	2.40	0.67
Negative affect	0.53	0.52	0.59	0.88	6.49***
Activation	2.51	2.60	2.20	1.61	25.70***

Note: times are GMT hours.

Table X compares (by 2-group *t*-tests) demographic and personality measures for the two groups of crewmembers. This information came from the Background Questionnaires. The 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; other.

The long-haul crewmembers were older, more experienced, and more morning-type than their short-haul counterparts. There were no significant differences between the groups in their height or weight, or in their scores on the personality inventories.

The average daily percentage sleep loss (including all sleeps and naps) was not significantly different during the two types of operations (2-group *t*-test; $t = 0.98$, $p = 0.33$). However, this statistic oversimplifies the sleep changes resulting from duty demands, in that it does not take into account sleep quality or whether the total is obtained in one or several episodes. Considering sleep loss per 24 h is also somewhat misleading in the long-haul operations, because of the non-24 h duty/rest schedule. **Fig. 8** compares the percentages of crewmembers reporting multiple sleep episodes (including naps) on pretrip, trip, and posttrip days, for different flight operations. During trips, long-haul crewmembers slept more than once in a third of all 24 h periods. However, as noted above, they slept twice in about two-thirds of all layovers (68%). This is markedly higher than the incidence of split sleep among the short-haul crews. **Fig. 9** examines the number of hours of sleep per 24 h which came from sleep episodes other than the longest. As expected, long-haul crews had more total sleep per 24 h coming from secondary sleep episodes.

Table XI compares the incidences of the three most common symptoms reported in the different types of operations. The helicopter cockpits were physically stressful, with high levels of vibration, poor ventilation, and high thermal loadings on crewmembers who often wore cold-water immersion suits (11).

The high incidence of back pain among long-haul crews, relative to the short-haul fixed-wing crews, could be due to the long flight segments requiring them to remain in their cockpit seats for much longer periods of time.

The responses of 32 long-haul crewmembers and 31 short-haul crewmembers over 40 yr of age were also compared (by 2-group *t*-tests) on questions from the Background Questionnaire concerning: general health; gastrointestinal problems, appetite, and diet on trips by comparison with home; time taken to return to normal after a trip; and the incidence and severity of fatigue effects on performance (14). Even with this age restriction, the long-haul crewmembers were significantly older (52.5 yr vs. 47.1 yr, 2-group *t*-test, $t = 4.83$, $p < 0.0001$). The only significant difference between the responses of the groups was that long-haul crewmembers reported taking longer to return to normal after a trip (3.2 d vs. 1.9 d, $t = 8.20$, $p < 0.0001$). There was also tendency for long-haul crewmembers to report that fatigue affected their performance more often during a trip than short-haul crewmembers. On a scale from 1 (never) to 5 (frequently), the average score for long-haul crewmembers was 3.17, vs. 2.71 for short-haul crewmembers ($t = 1.81$, $p = 0.08$).

DISCUSSION

The physiological challenges for long-haul crews are exceptionally complex. During the operations studied, the duty/rest cycle forced the sleep/wake cycle to a non-24 h pattern to which the circadian clock could not synchronize. Duty days were associated with long periods of wakefulness (average 20.6 h) while layovers, which averaged 24.8 h, usually included several sleep episodes and shorter periods of wakefulness. Individual sleep episodes during layovers averaged only 5 h 20 min, which was 105 min shorter than sleep episodes on pretrip nights. Comparing the total sleep per 24 h (including naps) on trip days vs. pretrip days, across the four trip patterns studied, 43% of crewmembers averaged more than 1 h of sleep loss on trip days, and 21% averaged more than 2 h of sleep loss. In the laboratory, these levels

TABLE VII. DAILY CONSUMPTION OF CAFFEINE, MEALS AND SNACKS BEFORE, DURING, AND AFTER TRIPS (MEAN, SD).

	Pretrip	Trip	Posttrip	F
Cups of caffeine	1.87 (1.83)	3.14 (1.58)	2.04 (1.88)	9.76***
Number of meals	2.44 (0.57)	2.12 (0.37)	2.28 (0.50)	3.58*
Number of snacks	0.87 (0.80)	1.56 (0.78)	0.67 (0.61)	19.39***

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

TABLE VIII. FREQUENCY OF REPORTS OF COMMON MEDICAL SYMPTOMS ON PRETRIP, TRIP, AND POSTTRIP DAYS.

