

EMCO SIPO EASA.2022.C17

**D-6.2 - ANCILLARY REPORT ON TASK 4 "DURATION OF SLEEP INERTIA"
AND TASK 6 "PILOT FATIGUE AND BOREDOM"**

eMCO-SiPO – Extended Minimum Crew Operations- Single Pilot Operations

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CONTRACT NUMBER: EASA.2022.C17
CONTRACTOR / AUTHOR: NLR / Dr. Dorothee Fischer, Jan-Philipp Buch, Dominik Niedermeier (DLR)
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APPROVED BY:	AUTHORS	REVIEWER	MANAGING DEPARTMENT
Alex Rutten	Dorothee Fischer (DLR) Jan-Philipp Buch (DLR) Dominik Niedermeier (DLR)	Alwin van Drongelen (NLR)	AOSH

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SUMMARY

In light of recent developments in technology and automation in commercial aviation, flights with reduced crews appear possible. In so-called *extended Minimum-Crew Operations* (eMCOs), one pilot has control over the aircraft ('Pilot Flying') while the other pilot is allowed to rest and sleep ('Pilot Resting'). In eMCOs, sleep inertia –a state of cognitive impairment immediately after awakening– is a potential safety hazard in case the eMCO segment is aborted and the Pilot Resting needs to take action while cognitively impaired by sleep inertia. In addition, fatigue and boredom levels may increase for the Pilot Flying due to being alone at the controls for an extended period of time. This study aimed to examine sleep inertia, fatigue and boredom of professional pilots during simulated eMCO segments in a flight simulator scenario.

Methods. The study was conducted at the AVES flight simulator center of the DLR-Institute for Flight Systems in Braunschweig, Germany. Five crews (n = 10 pilots) took part in the experiment, completing one of two conditions: aborted vs. non-aborted eMCO segment. In both conditions, the crew begins the simulation together in cruise phase. At 30 minutes into the simulation, the eMCO segment starts, with one pilot becoming Pilot Flying (PF) and the other becoming Pilot Resting (PR). In the aborted condition, the segment ends unexpectedly after 67 minutes due to an unforeseen airport closure, followed 3 minutes later by an engine fire. In the non-aborted condition, the eMCO segment ends as planned after 2.5 hours without interruption, and the airport closure (followed 3 minutes later by the engine fire) occurs at 37 minutes after the end of the eMCO segment. Self-reported ratings of fatigue, workload, and boredom were assessed at 30-min intervals throughout the simulated flight scenario. Sleep (e.g., duration, stages) was assessed objectively, using an adhesive, soft electrode grid, attached to the PR's face, recording brain activity (EEG), eye movements (EOG), and facial muscle movements (EMG). Crew performance was quantified as (i) time to complete several ECAM (Electronic Centralized Aircraft Monitor) actions, and (ii) success in clearing the engine fire warning, determined as 'full' (both PF and PR complete their respective tasks) vs. 'partial' (one or more tasks of the PR are taken over by the PF).

Results. In the non-aborted condition, pilots slept for 99 minutes on average out of a 130-minute sleep opportunity. Beneficial effects of the nap on subsequent fatigue levels were mixed, potentially due to a limited post-nap measurement period. Fatigue and boredom were higher during the eMCO segment than before or after the segment. Workload during the engine fire was perceived as slightly higher in the aborted-eMCO than the non-aborted-eMCO condition. PRs in the aborted-eMCO condition woke up within the time window of sleep inertia. Crew performance (i.e., time to complete several ECAM actions) did not differ between the two conditions. Out of three crews in the aborted-eMCO condition, the PR of one crew did not deem himself fit to act upon awakening in the aborted-eMCO group, leaving the PF to complete the ECAM actions by himself, which he managed to do but with reportedly higher effort.

Conclusions. In this specific scenario and based on a limited sample size, sleep inertia did not affect crew speed to complete several ECAM actions. Fatigue and boredom levels were rated higher during than before or after the eMCO segment, while workload was rated lower. The optimal length of eMCO segments should balance several aspects, including supporting restorative effects of the nap (PR), limiting sleep inertia upon waking (PR), and allowing for physiological breaks (PF). Caution is warranted not to offset potential positive effects of prolonged sleep opportunities by negative side effects, such as increased fatigue and boredom due to being alone at the controls for an extended period.

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ABBREVIATIONS

ACRONYM	DESCRIPTION
ANOVA	ANalysis Of VAriances
ATC	Air Traffic Control
AVES	Air Vehicle Simulator
BMI	Body Mass Index
D-4	Deliverable report on Task 4 „Duration of sleep inertia“
DLR	German Aerospace Centre (German: Deutsches Zentrum für Luft- und Raumfahrt)
DSGVO	Datenschutzgrundverordnung (German for: General Data Protection Regulation)
EASA	European Aviation Safety Agency
ECAM	Electronic Centralized Aircraft Monitor
EF	Engine Fire
EFC	Engine Fire Clear
EEG	Electroencephalogram
EOG	Electrooculogram
EMG	Electromyogram
eMCOs	extended Minimum Crew Operations
EU	European Union
FA1	Fire Agent 1
FA2	Fire Agent 2
FL	Flight Level
FMS	Flight Management System
ISA	Instantaneous Self-Assessment
KSS	Karolinska Sleepiness Scale
MSBS-8	Multi-dimensional State Boredom Scale
NASA	National Aeronautics and Space Administration
NLR	Royal Netherlands Aerospace Centre (Dutch: Koninklijk Nederlands Lucht- en Ruimtevaartcentrum)
NM	Nautical Mile
NREM	Non-Rapid Eye Movement sleep
OPF	Operational Flight Plan
PF	Pilot Flying
PR	Pilot Resting
REM	Rapid Eye Movement sleep
RT	Reaction Time
SD	Standard Deviation
SP	Samn-Perelli fatigue scale
ThLi	Thrust Lever Idle
TLX	Task Load index
ToD	Top of Descent

WOCL

Window of Circadian Low

1. Context

1.1 Background

With recent developments in technology and automation, interest in the feasibility to operate large airplanes with reduced flight crews in commercial aviation is growing rapidly. So-called 'extended Minimum-Crew Operations' (eMCOs) envision two-pilot crews assuming different roles during cruise phase: one pilot ('Pilot Flying') controls the aircraft, while the other pilot ('Pilot Resting') is resting and/or sleeping (inside or outside the cockpit, depending on manufacturer/airline specifications).

A key question for the safety of eMCOs is what happens if an event occurs that forces the abortion of the eMCO segment (i.e., incapacitation of PF, system failure) requiring the Pilot Resting (PR) to take action while being in a state of sleep inertia. Sleep inertia refers to a transient state of 'grogginess' and disorientation immediately after waking up, during which cognitive performance is impaired. To determine the operational safety of eMCOs, the effect of a pilot operating an aircraft while cognitively impaired due to sleep inertia needs to be further investigated.

Furthermore, being alone at the controls for an extended period of time may increase levels of fatigue and boredom of the Pilot Flying (PF) beyond time-awake and time-on-task effects. Hence, the impact of eMCOs on fatigue and boredom of the PF and potential implications for crew performance also need to be examined.

1.2 Scope and objectives

Deliverable D-4.2/6.2 is an ancillary report describing the set-up and results of a flight simulator experiment conducted as part of Task 4 "Duration of sleep inertia" and Task 6 "Pilot fatigue and boredom" of the research activity "Extended Minimum Crew Operations – Single Pilot Operations – Safety risk assessment framework" (EASA.2021.HVP.23). The experimental study combines objectives from Task 4 and 6 to empirically investigate sleep inertia, fatigue, workload, and boredom during eMCO segments in a flight simulator scenario.

The primary aims were to examine (i) effects of sleep inertia on crew performance, following an unscheduled abortion of the eMCO segment (part of Task 4); and (ii) trajectories of fatigue, workload, and boredom before, during, and after a non-aborted, 2.5-h long eMCO segment (part of Task 6). A secondary aim was to characterize sleep during eMCOs, including duration, efficiency, and structure (i.e., sleep stages).

The report is structured as follows: Chapter 2 provides a detailed description of the methods and the experimental approach used in this study, including study protocol, description of the flight simulator scenario, and application of subjective and objective measures. Chapter 3 presents the study results for sleep, fatigue, workload, boredom, and crew performance, including a qualitative summary of pilots' feedback gained during the debriefing. The report concludes with a discussion of the main findings, challenges and limitations of the study, and future directions in Chapter 4.

2. Methodology and experimental approach

2.1 Study protocol

The study was conducted collaboratively by the DLR-Institute of Aerospace Medicine (Cologne, Germany), Department of Sleep and Human Factors (KP-ME-SHF), and the DLR-Institute for Flight Systems (Braunschweig, Germany), Department of Flight Dynamics and Simulation (BS-FT-FDS). Data collection took place at the flight simulator center of the DLR-Institute for Flight Systems in Braunschweig, Germany. The flight simulator center includes the Air Vehicle Simulator (AVES), a high-fidelity simulator of an Airbus A320 cockpit. The main area of research is the investigation of the dynamic interaction between cockpit crew and air vehicle. The electro-mechanically driven motion system provides a highly immersive experience for participating cockpit crews, e.g., 15 LED projectors produce a 240° x 95° field of view and the simulator cockpit and its components are based on the real A320 cockpit. In addition to the flight dynamics including ground handling, the simulator software contains all flight management, autopilot and flight control functions of a real-world flight system.

