



AIRCREWFATIGUEINLONG-HAULOPERATIONS

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Abstract—The studies were conducted on the transmeridian routes Dusseldorf (DUS)–Atlanta (ATL) and Hamburg (HAM)–Los Angeles (LAX), and on the north-south route Frankfurt (FRA)–Mahe (SEZ). Scheduled flight duration was between 8:50 hours (ATL–DUS) and 11:50 hours (HAM–LAX). In total, 25 rotations (50 flights) have been investigated by pre-, in- and post-flight data collection of sleep, taskload, fatigue and stress by electroencephalogram and electrocardiogram measurements and subjective ratings. Inflight ratings of taskload showed low perceived exertion during the Atlantic flights, and were moderate during the north-south transitions. Fatigue ratings increased with progressing flight duration. Towards the end of long U.S.-westcoast flights performed at day-time, and in all night flights, fatigue was elevated compared to the 'baseline' ratings collected during the day-time DUS–ATL flights. Fatigue was rated as being 'critical' by several pilots, particularly during the return flight SEZ–FRA when fatigue was severely pronounced. From the findings it is concluded that duty schedules, as performed on the route HAM–LAX (because of long duty hours), and particularly on the route FRA–SEZ (because of consecutive night work), may place excessive demands on mental and physiological capacity. With respect to legal aspects, the results are significant and should promote further deliberations for advanced schemes of flight duty time limitations and rest requirements. © 1997 Elsevier Science Ltd.

Keywords—Aircrew, Long-haul flight, Fatigue, Taskload, Flight duty times

INTRODUCTION

Growth in the global aviation industry and the increasing range of air operations on international long-haul routes have raised serious concerns about maintaining flight safety. At present, whether the legal standards of flight duty regulations currently in force are still adequate for modern aircraft, is a matter of intense discussions between authorities and operator and pilot associations in the U.S.A., in Japan and in Europe. Flight time limitations and rest requirements have been extensively discussed during the Joint Aviation Authorities (JAA) endeavors for the harmonization of regulations among the member states of the European Union. Particularly, flight duty times of minimum two-pilot crew operations on long-haul routes are a focus of argumentation. Agreement has not yet been achieved between aircarriers, pilot associations and aviation authorities. It was concluded that aeromedical/scientific research is needed before the final decisions are taken concerning the flight duty times of two-pilot crews (Williams, 1992).

Currently, all new-generation passenger aircrafts are designed for two-pilot crews. While many short-haul aircraft have been flying for years under this configuration, there has been little experience in long-

haul flights. The A 340, B 747-400, B 777, B 767-300, and the MD11 are designed for ranges extending beyond 14 hours flight time. As required by current legislation in many countries (Wegmann et al., 1983a), most carriers will assign at least one extra crew member to such flights, since in most countries flight duty times that extend beyond 14 hours are not permitted to be performed by only the minimum required crew of two. There are world-wide discussions about what the actual differences between three- and two-crew cockpits are, particularly with respect to workload and fatigue of the operating crew. With the increase in automation of flight systems in a modern (glass-) cockpit and with a reduction of the crew complement, the working conditions of the pilots change substantially. The reduction of cockpit personnel requires sustained presence at the controls leading to increased physical inactivity. The monotonous work in the glass cockpit affects the ability to maintain a high level of vigilance and alertness over many duty hours. Among the international aviation authorities there is considerable uncertainty whether new regulatory limitations for two-crew operations are really needed and if so, what standards and norms are to be applied.

In view of this uncertainty, and because investigations concerning fatigue and workload of the two-

pilot crew have not been conducted, the DLR-Institute of Aerospace Medicine established a research programme in two-pilot crew operations with studies on different long-haul routes. The initialization of this programme was supported by the German Ministry of Transport (BMV). Later on, the JAA also became interested. Within this programme, three transmeridian routes and one trans-equatorial route were studied (Table 1) and are the subject of this report. All flights were performed with the aircraft type B 767-300. All flights were regularly scheduled for charter passenger transports, that is, line flying. They were conducted by two different German charter air carriers.

In 1991, the first study phase was started on the Dusseldorf (DUS)-Atlanta (ATL) route. The same cockpit crew performed both the outgoing and return flights. With flight duty times of about 11 hours (DUS-ATL) and 10 hours (ATL-DUS) and a layover of >48 hours, this rotation was considered to be 'normal' and safe with respect to long-haul operations for either a two- or three-pilot crew. The data derived from this first study phase were intended to serve as baseline data for the following investigations.

The second study phase was conducted on the routes Hamburg (HAM)-Los Angeles (LAX) and Frankfurt (FRA)-LAX/San Francisco (SFO). Flight duty times of these routes are extremely long, almost reaching the upper limits currently defined by German and JAA standards for day and night flights (2.DVOLuftBO, 1987; JAA, 1994). For the outgoing (westbound) sectors, taking place during daytime, flight times are more than 11 hours and 45 minutes, and the corresponding flight duty period (FDP) is close to 14 hours (FDP is calculated by flight time plus one and a half hours for pre- and post-flight activities). The homegoing eastbound flights are 45 minutes shorter. However, they are conducted during night hours (Table 1). During these transatlantic rotations, layover times are longer than 2 days. Thus, sufficient time is available for recuperation. However, the adverse effects of the time-zone change

on circadian rhythms and sleep must be taken into account. The U.S.-westcoast rotations differed from each other, depending on the airline. The rotation FRA-LAX/SFO were conducted by shuttle flights, that is, the same crew operated the aircraft on the outbound as well as the homebound flight (with a layover in LAX/SFO lasting 4.5 days and a dead-head flight LAX-SFO on the second layover day). The flights HAM-LAX and return were performed in the following way. Crew members had either to conduct the outbound flight HAM-LAX, then dead-headed to the U.S.-eastcoast (Miami, Atlanta) and performed the homegoing flight duty from that destination to Germany (duration of the entire rotation: 5 days); or crew members were scheduled vice versa with an additional flight rotation between Atlanta and San Jose/Costa Rica (the duration of the rotation was 8 days). In both cases, inflight investigations were only performed during the HAM-LAX or LAX-HAM flights, but whenever possible with the same crew members.

The third study phase was conducted on the route FRA-Mahe (SEZ) and was supported by the European Union (EU), Directorate-General of Transport. The same cockpit crew performed both the outgoing and the return flight. The duty roster as scheduled for the flight crew on this route is characterized by operational demands that were considered critical because the rotation involved two night flights, in contrast to only one during the North Atlantic flights. Additionally, the flights were operated during two consecutive nights, separated by only a short rest period in SEZ. This rest period came close to the required minimum of 12 hours [according to German regulations; 2.DVOLuftBO (1987)]. The data of this third study were analyzed before the data from study phases I and II, and results were reported to the EU-Commission (Samel et al., 1993).

This report presents the most important data and conclusions of all three study phases. The measures reported here assessed sleep, taskload and fatigue. Detailed descriptions, analyses and supple-

Table 1. Overview of flight schedules of DLR-investigations (times in GMT and LT)

Route	Flight leg	Departure			Arrival			Blocktime	
		Date	GMT	LT	Date	GMT	LT		
DUS-ATL	DUS-ATL	Mo	06:15	08:15	Mo	16:05	12:05	09:50	Dayflight
	ATL-DUS	Th	04:05	00:05	Th	12:55	14:55	08:50	Nightflight
HAM-LAX	HAM-LAX	Fr	11:30	13:30	Fr	23:15	16:15	11:45	Dayflight
	LAX-HAM	Fr/Sa	01:00	18:00	Sa	12:00	14:00	11:00	Nightflight
FRA-LAX	FRA-LAX	Th	07:10	09:10	Th	19:00	12:00	11:50	Dayflight
	SFO-FRA	Mo	20:50	13:50	Tu	07:55	09:55	11:05	Nightflight
FRA-SEZ	FRI-SEZ	Sa	20:45	21:45	Su	06:10	09:10	09:25	Nightflight
	SEZ-FRA	Su	19:30	22:30	Mo	06:00	07:00	10:30	Nightflight

mental results on specific routes were presented in Samel (1993); Samel et al. (1993, 1995).