Symptom	% Pretrip	% Trip	% Posttrip
Headache	19	52	30
Congested nose	5	86	10
Back pain	11	83	6

TABLE IX. COMPARISON OF DUTY CHARACTERISTICS, LONG-HAUL VS. SHORT-HAUL OPERATIONS.

	Mean (SD) Long-Haul	Mean (SD) Short-Haul	t
Duty duration (h)	10.22 (2.06)	10.66 (2.41)	1.76
Layover duration (h)	24.25 (3.96)	12.52 (2.52)	28.83***
Flight hours/day	6.88 (2.62)	4.50 (1.39)	11.25***
Flight segments/day	1.15 (0.36)	5.12 (1.34)	34.15***
Flight hours/month	69.20 (9.13)	70.21 (9.92)	0.41

*** $p < 0.001$.

of sleep loss produce cumulative reductions in alertness and poorer performance (5,30). On the other hand, 14% of crewmembers reported sleeping more on trips than prettrip. Looking at the total sleep per 24 h probably underestimates the potential impact of sleep loss on cockpit alertness and performance in these operations for three reasons. First, it ignores the fact that crewmembers did not obtain the same amount of sleep in each 24 h period. By the end of a duty day, they often had a large acute sleep debt, particularly after a night flight. However, in the subsequent layover, they tended to sleep more than during a normal 24 h period at home, thereby reducing their average sleep loss per 24 h. Second, it overlooks the cumulative effects of sleep loss across the entire 4–9 d trip. Third, it does not take into account the fact that layover sleep was often split into several short episodes, and was not always during local night or in the preferred part of the circadian cycle, which could have affected its duration and quality (8,9,37,42).

Greater sleep loss was associated with night flights. This was not due to a difference in how long crewmembers remained awake in association with eastbound overnight flights vs. westbound daytime flights. However, it may have been related to greater sleep disruption after eastward overnight flights. Polygraphic recordings of the sleep of long-haul flight crews during the first layover of scheduled international trips indicated that it was more disturbed after eastward night flights crossing 8 time zones than after daytime westward flights crossing 8–9

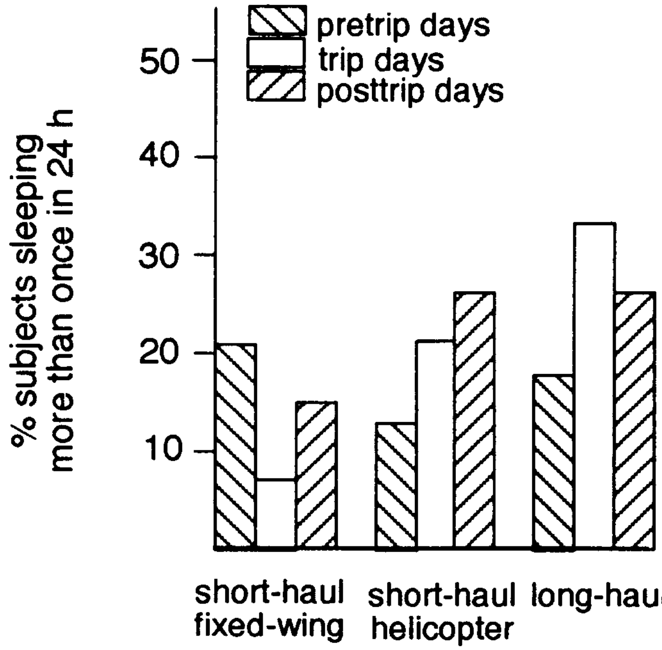

Fig. 8. Comparisons among different operations of the percentages of crewmembers sleeping more than once per 24 h.

time zones (20). In the NASA field study of cockpit naps as a fatigue countermeasure in long-haul operations (29), crewmembers reported feeling more fatigued during eastward night flights than during westward daytime flights. Those who were allowed to nap also experienced deeper sleep (confirmed polygraphically) during night flights than during daytime flights.