The original study protocol (Figure 1A) was designed as a counterbalanced, within-subject design that aimed for ten crews (n = 20 participants) to make two visits in randomized order to the flight simulator center. Recruitment for this study proved difficult (see Chapter 4.2 “Challenges, limitations, and future directions”) and ultimately, the design was adapted to a between-subject design, with one visit per crew to the Braunschweig research center (Figure 1B).

Each visit included one test day, preceded by an overnight stay to facilitate early-morning arrival at the flight simulator site. Participants were reimbursed for their travel and accommodation costs. Each test day lasted 6-8 hours and included a 2-hr briefing and a 2-hr to 4-hr test session, during which participants performed an eMCO segment in the flight simulator, that either ended as scheduled (i.e., PR shows no sleep inertia) or was aborted due to an unexpected airport closure and followed by a system failure that required the PR to take action (i.e., PR shows potential sleep inertia). Participants were not informed a-priori about the possible abortion of eMCO segments nor about the focus of the study on the effects of sleep inertia on flight simulator performance.

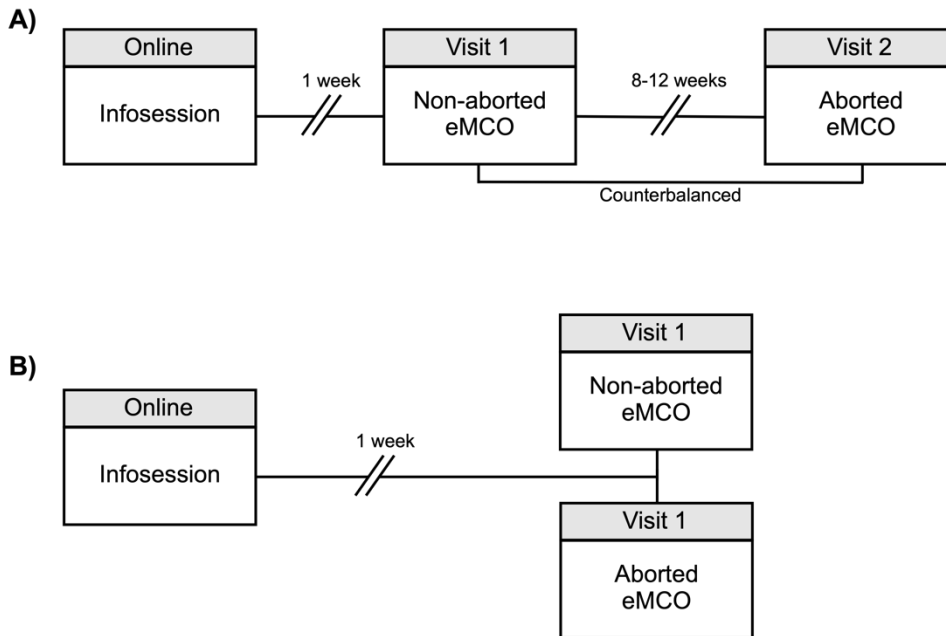


Figure 1: Study protocol. A) In the original study protocol, crews would visit the AVES flight simulator center at the DLR-Institute for Flight Systems in Braunschweig, Germany, twice in a counterbalanced, within-subject design. B) In the adapted study protocol, crews visited the AVES flight simulator center performing either a non-aborted or an aborted eMCO scenario in a between-subject design.

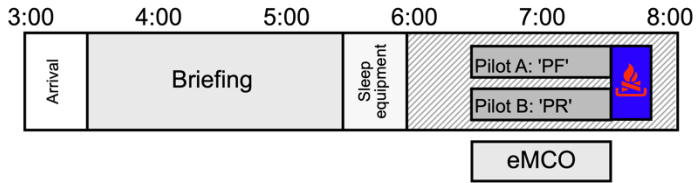
2.2 Examination protocol

Participants (N = 2 pilots per test day) arrived at 3:00 in the morning at the flight simulator center and participated in a 2-hr briefing, including a familiarization/training session in the flight simulator (Figure 2). After the briefing, the sleep-measuring equipment (i.e., EEG soft-grid) was attached to the PR. At 6:00, the test session started in cruise-phase, with both pilot A (Captain) and pilot B (First Officer) at the controls. At 6:30, the eMCO segment commenced, with Pilot B assuming the role of P R, while Pilot A continued in his role of PF. The role of PF was always assumed by the Captain and that of PR by the First Officer, to increase comparability across conditions and crews.

In case of an aborted eMCO, the segment was interrupted at 7:37 (67 min after the segment started) due to an unexpected airport closure, that fulfilled the criteria for eMCO abortion and thus required the PF to wake up the PR (Figure 2A). Within three minutes of the airport closure, a system failure was triggered (i.e., engine fire), that required the PR to become actively involved while potentially in a state of sleep inertia. After the system failure had been cleared, the simulator session was over and participants joined a de-briefing and feedback round, after which the test day was concluded.

In case of a non-aborted eMCO, the segment ended according to procedure without interruptions after 2.5 hours and the PR resumed his regular duties as Pilot Monitoring (Figure 2B). At 9:37 (37 min after the end of the eMCO segment), the same system failure as in the aborted-scenario occurred (airport closure, followed by engine 2 fire), requiring Pilot B (who assumed the role of PR during the eMCO segment) to take action. As in the aborted-eMCO condition, the simulator session was over after the system failure had been dealt with and participants joined a de-briefing and feedback round, after which the test day was concluded.

A) Aborted eMCO



B) Non-aborted eMCO

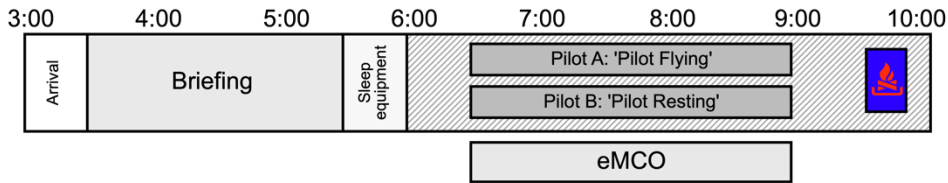


Figure 2: Examination protocol. A) In the aborted-eMCO condition, crews encountered the system failure (“engine 2 fire”, red fire symbol) 70 minutes into the eMCO segment, with the Pilot Resting (PR) potentially experiencing sleep inertia at the time of the failure. B) In the non-aborted-eMCO condition, the eMCO segment ended regularly after 2.5 hours and the system failure was triggered 40 minutes after the end of the eMCO segment (no inertia).

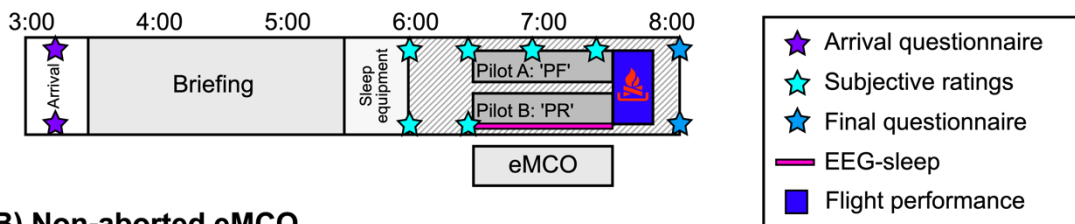
Table 1: Scheduled events during the examination protocol.

Time	Event
3:00	Arrival
3:15	Briefing (incl. training session in the flight simulator)
5:15	Attachment of sleep-measuring equipment
5:45	Preparations in the flight simulator (e.g., taking seats, getting ready)
6:00	Simulator session starts
6:30	eMCO segment starts
In case of aborted eMCO segment:	
7:37	Airport closure
7:40	Engine fire
~8:15	Simulator session ends, debriefing
In case of non-aborted eMCO segment:	
9:00	Segment ends
9:37	Airport closure
9:40	Engine fire
~10:15	Simulator session ends, debriefing

2.3 Methods

Several measurement methods were applied in the study (Figure 3), including subjective ratings (e.g., self-report scales of fatigue) and objective markers of sleep and performance (e.g., EEG-measures, reaction times).

A) Aborted eMCO



B) Non-aborted eMCO

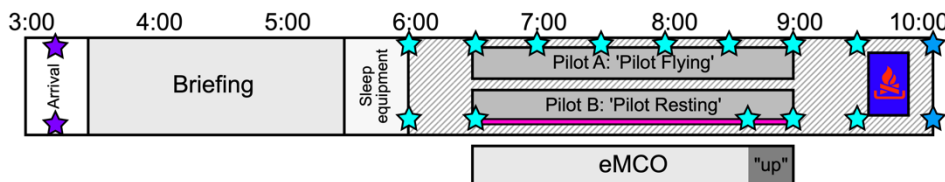


Figure 3: Data collection. Participants filled out questionnaires at arrival and upon completing the flight scenario, including sleep log and demographics (arrival), and the NASA Task Load index (completion). Subjective ratings of levels of fatigue, sleepiness, workload and boredom were collected every 30 minutes by the Pilot Flying (PF). The Pilot Resting (PR) filled out the scales at the beginning of the eMCO segment and again at 20 minutes before the end, when wakefulness was mandatory to dissipate potential sleep inertia effects before resuming the role of Pilot Monitoring. In the aborted-eMCO condition (panel A), the last timepoint for completing the scales was at 60 minutes into the eMCO segment for the PF, before the system failure was triggered.

