Heliyon 9 (2023) e21669

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Fatigue among Air crews on (Ultra)-Long-Range flights – A comparison of subjective fatigue with objective concentration ability

David Gläsener [a,b,1], Janina Post [a,1], David Cyrol [a], Stefan Sammito [a,c,*]

[a] German Air Force Centre of Aerospace Medicine, Cologne, Wahn, Germany
[b] Faculty of Aerospace Engineering, Bundeswehr University Munich, Germany
[c] Occupational Medicine, Faculty of Medicine, Otto-von-Guericke-University of Magdeburg, Germany

A R T I C L E I N F O

Keywords:
Fatigue
Concentration
Long duration flight
Aircrew
Aerospace

A B S T R A C T

Introduction: Long duty times are common in the aviation industry, especially with the introduction of ultra long range flights (ULR). This article aims to compare the subjective fatigue assessment and concentration ability of flight crews with objective concentration and alertness tests during (U)LR-flights.
Method: The study examined different (U)LR-flights. Before, during and after the flights subjective fatigue and concentration ability of the flight crew was examined with visual analog scale and objective attention and concentration ability with the FAIR-2 test respectively the 3-min Psychomotor Vigilance Test. For statistical analysis we used a repeated ANOVA with a post-hoc-analysis and a Wilcoxon signed-rank test for connected samples.
Results: In total 28 crew members were examined. Subjective concentration ability declined and fatigue increased significantly over the course of flights. However, no significant changes were observed in the objective concentration tests performed before and after the flights.
Conclusions: The study found that fatigue significantly increased with flight time, particularly during night hours at the window of circadian low of the crews. However, objective concentration performance showed no significant deterioration over time. The study's results were consistent with previous research, except for the finding that objective concentration was still stable. The study also compared the findings to another profession and found similar results regarding the performance of complex tasks after long working hours while experiencing fatigue.
Pratical applications: This study helps to understand the effects of ultra long-range flight on fatigue and concentration of the air crew and can help to improve safety issues on such flights.

1. Introduction

Long working hours and shift work are common and unavoidable in various industries. Both are associated with fatigue, which causes a thread to safety especially in the transport sector [1]. Several studies have examined the consequences of fatigue in the workplace. Prolonged work shifts longer than 8 h lead to a decrease in alertness and performance [2]. Pilot fatigue was found to

* Corresponding author. German Air Force Centre of Aerospace Medicine, Flughafenstr. 1, 51147 Cologne, Germany.
E-mail address: stefansammito@bundeswehr.org (S. Sammito).
[1] These authors share first authorship.

https://doi.org/10.1016/j.heliyon.2023.e21669
Received 1 August 2023; Received in revised form 21 October 2023; Accepted 25 October 2023
Available online 2 November 2023

increase relative to flight length [3] and the risk of accidents occurring increases with duty time [4].

Long haul operating aircrews are not only challenged with varying schedules and long and irregular working hours, they also experience jetlag on transmeridian flights and are exposed to challenging environmental conditions (low oxygen partial pressure, low humidity, noise, vibrations, radiation) aboard an airplane flying at cruise altitude [5,6].

Although commercial air traffic and the yearly number of flights has been steadily increasing until the COVID-19-pandemic in 2020, accident rates have been decreasing over the last decades [7]. The introduction of ultra long range (ULR) capable aircraft did not influence these safety statistics, however cockpit and cabin crew operating ULR-flights face various challenges regarding long working hours, inflight rest and circadian misalignment. Therefore, it is surprising, that on the one hand the accident rates are still low, on the other hand the fatigue of air crews has increased with the extension of the flight duty. So previous studies on ULR-flights found that sleep requirement of pilots increases by 12.3 min for each additional hour of flight time on the subsequent first night and the sleep duration on layover nights is increased on the first night [8]. A departure time for corresponding ULR-flights between 2 and 6 p.m. local time is associated with the lowest pre-flight fatigue [9]. Previous research on cabin crew has been limited to a determination of sleep duration during the layover [10], a survey of 73 cabin crew members on general fatigue and lifestyle factors [11] and to the subjective fatigue on ULR flight [12].

Most of these studies have examined the air crew before or after the flight duty. There are only rare data available about objective measurements of the ability to concentrate before, during and after the flight duty of (U)LR-flight.

The present studies aim to accompany (U)LR-flights and compare subjective fatigue assessment and concentration ability of flight crews with objective concentration and alertness tests.