When asked about their layover strategies, most crewmembers indicated that they tried to adapt to local time, but considered that they were only moderately successful. It is not surprising that few tried to remain on home time, since this strategy would be incompatible with a 35 h duty-rest pattern. There was a clear preference for sleeping during the local night, with a secondary preferred sleep time in the local afternoon. The majority of

TABLE X. COMPARISON OF CREWMEMBER CHARACTERISTICS, LONG-HAUL VS. SHORT-HAUL OPERATIONS.

	Mean (SD) Long-Haul	Short-Haul	t
Age (yr)	52.68 (4.96)	43.02 (7.65)	5.66***
Experience (y)	22.80 (7.58)	17.07 (6.56)	3.29**
Height (in)	71.00 (2.15)	70.59 (1.86)	0.87
Weight (lb)	181.6 (17.10)	174.84 (2.15)	1.70
Eysenck Personality Inventory (ref. 23)			
Neuroticism	6.63 (3.68)	6.58 (4.51)	0.04
Extraversion	9.44 (4.33)	10.91 (3.46)	1.52
Morning/Eveningness Questionnaire (ref. 24)	67.70 (8.37)	63.41 (9.47)	2.06*
Personal Attributes Questionnaire (ref. 25)			
Instrumentality	22.76 (4.69)	23.27 (3.94)	0.52
Expressiveness	22.09 (3.84)	22.34 (4.40)	0.27
i + e	2.74 (1.19)	2.84 (1.01)	0.42
Work and Family Orientation Questionnaire (ref. 26)			
Mastery	20.67 (4.04)	19.95 (4.10)	0.76
Competitiveness	13.61 (2.94)	12.57 (3.49)	1.38
Work	17.48 (2.25)	17.66 (2.09)	0.35

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

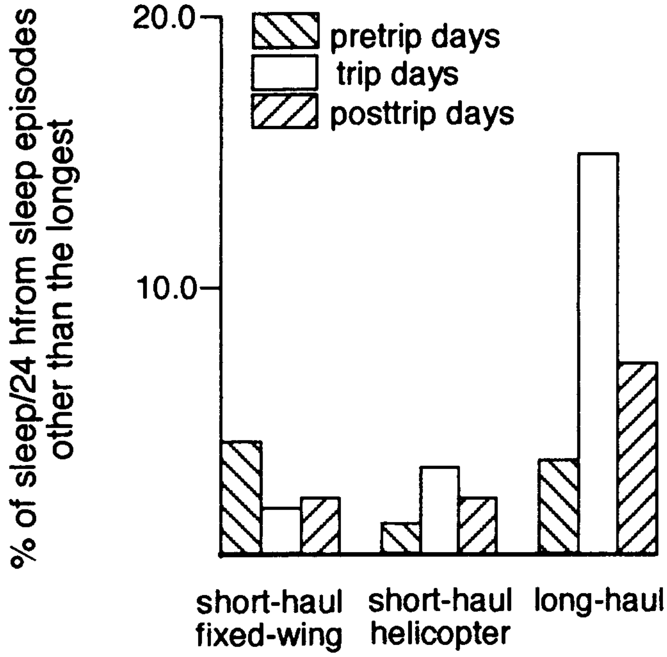

Fig. 9. Comparisons among different operations of the amount of daily sleep accrued from sleep episodes other than the longest.

the afternoon sleep episodes followed eastward night flights crossing four or more time zones. The average off-duty time after these flights was about 1100 hours local time. Two-thirds of crewmembers went to sleep for several hours in the afternoon, and then slept again later in the local night. In contrast, after westward flights crossed four or more time zones, the first sleep episode in the layover was the longest for 80% of crewmembers, and it tended to coincide with local night. The average off-duty time after these flights was around 1400 hours local time.

Crewmembers were most likely to fall asleep around the time of the temperature minimum and to wake up while temperature was rising. Two types of sleep episodes could be identified which were not consistently linked to the preferred part of the circadian cycle. The afternoon sleep episodes after eastward night flights crossing four or more time zones were broadly distributed in the circadian cycle (12), which suggests that they were primarily a response to sleep loss rather than to circadian physiology. In westward flights crossing four or more time zones, 50% of crewmembers took a shorter second sleep toward the end of the layover. Most (85%) of the sleep episodes which ended as temperature was falling (Fig. 7) are of this type. In these cases, it seems likely that crewmembers woke up because of the imminent duty report time, rather than in response to the circadian wakeup signal, which normally occurs about 6 h after the temperature minimum (15,37).