2.3.1 Questionnaires and self-rating scales

All questionnaires and subjective scales were filled out on smartphones using the DLR Fit4Duty app (Figure 4).



Figure 4: Completing self-report scales in the AVES cockpit using the Fit4Duty app. ©Fraunhofer IDMT/Leona Hofmann.

2.3.1.1 Arrival questionnaire

Upon arrival, participants filled out a short sleep diary to assess their sleep-wake behavior right before arriving at the flight simulator center (including sleep duration and quality). The questionnaire further contained demographic questions regarding age, gender, and flying experience (e.g., years on aircraft type), an open question regarding their roster in the previous 3-5 days (to approximate accumulated fatigue), and a free-text field for any other comments.

2.3.1.2 Subjective assessments: sleepiness, fatigue, workload, and boredom

Throughout the test session in the flight simulator, participants rated their subjective levels of sleepiness, fatigue, workload, and boredom at several timepoints, e.g., start and end of the simulation, start and end of the eMCO segment, and, for PF only, at 30-min intervals during the eMCO segment (see Figure 3 above).

- **Karolinska Sleepiness Scale:** The KSS is a 9-pt Likert scale to assess subjective, acute sleepiness (Figure 5A).
- **Samn-Perelli Fatigue Scale:** The SP is a 7-pt Likert scale to assess subjective, acute fatigue (Figure 5B).
- **Instantaneous Self Assessment:** The ISA is a 5-pt Likert scale to assess subjective, acute workload (Figure 5C).
- **Multi-dimensional State Boredom Scale-8:** The MSBS-8 is a 7-pt Likert scale to assess subjective, acute feelings of boredom (Figure 5D).

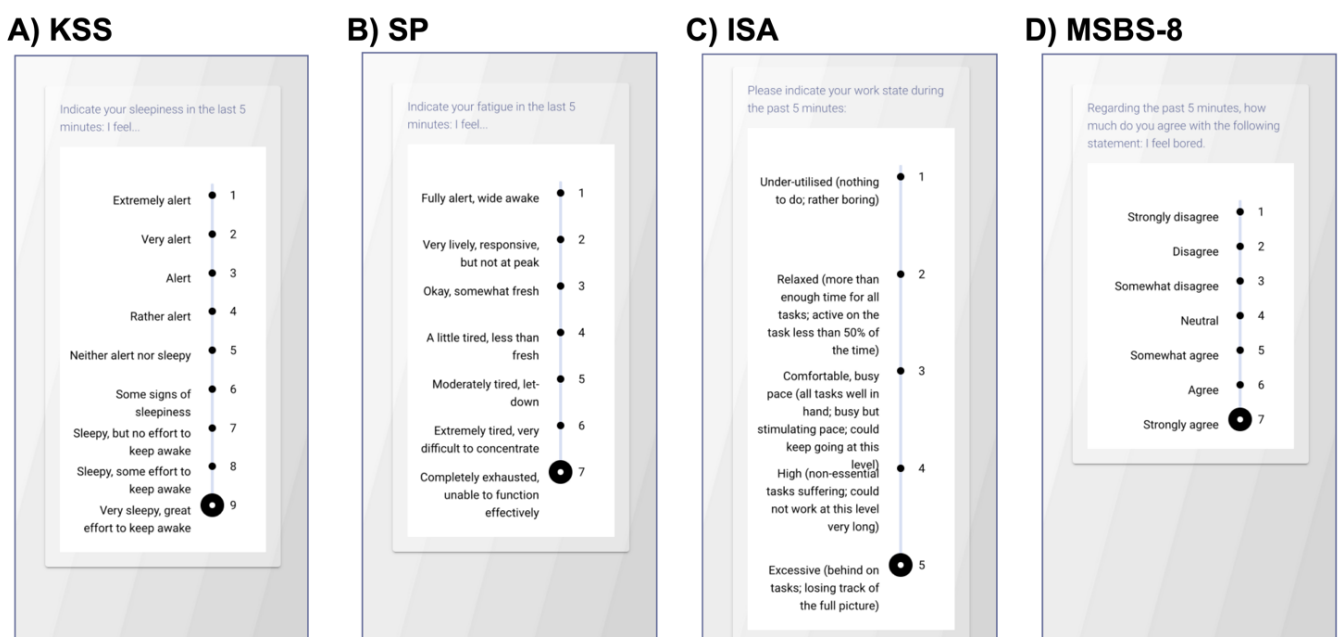


Figure 5: Subjective rating scales of A) sleepiness, B) fatigue, C) workload, and D) boredom. KSS = Karolinska Sleepiness Scale. Sp = Samn-Perelli Fatigue Scale. ISA = Instantaneous Self-Assessment. MSBS-8 = Multi-dimensional State Boredom Scale-8.

2.3.1.3 Final questionnaire

At the end of the simulation, before leaving the cockpit for the de-briefing session, pilots completed a final questionnaire, containing another round of ratings for sleepiness, fatigue, workload and boredom, as well as the NASA-Task Load Index (NASA-TLX). The NASA-TLX assesses workload in six dimensions: mental demand,

physical demand, temporal demand, performance, effort, and frustration. Pilots were instructed to rate the NASA-TLX for the period of the system failure.

2.3.2 Sleep

The PR was allowed to sleep in the cockpit during the eMCO segment. Head phones were taken off and neck pillow, ear plugs, sleeping mask and blanket were provided. The participants used all items, except for one pilot, who used the sleeping mask and ear plugs but no blanket or neck pillow. Sleep of the PR was assessed during both aborted and non-aborted eMCOs, using the *trEEGrid*-device ((da Silva Souto et al., 2022), a lightweight, flexible adhesive pad with a total of 10 electrodes that is attached to the side of the face and behind the ear (Figure 6). It measures one-channel EEG (brain activity), EOG (eye movements) and EMG (facial muscle movement), to determine sleep onset, offset, duration, and sleep stages (NREM (N1, N2, N3) and REM sleep). The *trEEGrid* is a validated alternative to assessing sleep by polysomnography, the gold standard for measuring sleep, that requires attaching a vast array of cables and electrodes to the head, face, and upper body (da Silva Souto et al., 2021). Using the *trEEGrid* allows to record sleep with minimal operational interference to pilots' flight simulator performance in a cockpit environment.



Figure 6: Measuring sleep. Sleep was assessed objectively using an adhesive, soft electrode grid that was attached to the participants' right side of the face. The grid has a comfortable wear, allows for flexible movements and does not interfere with pilots' tasks. ©Fraunhofer IDMT/Anika Bödecker/Leona Hofmann.

2.3.3 Flight simulation

2.3.3.1 Scenario

The simulated scenario was a long-distance ferry flight from Munich/Germany to Sal/Cape Verde with a total flight time of 6 h 13 m and a total distance of 2638 nm. The route is shown in Figure 7 and follows almost a great circle. For the non-aborted eMCO group, the scenario started in cruise flight at FL 370 near the German-Swiss border. The eMCO segment, with a duration of 150 minutes, extended from southern France to 170 nm beyond the south-eastern tip of Portugal. The scenario for the aborted eMCO control group started over mid-Spain with the eMCO segment extending from south-east Portugal to the northern tropics, but was aborted 470 nm out of Portugal by the notification of an unexpected closure of the destination airport by ATC. For both scenario variants, OFPs were generated containing eMCO entry and exit waypoints. These waypoints were later programmed into the FMS flight plan and displayed on the aircraft navigation display. The main time-critical scenario event selected was an Engine 2 fire triggered when the aircraft was in the centre of the triangle between the Canary Islands, Madeira and Morocco (see Figure 8). The weather situation is designed so that there is no best diversion decision and the crew has to choose between non-optimal alternatives.

The scenario timeline is shown in Table 2 with the distinction between the two scenario variants aborted vs. non-aborted eMCO. In the aborted eMCO scenario, 67 minutes after the start of the eMCO segment, ATC

informed the PF that the destination airport had unexpectedly closed, which should lead the PF to abort the eMCO segment according to the previously briefed abort-criteria. If the PF had not alerted the PR within one minute of the ATC call, the experiment lead gave the instruction to awaken the PR over the intercom. In case of the non-aborted eMCO, the PF woke the PR up 20 minutes before the eMCO exit waypoint, for sleep inertia dissipation. For comparability between the two conditions, when overflying the eMCO exit waypoint, ATC made the same "destination airport closed" announcement, occurring three minutes before the Engine 2 fire event in both scenarios.