2. Methods

For participation in this study, the actively scheduled crews of the flights were approached during the flight briefing about the possibility of participating in the study. The participants agreeded in writing after they were informed about the study's purpose and the belonging data protection. Participation in the study was voluntary; non-participation did not lead to any disadvantages for the persons concerned. Two different flight crews were examined for this analysis. Both flight crews were handed out a questionnaire (see questionnaire 1 in the attachment), during the preflight briefing. Gender, age, body length, weight and smoking status (smoker, former smoker, never smoker) were assessed. The body mass index (BMI) was calculated from the data collected using the formula body weight [kg]/body length [m]^2.

The 1st flight crew conducted an around-the-world flight with a German Air Force *Airbus 350-900ULR* from Cologne-Bonn (CGN) to Canberra (CBR) to Papeete (PPT) and back to CGN. Due to their duration of more than 16 h, the segments from CGN to CBR and from PPT to CGN were classified as ULR. These flights are numbered as flight no. 1–3. All flights were operated by the same crew, which consisted of four pilots and 16 cabin crew members (flight crew) and five additional crew members (ACM), who are not considered in this study, because during flight they only were passengers without any duty task during the flight.

The 2nd flight crew conducted a test flight of a German Air Force *Airbus A321neo LR* from CGN via Washington DC, USA (IAD) to Las Vegas, NV, USA (LAS). The return flight to CGN (3 days later) included a stopover in Shannon, Ireland (SNN). All flights were operated by the same crew, which consisted of three pilots and five cabin crew members (flight crew). Eight ACMs were also onboard but are not considered in this study, because during flight they only were passengers without any duty task during the flight.

While the single segments cannot be classified as ULR, the actual duty time of the crew for the inbound and return flight was longer than 16 h, as the stopovers in IAD and SNN were necessary for refueling and were used for administrative duties by the cabin crew and flight planning for the next segment by the pilot crew. These flights are numbered as flight no. 4–7. Crew rest was only possible during cruise flight. For the analysis the flight nr. 4 and 5 and the flight nr. 6 and 7 were combined, because for the flight crew it was only one duty day without any duty break during the short phase at IAD or SNN. Further details of the flights accompanied for this study are shown in Table 1. For both flights all flight crew members took part in the study (participation rate 100 %).

Both flights were test flight and all crew members (pilots and cabin crew) were military personal. Test flight means, that some additional crew members with other tasks (mentioned above) were on board, but there weren't additional normal passengers on board during these flights.

To assess subjective fatigue and concentration ability, a visual analog scale (VAS) was used in both studies (see questionnaire 2 in the attachment). Participants were asked "How do you rate your ability to concentrate?"; with 0 meaning "minimum" and 100 meaning "maximum" and "How tired do you feel?"; with 0 meaning "maximally tired" and 100 meaning "not at all". This approach

Table 1
Flight details.

No.	Route	Distance [km]	Departure UTC +2	Arrival UTC +2	Duration [hh:min]	Aircraft Type
1	CGN - CBR	17.486	Nov. 20, 2020; 10:58	Nov. 21, 2020; 06:41	19:43	*Airbus A 350–900 ULR*
2	CBR - PPT	6.390	Nov. 22, 2020; 09:04	Nov. 22, 2020; 15:58	06:54	*Airbus A 350–900 ULR*
3	PPT - CGN	16.760	Nov. 23, 2020; 19:46	Nov. 24, 2020; 13:53	18:07	*Airbus A 350–900 ULR*
4	CGN - IAD	6.438	Jul. 21, 2022; 09:55	Jul. 21, 2022; 18:40	08:45	*Airbus A 321neo LR*
5	IAD - LAS	3.325	Jul. 21, 2022; 19:53	Jul. 22, 2022; 00:41	04:48	*Airbus A 321neo LR*
6	LAS - SNN	7.875	Jul. 24, 2022; 18:02	Jul. 25, 2022; 03:25	09:22	*Airbus A 321neo LR*
7	SNN - CGN	1.124	Jul. 25, 2022; 04:33	Jul. 25, 2022; 06:27	01:54	*Airbus A 321neo LR*

CBR = Canberra, CGN = Cologne/Bonn, IAD = Washington DC, LAS = Las Vegas, PPT = Papeete, SNN = Shannon was chosen because the assessment of subjective fatigue by VAS correlates strongly with objective polysomnography [13]. This means, that a lower level of the VAS in the fatigue questionnaire means higher subjective fatigue and versa visa, a lower level of the VAS in concentration means also a lower subjective level of concentration. In total higher values are synonym with higher performance ability (lower fatigue and/or higher concentration level).

