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Assessment of the acceptability of sonic booms

of planned supersonic commercial aircraft or business jets

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Abstract: Assessment of the acceptability of sonic booms of planned supersonic commercial aircraft or business jets Assessment of the acceptability of sonic booms

Future civil supersonic aircraft, known as low-boom aircraft, are expected to produce significantly quieter sonic booms to enable supersonic flights over populated areas. The effect of these new types of sonic booms on humans, particularly on sleep, is still unclear. In one study, 37 healthy participants (age M = 35 ± 12 years SD, 18 women) were examined in a sleep laboratory for three nights. The first night served as a control condition, in the two following nights 40 simulated sonic booms from either low-boom aircraft (Low-boom condition) or under additional application of a noise-reducing flight procedure (Mach cut-off condition) were played back. Sleep was measured polysomnographically. In the morning, short-term annoyance and self-assessed sleep quality were recorded and heart rate and blood pressure were measured. The results show that sleep was disturbed in the Low-boom condition, annoyance was higher and self-assessed sleep quality was worse than in the Mach cut-off condition. While heart rate variability and blood pressure did not differ detectably between conditions, heart rate decreased after the low-boom events. In addition, a literature review was carried out, the results of which were used to derive criteria for assessing the acceptability of sonic booms from future civil supersonic aircraft for the population. The project provides important findings for predicting the noise impact of future sonic booms and enables them to be ranked in comparison with conventional traffic noise. Although the resulting noise immission are lower than those of conventional supersonic aircraft, they can impair sleep and cause annoyance reactions. The use of the noise-reducing Mach cut-off flight procedure can lead to a lower level of adverse reactions.

Kurzbeschreibung: Beurteilung der Zumutbarkeit von Überschallknallen geplanter Überschall-Verkehrsflugzeuge bzw. -Geschäftsreiseflugzeuge

Zukünftige zivile Überschallflugzeuge, sogenannte Low-Boom-Flugzeuge, sollen deutlich leisere Überschallknalle verursachen, um Überschallflüge über bewohntem Gebiet zu ermöglichen. Die Wirkung dieser neuartigen Überschallknalle auf den Menschen, insbesondere auf den Schlaf, ist bisher unklar. In einer Studie wurden 37 gesunde Personen (Alter M = 35 ± 12 Jahre SD, 18 Frauen) drei Nächte im Schlaflabor untersucht. Die erste Nacht diente als Kontrollbedingung, in den zwei folgenden Nächten wurden je 40 simulierte Überschallknalle von entweder Low-Boom-Flugzeugen (Low-Boom-Bedingung) oder unter zusätzlicher Anwendung eines lärmmindernden Flugverfahrens (Mach-Cut-off-Bedingung) eingespielt. Der Schlaf wurde polysomnografisch untersucht. Am Morgen wurden die Kurzzeit-Belästigung und selbst eingeschätzte Schlafqualität erfasst sowie Herzrate und Blutdruck gemessen. Die Ergebnisse zeigen, dass der Schlaf in der Low-Boom-Bedingung gestörter war, die Belästigung höher und die selbst eingeschätzte Schlafqualität schlechter als in der Mach-Cut-off-Bedingung. Während sich Herzratenvariabilität und Blutdruck nicht nachweisbar zwischen den Bedingungen unterschieden, sank die Herzrate nach den Low-Boom-Ereignissen. Ergänzend wurde eine Literaturrecherche durchgeführt, aus deren Ergebnissen Kriterien zur Beurteilung der Zumutbarkeit von Überschallknallen durch zukünftige zivile Überschallflugzeuge für die Bevölkerung abgeleitet wurden. Das Projekt liefert wichtige Erkenntnisse zur Prognose der Lärmwirkung von zukünftigen Überschallknallen und ermöglicht deren Einordnung im Vergleich zu konventionellem Verkehrslärm. Obwohl die resultierenden Lärmimmissionen im Vergleich zu denen von konventionellen Überschallflugzeugen niedriger ausfallen, können sie den Schlaf beeinträchtigen und Belästigungsreaktionen hervorrufen. Die Anwendung des lärmmindernden Mach-Cut-off-Flugverfahrens kann dazu führen, dass die Beeinträchtigungsreaktionen geringer ausfallen.