Table 2: Scenario timeline for the aborted and non-aborted scenario variants

Timeline		
When		Event
Aborted	Non-aborted	
		Crew enters cockpit
		Sim will be set up (10 min)
	T0	Crew ready to fly → sim is released
	T0 + 25	eMCO Briefing (5 min)
	T0 + 30	Start of eMCO-Segment at 17 nm inbound MEBAK (non-aborted eMCO) or 23 nm inbound ADINO (aborted eMCO)
		PR (FO) begins rest
	T0 + 97	If aborted eMCO: ATC advises that the destination airport unexpectedly closed due to a landing accident. The closure is expected to continue for the next five hours.
	T0 + 98	If aborted eMCO: if the PF has not alerted the PR within 1 min, the PF will be notified by the experiment leader to abort the eMCO segment and alert the PR
	T0 + 160	If non-aborted eMCO: the PR is woken up (by the PF)
	T0 + 180	If non-aborted eMCO: planned end of eMCO segment, PF on duty again
	T0 + 217	If non-aborted eMCO: ATC advises that the destination airport unexpectedly closed due to a landing accident. The closure is expected to continue for the next five hours.
T0 + 100	T0 + 220	Engine 2 Fire is triggered



Figure 7: Flight route from Munich to Sal with eMCO entry and exit waypoints and the location where the Engine 2 fire is triggered.

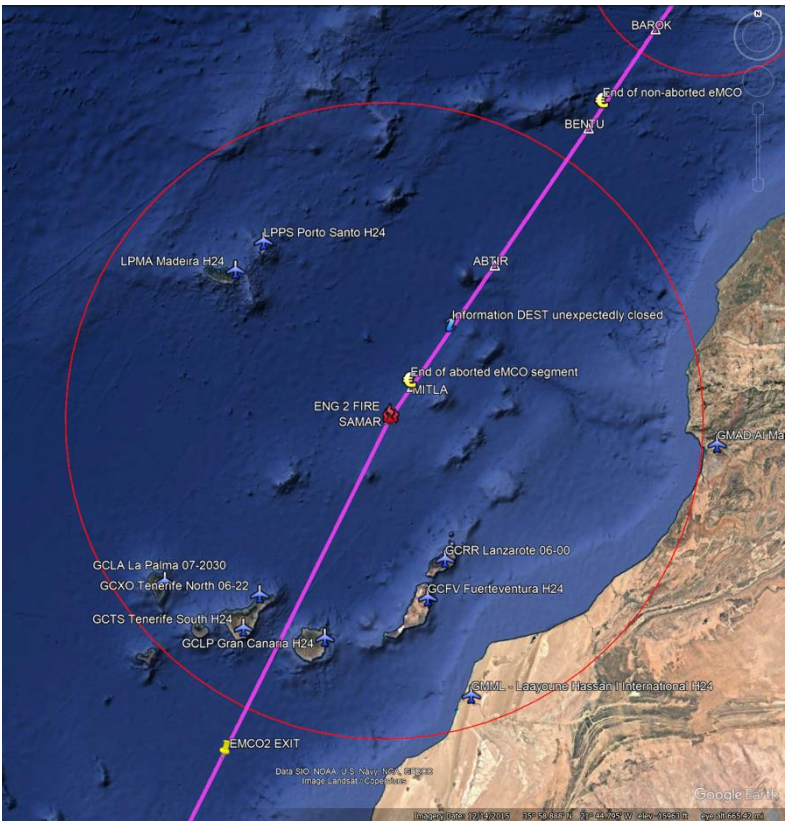


Figure 8: Zoom of the flight route around the Engine 2 fire trigger location.

2.3.3.2 Performance

Flight simulator performance was assessed based on speed and accuracy, i.e., by measuring the time to solve the simulated system failure (i.e., executing multiple ECAM (Electronic Centralized Aircraft Monitor) action items) respectively, by success in solving the failure (yes/partial) (Figure 9). Partial failure of the PR was determined by the PF taking over any of the PR's tasks, assessed from video recordings. During the eMCO segment, the PR was resting/sleeping, while the PF was in charge of operating the aircraft. At 67 minutes after the start of the eMCO segment, the PF was informed by ATC (acted by a DLR study staff member) about an unexpected airport closure, requiring him to alert the PR (as per eMCO guidelines; if the PF had not alerted the PR within 1 min, the PF was notified by the principal investigator to do so). Within 3 minutes of the airport closure, an Engine 2 fire was triggered. The rationale for announcing an airport closure before triggering the engine fire was to make sure that the PR was already alerted, but still in a state of sleep inertia at the time of the system failure. Otherwise, the PF (i.e., the Captain in the study's assignment of roles) may start clearing the ECAM actions on his own, while the PR is still in the process of waking up. As performance indicators, durations ("reaction times", RT) from Engine 2 fire to the execution of several ECAM action items (RT_1 , RT_2 , RT_n) until the clearance of the system failure (i.e., successful execution of the last action item, $RT_{overall}$) were calculated. Specifically: Engine 2 thrust lever idle time (ThLI); fire push button pushed (FBP); fire agent 1 release (FA1); fire agent 2 release (FA2); and engine fire clear (EFC) were measured.

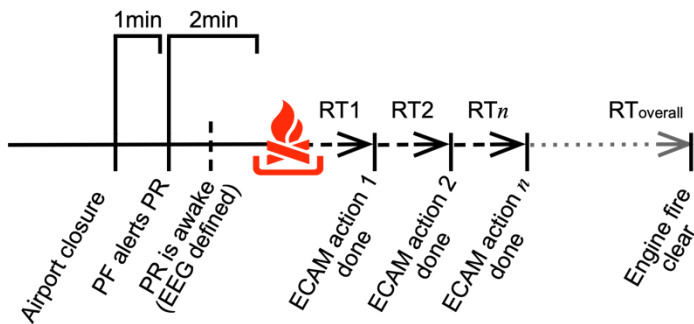


Figure 9: Crew performance endpoints. Reaction times were measured from the onset of Engine 2 fire to several ECAM actions (RT_1 , RT_2 , ...) until the engine fire warning was cleared ($RT_{overall}$).

2.3.3.3 Debriefing

After having completed the flight simulation, pilots joined a ~30-min debriefing session, during which they were given the opportunity to provide feedback about aspects they deemed important regarding the study's execution, their experience in their respective roles, as well as eMCOs in general. Excerpts from the video records were shown to go over the pilots' performance. The debriefing was non-standardized and served a two-fold purpose: to get qualitative input from participants and to show and discuss with them case-specific scenes.

2.4 Study population and recruitment

Participants were recruited via several means: from (i) the institutional database of the DLR-Institute for Flight Systems, comprising pilots who have previously participated in flight simulator sessions, (ii) publicly available type rating examiner databases from several aviation authorities, (iii) pilot unions that disseminated the invitation among their members, and (iv) invitations sent out by the NLR and EASA to their industry contacts. Interested pilots then participated in an online information session. The session included a medical briefing conducted by the responsible study physician. Participants were also offered a one-on-one follow-up meeting with the physician if they had more questions and/or personal concerns. No participant followed up on the offer. After the online information session, participants received supplemental study materials, including the

information for test subjects, consent form for test subjects, contract for test subjects, data protection declaration, and insurance policy information, based on which they could further familiarize themselves with the study procedures and implications of participation.

Participants were included if they signed the informed consent, the contract for test subjects, and the data protection declaration, and if they fulfilled the following criteria: valid A320 family type rating; between 18 and 60 years; BMI ≥ 18 or ≤ 30 kg/m²; no medication influencing the examination parameters (e.g., sleeping aids); no acute or chronic diseases; no alcohol and/or drug addiction; no above-average caffeine consumption (i.e. >4 cups of coffee/black tea per day); no nicotine consumption (e.g., smoker). All health-related information were self-reported and not verified independently.

2.5 Statistical and descriptive analyses

The primary statistical analysis was planned as a paired t-test, comparing flight simulator performance of the PR (i.e. reaction times in response to the system failure) between aborted vs. non-aborted eMCOs. For this comparison, only PRs who were asleep before the system failure occurred in the aborted eMCO (i.e. in a state of sleep inertia) were to be included. In a secondary analysis, PRs, who were awake before the system failure during the aborted eMCO segment, would serve as a second control group (e.g., pilots not suffering from sleep inertia but in a state of increased stress and/or rest inertia), using a 2 x 2 mixed-effects ANOVA to compare reaction times of PRs with and without sleep inertia (2-level between-subject factor) between aborted vs. non-aborted eMCO segments (2-level within-subject factor). However, due to the limited sample size and the resulting between-subject design, no inferential statistics can be conducted and the report provides descriptive analyses of the collected data.

2.6 Ethical approval and data protection

The study was conducted in accordance with the guidelines of the Declaration of Helsinki (64th WMA General Assembly, Fortaleza, Brazil, October 2013) and is registered at the German Clinical Trials Register (No. DRKS00033247). Ethical approval was granted through the ethical committee of the Ärztekammer Nordrhein before the start of the study. As part of the ethical approval requirement, participants were given sufficient time to reflect after a detailed explanation of the study aims and procedure took place in an online meeting, with the study PIs and the responsible study physician present. Participants had the option at any time to terminate the study at their own request without giving reasons.

Participants were insured by a commuting accident insurance policy. Expenses for travel and overnight stay were covered but participants did not receive reimbursement for their study participation. Participants were advised not to operate heavy machinery or drive vehicles on the day of the study due to potential sleep-loss induced cognitive impairments.