METHODS

Fifty male pilots (25 captains and 25 flight officers) volunteered to participate in the three study phases. All of them had > 2 years of experience on the aircraft B 767-300. The average age was 35.0 years ($SD=8.4$ years), ranging from 25 to 56 years.

Physiological measurements

Electroencephalogram (EEG), electrooculogram (EOG), and electrocardiogram (ECG) were continuously recorded during flight, using an 8-channel recorder (Gundel et al., 1993; Samel et al., 1993). The EEG and EOG recordings obtained under waking conditions provided information about sleepiness. The EEG and EOG electrodes were attached according to the international 10-20 system (Rechtschaffen and Kales, 1968) by means of a stretchable band (Gundel et al., 1993; Samel, 1993) with integrated C3-, C4-, O2-, ROC- and LOC-electrodes, so that electrodes did not need to be affixed one by one in a time-consuming procedure. The band was affixed in the cockpit within 15 minutes of take-off and did not interfere with the operational requirements. At the A1- and A2-positions, baby-ECG electrodes were attached.

If operational demands did not prohibit, pilot and flight officer took staggered rest periods of 90 seconds at 1-hour intervals during flight and after landing. They were asked to sit in a comfortable, relaxed position and to close their eyes while remaining awake. These periods were called 'pre-planned rest' and served as control recordings.

From the set of electrodes, five channels, C4-A1, C3-A2, O2-A1 (EEG-signals), ROC-A1 and LOC-A2 (EOG-signals), were recorded and digitized (256 Hz per channel). EEG and EOG recordings were analyzed in two different approaches. The first only considered the controlled and pre-planned rest phases (and is not subject of this report); the second considered recordings obtained during the entire flight.

The digitized signals were scanned for the occurrence of alpha-waves (electrical signals in the frequency band between 8 and 12 Hz) and, in particular, for increasing alpha-activity during nonresting phases, that is, for micro-sleeps (Akerstedt, 1992; Torsvall et al., 1989). In a first step, a bandpass filter removed all frequencies not between 2 and 33 Hz. The filtered signal was subjected to spectral analysis in 8-second segments. For each segment, the resulting power spectrum was calculated within 4-Hz intervals

between 0 and 16 Hz. For the discrimination of alpha frequencies from background noise and artefacts, the ratio of alpha-band power to the power in the frequency band between 12 and 16 Hz was computed. If it exceeded a defined threshold, an 8-second segment was interpreted as a micro-sleep. The number of micro-sleeps were averaged in consecutive 1-hour intervals for all flights and pilots.

ECG recordings were included in the electrophysiological investigations to obtain information on workload and circadian variations. ECG recordings started prior to embarking the aircraft. ECG was recorded continuously during pre-flight preparations and during flight until the end after landing. Simultaneously with EEG and EOG, ECG recordings were digitized at a rate of 256 Hz. A QRS-detection algorithm was used for the detection of R-waves and the calculation of peak-to-peak intervals (Pan and Tompkins, 1985). These RR-intervals were used to calculate the mean heart rate and the spectral distribution of heart rate variability.

Subjective measurements

A general questionnaire was developed for the assessment of stress related factors. Questions regarding the actual duty roster were combined with questions covering more general issues. A daily log was used to assess sleep duration, sleep distribution over 24-hour periods and sleep quality (Samel et al., 1991, 1993; Wegmann et al., 1986). For each sleep period, the crew members had to respond to questions concerning beginning and end of sleep, occurrence of awakenings and sleep quality. They were asked to start filling out the daily log at least 3 days before commencing the rotation and to continue the recordings at least 3 days after return to home base. The data of the days preceding each rotation were used as baseline data. Data from the subsequent days were expressed as changes from these baseline data.

Two different questionnaires were used for assessing psychophysiological factors and actual perceived taskload during flight. The first one consisted of a checklist reflecting subjective feelings of fatigue (Samel and Wegmann, 1989; Samel et al., 1993; Samn and Pirelli, 1982; Storm and Merrifield, 1980), and two analog scales regarding tenseness and alertness. This questionnaire form had to be filled in ca 1 hour before each flight, at 1-hour intervals during flight, and immediately after landing (at the park position). Fatigue was rated using a scale that ranged from 0 (very alert) to 20 (exhausted). Ranges of fatigue ratings are related to performance levels (Samn and Pirelli, 1982) as follows. As long as the fatigue ratings remain below 8, pilots are sufficiently alert and

performance decrement should not occur; ratings between 9 and 12 imply mild fatigue and performance impairment is possible but should not be significant; ratings between 12 and 16 reflect moderate to severe fatigue and significant performance decrements are possible-flying duty is still permissible, but not recommended; and beyond 16, ratings indicate severe fatigue, performance definitely should be impaired and flight duty is no longer recommended. The relation between aircrew fatigue ratings and performance was validated in investigations on military aircrews in field and simulation experiments (Samn and Firelli, 1982; Storm and Merrifield, 1980). The procedure was also successfully utilized in studies on civil airline operations (Samel and Wegmann, 1989; Wegmann et al., 1986).

A second questionnaire, the NASA-Task Load Index (NASA-TLX) was given during flight jointly with the fatigue checklist. It consists of six scales used to assess the dimensions 'mental demand', 'physical demand', 'temporal demand', 'performance', 'effort', 'frustration level' (Hart and Staveland, 1988). Each scale ranges from 0 to 20. Once during the rotation, pilots had to rank the six dimensions with respect to their significance as a source of workload. Ratings made using each scale were weighted by these ranks (0-5) and added together resulting in a taskload index ranging from 0 to 300 points (where 0 means the lowest and 300 the highest load).

RESULTS

Duty roster

Scheduled and actual flight times (time between block-off at the start position and block-on at the destination) differed to some extent. An overview of the actual flight times are presented in Table 2. Most of the flights could be conducted within the scheduled limits. Delays of >60 minutes occurred at two occasions. Table 2 also shows that FDPs were extremely

long (between 10 and 14 hours, depending on the route). At one occasion (FRA-LAX), the regulatory limit of 14 hours was exceeded by 25 minutes, and the crew operated under the 'captain's discretion'.

General questionnaire

The results concerning the ratings of overall stress caused by the flight duty showed that the outgoing flights were rated less stressful than the return flights. Additionally, the day-time flights were rated less stressful than the night flights. When collapsing across all flight legs, the following rank order was observed: LAX-HAM (highest stress); SEZ-FRA; FRA-SEZ; ATL-DUS; HAM-LAX; and DUS-ATL (lowest stress).

When asked which factors (out of six) contributed most to the stress experienced during the different rotations, pilots ranked night flying to have the highest impact, on average. Duration of flight was ranked as second, on average. In response to the question 'Could you fly longer?', between 28 and 43% of the pilots on each route felt unable after the outgoing, and 43-78% after the return flight.

Sleep-wake cycle

Figures 1 and 2 present an overview of the average sleep and wake periods of the crew members during the ATL- and SEZ-rotation. Flight times and local night time [assumed to be between 23:00 and 07:00 local time (LT)] are also indicated. During the ATL-rotation, scheduled layover periods lasted 2.5 days. For five rotations (10 pilots), the actual roster could be maintained as scheduled (Fig. 1).

Transmeridian rotations. The results regarding transatlantic rotations indicate that normal (i.e. baseline) sleep before the trip lasted between 7 and 8 hours. Depending on the scheduled time of departure from home base, sleep was curtailed by an average of 1.5 hours in the night preceding the first flight (DUS-ATL, FRA-LAX). After arrival at the

Table 2. Actual flight time (block-to-block), flight duty period and delays to scheduled departure time (see Table 1) (in hours:minutes)

Route	Flight leg	Flight time		FDP		Delay Mean
		Mean	SD	Mean	SD	
DUS-ATL	DUS-ATL	10:17	0:14	11:42	0:50	0:34
	ATL-DUS	8:27	0:12	9:58	0:41	0:22*
HAM-LAX	HAM-LAX	11:13	0:09	13:05	0:38	0:41
	LAX-HAM	11:03	0:13	12:29	0:08	0:27
FRA-LAX	FRA-LAX	11:55	0:12	13:54	0:20	0:39
	SFO-FRA	11:21	0:13	12:51	0:23	1:35†
FRA-SEZ	FRA-SEZ	9:32	0:36	10:58	0:17	0:14
	SEZ-FRA	9:53	0:21	11:15	0:22	0:02

*Delay of 24 hours excluded (one flight).