For at least 2 nights after the trip, crewmembers continued to have shorter individual sleep episodes than pretrip (average 65 min less). However, they often slept more than once per 24 h, so that their total sleep duration regained pretrip levels. This continued disruption of the normal pattern of consolidated sleep at night presumably reflects the readaptation of the circadian clock to the home time zone. Long-haul crewmembers reported taking longer to return to normal after a trip than did their daytime short-haul counterparts.

The finding that the temperature rhythm was unable to synchronize to the rapid sequences of time zone changes and non-24 h duty-rest cycles in these operations confirms similar findings for flight crews on polar route schedules between Europe and Japan (32,35,36). As a consequence, the circadian temperature minimum, and hence the low point in alertness and performance (1,10,23,26,30), sometimes occurred in flight (Fig. 6). At the same time, the majority of crewmembers were operating with a sleep debt. In the laboratory, working through the time of the circadian low point with a sleep debt results in lowest alertness and greatest vulnerability to performance errors (10).

From the daily logbooks, and from the cockpit observers' notes, it was ascertained that the crewmembers in this study were asleep in their cockpit seats 11% of the available time (21), in spite of the fact that this is not currently sanctioned by the FAA. High levels of sleepiness on the flightdeck were confirmed polygraphically for three-person long-haul crews on scheduled trans-Pacific flights, in the field test of cockpit napping as a fatigue countermeasure (29). When crewmembers were given a preplanned 40-min opportunity to nap in their cockpit seats, they fell asleep on 93% of the available occasions. They fell asleep quickly (average 5.6 min), which is close to the threshold (5 min) considered to indicate pathological sleepiness in clinical situations. The study also included a control group of crewmembers who were instructed not to nap. On five occasions crewmembers in this group also fell asleep, despite being monitored polygraphically for sleep and having two NASA observers in the cockpit. The high level of sleepiness of the no-rest group was confirmed by the fact that they had five times as many in-flight EEG microevents and poorer probed performance. Of these microevents, which signal transient disengagement from the environment, 22 occurred among no-rest crewmembers during descent into the destination airport.

In the present study, crewmembers rated their subjective fatigue as higher, and their activation as lower, on duty days than on pretrip days. They perceived that fa-

TABLE XI. PERCENTAGE OF CREWMEMBERS REPORTING THE THREE MOST COMMON MEDICAL SYMPTOMS IN DIFFERENT FLIGHT OPERATIONS.

	1st Symptom	2nd Symptom	3rd Symptom
Long-Haul	Headache (56%)	Congested nose (28%)	Back pain (20%)
Short-Haul Fixed-Wing	Headache (27%)	Congested nose (20%)	Back pain (11%)
Short-Haul Helicopter	Headache (73%)	Back pain (32%)	Burning eyes (18%)

tigue had some effect on their performance, with an average rating of 3.4 on a scale from 1 (none) to 5 (very much). They also indicated that, on a typical trip, fatigue sometimes affected their performance, with an average rating of 3.2 on a scale from 1 (never) to 5 (frequently). On trips, they consumed more caffeine and snacks, and fewer meals per 24 h than at home pretrip. The availability of meals at unusual local times is a common problem for long-haul crewmembers, whose duty schedules and hunger patterns do not necessarily coincide with local meal times. The incidence of headaches (reported by 56% of crewmembers during the study) tripled on trip days by comparison with pretrip. The incidence of congested nose (reported by 28% of crewmembers) increased 17-fold, while the incidence of back pain (reported by 20% of crewmembers) increased 7.5-fold.