All data collected was handled according to German data protection (DSGVO) and medical confidentiality regulations. Protection of personal identifiers was realized by pseudonymization: personal identifiers (e.g., names) were replaced by a randomly generated alpha-numerical code (e.g., JHKS567). The key file, connecting the personal data to the code number, is stored on a protected DLR server with access restricted to the study personnel. After the legal retention period of ten years has expired, the key file will be deleted and the data are then available in anonymized form only.

3. Results

3.1 Descriptives

3.1.1 Study sample

Five crews (ten pilots) with Captain – First Officer pairings made one visit to the AVES flight simulator center at the DLR-Institute for Flight Systems in Braunschweig, Germany. Two crews completed a non-aborted eMCO scenario and three crews completed an aborted eMCO scenario. One crew in the aborted eMCO condition had a technical malfunction of the EEG-amplifiers leaving sleep data from $n = 4$ crews for analysis. Table 3 shows the sample descriptives.

Table 3: Sample descriptives (n = 5 crews / 10 pilots).

Variable (mean \pm sd)	Non-aborted eMCO (n = 4)	Aborted eMCO (n = 6)	Total sample (n = 10)
Age (years)	38.3 (\pm 8.0)	43.7 (\pm 12.2)	42.3 (\pm 9.6)
Gender (% male)	100	100	100
Flight experience			
Years on model (range)	6.4 (1.5 – 18)	10.5 (5 – 22)	8.9 (1.5 – 22)
Hours on model (range)	3,513 (750 – 8500)	5,717 (2000 – 14,500)	4,970 (750 – 14,500)
Sleep duration [§] (hours)	3.4 (\pm 0.4)	4.1 (\pm 0.5)	3.6 (\pm 0.6)

[§]sleep duration immediately before visiting the flight simulator center.

3.2 Sleep

Table 4 shows an overview of the EEG-derived sleep parameters. The non-aborted scenario provided a sleep opportunity of 130 minutes during the eMCO segment (150 minutes eMCO duration minus 20 minutes of wakefulness before resuming duties), compared to 67 minutes in the aborted scenario. Of these 130 minutes, PRs managed an average sleep period time of 112 minutes (86% of the sleep opportunity), of which 99 minutes were spent asleep (i.e., in sleep stages N1-3 and REM sleep, excluding short wake periods after sleep onset) (76% of the sleep opportunity). Across the two scenarios, it took PRs an average of 14 minutes to fall asleep (range = 10 – 20 min). As expected, in the non-aborted scenario, most of the sleep time (78%) was spent in lighter sleep stages (N1: 34 minutes; N2: 39 minutes), with 15% spent in deep sleep (N3: 18 minutes) and 7% minutes in REM sleep (8 minutes). PRs in the aborted scenario did not enter REM sleep but did experience short bouts of deep sleep, equaling 9% of their total sleep time (N3: 3 minutes). None of the PRs woke up from deep sleep but from either stage N1 or N2. Both PRs in the aborted scenario woke up from the light sleep stage N1, after an average total sleep time of 38 minutes. Time since sleep offset at the time of the engine fire was 3.9 minutes for the PRs in the aborted condition (range = 3.6 – 4.2 minutes).

Table 4: EEG-derived sleep parameters of the Pilot Resting (PR) during simulated flight scenarios with non-aborted vs. aborted eMCO segments.

Variable (mean ± sd)	Non-aborted eMCO (n = 2)	Aborted eMCO (n = 2)
Sleep Period Time ¹ (min)	111.5 (± 12.0)	55.0 (± 7.8)
Total Sleep Time ² (min)	99.3 (± 24.4)	38.0 (± 9.9)
Wake After Sleep Onset ³ (min)	12.3 (± 12.4)	17.0 (± 2.1)
Sleep Onset Latency ⁴ (min)	15.0 (± 7.1)	13.8 (± 4.6)
Sleep Efficiency ⁵ (%)	76.4	--
N1 (min/%)	34.3 (± 8.8) / 36.7	9.8 (± 7.3) / 34.0
N2 (min/%)	39.3 (± 3.2) / 41.2	21.5 (± 4.9) / 56.8
N3 (min/%)	17.5 (± 24.8) / 15.0	3.3 (± 1.1) / 9.2
REM (min/%)	8.3 (± 11.7) / 7.1	0.0 (± 0.0) / 0.0
Last Sleep Stage Before Awakening (%)		
N1	50	100
N2	50	0
Sleep Offset to Engine 2 Fire ⁶	61.5 (± 7.9)	3.9 (± 0.4)

¹duration from sleep onset to final sleep offset

²total duration of sleep stages N1, N2, N3, and REM

³duration of wake periods within Sleep Period Time

⁴time from eMCO start to sleep onset

⁵time spent asleep relative to eMCO sleep opportunity of 130 minutes (calculated for non-aborted eMCOs)

⁶time between final sleep offset and the onset of Engine 2 fire

3.3 Subjective ratings

Figure 10 shows the trajectories of sleepiness/fatigue (KSS, SP; panel A), workload (ISA; panel B) and boredom (MSBS-8; panel C) throughout the flight simulation for each crew.

3.3.1 Sleepiness/fatigue

Four out of five PFs (80%) reported high fatigue levels ($KSS \geq 7$, $SP \geq 5$) during the eMCO segment (Figure 10A and B, Table 5). In the non-aborted scenario, fatigue stayed at high levels until the end of the segment (Crew 1-2). Fatigue levels of one PF (Crew 2) decreased after the end of the eMCO segment, reportedly due to a mixture of higher workload and increased communication (e.g., transition briefing) as well as simply the fact of not being alone in the cockpit anymore. Yet, fatigue assessed by the SP scale remained at high levels despite decreasing, and fatigue levels of the other PF (Crew 1) remained unchanged and consistently high at $KSS = 7$ and $SP = 5$. In the aborted scenarios, fatigue levels of all PFs were rising before the engine fire was triggered (Crews 3-5).

Findings of delayed benefits by the sleep period of the PR (i.e., less sleepiness/fatigue after some time after awakening) were mixed at 20-50 minutes after the end of the eMCO segment: in the non-aborted condition, one PR reported identical fatigue levels to that of the PF, whereas the PR of the other crew was notably less fatigued than the PF (i) at the end of the 20-min inertia-dissipation period, and (ii) at 30 minutes past the end of the eMCO segment (Crew 2). Fatigue levels were overall similar between the PR and PF of all crews at the end of the simulation, potentially due to the alerting effect of the engine fire. One PR in the aborted scenario

rated his fatigue levels consistently high at KSS = 7 (Crew 5), while another reported consistently low levels of fatigue at KSS = 2-3 (Crew 4), illustrating the variation between individuals under comparable circumstances.

3.3.2 Workload

Workload was rated at or below a comfortable, busy pace (ISA = 3) before and during the eMCO segment in both conditions (Figure 10C, Table 6). When handling the engine fire, all crews expectedly reported higher levels than before, at an average of 3.9 ± 0.6 , rated as “high workload, non-essential tasks suffering, could not work at this level very long”. Workload was experienced as slightly higher in the aborted compared with the non-aborted condition (3.75 ± 0.50 vs. 4.00 ± 0.63), though significance testing was not possible due to limited sample size. One PR (Crew 3) reported reaching the highest work load level (ISA = 5, “Excessive; behind on tasks, losing track of the full picture”).

3.3.3 Boredom

The PFs of both crews in the non-aborted scenario reported high levels of boredom (MSBS = 6, “Agree” with “I feel bored”), though never the highest level (Figure 10D, Table 6). Initial levels of boredom during the eMCO segment did not differ between aborted and non-aborted conditions, as would be expected, since crews did not know that the eMCO segment would be aborted, further supporting increased levels of boredom during eMCO segments for the PF.