The 1st flight crew (flight no. 1–3) was examined by using the FAIR-2 (Frankfurter Aufmerksamkeits-Inventar 2) test to assess attention and concentration ability. The FAIR-2 is a well-established procedure for assessing interindividual differences in attentional performance and concentration ability [14]. The FAIR-2 is a paper-pencil test and requires the accurate and rapid discrimination of visually similar signs while simultaneously masking out task-irrelevant information. This test lasts 6 min (2 × 3 min) in total and the crew members were able to conduct the test in the conference area of the airplane in a sitting position with a table.

VAS questionnaire and the FAIR-2 test were conducted on paper. During the three flights, data was collected before or directly after each take-off, before or direct after each landing and at shift change during the two ULR segments and one time in the middle of the flight from CBR to PPT. All subjects received a subject identifier at the beginning of the study and all data collection was pseudonymized via this subject identifier. A total of eleven measurements were performed (T1-1 to T1-11). After returning to CGN, the data was digitalized in Microsoft Access (Microsoft, Redmond, WA, USA) and transferred to IBM SPSS Version 24.0 (IBM, Armonk, NY, USA) for statistical analysis.

The 2nd flight crew (flight no. 4–7) was examined by using the Psychomotor Vigilance Test (PVT) to assess attention and vigilance. The PVT is a concentration test with high sensitivity to delayed reaction time due to fatigue [15]. The PVT is a widely used scientific method for assessing attention and vigilance. It has been shown that measured performance is highly sensitive to fatigue, the effects of acute and chronic sleep deprivation and disruption of circadian rhythms. With the aid of the PVT, reaction time is used as an objective parameter to determine crew fatigue.

On these flights, the data were collected digitally on a Microsoft Surface (Microsoft, Redmond, WA, USA) tablet computer. Subjective analysis of the participants were collected every 2 h beginning before take-off up to before or directly after landing. The PVT was conducted onetime before the first take-off of the day and before or directly after landing. A total of fifteen measurements were performed (T2-1 to T2-15). All subjects received a subject identifier at the beginning of the study and further digital or analogue storage was pseudonymized via this subject identifier. The PVT data were exported to Microsoft Excel (Microsoft, Redmond, WA, USA). Statistical analysis was also performed using IBM SPSS.

All values were presented as median with interquartile range (IQR) and range due to lack of normal distribution. For repeated measurement we used a repeated ANOVA with a post-hoc-analysis. The Greenhouse–Geisser adjustment was used to correct for violations of sphericity. Differences over time to baseline measurement at the beginning of each flight were analyzed using Wilcoxon signed-rank test for connected samples. Group comparison was analyzed using Mann-Whitney-U-Test. A significance level of $p < 0.05$ was assumed to be statistically significant.

The study was conducted as part of the departmental research contract of the German Air Force Centre for Aerospace Medicine and is part of the research project "Fatigue and Attention Ability in Crew Members of Long-Range Flights," which was advised by the Ethics Committee of the Medical Faculty of Otto-von-Guericke-University Magdeburg (Az 153/21).

Table 2

Median Results of the assessment of subjective fatigue, concentration ability and FAIR-2 results of 1st flight crew, p-values are calculated to the last measurement time point before (e.g. T1-2 vs. T1-1) or in comparison to baseline at take-off ($p_{baseline}$). Significant results are highlighted in bold.