Comparing these operations with the daytime fixed-wing short-haul operations examined in the first NASA fatigue field study (13,16), the long-haul crews worked duty days of comparable length, but with fewer flights and more flight hours than their short-haul counterparts. Long-haul crews crossed up to eight time zones in a duty day, whereas short-haul crews crossed no more than one. The long-haul crewmembers were older (by an average of 9.7 yr), more experienced (by an average of 5.7 yr), and were more morning-type than their short-haul counterparts. This is consistent with the trend for people to become more morning-type as they get older (19). A number of studies have suggested that morning-types have more difficulty adapting to shift work and time zone changes than evening types (19). One study of commercial long-haul flight crewmembers (34) found that morning types showed higher levels of daytime sleepiness than evening types, after operating an eastward flight crossing eight time zones. Thus, the common practice of promoting crews from short-haul to long-haul operations as they become more senior results in people flying more physiologically challenging operations when normal aging processes dictate that they may be less able to cope with those challenges.

Long-haul layovers were twice as long as short-haul layovers. Both groups lost a comparable amount of sleep per 24 on trips with respect to pretrip. However, this comparison is somewhat misleading because of the non-24 h sleep/wake patterns of the long-haul crews, and the fact that they often slept more than once during layovers averaging 24.8 h. On trips, long-haul crewmembers gained 7.5 times more sleep per 24 h from secondary sleep episodes than did their short-haul counterparts. They also reported higher fatigue and lower activation on duty days by comparison with pretrip days. Comparable changes were not reported by the short-haul crewmembers after allowing for the time-of-day variation in these measures (13,16). Long-haul crewmembers reported headaches and back pain twice as often as their short-haul counterparts. Both groups consumed more caffeine and snacks on trips. However, only the long-haul crewmembers reported eating fewer meals per 24 h on trips by comparison with pretrip. Long-haul crews also reported taking a day longer to return to normal after a trip.

In summary, this study confirms that crewmembers on a variety of three-person long-haul trip patterns lost sleep at a rate expected to have cumulative effects on sleepiness and performance. Because the circadian clock did not synchronize to the duty/rest cycle, the circadian low point in alertness and performance sometimes occurred in flight. On these occasions, long-haul crews were working when sleep loss and circadian factors combined to produce the greatest vulnerability to performance errors. The present study suggests a number of ways in which these problems could be addressed.

With regard to the issue of cockpit alertness, the only countermeasure which addresses the underlying physiological sleepiness is sleep. The cockpit napping study already alluded to (29) clearly demonstrated improvements in performance (on a sustained attention, vigilance-reaction time test) and physiological alertness after crewmembers were allowed a preplanned 40-min nap opportunity in their cockpit seats. There is currently an FAA Notice of Proposed Rule Making to make cockpit napping legal in three-person long-haul operations. Careful consideration needs to be given to how cockpit napping might be safely implemented in two-person long-haul crews.

Until such time as supersonic travel enables crews to return to their home time zone each night, long-haul operations will involve crewmembers being in different time zones on consecutive layovers. It is not clear that circadian readaptation to a new time zone every 35 h is possible, practical, or desirable. One alternative is to design duty/rest schedules that are multiples of 24 h so that crewmembers can try to remain on home time throughout a trip pattern. If successful, this strategy would make times of peak sleepiness more predictable and facilitate layover sleep planning. It would eliminate the internal desynchronization between different physiological systems which is characteristic of jet-lag. By synchronizing the whole crew to the same time zone, it would reduce inter-individual variability, making it easier to design schedules meeting the physiological requirements of a larger proportion of crewmembers. While theoretically attractive, there are many practical considerations which may limit the feasibility of this approach. It would require dark, quiet sleeping accommodation and availability of meals at unusual local times in layover hotels. It would be facilitated if crewmembers minimized their exposure to local time cues during layovers (for example wearing dark glasses when exposed to sunlight and not adapting to the local social routine). Crewmember acceptance of such structuring of their layover activities would be a major issue. This approach would appear to be more feasible in military operations where larger groups of people are working on the same schedule.

The quantity and quality of sleep that crewmembers are able to obtain during layovers depends on a variety of environmental and physiological factors, including prior flight direction, the local day/night cycle and social routine, the circadian cycle, the duration of prior wakefulness (3), and age (19). This complexity, and individual variability, preclude simple universal solutions to the problem of sleep loss during long-haul operations. One useful approach to these issues is to provide crewmembers, schedulers, and regulators with education about sleep and circadian physiology together with practical information on countermeasures which they can tailor to their own needs and specific operational demands (28).

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