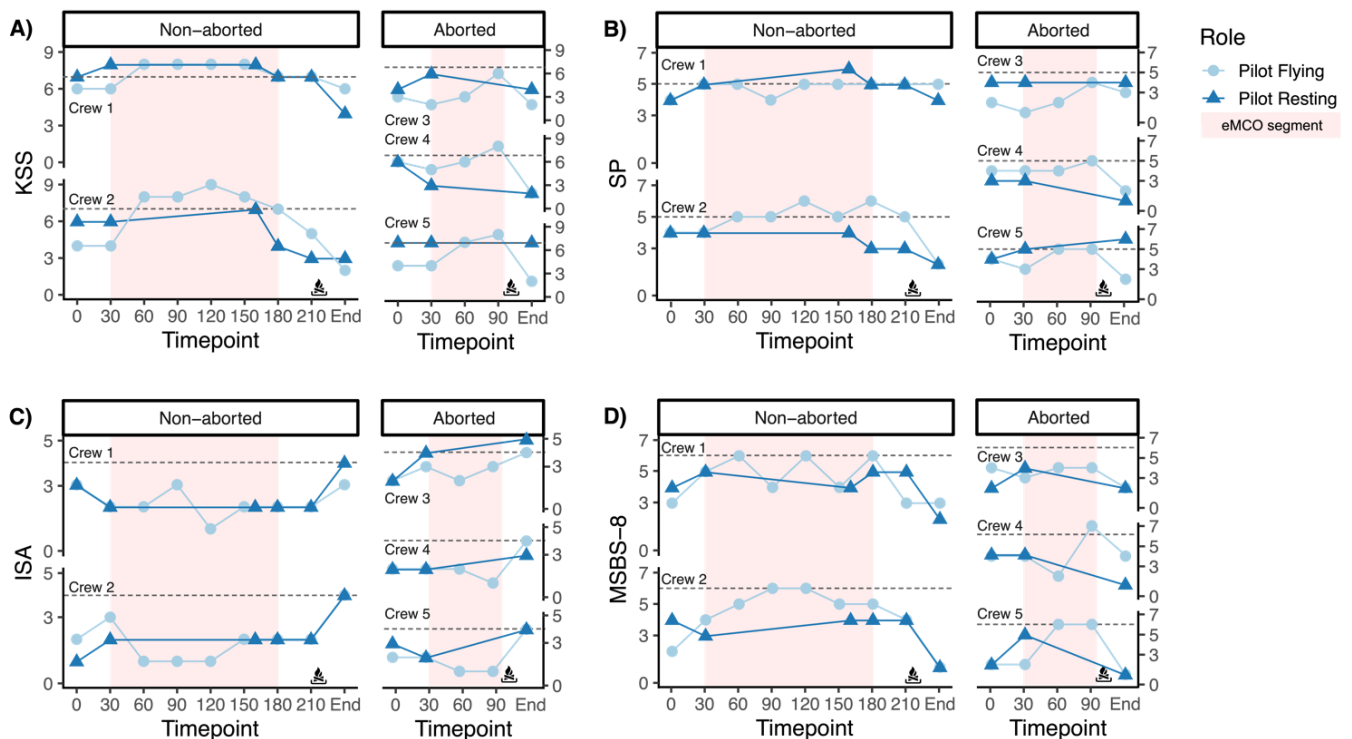


Figure 10: Sleepiness, fatigue, workload and boredom over the course of the simulated flight scenario. Pilots completed the ratings every 30 minutes, including at the beginning and end of the eMCO segment. During the non-aborted eMCO segment, PRs filled out the scales once, at 160 minutes into the simulation, i.e., when required to be awake 20 minutes before the regular end of the segment.

Table 5: Average subjective ratings of sleepiness/fatigue during simulated flight scenarios with non-aborted vs. aborted eMCO segments. Higher values indicate higher sleepiness (KSS), respectively, fatigue (SP).

Variable (mean ± sd)	Time- point	Non-aborted eMCO		Aborted eMCO	
		PF (n = 2)	PR (n = 2)	PF (n = 3)	PR (n = 3)
KSS (1-9)	Start	5.0 (± 1.4)	6.5 (± 0.7)	4.3 (± 1.5)	5.7 (± 1.5)
	30 min	5.0 (± 1.4)	7.0 (± 1.4)	3.7 (± 1.5)	5.3 (± 2.1)
	60 min	8.0 (± 0.0)	--	5.3 (± 2.1)	--
	90 min	8.0 (± 0.0)	--	7.3 (± 1.2)	--
	120 min (respectively, End)	8.5 (± 0.7)	--	2.0 (± 0.0)	4.3 (± 2.5)
	150 min	5.5 (± 3.5)	--	--	--
	160 min	--	7.5 (± 0.7)	--	--
	180 min	7.0 (± 0.0)	5.5 (± 2.1)	--	--
	210 min	4.0 (± 2.8)	5.0 (± 2.8)	--	--
	End	5.0 (± 1.4)	3.5 (± 0.7)	--	--
SP (1-7)	Start	4.0 (± 0.0)	4.0 (± 0.7)	3.3 (± 1.2)	3.7 (± 0.6)
	30 min	4.5 (± 0.7)	4.5 (± 0.7)	2.7 (± 1.5)	4.0 (± 1.0)
	60 min	5.0 (± 0.0)	--	3.7 (± 1.5)	--
	90 min	4.5 (± 0.7)	--	4.7 (± 0.6)	--
	120 min (respectively, End)	5.5 (± 0.7)	--	2.3 (± 0.6)	3.7 (± 2.5)
	150 min	4.0 (± 1.4)	--	--	--
	160 min	--	5.0 (± 1.4)	--	--
	180 min	5.5 (± 0.7)	4.0 (± 1.4)	--	--
	210 min	5.0 (± 0.0)	4.0 (± 1.4)	--	--
	End	3.5 (± 2.1)	3.0 (± 1.4)	--	--

PF = Pilot Flying; PR = Pilot Resting. KSS = Karolinska Sleepiness Scale. SP = Samn-Perelli Fatigue Scale.

Table 6: Average subjective ratings of workload and boredom during simulated flight scenarios with non-aborted vs. aborted eMCO segments. Higher values indicate higher workload (ISA), respectively, higher levels of boredom (MSBS-8).

Variable (mean ± sd)	Time- point	Non-aborted eMCO		Aborted eMCO	
		PF (n = 2)	PR (n = 2)	PF (n = 3)	PR (n = 3)
ISA (1-5)	Start	2.5 (±0.7)	2.0 (± 1.4)	2.0 (± 0.0)	2.3 (± 0.6)
	30 min	2.5 (±0.7)	2.0 (± 0.0)	2.3 (± 0.6)	2.7 (± 1.2)
	60 min	1.5 (±0.7)	--	1.7 (± 0.6)	--
	90 min	2.0 (± 1.4)	--	1.7 (± 1.2)	--
	120 min (respectively, End)	1.0 (± 0.0)	--	4.0 (± 0.0)	4.0 (± 1.0)
	150 min	2.5 (±0.7)	--	--	--
	160 min	--	2.0 (± 0.0)	--	--
	180 min	2.0 (± 0.0)	2.0 (± 0.0)	--	--
	210 min	2.0 (± 0.0)	2.0 (± 0.0)	--	--
	End	3.5 (± 0.7)	4.0 (± 0.0)	--	--
MSBS-8 (1-7)	Start	2.5 (± 0.7)	4.0 (± 0.0)	3.3 (± 1.2)	2.7 (± 1.2)
	30 min	4.5 (± 0.7)	4.0 (± 1.4)	3.0 (± 1.0)	4.3 (± 0.6)
	60 min	5.5 (±0.7)	--	4.0 (± 2.0)	--
	90 min	5.0 (± 1.4)	--	5.7 (± 1.5)	--
	120 min (respectively, End)	6.0 (± 0.0)	--	2.3 (± 1.5)	1.3 (± 0.6)
	150 min	3.0 (± 1.4)	--	--	--
	160 min	--	4.0 (± 0.0)	--	--
	180 min	5.5 (± 0.7)	4.5 (± 0.7)	--	--
	210 min	3.5 (± 0.7)	4.5 (± 0.7)	--	--
	End	2.0 (± 1.4)	1.5 (± 0.7)	--	--

PF = Pilot Flying; PR = Pilot Resting. ISA = Instantaneous Self-Assessment. MSBS-8 = Multi-dimensional State Boredom Scale.

3.4 Flight simulator performance

3.4.1 Speed

Figure 11 shows the time trajectory since 70 minutes before engine 2 fire was triggered and until the completion of several ECAM actions, including clearance of the engine fire. Time between awakening of the PR and the onset of the Engine 2 fire was 3.9 (± 0.4) minutes on average, well within the duration of sleep inertia. No discernible differences were observed between crews in the aborted vs. non-aborted scenario with regards to fire push button pushed, fire agent 1 released, and fire agent 2 released (Table 7). Crews in the aborted scenario were slower by 3.8 minutes to reach engine fire clear, when averaged across the three crews, and by 1.3 minutes when excluding Crew 3, which took 11 minutes until the engine fire warning was cleared from the ECAM. Engine fire clear is, however, not a time-critical action.

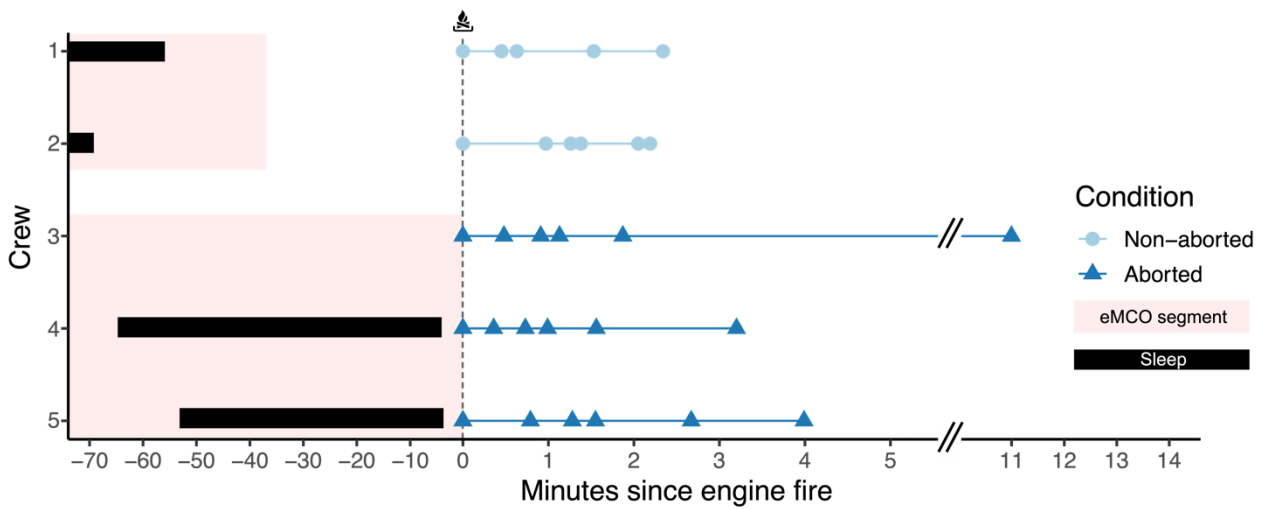


Figure 11: Crew performance measured as reaction times to complete several ECAM actions since onset of Engine 2 fire. The dots/triangles stand for the following ECAM actions (in this order): Engine 2 fire warning, Engine 2 Thrust Lever Idle, Fire Push Button Pushed, Fire Agent 1 released, Fire Agent 2 released, Engine 2 Fire Clear.