Time-point	Time based on local time in CGN	Time in comparison to flight situation	Fatigue (VAS)	p	$p_{baseline}$	Concentration (VAS)	p	$p_{baseline}$	Attention and concentration (FAIR-2)	p	$p_{baseline}$
T1-1	Day 1, 09:41	1 h before take-off	76.0 (27.0)	–	–	70.5 (25.0)	–	–	99.1 % (1.3 %)	–	–
T1-2	Day 1, 14:56	~4 h after take-off	70.0 (19.0)	0.073	0.073	65.5 (27.0)	**0.009**	**0.009**	99.6 %(1.0 %)	0.845	0.845
T1-3	Day 2, 18:20	~7,5 h after take-off	56.0 (31.0)	0.059	**0.014**	61.5 (24.0)	0.173	**0.012**	99.8 (1.0 %)	0.381	**0.043**
T1-4	Day 2, 05:59	1 h before landing	41.5 (30.0)	0.086	**0.004**	44.5 (39.0)	0.067	**0.001**	99.7 % (0.9 %	0.554	0.055
T1-5	Day 3, 09:17	directly after take-off	84.0 (24.0)	–	–	85.0 (19.0)	–	–	99.6 % (0.6 %)	–	–
T1-6	Day 3, 13:05	~4 h after take-off	75.0 (28.0)	**0.002**	**0.002**	67.5 (29.0)	**0.001**	**0.001**	99.6 % (0.8 %)	0.212	0.212
T1-7	Day 3, 17:08	1 h after landing	65.0 (36.0)	0.096	**0.001**	60.5 (36.0)	**0.003**	**0.001**	99.5 % (0.8 %)	0.748	0.469
T1-8	Day 3, 20:20	directly after take-off	76.0 (29.0)	–	–	72.5 (18.0)	–	–	99.3 % (1.0 %)	–	–
T1-9	Day 4, ×06:35	~10,5 h after take-off	42.0 (31.0)	< **0.001**	< **0.001**	49.5 (27.0)	**0.001**	**0.001**	99.6 % (0.9 %)	0.327	0.327
T1-10	Day 4, 10:12	~14 h after take-off	39.0 (30.0)	0.513	< **0.001**	45.5 (41.0)	0.672	**0.001**	99.5 % (0.6 %)	0.469	0.113
T1-11	Day 4, 14:02	directly after landing	46.0 (35.0)	0.433	**0.003**	48.5 (36.0)	0.478	**0.004**	99.4 % (0.9 %)	0.360	0.687

3. Results

The 1st flight crew consisted of four male pilots (median age: 39.4 [IQR: 12.8] years, BMI: 24.0 [IQR: 3.2] kg/m^2, no active smokers) and 16 cabin crew members (ten male subjects and six female subjects, median age: 31.0 [IQR: 9.8] years, BMI: 25.1 [IQR: 7.5] kg/m^2, six active smokers). All flight crew members (n = 20) took part in the study (participation rate = 100 %).

The subjective assessment of fatigue, which means the value of the VAS became lower, increased over all three flights significantly. The median decreased during the first flight from 76.0 to 41.5 ($F(3, 57) = 9.317$, $p < 0.001$, $\eta^2 = 0.329$), during the second flight from 84.0 to 65.0 ($F(2, 38) = 10.578$, $p < 0.001$, $\eta^2 = 0.358$) and during the third and last flight from 76.0 to 46.0 ($F (3, 57) = 15.488$, $p < 0.001$, $\eta^2 = 0.449$). A comparison to baseline measurement at the beginning of each flight shows an increasing of fatigue in the first flight after 7,5 h flight duty and for both additional flights already during the second measurement after take-off.

Subjective concentration ability declined significantly over the course of all three flights and was especially reduced during central European nighttime. The median decreased during the first flight from 70.5 to 44.5 ($F(3, 57) = 8.534$, $p < 0.001$, $\eta^2 = 0.310$), during the second flight from 85.0 to 60.5 ($F(2, 38) = 17.303$, $p < 0.001$, $\eta^2 = 0.477$) and during the third and last flight from 72.5 to 48.5 ($F (3, 57) = 15.817$, $p < 0.001$, $\eta^2 = 0.454$). A significant ($p < 0.05$) reduction could be observed between T1-1 - T1-2 on the first flight (CGN-CBR), between T1-5 - T1-6 - T1-7 on the second flight (CBR-PPT) and between T1-8 - T1-9 on the third flight (PPT-CGN). In comparison to the baseline at take-off nearly each measurement shows a significant reduction.

Analysis of objective attention and concentration ability using the FAIR-2 test revealed a stable picture across all three flights with consistently high attention. The repeated ANOVA shows no significant change over time during the flights ($p > 0.05$). There were no significant differences between individual test time points ($p > 0.05$) and with one exception (T1-3) also no significant differences in comparison zu baseline at take-off. The subjects correctly processed a median of 94.9 %–97.6 % of test items. An overview of all analysis is shown in Table 2.

The 2nd flight crew (median age: 39.5 [IQR: 14.0] years, BMI: 25.5 [IQR: 2.1] kg/m^2, four active smokers) consisted of three male pilots and five cabin crew members (three male subjects and two female subjects). All flight crew members (n = 8) took part in the study (participation rate = 100 %).