†One delay of 3 hours and 45 minutes included (one flight).

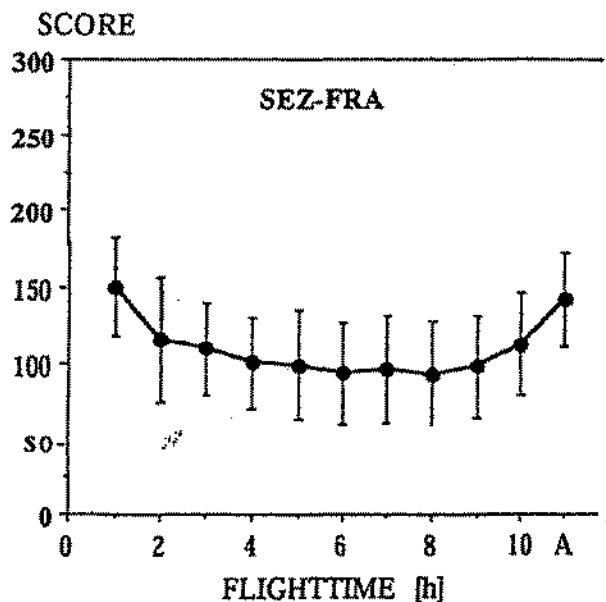
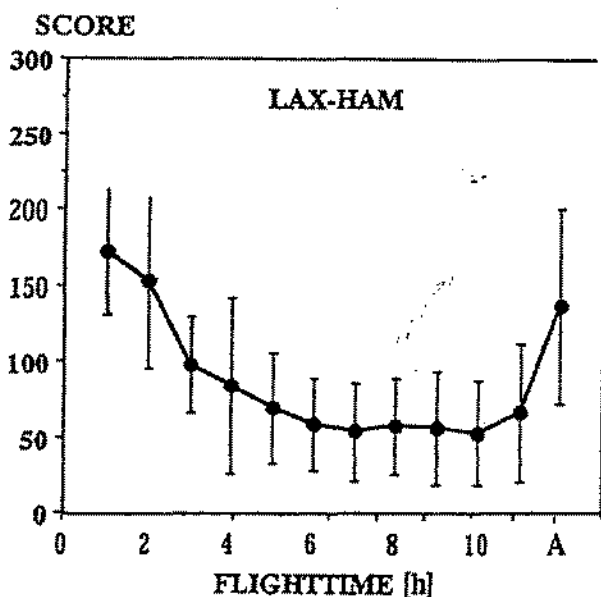
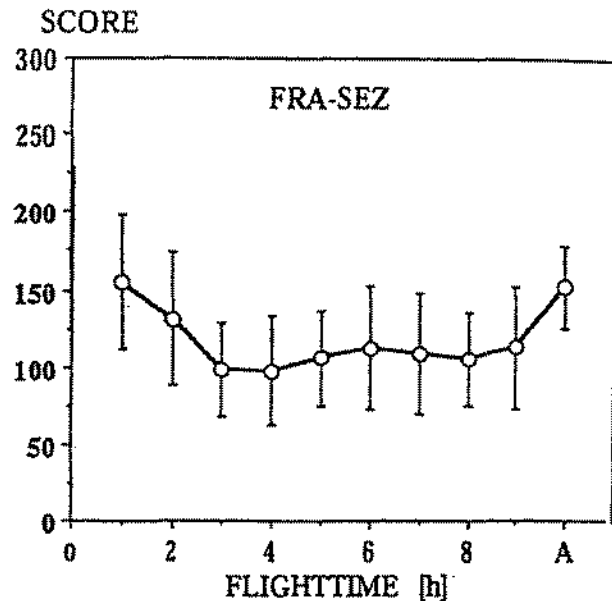
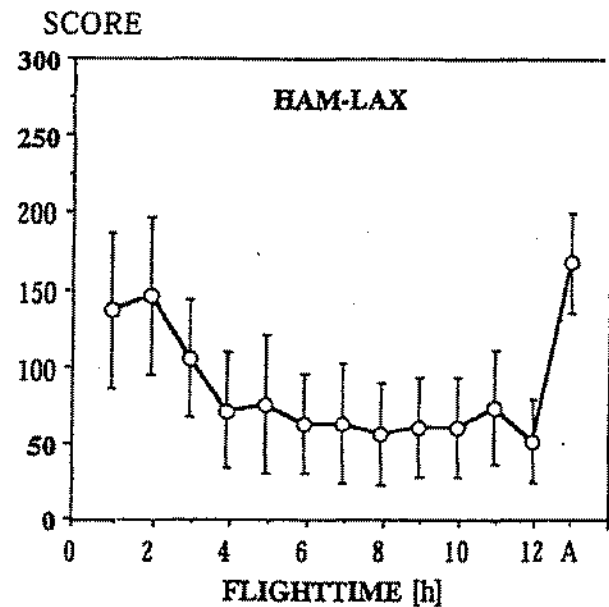


Fig. 4. Average TLX scores during flight HAM-LAX (upper panel) and LAX-HAM (lower panel) (see Fig. 3 for further explanation).

Fig. 5. Average TLX scores during flight FRA-SEZ (upper panel) and SEZ-FRA (lower panel) (see Fig. 3 for further explanation).

(HAM/FRA-LAX: $r=0.91$, $F=43.2$, $p<0.001$; LAX/SFO-HAM/FRA: $r=0.83$, $F=20.5$, $p=0.001$). After 8 hours of flying outbound, ca 8% of the pilots rated their fatigue level as being in the critical region (Fig. 7, upper panel). The maximum of critical ratings (19% of the 16 pilots) appeared after 10 hours of flight, and after landing. On the return flights, critical fatigue ratings started after 3 hours (6%) and increased to 11% after 6 hours of flying. In the interval between 7 and 10 hours on average, 23% of the pilots indicated a critical fatigue level.

Fatigue ratings of the different transmeridian flights were significantly different (one-way ANOVA): DUS-ATL versus ATL-DUS ($p<0.001$; $F=75.0$; d.f. = 1216), HAM-LAX versus LAX-HAM ($p<0.001$; $F=14.2$; d.f. = 1251), DUS-ATL versus LAX-HAM ($p<0.001$; $F=23.1$; d.f. = 1229) and ATL-DUS versus HAM-LAX ($p<0.001$; $F=45.7$; d.f. = 1239). Furthermore, the number of critical fatigue ratings were significantly different between day-time (DUS-ATL: average rate per hour and pilot: 0.0, HAM-LAX: 0.08) and night-time opera-

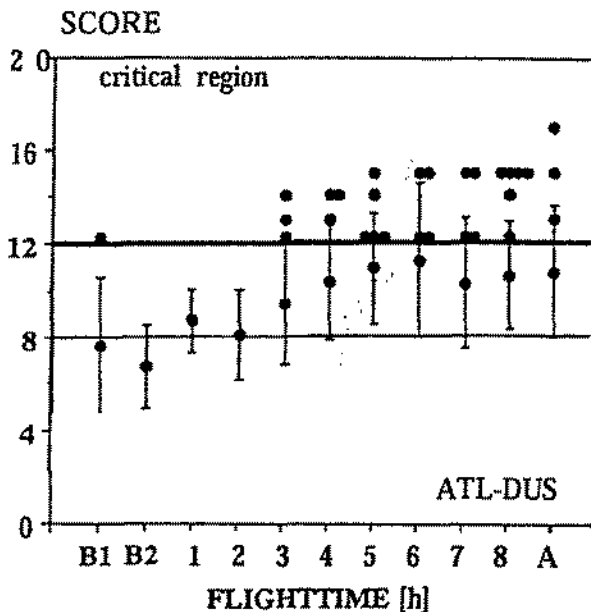
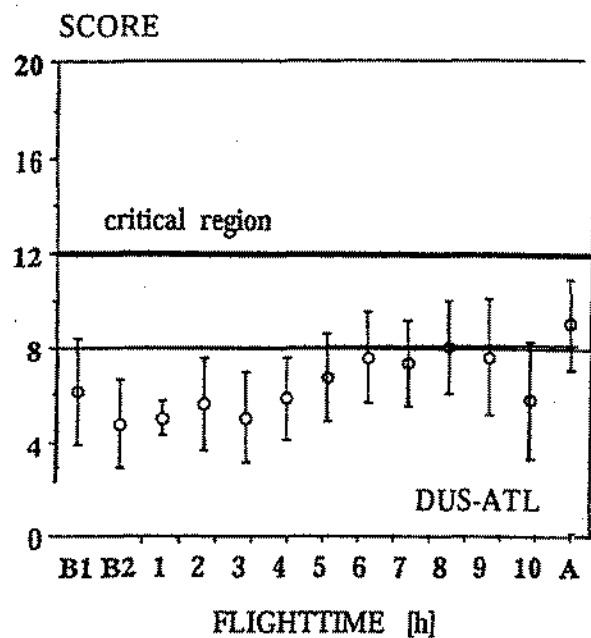