Table 7: Crew flight simulator performance measured as time elapsed between the onset of the system failure (i.e., Engine 2 fire) to completion of ECAM actions.

Variable (mean \pm sd)	Non-aborted eMCO (n = 2 crews)	Aborted eMCO (n = 3 crews)
Engine 2 Thrust Lever Idle (min)	0.9 (± 0.0) [#]	0.5 (± 0.2)
Fire Push Button Pushed (min)	0.9 (± 0.6)	1.0 (± 0.3)
Fire Agent 1 (min)	1.0 (± 0.5)	1.2 (± 0.3)
Fire Agent 2 (min)	1.8 (± 0.4)	2.0 (± 0.6)
Engine 2 Fire Clear (min)	2.3 (± 0.1)	6.1 (± 4.3)

3.4.2 Accuracy

Four out of five groups (80%) were able to successfully execute the ECAM actions, with PF and PR fulfilling their respective roles (e.g., PR, who by then is Pilot Monitoring, cross-checks actions by the PF). One out of three crews in the non-aborted condition succeeded partially, meaning that the ECAM actions and subsequent Engine 2 shutdown checklist were formally completed but the crew's PR did not judge himself to be fit to act, prompting the PF to take over the PM's role and cross-checking himself as best he could.

3.4.3 Debriefing

During the debriefing, participants had the chance to mention additional aspects they deemed important, to re-capitulate their experience and to air general comments about the study in particular and eMCOs in general. They were also shown scenes from the video material to go over and discuss key events.

- PFs reported different strategies to cope with flying alone and combatting fatigue during the eMCO simulation, such as frequently changing their posture (albeit in a manner that would not disturb the PR), getting frequent weather updates from ATC, checking-in with cabin (although much less frequently than they would outside of a simulation, changing the lights, checking data, and counting down the 30-min interval to the next fatigue assessment. They further reported that they would normally use strategies to mitigate fatigue and boredom that were not permitted during the simulation, such as consuming caffeine, food or sugary drinks, and that the absence of these otherwise applied countermeasures likely increased their fatigue and boredom levels. They also reported to have been careful not to disturb or accidentally wake their co-pilot, which sometimes affected their own behavior, e.g., moving not as much or not contacting cabin or ATC as often, as they may have or would have liked in other circumstances. They were also quite hesitant about aborting the eMCO, even though they quickly realized that airport closure was an abortion criteria.
- One PF mentioned that being awake and flying alone for an extended period may raise fatigue to such levels that the PF may be the bigger problem in case of an emergency than the PR who just woke up and is in a state of sleep inertia. The combination of both may be especially worrisome, where the crew consists of a bored, fatigued PF and an inertia-impaired PR. One PF in the aborted-eMCO condition said that, had the segment not be aborted due to the airport closure, he likely would have aborted the segment soon, in light of critically high fatigue he was expecting. Another crew raised the concern that positive effects gained through an extended sleep opportunity for the PR may be neutralized by increased fatigue and boredom of the PF due to being alone for an extended period.
- Several PFs said they believed to have had micro-sleep episodes and were at times at risk of falling asleep.
- Some PRs reported that sleep was not quite as restorative as crew rest, due to resting in the cockpit seat but also due to knowing that the other one was flying alone, which may have increased pressure to try to maintain a certain readiness-level. They further reported that they felt they had to make a greater effort to sustain their focus and concentration to clear the engine fire than they would have had to under rested conditions.
- Both PFs and PRs expressed concern that flying alone for extended periods will likely limit the opportunity of "learning on the job" and the important transfer of knowledge between more experienced and novice pilots. They also said that waiting for 20 minutes to dissipate sleep inertia without interaction felt artificial and may not be practical in real-life, suggesting that engaging with each other may even speed up the dissipation of sleep inertia.

- There was general feedback about the duration of the eMCO segment, with most pilots feeling that the duration of 2.5h could be shortened, primarily to facilitate physiological breaks-without having to abort the eMCO but also because sleeping for much longer (i.e., > 130min) may be difficult. Not using the restroom for more than two hours was perceived as near-impossible and potentially as the bigger problem than coping with fatigue. Dynamic scheduling of the length of eMCO segments was proposed, such as having longer or shorter segments according to, e.g. need for rest, time of day, time on task, level of fatigue, weather conditions, etc.
- There was general feedback from the crews in the aborted-eMCO condition that it was difficult and took longer to come together as a crew again, partially due to the PR just waking up, but also due to the PR being out of the loop for an extended time.
- One PF in the aborted condition said that at the time of the airport closure, he reduced the speed at which he performed his tasks, to give the PR more time to fully wake up. He later wondered whether some aspects of eMCOs may unintentionally lead to potentially unsafe decisions in other areas.
- The scenario of airport closure and subsequent Engine 2 fire was generally perceived as quite alerting, which may have helped overcome fatigue and/or inertia effects.
- One crew raised the question, what it would mean for the length of the flight duty period, if one or several eMCO segments had to be aborted and consequently the actual rest periods were much shorter than scheduled. This was seen as a key challenge: to determine which provisions to make for safe eMCOs, if one or several segments have to be aborted and consequently, fatigue is not managed as originally planned.

4. Summary and discussion

The report D-4.2/6.2 describes the set-up and findings of the experimental study conducted as part of Task 4 (“Duration of sleep inertia”) and Task 6 (“Pilot fatigue and boredom”) of the research activity “Extended Minimum Crew Operations – Single Pilot Operations – Safety risk assessment framework” (EASA.2021.HVP.23). Five 2-pilot crews participated in a flight simulator study, in which they experienced an eMCO segment, that was either aborted unexpectedly after approximately 60 minutes (i.e., sleep-inertia condition) or ended as planned after 2.5 hours (i.e., fatigue-boredom condition). Self-reported fatigue, workload, and boredom levels were assessed every 30 minutes throughout the flight simulation. Sleep of the PR was determined objectively using an adhesive electrode grid. In both conditions, crews were confronted with an engine fire, and crew performance was assessed as time to complete several ECAM actions (until clearance of the warning) and whether the crew succeeded fully (both PF and PR fulfil their respective roles) vs. partially (i.e., PF takes over one or more tasks of the PR) in clearing the warning.

In the following section we briefly summarize the results, followed by a discussion of the challenges encountered during the study, its limitations, and open questions for future work.

4.1 Results summary

Sleep. Participants came in partially sleep deprived after ~3.5h of sleep before the start of the experiment at 3:00 in the morning. The simulation started at 6:00, mimicking an early-start flight. All PRs managed to sleep in the cockpit seat during the eMCO segment, with an eMCO-related sleep efficiency of 86% and a total sleep time of 99 minutes on average (out of a 130-minute sleep opportunity) in the non-aborted eMCO segment. Deep sleep stages (N3) were reached in both groups, but all pilots woke up from lighter sleep stages (N1 and N2). PRs in the aborted condition averaged 38 minutes of sleep and woke up 4 minutes before Engine 2 fire was triggered. Sleep inertia may not have been very severe, but appeared to have been present based on time elapsed since awakening (i.e., well within the general duration of sleep inertia of 20-35 minutes, see deliverable report D-4 “Duration of sleep inertia”), on the high subjective fatigue ratings, and the PR pilots’ feedback provided during the debriefing. Awakening from deep sleep or during the night, especially during the WOCL (Window of Circadian Low), would be expected to worsen sleep inertia (Scheer et al., 2008). In turn, a full night’s sleep before the study may have attenuated sleep inertia effects on fatigue (McHill et al., 2019).

Fatigue/sleepiness, workload, and boredom. Self-reported fatigue of the PF was generally high, reaching or crossing the threshold of high fatigue ($KSS \geq 7$, $SP \geq 5$), and appeared higher during the eMCO segment than before or after the segment. Delayed benefits by the sleep/resting period for the PR (i.e., less fatigue/sleepiness after some time post-awakening) were not uniformly seen at 20-50 minutes after the end of the eMCO segment, and PF and PR of most crews reported similar levels of fatigue at the end of the simulation (i.e., after the Engine 2 fire). Potential beneficial effects of the sleep period on fatigue and sleepiness may take a little longer to emerge (e.g., ~60 minutes, see deliverable report D-4 “Duration of sleep inertia”), than was measured in this study. PFs reported feeling bored throughout the eMCO segment, which may have contributed to the high fatigue levels. Workload during the engine fire was perceived as high in both conditions and as slightly higher (0.25 points on a 5-pt scale) in the aborted-eMCO condition.