On the outbound flight (CGN-IAD-LAS), the 2nd flight crew showed a significant increase (which means lower values in VAS) over time in the repeated ANOVA analyze for fatigue from 72.5 at take-off to 51.5 at landing ($F(7, 49) = 3.429$, $p = 0.005$, $\eta^2 = 0.329$). The same was shown for the return flight (LAS–SNN–CGN) were the fatigue also increased from 82.0 at take-off to 31.0 at landing (F(6, 42)

Table 3
Median Results of the assessment of subjective fatigue, concentration ability and Psychomotor Vigilance Test (PVT) results of 2nd flight crew, p-values are calculated to the last measurement time point before (e.g. T2-2 vs. T2-1) or in comparison to baseline ($p_{baseline}$). Significant results are highlighted in bold.

Time-point	Time based on local time in CGN	Time in comparison to flight situation	Fatigue (VAS)	p	$p_{baseline}$	Concen-Tration (VAS)	p	$p_{baseline}$	attention and vigilance (PVT [ms])	$p_{baseline}$
T2-1	Day 1, 09:10	0,5 h before take-off	72.5 (43.0)	–	–	76.5 (34.0)	–	–	400 (80)	–
T2-2	Day 1, 12:13	2 h after take-off	81.0 (44.0)	0.397	0.397	82.5 (19.0)	**0.046**	**0.046**	–	–
T2-3	Day 1, 14:09	4 h after take-off	80.5 (26.0)	0.624	0.260	75.0 (15.0)	0.930	0.249	–	–
T2-4	Day 1, 16:06	6 h after take-off	78.0 (24.0)	0.933	0.484	73.5 (16.0)	0.235	0.866	–	–
T2-5	Day 1, 18:00	8 h after take-off	78.0 (18.0)	0.438	0.310	84.0 (25.0)	0.108	0.123	–	–
T2-6	Day 1, 20:21	10 h after take-off	71.0 (40.0)	**0.025**	0.484	74.0 (20.0)	0.091	0.944	–	–
T2-7	Day 1, 22:19	12 h after take-off	53.5 (36.0)	0.575	0.441	63.0 (22.0)	0.141	0.327	–	–
T2-8	Day 2, 00:05	0,5 before landing	51.5 (30.0)	0.263	0.092	52.0 (21.0)	0.058	**0.025**	382 (55)	0.093
T2-9	Day 4, 17:37	0,5 before take-off	82.0 (23.0)	–	–	79.5 (24.0)	–	–	380 (70)	–
T2-10	Day 4, 20:43	2,5 after take-off	63.0 (66.0)	0.050	0.050	81.5 (30.0)	0.345	0.345	–	–
T2-11	Day 4, 22:31	4,5 h after take-off	68.5 (48.0)	0.498	0.161	79.0 (38.0)	0.753	0.446	–	–
T2-12	Day 5, 00:35	6,5 after take-off	64.5 (40.0)	0.612	0.093	80.5 (24.0)	0.498	0.575	-	–
T2-13	Day 5, 02:35	8,5 h after take-off	42.5 (40.0)	0.050	**0.025**	65.0 (33.0)	0.050	**0.025**	–	–
T2-14	Day 5, 04:22	10,5 h after take-off	49.5 (32.0)	0.575	**0.012**	61.0 (29.0)	0.553	**0.012**	-	–
T2-15	Day 5, 06:17	Directly before landing	31.0 (35.0)	**0.021**	**0.012**	41.5 (36.0)	**0.025**	**0.012**	375 (47)	1.000

$= 4.194$, $p = 0.002$, $\eta^2 = 0.375$). Especially during the last three measurement of the return flight the air crew reported significantly higher subjective fatigue, which means lower values in VAS, in comparison to the baseline at the beginning of this flight.

There was also a decrease in the concentration ability on the outbound flight from 76.5 at take-off to 52.0 at landing ($F(7, 49) = 6.139$, $p < 0.001$, $\eta^2 = 0.467$). The subjective concentration ability was significantly lower during the first flight in comparison to the baseline at take-off only directly after take-off during the second measurement ($p = 0.046$) and at landing ($p = 0.025$). All other parameters show no significant difference in comparison to the first measurement at take-off.

On the return flight (LAS–SNN–CGN), the 2nd flight crew showed a significant decrease ($F(6, 42) = 8.552$, $p < 0.001$, $\eta^2 = 0.550$) in concentration ability from a median of 79.5 after take-off in Las Vegas (T2-9) to 41.5 after landing in CGN (T2-15). A significant decrease in concentration ability was observed between T2-14 and T2-15 ($p = 0.025$). During this flight the subjective concentration ability was significant lower after 8,5 h of flight duty up to landing at the final destination in comparison to the baseline at take-off.

The PVTs performed before and after the outbound and return flights with the 2nd flight crew show no significant changes over the flight time ($p > 0.05$). The flight crew was slightly faster at landing in LAS and also at the end in CGN than at take-off before. An overview of all analysis is shown in Table 3.