Fig. 6. Average fatigue ratings (means \pm SD) during flight DUS-ATL (upper panel) and ATL-DUS (lower panel). Range of scale is 0 (no fatigue) to 20 (maximum fatigue). B1 and B2 indicate ratings before take-off. Individual scores are indicated when they were at or beyond the critical limit of 12.

tions (ATL-DUS: 0.23, LAX-HAM: 0.19) on transmeridian routes (DUS-ATL: $U=0$; $p<0.001$; $n=8, 8$; HAM-LAX: $U=25$; $p<0.05$; $n=10, 10$; Mann-Whitney U-test).

During the night operations of the SEZ-rotation, subjective fatigue also increased with progressing flight duty (FRA-SEZ: $r=0.96$, $F=89.7$, $p<0.001$; SEZ-FRA: $r=0.89$, $F=35.3$, $p<0.001$). As in the

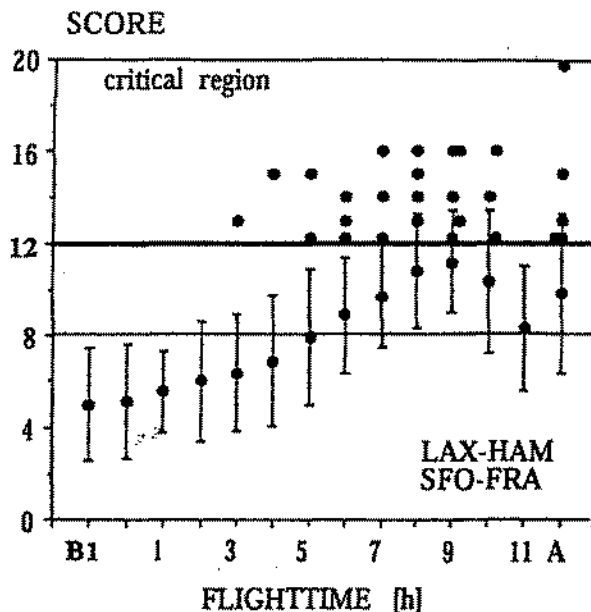
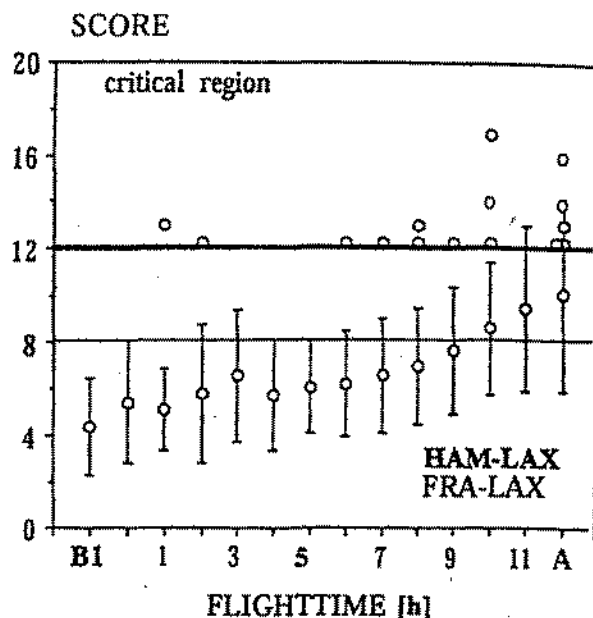


Fig. 7. Average fatigue ratings (means \pm SD) during flights HAM-LAX and FRA-LAX (upper panel) and LAX-HAM and SFO-FRA (lower panel) (see Fig. 6 for further explanation).

transmeridian flights, mean ratings remained in the noncritical region (Fig. 8). However, the ratings were significantly lower during the homegoing night flight SEZ-FRA than during the outgoing night flight FRA-SEZ ($p<0.001$, $F=33.9$, d.f. = 1,490, one-way ANOVA). Individual ratings >11 were observed in 16 cases starting after 6 hours of the FRA-SEZ flight until the end, whereas during the return flight

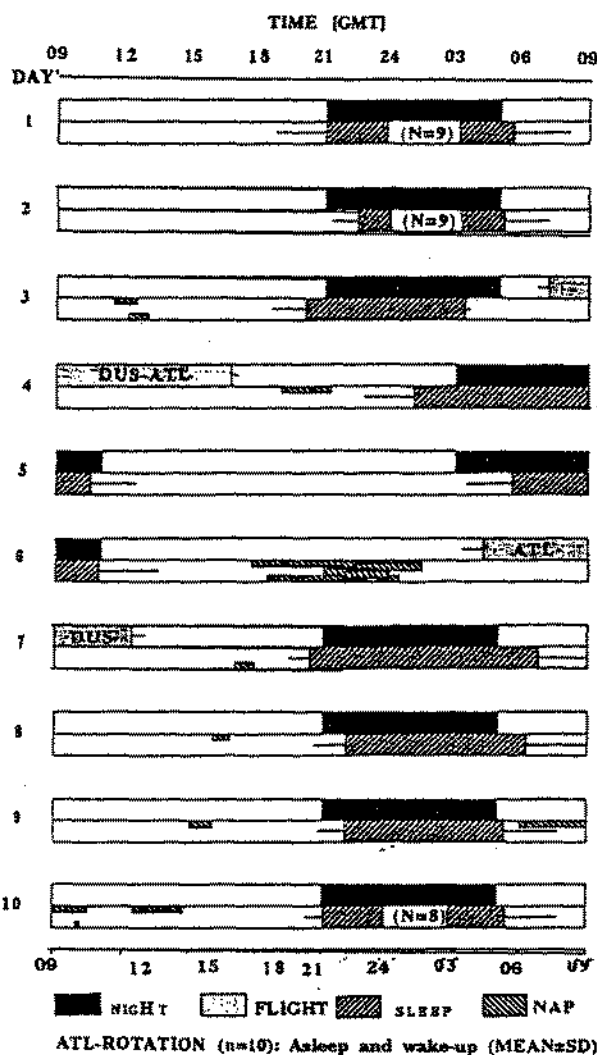


Fig. 1. Overview of average sleep, nap and FDT of the DUS-ATL rotation. Time axis extends from 09:00 to 09:00 GMT (Greenwich mean time). Local night-time is indicated for the interval between 23:00 and 07:00 hours LT. Single naps are illustrated by partial bars.