It is important to note that due to the absence of a second control condition (i.e., crew performing the same flight scenario with no eMCO segment under normal operations), it is unclear whether the higher levels of fatigue/sleepiness and boredom during the eMCO segment, and the high workload during the engine fire, are directly attributable to the eMCO segment itself or a result of progressing time awake and/or time on task. However, the trajectories of fatigue/sleepiness, workload and boredom over the course of the simulation,

together with the feedback during the debriefing, suggest that flying alone for a period of 2.5 hours can be considered challenging for pilot alertness.

Crew performance. In the specific scenario of encountering an engine fire at ~4 minutes after the PR woke up from lighter sleep stages (N1 or N2) after Ø38 minutes of sleep between 6:30 – 7:30 did not adversely affect crew speed: time to complete several ECAM actions did not differ across the two conditions, with the exception of time until clearance of the Engine 2 fire warning, which took 4 minutes longer in the aborted-eMCO condition. This is, however, not a time-critical action and differences between the two scenarios may not be due to the PR experiencing sleep inertia, since all previous actions were executed on time. One out of three crews in the aborted-eMCO condition did only partially succeed in clearing the Engine 2 fire, since the PR did not deem himself fit to act upon awakening, prompting the PF to take over the PR's tasks as well. The PF did so successfully but later reported to have invested more effort in order to achieve this result.

4.2 Challenges, limitations and future work

Sample size. Recruitment for this study posed a challenge. Even though participation was advertised using several channels and over the course of ten months (January – October 2024), only five crews were willing to participate. Challenges may have been the location of the flight simulator center, the length and timing of the experiment, the lack of reimbursement (travel and accommodation expenses were compensated but not participation itself), and eMCOs currently being a politically sensitive topic inside the aviation community. Due to the resulting small sample size, results should be interpreted with caution. Reimbursing pilots may be a promising means to increase participation rate in the future.

Performance endpoints. Determining the key tasks (highest criticality for maintaining safety / that ensure safe flying) and the underlying cognitive domains (e.g., sustained alertness, selective attention) is critical to assessing potential safety risks due to sleep inertia and fatigue. Reaction speed is a standard, well-documented, and easy-to-quantify metric to assess cognitive performance and was thus selected as the outcome measure for crew performance in this study. Speed is, however, generally less affected by sleep inertia than accuracy (see deliverable report D-4). Speed may also be of less relevance for crew performance, if the differences in reaction time are within the seconds-to-minutes range, since most actions appear time-critical on a timescale longer than that. Decision-making was included in the scenario design (i.e., selection of a diversion airport), but its analysis requires larger sample sizes due to its complexity, which is partly why decision-making has not been frequently investigated (see deliverable report D-4).

Simulator studies. High stress is difficult to induce in a flight simulator. The (physiological) response to a real-world engine fire may differ and thus have a different impact on crew alertness, performance and the duration to overcome sleep inertia; yet, the direction of the impact is not entirely clear, as stress could act both ways (e.g., sharpen mental focus vs. overwhelm available cognitive capacities) and research in this area is limited (see deliverable report D-4). However, a flight simulator study offers increased ecological validity, examining professional pilots in an applied study setting, compared to studies with non-professional participants and standardized performance tests or generic simulation tasks.

Sleep. PRs in the aborted condition woke up from lighter sleep stages, which may have attenuated sleep inertia compared to waking up from deep sleep. Awakening during the night, especially during the WOCL, would be expected to further worsen sleep inertia. The fact that PRs slept in the reclined cockpit seat may have affected their sleep quality, latency to fall asleep, sleep structure, and/or ability to stay asleep. However, sleep efficiency was quite good, sleep onset latency was within the normal range, and deep sleep stages were entered, if only briefly, suggesting that a restorative sleep quality under these circumstances may be possible.

Duration of eMCO segment. Two-and-a-half hour was generally perceived as too long by the participating pilots, due to the need for physiological breaks (PF) and limits on how long they believed they could sleep on

end (PR; referring to a simulated eMCO segment during the morning hours with previous sleep restriction). The latter belief may change if the simulated eMCO segment had taken place during the night. However, shorter eMCO segments may be especially beneficial when eMCO segments take place during very fatiguing periods, such as at night, after multiple sectors, long duty hours or extended wakefulness. For instance, shorter segments and switching more frequently between the roles of PF and PR may be beneficial during the night to relieve some fatigue of the sleeping PR, while limiting time alone at the controls during a precarious time of day for the PF and thereby preventing excessive high boredom and fatigue levels.

Procedures for aborted eMCOs. As indicated by participants during the debriefing session, procedures need to be worked out for when eMCO segments end prematurely (due to e.g., high fatigue or physiological breaks of the PF, or in case of emergencies). If eMCOs involve scheduled extensions of flight time limitations, aborting eMCO segments may require the flight duty period to be shorter than planned, with potentially severe and/or costly consequences for airlines, crew, and passengers (e.g., not being able to reach the destination airport).

Future work on the safety impact of eMCOs will need to further examine the optimal duration of eMCO segments, that e.g., reconciles the PF's need for physiological breaks and protection against high fatigue due to being alone with a sufficiently long rest opportunity for the PR to mitigate existing fatigue and/or protect against expected fatigue; and minimizes sleep inertia effects by limiting sleep while maximizing restorative effects by extending sleep. In addition, future work might: increase the (time) pressure of the scenario; simulate eMCOs during other challenging times of day (e.g., late finishes, during the WOCL); add a comparison with crews flying nominal operations; compare different sleep facilities (e.g. cockpit vs. bunk bed), include multiple eMCO segments and thereby longer scenarios; and further study and identify key pilot tasks (which may well be unique to aviation) and their underlying cognitive functions to maintain safe operations.

4.3 Conclusion

The primary aims of the experiment described in this report were to examine (i) effects of sleep inertia on crew performance, following an unscheduled abortion of the eMCO segment and (ii) trajectories of fatigue, workload, and boredom before, during, and after a non-aborted, 2.5-h long eMCO segment.

Sleep inertia, in this very specific scenario and based on a limited sample size, had no adverse effect on crew speed to complete several ECAM actions. In one out of three aborted-eMCO crews, the PR deemed himself impaired to such an extent that he did not want to take action. The PF of said crew completed the ECAM actions successfully alone, with reportedly higher effort to sustain his performance level. Follow-up studies are required to determine whether crew performance would be differently affected in scenarios that are more likely to elicit severe sleep inertia (e.g., waking up during the WOCL) and/or require more time-critical actions.

Fatigue, workload and boredom appeared to be higher during the eMCO segment than before or after. Effects of the ~1.5 hour sleep period during the eMCO segment on subsequent fatigue of the PR were mixed: while one PR's fatigue levels remained identical to that of the PF, the other PR reported notably lower fatigue at 20 to 50 minutes after awakening.

In addition, careful consideration needs to be given to the optimal duration of eMCO segments. The length of an eMCO segment should balance supporting restorative effects of the sleep period of the PR, limiting sleep inertia upon wakening, allowing for physiological breaks, and should not itself cause negative side effects, such as increased boredom and fewer learning-on-the-job opportunities. A key challenge appears to avoid neutralizing positive effects of having prolonged sleep opportunities by negative effects of flying alone for an extended period, which in itself may increase fatigue and boredom. Another key challenge seems to determine which provisions to make for safe eMCOs, if one or several segments have to be aborted and consequently, fatigue is not managed as originally planned.

5. Bibliography

- D-4 deliverable report on Task 4 „Duration of sleep inertia” of the research activity “eMCO-SiPO – Extended Minimum Crew Operations-Single Pilot Operations”. Download from:
<https://www.easa.europa.eu/en/research-projects/emco-sipo-extended-minimum-crew-operations-single-pilot-operations-safety-risk#group-downloads>
- da Silva Souto, C. F., Pätzold, W., Paul, M., Debener, S., & Wolf, K. I. (2022). Pre-gelled Electrode Grid for Self-Applied EEG Sleep Monitoring at Home. *Frontiers in Neuroscience*, 16.
- da Silva Souto, C. F., Pätzold, W., Wolf, K. I., Paul, M., Matthiesen, I., Bleichner, M. G., & Debener, S. (2021). Flex-Printed Ear-EEG Sensors for Adequate Sleep Staging at Home. *Frontiers in Digital Health*, 3.
- McHill, A. W., Hull, J. T., Cohen, D. A., Wang, W., Czeisler, C. A., & Klerman, E. B. (2019). Chronic sleep restriction greatly magnifies performance decrements immediately after awakening. *Sleep*, 42(5).
- Scheer, F. A. J. L., Shea, T. J., Hilton, M. F., & Shea, S. A. (2008). An endogenous circadian rhythm in sleep inertia results in greatest cognitive impairment upon awakening during the biological night. *Journal of Biological Rhythms*, 23(4), 353–361.



European Union Aviation Safety Agency

Konrad-Adenauer-Ufer 3
50668 Cologne
Germany

Mail EASA.research@easa.europa.eu
Web www.easa.europa.eu

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