4. Discussion

The main finding of our study is that on the one hand during the course of all flights, fatigue increased significantly with the flight time and especially during night hours at the window of circadian low of the crews. On the other hand objective concentration performance, examined using the FAIR-2 concentration test as well the 3-min PVT, showed no significant deterioration over time. Thus, a selective concentration retrieval seems to be possible in a short period of time despite progressive fatigue. Punctual concentration performance explains why, despite increasing fatigue, no increased accident rates are found during landing compared to take-off [7].

The results of increasing fatigue are consistent with several studies. Subjective fatigue measured before, during and after flights using the Karolinska Sleepiness Scale was highly significant ($p < 0.001$) increased over the duration of the flight [16]. In addition to this finding 739 airline pilots, who worked on both short- and long-haul flights, also reported in a survey a significant increase in fatigue with advancing duty time [17]. A comparison between short-haul and long-haul pilots showed no difference; progressive fatigue occurred in both groups as duty time progressed.

The finding that the objective concentration ability was still stabil partially contradicts the rest of the literature. A study by Arsintescu et al. [16] with 44 airline pilots performed a 5-min PVT pre-flight, mid-flight, and post-flight have shown a significantly prolonged reaction time between the pre-flight and in-flight test points and pre-flight and post-flight test points. However, our PVT results are consistent with a laboratory study [18]. Two test groups were observed for 88 h. One group was subjected to total sleep deprivation, while the other group slept for a total of seven times at 12-h intervals for 2 h. A 10-min PVT was performed every 2 h. During the first 16 h of wakefulness, mean reaction time and number of lapses did not differ significantly between groups, only after this time did the results of the total sleep deprivation group become significantly worse. With a flight duration of 14:46 h on the outbound flight and 12:25 h on the return flight, including stopovers, the duration of the subjects' use, including flight preparation and travel to the airport, was not far above the 16 h mentioned. In addition, each subject had the opportunity to sleep during the flights. A crew rest department was available for the flight crew during all flights with the *Airbus A350*. However, on the *Airbus A321* there was only one shared bed available for the pilots, the cabin crew rested on passenger seats separated with a curtain.

Furthermore, it must be recognized that the long exposure to mild hypoxia has an additional impact on fatigue and sleep quality of the flight crew during the flight. With the presented data, it is not possible to identify how prominent this impact is. Because all commercial aircraft usually operate at altitude of 30,000 ft, linked to a cabin altitude of almost 8000 ft, the flight crew also in modern aircraft is stressed by mild hypoxia during each flight [19,20]. Development in modern aircraft regarding composite structures and increased engine performance allow a modern airliner like the Airbus A350-900 to increase its operational range while also improving the cabin atmosphere on board. With a cabin altitude of only 6000 ft, the strain on crew and passengers through mild hypoxia is reduced. This has reduced the impact of mild hypoxia on cabin crew on these ULR flights.

In addition to this, factors related to the flight operation (like vibration, noise) or lifestyle factors (like smoking habits) can have an impact on the aircrew. Especially flight related factors will reduce the quality of sleep during rest and reduced the ability of concentration over time. Smoking habits of the air crew could also become a problem, because during every flight smoking is not possible. We think because the flight crews are adapted to flight operation procedures these habits will only have a small impact on concentration ability. Especially in our data we couldn't find a decrease of this ability in the FAIR-2-test or the PVT. It has to recognized that only a small number of the aircrew (in total 10 out of 28) were active smokers.

Because of the lack of scientific literature for this special occupational setting we have considered additional literature from other proffesionals who are also challenged with performing complex tasks at different times after long working hours while possibly experiencing fatigue. A study which has focused on surgeons performing emergency surgeries has analyzed rates of complications in postnighttime procedures as compared with controls found nonsignificant complication rates for procedures completed after working more than 12 h compared with 12 h or less (6.5 % complication rate vs. 4.3 % complication rate) [21]. The study also found that the risk of complications increases when the performing physician has slept less then 6 h vs. more than 6 h before the procedure. These findings support the findings in our study as there is no higher accident rate on ULR-flights than on shortler long haul flights. Also, pilots and cabin crew member do have access to crew rest compartments on long haul airliner and are required by law to rest after a certain duty time, so that there is the possibility to rest on these flights for decreasing fatigue before the more challenging final phase of the flight compared to the relatively uneventful cruise flight. These findings are in line with several other studies regarding patient outcome and errors during procedures performed by fatigued surgeons [22,23]. No significant difference was found comparing the primary outcome (death, readmission or complication) between patients who underwent a daytime procedure performed by a physician who had provided patient care after midnight and those who underwent a procedure performed by a physician who had not treated patients after midnight [22]. Sleep deficiency was not related to greater errors during procedures performed the next day, however surgeons compensated by working more slowly [23].