U.S.-eastcoast (6 hours time difference), pilots went to bed 4 hours later compared to home base, but 7 hours later after arrival at the U.S.-westcoast (9 hours time difference). The average sleep period was extended by 1.5 hours beyond the baseline sleep period during the first layover night at both destinations. During subsequent layover days, sleep adapted to normal length and to local night time. Before commencing flight duty for the return flight to Germany, subjects tried to nap when local departure time was in the late afternoon or night. Before the flight ATL-DUS, pilots got up at a normal time in the morning and attempted to nap in the afternoon or early evening. However, not all pilots were able to sleep during this nap (Fig. 1, day 6). In this case,

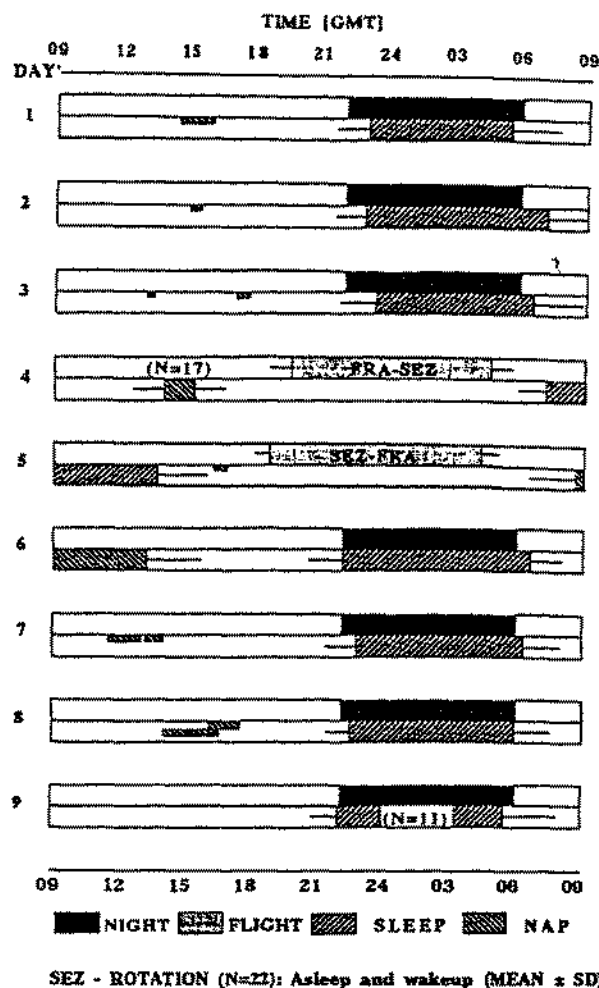


Fig. 2. Overview of average sleep, nap and FDT of the FRA-SEZ rotation (see Fig. 1 for further explanation).

pilots were already awake for > 15 hours when commencing their night duty. Before the flight LAX-HAM, seven pilots slept longer (i.e. 1.5 hours on average), whereas three pilots got up at normal time and napped in the afternoon. The return night flight prevented pilots from getting a normal night sleep. Thus, upon return to home base, an average sleep deficit of 8 hours was observed. Several pilots either had a nap immediately after arrival at home (FRA-LAX) or slept for longer times in the following night (DUS-ATL, Fig. 1, day 7). During subsequent nights, sleep length returned to baseline values.

North-south rotations. While the average sleep period of the first night reported in this study was short (6 hours 40 minutes, Fig. 2, day 1), the average sleep duration was 8 hours in the two nights preceding the rotation. Hence, baseline sleep is considered to be 8 hours. Seventeen pilots napped before commencing flight duty FRA-SEZ. After arrival in Mahe (SEZ), they were transferred by bus to the hotel

(45 minutes duration). Because the layover period was only 14 hours, they went to bed upon arrival at the hotel (11:00 LT) and slept during daytime. This sleep was 2 hours shorter, on average, than normal (Fig. 2, day 5), and was disturbed by frequent awakenings. Five pilots (out of 22) slept for < 5 hours. Before starting the return flight, the crews were transported to the airport (again 45 minutes duration). On average, 4.25 hours after arrival at home base, 20 pilots went to bed (Fig. 2, day 6), whereas the other two pilots stayed awake until evening. In the following night, average sleep duration was substantially longer than baseline. On subsequent days, sleep duration normalized. When calculating sleep surplus or deficit as difference from baseline through the two consecutive night duties, pilots on average had an accumulated sleep deficit of 6 hours at the end of the first night and of 9.3 hours at the end of the second night.

Inflight questionnaires

The results of the taskload questionnaires are presented in Figs 3-5. In general, average NASA-Task Load Index scores were between 40 and 170 on the 300-point scale. A significant difference was not detected between outbound and return flights in the various rotations ($t=0.46$, $p=0.65$, t -test). For all flight legs, the load index showed a U-shaped curve. Values of 150-170 points were observed after the take-off procedure and after landing, indicating a moderate level of perceived taskload. During cruising, scores were significantly lower, denoting low levels of perceived taskload. An interesting difference is observed when comparing transmeridian and trans-equatorial flights. Scores were substantially higher while cruising during north-south flights than during transatlantic flights (overall mean difference = 45).

The results of the subjective fatigue ratings are illustrated in Figs 6-8. During the entire outgoing flight DUS-ATL, pilots showed a low level of fatigue (upper panel). Although a trend towards increased fatigue with ongoing flight duty was observed ($r=0.75$, $F=11.7$, $p=0.008$), the ratings remained in a noncritical region with respect to operational implications. No individual rated fatigue as > 11. Before the return flight ATL-DUS and for 2 hours after departure, pilots rated their fatigue again quite low, on average. However, fatigue again increased with progressing flight duty ($r=0.91$, $F=44.9$, $p<0.001$). Furthermore, as can be seen from individual scores (Fig. 6, lower panel), ratings by some pilots increased to or beyond the critical limit of 12, indicating possible performance impairments. After 3 hours of flying and until the end of the flight ATL-DUS, 25 such ratings were observed. Of the 12 pilots, 35%

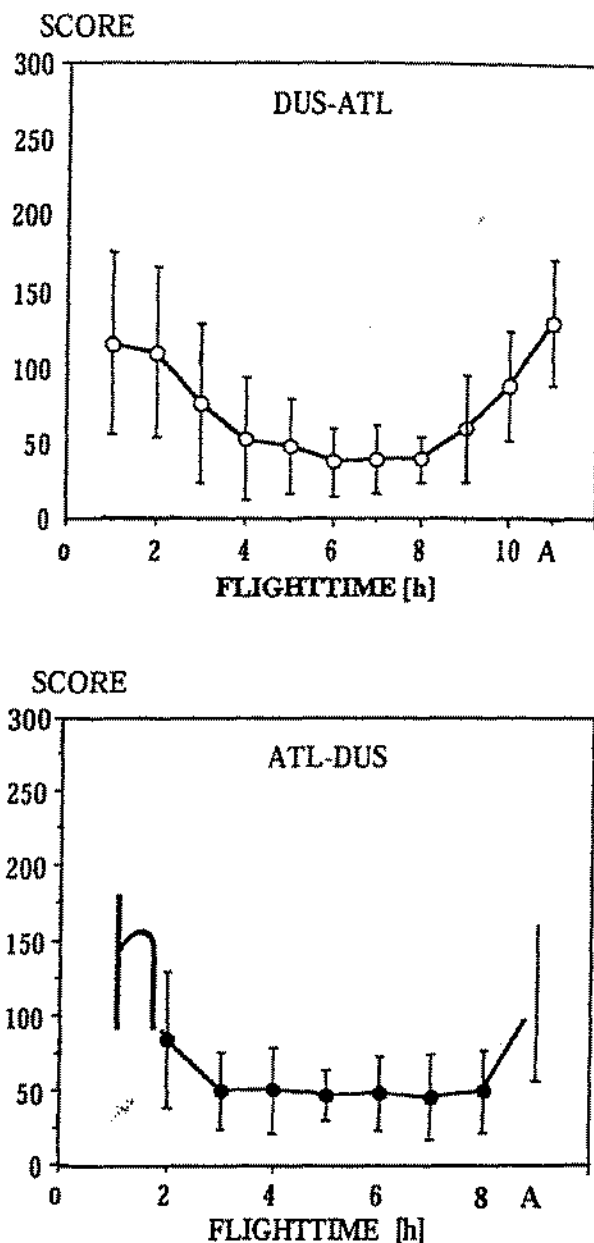


Fig. 3. Average TLX scores during flight DUS-ATL (upper panel) and ATL-DUS (lower panel). Time axis indicates time of flying (A, after flight). Range of scale is between 0 (no taskload) and 300 (maximum taskload). Presented are means \pm SD.

made ratings above the critical limit. The increase was correlated with ongoing flight duty ($r=0.80$, $F=10.4$, $p=0.018$). The interval between 3 and 8 hours of flight time coincides with a LT in ATL between 03:00 and 08:00. Hence, this time interval fell into the period of the circadian low.