Our study has some strengths and limitations. Due to the very good cooperation of the test persons, there were almost no data failures during the surveys. Also, the 100 % participation rate did not lead to any distortions in the data collection, since all crew members flying with the aircraft and with a task as a pilot or a cabin crew member were included. Access to the flight deck was possible throughout all the flights, so the pilots could be assessed while on duty. The study used the FAIR-2 test and the PVT, two scientifically validated tests to measure objective attentional performance and concentration ability [15,14]. In addition to this the data for the 2nd flight crew was collected digitally on tablet computers. Digital data processing of the VAS eliminated reading and transmission errors during the evaluation.

A limitation of the study is, that it was the subjective assessment that was recorded instead of data obtained through an appropriate examination, such as polysomnography. This procedure was chosen, first, because other studies have shown that there is a high correlation between self-assessment by means of VASs and results of polysomnography [13] and, second, because it was not possible to carry out extensive testing of the aircrew during flight operations. Furthermore, the use of polysomnography instruments during the flight would have entailed the need for prior aviation certification linked to the aircraft type, which was not possibly for this study.

A weakness of the study is that only 28 subjects were assessed during the study. The fact that the flights performed were test flights with only ACM without any task and with no additional passengers on board, resulted in a lower workload for the cabin crew compared to a full passenger or VIP flight. It would be reasonable to assume that a similar study with a significantly higher workload would have resulted in significantly higher effort levels, particularly for cabin crew and possibly higher fatigue and exhaustion symptoms. However, this cannot be conclusively stated, based on the available data. For the pilots the workload is similar to every other flight, because it makes no real difference because the flight operation procedure is the same regardless of how full the airplane is.

Similarly, there are no records of sleep duration and physical activity from the days before and after the flights, which would have simplified the longitudinal classification of these data. With the chosen study methods, a comparison of the data collected during the flights with the everyday life of the subjects was not possible due to the short duration of the study.

In summary, the results showed a significant increase of subjective fatigue with flight time, especially during night hours at the window of circadian low. However, objective concentration performance, measured by the FAIR-2 test and the 3-min PVT, did not significantly deteriorate over time. This may explain why there is no evidence of increased accident rates during landing compared to take-off, which may be due to selective concentration retrieval.

Ethics statement

This study was reviewed and approved by Ethics Committee of the Medical Faculty of Otto-von-Guericke-University Magdeburg, with the approval number: Az 153/21. All participants provided informed consent to participate in the study.

Data availability statement

The data associated with this study aren't deposited into a publicly available repository. The data will be made available on request. Request has to been addressed to the German Ministry of Defense.

CRediT authorship contribution statement

David Gläsener: Writing – original draft, Data curation, Conceptualization. **Janina Post:** Writing – review & editing, Writing – original draft, Data curation. **David Cyrol:** Writing – review & editing, Formal analysis. **Stefan Sammito:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Janina Post reports a relationship with German Armed Forces (Bundeswehr) that includes: employment. David Glaesener reports a relationship with German Armed Forces (Bundeswehr) that includes: employment. David Cyrol reports a relationship with German Armed Forces (Bundeswehr) that includes: employment. Stefan Sammito reports a relationship with German Armed Forces (Bundeswehr) that includes: employment.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e21669.

References

[1] J.A. Caldwell, M.M. Mallis, J.L. Caldwell, M.A. Paul, J.C. Miller, D.F. Neri, Fatigue countermeasures in aviation, Aviat Space Environ. Med. 80 (1) (2009) 29–59 (eng).
[2] R.R. Rosa, M.H. Bonnet, Performance and alertness on 8 h and 12 h rotating shifts at a natural gas utility, Ergonomics 36 (10) (1993) 1177–1193 (eng).
[3] A. Samel, H.M. Wegmann, M. Vejvoda, Aircrew fatigue in long-haul operations, Accid. Anal. Prev. 29 (4) (1997) 439–452 (eng).
[4] J.H. Goode, Are pilots at risk of accidents due to fatigue? J. Saf. Res. 34 (3) (2003) 309–313 (eng).
[5] J. Graf, U. Stüben, S. Pump, In-flight medical emergencies, Dtsch Arztebl Int 109 (37) (2012) 591–602.
[6] W. Hurd Wiliam, W. Beninati (Eds.), Aeromedical Evacuation. Management of Acute and Stabilized Patients, second ed., Springer Medizin Verlag, Cham (Switzerland), 2019.
[7] Airbus, A Statistical Analysis of Commercial Aviation Accidents 1958 - 2021, Saf. First, 2022, pp. 1–34.
[8] P. Gander, M. van den Berg, H. Mulrine, L. Signal, J. Mangie, Circadian adaptation of airline pilots during extended duration operations between the USA and Asia, Chronobiol. Int. 30 (8) (2013) 963–972 (eng).
[9] P.H. Gander, H.M. Mulrine, van den Berg, J. Margo, A.A.T. Smith, T.L. Signal, L.J. Wu, et al., Pilot fatigue: relationships with departure and arrival times, flight duration, and direction, Aviat Space Environ. Med. 85 (8) (2014) 833–840 (eng).
[10] M.J. van den Berg, T.L. Signal, H.M. Mulrine, A.A.T. Smith, P.H. Gander, W. Serfontein, Monitoring and managing cabin crew sleep and fatigue during an ultra-long range trip, Aerospace medicine and human performance 86 (8) (2015) 705–713 (eng).
[11] M. Castro, J. Carvalhais, J. Teles, Irregular working hours and fatigue of cabin crew, Work 51 (3) (2015) 505–511 (eng).
[12] S. Sammito, D. Cyrol, J. Post, Fatigue and ability to concentrate in flight attendants during ultra-long-range flights, High Alt. Med. Biol. 23 (2) (2022) 159–164. https://pubmed.ncbi.nlm.nih.gov/35394345/.(eng.
[13] P. Philip, P. Sagaspe, J. Taillard, C. Valtat, N. Moore, T. Akerstedt, et al., Fatigue, sleepiness, and performance in simulated versus real driving conditions, Sleep 28 (12) (2005) 1511–1516 (eng).
[14] F. Petermann, Frankfurter aufmerksamkeits-inventar 2 (FAIR-2), Z. Psychiatr. Psychol. Psychother. 59 (2011) 325–326.
[15] L. Arsintescu, K.H. Kato, P.F. Cravalho, N.H. Feick, L.S. Stone, E.E. Flynn-Evans, Validation of a touchscreen psychomotor vigilance task, Accid. Anal. Prev. 126 (2019) 173–176 (eng).
[16] L. Arsintescu, C. Hilditch, K. Kato, K. Gregory, Changes in alertness and performance over time during long-haul flying across multiple time zones, Aerosp Med Hum Perf 93 (3) (2022) 248.
[17] S. Bourgeois-Bougrine, P. Carbon, C. Gounelle, R. Mollard, A. Coblentz, Perceived fatigue for short- and long-haul flights: a survey of 739 airline pilots, Aviat Space Environ. Med. 74 (10) (2003) 1072–1077 (eng).
[18] S.M. Doran, H.P. van Dongen, D.F. Dinges, Sustained attention performance during sleep deprivation: evidence of state instability, Arch. Ital. Biol. 139 (3) (2001) 253–267 (eng).
[19] Aerospace Medical Association, Aviation Safety Commitee, Civil Aviation Subcommittee, Cabin cruising altitudes for regular transport aircraft, Aviat Space Environ. Med. 79 (4) (2008) 433–439 (eng).
[20] J.J. Cottrell, Altitude exposures during aircraft flight. Flying higher, Chest 93 (1) (1988) 81–84 (eng).
[21] J.M. Rothschild, C.A. Keohane, S. Rogers, R. Gardner, S.R. Lipsitz, C.A. Salzberg, et al., Risks of complications by attending physicians after performing nighttime procedures, JAMA 302 (14) (2009) 1565–1572 (eng).
[22] A. Govindarajan, D.R. Urbach, M. Kumar, Q. Li, B.J. Murray, D. Juurlink, et al., Outcomes of daytime procedures performed by attending surgeons after night work, N. Engl. J. Med. 373 (9) (2015) 845–853 (eng).
[23] S.F. Quan, C.P. Landrigan, L.K. Barger, J.D. Buie, C. Dominguez, J.M. Iyer, et al., Impact of sleep deficiency on surgical performance: a prospective assessment, J. Clin. Sleep Med. : JCSM : official publication of the American Academy of Sleep Medicine 19 (4) (2023) 673–683 (eng).