During the longer day-time flights between Germany and the U.S.-westcoast, an increasing level of fatigue with progressing flight duty was also observed. The correlation was significant

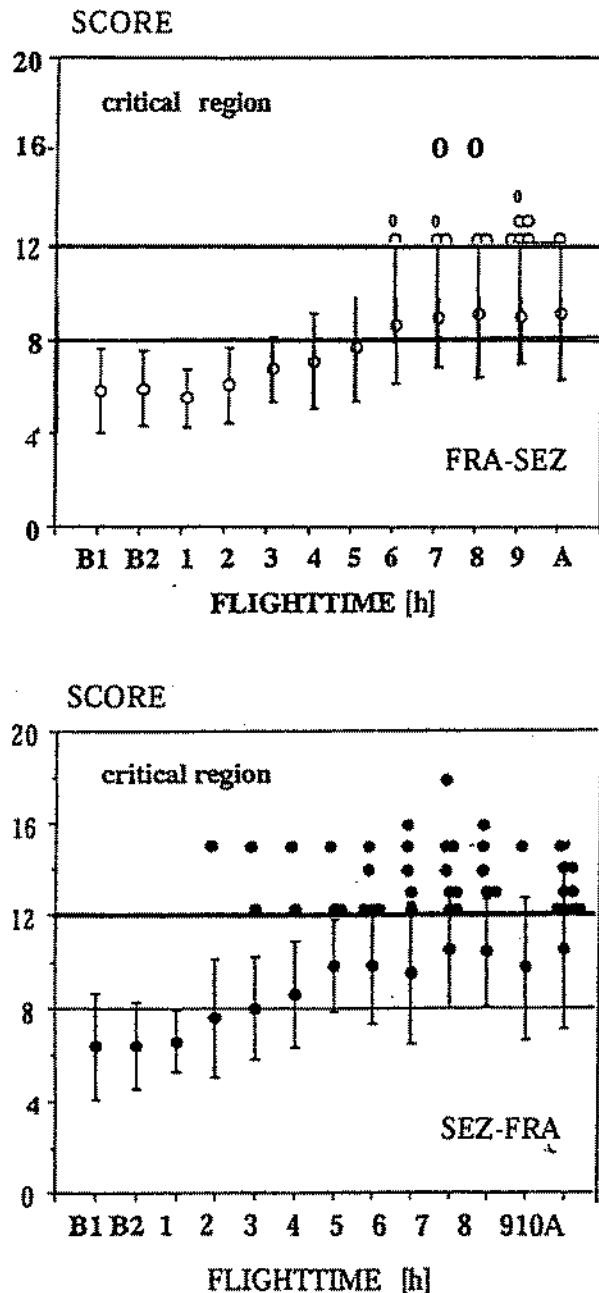


Fig. 8. Average fatigue ratings (means \pm SD) during flight FRA-SEZ (upper panel) and SEZ-FRA (lower panel) (see Fig. 6 for further explanation).

SEZ-FRA ratings of 12 or higher occurred already after 2 hours of flight and totalled to 32. Thus, the average level of fatigue was higher (overall mean per hour and pilot: 0.15) than that observed during the outbound flight (mean: 0.08). Critical ratings further increased after 5 hours of the SEZ-FRA flight. A comparison of the time interval from 6 and 10 hours between the FRA-SEZ and SEZ-FRA flight indicated a substantially higher rate of subjective fatigue

(6.3% versus 20.5% of ratings in the critical region) for the return flight.

Electroencephalogramme and electrooculogramme

The analysis of the total EEG/EOG-records showed that spontaneous micro-sleeps increased with progressing flight duty (Fig. 9). As already mentioned in the methodology section, the 'pre-planned rest phases' were excluded in this part of the evaluation.

During the outgoing flight DUS-ATL, micro-sleeps occurred in 83 cases, whereas during the homegoing flight this number was nearly twice as high, that is, 156 cases. Thus, the average number per hour per pilot was 0.69 (DUS-ATL), and 1.63 (ATL-DUS), respectively. The number of micro-sleeps in individual pilots varied between 2 and 28 occurrences (DUS-ATL) and 0 and 62 (ATL-DUS). Micro-sleeps multiplied after 8 hours of flight time during the day-time operations (from 0.5 occurrences per pilot per hour on average between start and the seventh hour of flight to 1.2 on average between the eighth hour and the end of flight), and after 3 hours already during night-time operations (from 0.4 to 1.9). During the homegoing flight, a sharp increase was detected after 5 hours since take-off (Fig. 9, upper panel). During approach and landing, the rates (both during day- and night-time flights) decreased. However, two pilots had several micro-sleeps 50 minutes before landing in ATL, thus contributing to a relatively high rate in this time interval.

During the U.S.-westcoast operations, the mean number of micro-sleeps was 1.35 during the outgoing and 2.35 during the return flight. During the out-bound daytime operation, the mean increased from 0.8 to a maximum of 2.4 (after 8 hours) and decreased afterwards (Fig. 9, center, open bars). During night duty, micro-sleeps were 1.2 per pilot per hour during the first 4 hours, and increased to more than 2.5 during the residual of the flight. A maximum was observed after 7 hours (with a rate of 4.5). During approach and landing, the numbers (both during day- and night-time operation) decreased (as was also noted in subjective fatigue). Not counting the numbers during the last hour of flight (when descent and landing was prepared), the linear trend between progressing flight time and number of micro-sleeps was significant ($r=0.67$, $F=6.4$, $p=0.035$).

For the night flights on the transmeridian routes, the number of critical fatigue scores was significantly correlated with the number of micro-sleeps (ATL-DUS: $r=0.95$, $p<0.01$; LAX/SFO-HAM/FRA: $r=0.67$, $p=0.033$; Spearman rank-test). In the north-south rotation, 273 micro-sleeps (on average 1.38 occurrences per pilot per hour) were detected during flights FRA-SEZ, whereas during the return flight

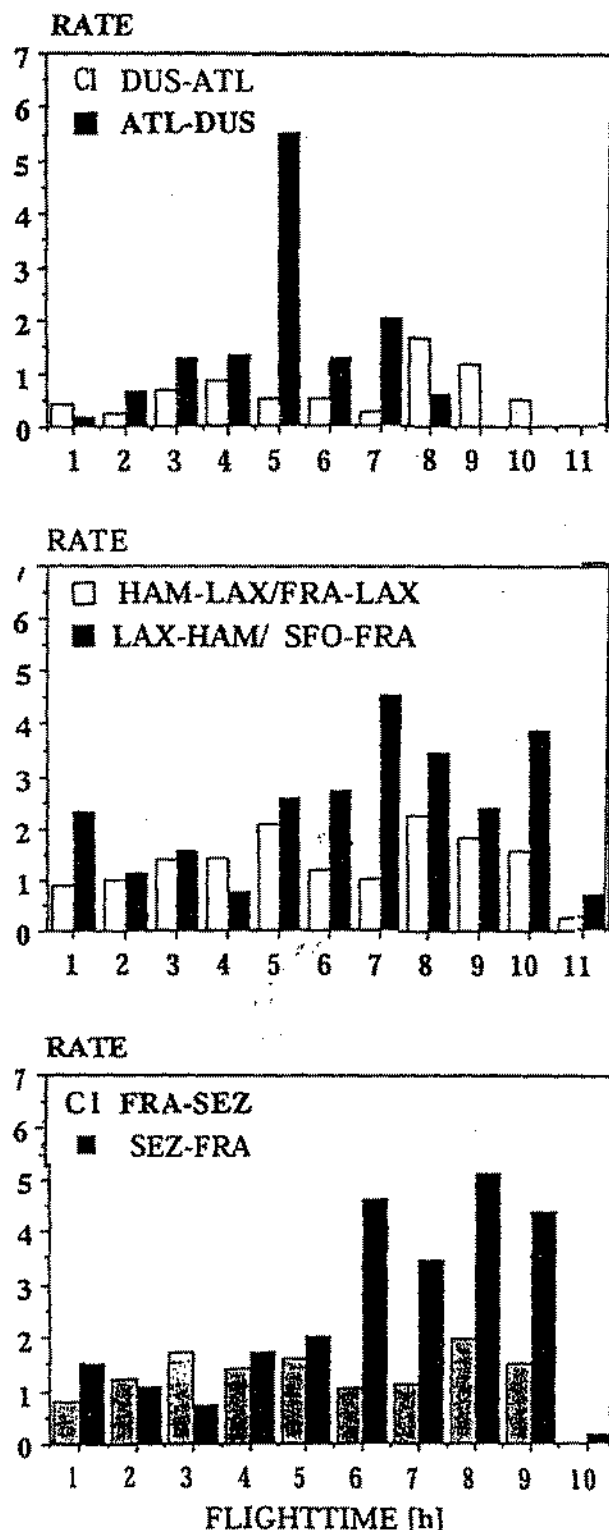


Fig. 9. Occurrence of micro-sleeps (average number per pilot and per hour of flight). Upper panel, DUS-ATL and ATL-DUS ($n=12$); center, HAM-LAX/FRA-LAX and LAX-HAM/SFO-FRA ($n=16$); lower panel, FRA-SEZ and SEZ-FRA ($n=22$). Open bars indicate day-time operations, shaded and black bars night-time operations.

SEZ-FRA, this number was twice as much, that is, 544 cases (mean=2.47). The number per pilot was between 0 and 47 events (outgoing) and 0 and 96 (homegoing), accumulated over the entire flight. The differences of micro-sleeps between the two night flights were significant ($U=23.5$; $p<0.05$; $n=9, 10$; Mann-Whitney U-test). Whereas no substantial change in the number of micro-sleeps was detected during the first night flight, an increase was observed during the following (homebound) night flight (Fig. 9, lower panel). The mean rate of micro-sleeps during the return flight (SEZ-FRA) increased from less than two occurrences per hour per pilot to more than 3.5 events after 6 hours of flight. The correlation between ongoing flight time and number of micro-sleeps was significant ($r=0.758$, $F=10.8$, $p=0.011$). Episodes of extended micro-sleeps, that is, alpha-activity lasting longer than 30 seconds, were observed in two cases during the outgoing flight and six cases during the return flight.

DISCUSSION

Duty hours

In general, the work hours (FDP) of the actual operations studied exceeded the normal duty time, as stipulated by the German regulations (i.e. 10 hours) on most routes. This was the case on the flights FRA-SEZ (58 minutes excess on average), DUS-ATL (1 hour and 42 minutes), SEZ-FRA (1 hour and 15 minutes), LAX-HAM (2 hours and 29 minutes), SFO-FRA (2 hours and 51 minutes), HAM-LAX (3 hours and 5 minutes) and FRA-LAX (3 hours and 54 minutes).

With respect to German regulations, extensions of flight duty time up to 4 hours (to a total of 14 hours) are permitted with some restrictions. Nearly all flights were operated within this limit. One exception occurred on the route FRA-LAX where FDP exceeded the 14-hour limit by 25 minutes. When FDPs encroach the full range of night hours (01:00 to 07:00 LT according to German rules), the maximum permissible FDP has to be reduced from 14 to 12 hours, or if only partly encroaching the night hours, the reduction is from 14 to 13 hours. For all flights under study, these conditions were met. German regulations require a minimum rest time of 10 hours within each 24-hour period. This condition was also fulfilled during all rotations. However, during the FRA-SEZ rotation layover rest times were very short (13 hours and 54 minutes on average) compared with the other rotations when several days lay between flight operations.

Sleep and rest

The results from the sleep log concerning sleep quantity and sleep distribution over the 24-hour cycle reflect subjective assessments by pilots. Previous studies with similar pilot populations (Samel and Wegmann, 1989; Wegmann et al., 1986) showed that evaluation of sleep by subjective ratings and by polysomnographic recordings revealed nearly congruent results. Additionally, subjectively rated sleep length and objectively measured sleep duration by actometry led to the same results (Samel et al., 1993). Insofar, it can be concluded that the data obtained from the sleep log reflect the real and actual sleep behavior in the present studies.

Our sleep data indicate that the westward flights are associated with an increase of sleep duration (relative to baseline sleep) during the following local night. The reason for this extension is the delay of sleep onset due to the shifted LT which results in staying awake for longer times, and thus creates sleep deprivation by several hours. During the following layover night(s), sleep was on average not much shorter than a baseline night sleep, and sleep disturbances by awakenings were not greater than at home. One reason may be the further delay of sleep onset by several hours leading to further sleep deprivation. This result indicates that disturbances of circadian rhythmicity did not so severely affect sleep as it was observed in three-crew cockpit studies (Graeber, 1986; Samel and Wegmann, 1987; Wegmann et al., 1986). An explanation for this difference may be that for the DUS-ATL rotation, the number of time-zones crossed was smaller (that is, six instead of nine), and for the HAM-LAX rotation that pilots stayed only for one day in LAX (they either went to ATL one day after the HAM-LAX flight or came from Miami the day before they performed the LAX-HAM flight). Thus, desynchronization of the circadian system was smaller (Wegmann et al., 1983b).

Often, pilots were able to sleep > 1 hour before reporting for the eastbound return flight. A nap of at least 1 hour has been proven to benefit alertness and vigilance (Dinges et al., 1988; Nicholson et al., 1985). However, a number of pilots (59%) did not nap. At least in this group, sleep deprivation can be expected to affect wakefulness during the following night-duty period. But also not all of the other pilots were completely fresh before commencing flight duty between ATL and DUS, as has been confirmed by the subjective ratings indicating only 33% of the pilots being sufficiently rested at this time, when 50% had napped. On the other hand, in the LAX-HAM group, 55% felt not sufficiently rested, but only 30% had taken a nap. The most striking result concerning sleep quantity is the sleep loss after the return flight

to Germany. It demonstrates again that eastward transmeridian flying associated with night duty, results in a deficit in sleep duration. The average sleep loss of 8 hours as found in this study is in agreement with several studies performed in previous years (Buck et al., 1989; Graeber, 1986; Wegmann et al., 1986). The resulting sleep deficit occurring during night flight could only partly be compensated at the home base during the subsequent days. In our case, sleep length normalized during the second night in most pilots, and was not shortened as observed in similar investigations on pilots of the three-crew flight deck (Samel and Wegmann, 1989; Wegmann et al., 1986).

In the north-south rotation, our sleep data indicate again that night flying is associated with a significant sleep deficit. This was already the case for the first night duty. During layover, the sleep loss could not completely be compensated by a day-time sleep. In addition to a substantial reduction in sleep length (2 hours on average), the day-sleep was more disturbed by frequent awakenings (in 13 pilots) than the baseline night sleep at home (awakenings occurred in five pilots). Although exhausted from the preceding flight duty, sleep was less efficient. Consequently, it must be assumed that the recuperation of the crew members was not sufficient when commencing duty on the return flight. This conclusion is confirmed by the subjective ratings of the general questionnaire indicating only 30% of the pilots being sufficiently rested after the layover period. Fatigue and stress were more pronounced during the return trip as demonstrated by the general questionnaire of the two duty periods. Due to the combination of the consecutive night flights and the short layover period, sleep deprivation was more severe and led to an increase of overall stress. After arriving at home base at the end of the rotation, almost all pilots went to bed in the morning for a nap of 4 hours, on average. During the following night, pilots slept longer than normal, but did not recover completely from the 9.3-hour night sleep deficit (on average) caused by unfavorable duty and rest times of the previous rotation. Yet, sleep length normalized during the second and subsequent night after return.

Based on the results from sleep, it must be concluded that at least 48 hours of rest (if not more, to be on the safe side) are necessary for recovery from sleep deprivation after rotations as described in this report. In the case of transatlantic flights, the adaptation of the circadian system to LT after time-zone changes adds a further dimension to the problem of adequate rest (Klein and Wegmann, 1980; Wegmann and Klein, 1981, 1985). After returning to home base time, at least a rest time of 48 hours should be provided. These recommendations must be

= 2 Good Nights

taken into consideration when discussing new regulations in the context of the European harmonization or of FAA-amendments.

Operational demands

Taskload was found not critical during all flights. When comparing the results from the different routes, the taskload during the cruising phase was rated to be lower during the transatlantic crossings than on the north-south route. The difference can be explained by the extended oversea sections of the atlantic flights and by good air traffic control (ATC) in the U.S.A. and in Western Europe (in contrast to that in North Africa), resulting in lower demands for communication with ATC. On the other hand, this situation creates monotonous flight conditions on the flight deck. At the same time, there is no doubt that under all flight conditions investigated here during minimum crew operations, taskload and workload remained acceptable. From the findings it must be concluded that taskload is in a moderate or even low range for the minimum two-pilot crew under the conditions investigated.

Fatigue depends on several factors including time since sleep, circadian rhythms and time on task. The first factor on fatigue is the duration of wakefulness since the last sleep. When a flight duty commenced during morning hours as was the case in the transmeridian outbound flights, pilots were awake for only a few hours before departure. Thus, subjective fatigue levels remained in the operationally noncritical region for the entire flight as observed in the DUS-ATL flights. However, when FDP was started in the late afternoon or at night, as was the case in the homegoing transmeridian flights (and in both flights of the SEZ-rotation), pilots were often awake for > 12 hours (LAX-HAM) or even 16 hours (ATL-DUS). For the ATL-DUS and FRA-SEZ flights, pilots commenced duty at a time when normally they would go to sleep. Consequently, fatigue began to increase soon after departure and fatigue was rated more frequently in the critical region. With progressing duty, time since sleep extended and sleep pressure amplified. This conclusion was confirmed by the occurrence of micro-sleeps. In the DUS-ATL study, the number increased from one to two micro-sleeps per pilot per hour to about five after 5 hours of the night flight, and in the night flights from the U.S.-westcoast the number was between 3 and 4.5 after 6 hours flight time.

There is a second factor that influences fatigue. During night flights, the circadian system contributes to a lower physical and mental state, because it is passing its trough during night hours. Most, if not all, body functions are affected by circadian rhyth-

micity including body temperature, heart rate, brain activity, vigilance and performance (Klein and Wegmann, 1980). Circadian rhythmicity in brain activity and heart rate were observed in the present studies (Gundel et al., 1995; Samel et al., 1993). In the SEZ-rotation, during pre-planned rest phases, total alpha power and peak frequency in EEG-recordings decreased during the first hours of flight and reached a minimum at a time that corresponded well with the circadian trough between 03:00 and 05:00 LT (Gundel et al., 1995). Similarly, decreasing heart rate was observed with a minimum at about the same time. After the circadian minimum, changes in a favorable direction were observed, in the form of an increasing heart rate and decreasing alpha broadband power (Gundel et al., 1995; Samel et al., 1993).

The third factor influencing fatigue is time on task. In the present studies, the mean flight duty time was 10 hours (ATL-DUS) or more. Most fatigue ratings and the number of micro-sleeps showed an increasing trend with progressing flight duty. Critical fatigue ratings did not occur during the 10 hours and 15 minutes day-time flight DUS-ATL; however, they were observed during the longer 11 hours and 15 minutes day-time flight HAM/FRA-LAX. Fatigue ratings and the number of micro-sleeps were significantly higher during night flights than during day-time flights, indicating a pronounced decrease of alertness and vigilance with progressing night duty. When two consecutive night flights were conducted with flight duty times of ca 11 hours as was the case with the FRA-SEZ rotation, fatigue and micro-sleeps were more prominent during the second flight, again increasing with progressing duty.

From the north-south-route investigations we can conclude that 10-hour night flying is too long when considering operational implications of the fatigue increments. Since not all (mainly physiological) functions showed such a clear trend in the DUS-ATL rotation, we cannot unequivocally conclude that an 8- or 9-hour night flight is too long to be performed safely. However, the results from the majority of parameters investigated in this study leads to the conclusion that night duty imposes an extra burden on human physiology, and, therefore, time-on-task during night is particularly a critical issue. The findings of high fatigue levels during night duty are emphasized by the fact that >62% of the pilots (average of all night flights) indicated that they were not able to fly any longer after the night flights.

CONCLUSIONS AND RECOMMENDATIONS

From the results two different conclusions can be drawn. First, the day-time flight operated on the

route DUS-ATL, although exceeding the normal duty time as defined in the German regulations, does not produce critical impairments of the minimum required crew. Flight duty periods of < 12 hours during normal daytime can be accepted under the conditions investigated. This conclusion is based primarily on fatigue ratings, which remained below the critical region, and on low numbers of micro-sleeps. However, as has been shown for the extended flight operations of > 12 hours (between HAM-LAX and FRA-LAX), FDPs > 12 hours have to be considered critical in terms of fatigue and alertness for some pilots on the flight deck. As a second conclusion, night duty is associated with lower alertness and vigilance than daytime duty. The mainly contributing factors are:

- (1) night duty, since human functioning is depressed during the trough in circadian rhythmicity;
- (2) sleep deprivation, because normal sleep is not possible during day-light hours; and
- (3) a long duty period which does not allow breaks for recuperation.

The first two factors can be affected by disturbances of the circadian system when transmeridian flights are involved, and, therefore, can worsen the already lowered state of alertness and performance (Klein and Wegmann, 1980; Klein et al., 1976). Because physiological factors (e.g. circadian-rhythms, sleep pressure, fatigue) are difficult to modify directly, other factors which can be modified (e.g. regulatory provisions) have to be seriously taken into consideration. First, because aircraft operation does not contribute critically to taskload, modifications of aircraft control or cockpit design will not improve the situation regarding human operator capabilities. Second, the duration of safe aircraft operation is dependent on human vigilance and performance being available at any time of a FDP. During day-time, fatigue-dependent vigilance decreases with task duration, and fatigue becomes critical after 12 hours of constant work. During night hours fatigue increases faster with ongoing duty. This leads to the conclusion that 10 hours of work should be the maximum for night flying.

When considering new provisions, these variations of human factors should be taken into account, and, eventually, regulations should be stricter than currently proposed. The aviation industry requires around-the-clock activities to satisfy commercial demands. The increasing need for intercontinental long-haul, regional medium- and domestic short-haul operations for line, charter and cargo air carriers will continue to increase the 24-hour requirements. Flight crews must be available and able to support 24-hour-a-day operation to fulfil these industrial demands. Both domestic and international aviation may also

require transmeridian flights. Therefore, shiftwork, night work, irregular duty rosters, unpredictable duty schedules and crossing of time-zones will remain inevitable components of the aviation industry. These factors present challenges to human physiology. Because they will result in jet-lag, sleepiness and fatigue and thus may impair human performance, they pose a risk to safety. It is critical for regulating authorities, air transport operators and aircrew to acknowledge and, whenever possible, to incorporate scientific information on fatigue, human sleep and sleepiness, and circadian physiology into 24-hour air operations. Such scientific information and its introduction in aviation operations can help to maintain and improve the safety margin.

In particular, the introduction of the glass-cockpit on long-haul operation and decreasing the number of crew members changes the operational conditions in the cockpit, while the principles of human physiology remain the same. Under these circumstances, flight duty time regulations should provide for sufficient rest-times during flight duty schedules as well as after return to home base. Given what is known about the interference of long-haul operations with the circadian system and with the sleep-wake cycle, as well as the vigilance and alertness of the flight deck crew, it is somewhat surprising that only a few of the national rest-duty regulations presently in force sufficiently consider these aspects (Wegmann et al., 1983a). This is especially true for JAA-proposals under current deliberations in Europe (Wegmann, 1994). It must be emphasized that regulations should take account these aspects, particularly concerning the length of flight duty during day and night, and duration of rest time after transmeridian flights (Dinges, et al., 1996). Based on the findings of the present studies two-pilot crews should be limited to 12-hour FDPs during day-time operations and to 10-hour FDPs during night-time operations.

Acknowledgements—The cooperation of the pilots and the airline management of LTU-Stud and Condor was excellent and is gratefully acknowledged. We thank A. Diedrich, J. Drescher, A. Gundel, G. Kraus, J. Hjorth-Müller, H. Maaß and J. Wenzel for technical support. The research was supported by the European Union (Grant No. C2.B93.B2-7020.SIN004101) and by the German Ministry of Transport.

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