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%HA	Percent highly annoyed; percentage of people highly annoyed
AFC	Adapted Forced Choice Procedure for varying a parameter in a psychophysical experiment based on response behavior, e.g., for measuring detection and difference thresholds
AGL	Above Ground Level, typically given in feet (ft)
AIAA	American Institute of Aeronautics and Astronautics US professional society for aerospace engineering
AIC	Akaike Information Criterion
AMSAN	Occupational Medicine Simulation Facility (DLR)
APV	LAGA Committee for Product Responsibility; FV
ASCENT	Aviation Sustainability Center Cooperative aviation research organization jointly led by Washington State University and the Massachusetts Institute of Technology
ASEL	A-weighted Sound Exposure Level The A-weighting is a frequency weighting of sound levels
BGBI	Federal Law Gazette
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
BV Glas	Federal Association of the Glass Industry, Düsseldorf
CI	Confidence interval
COVID-19	Coronavirus Disease 2019
dB	Decibel
dB(A)	A-weighted decibel The A-weighting is a frequency weighting based on the 40-phon equal-loudness curve
dB/Okt.	Decibel per octave
Destatis	Federal Statistical Office, Wiesbaden
DiätV	Dietary Regulation (Diätverordnung)
DLMB	German Food Code (Deutsches Lebensmittelbuch)
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EEG	Electroencephalogram
EKG	Electrocardiogram
EMG	Electromyogram
:enivhab	DLR's aerospace medicine research facility ("envi" = environment and "hab" = habitat)
EOG	Electrooculogram
et al.	et alii (and others)

EU	European Union
FaINT	FArfield Investigation of No boom Threshold
FFP2-Maske	Filtering face piece Class 2 particle-filtering respiratory protection mask
FluLärmG	Law on protection against aircraft noise
FrSaftErfrischGetrV	Ordinance on fruit juice, certain similar products, fruit nectar and caffeinated soft drinks (Fruchtsaft- und Erfrischungsgetränkeverordnung)
ft	Foot (1 ft = 30.48 cm)
GDB	German Wells Cooperative, Bonn
GfK	GfK SE, Nürnberg
GVM	GVM Society for Packaging Market Research, Mainz
h	Hour(s); time
HRV	Heart rate variability
HSD	Honest Significant Difference
Hz	Hertz, a unit of measurement of frequency
ICAO	International Civil Aviation Organization
ICBEN	International Commission on Biological Effects of Noise
ICP	Integrated Circuit Piezoelectric
IN	Impulsive Noise
JAXA	Japan Aerospace Exploration Agency
kHz	Kilohertz Unit of measurement of frequency
km	Kilometre(s)
KSS	Karolinska Sleepiness Scale
L_{Aeq}	A-weighted, equivalent sound pressure level
LAGA	Federal/State Working Group on Waste
LEF-K	Short version of the Weinstein scale for measuring noise sensitivity
LFN	Low Frequency Noise
LuftVO	Air Traffic Regulations (Luftverkehrsordnung)
$L_{Z,eq}$	Z-weighted (unweighted), equivalent sound pressure level
M	Mean value
M5	Module 5, Psychology Laboratory (:envihab, DLR)
MDiff	Mean difference
MövE	Reusable and ecologically advantageous disposable drinks
Mo.	Mode or modal value Value that occurs most frequently in a data series
ms	Millisecond(s)

N	Number of participants
NASA	National Aeronautics and Space Administration
NREMS	Non-REM sleep
övE	Ecologically advantageous disposable drinks
p	Probability
Pa	Pascal Unit of pressure
PANAS	Positive and negative affect schedule
p_{peak}	Maximum sound overpressure in Pascal
PSQI	Pittsburgh Sleep Quality Index
R	Recoding
REMS	Rapid Eye Movement sleep
RUMBLE	RegUlation and norM for low sonic Boom LEvels
s	second(s)
S1 - S4	Sleep stage 1 to 4
SD	Standard deviation
SE	Standard error
SENECA	EU-Project „noiSe and EmissioNs of supErsoniC Aircraft“
SOL	Sleep onset latency
SWS	Slow wave sleep (deep sleep or sleep stage S3 and S4)
TIB	Time in bed
TST	Total sleep time
UBA	Federal Environment Agency (Umweltbundesamt), Dessau
UOL	Carl von Ossietzky, University of Oldenburg
VdF	Association of the German Fruit Juice Industry, Bonn
VerpackV	Packaging Ordinance
VDM	Association of German Mineral Springs, Bonn
VIF	Variance Inflation Factor
vs.	versus
wafg	Economic Association for Non-Alcoholic Beverages, Berlin
WASO	Wake After Sleep Onset (time spent awake after falling asleep until the end of bedtime)
WHO	World Health Organisation
z	Distance to the caustic line
ZEUS GmbH	Center for Applied Psychology, Environmental and Social Research

Summary

Introduction and task

Supersonic aircraft flying at supersonic speed generate a pressure wave that is perceived as a loud sonic boom when it reaches the ground. In order to avoid negative effects such as sleep disturbances, startle reactions and annoyance, flying at supersonic speeds over land was explicitly prohibited in Germany until 2015. The industry is currently striving to reintroduce civil supersonic flights. New aircraft configurations, so-called low-boom designs, and flight procedures such as the Mach cut-off procedure are being developed in order to reduce the noise emissions of supersonic aircraft and achieve certification for civil use. While there are only a few studies to date on the effect of these low-boom designs on annoyance, subjectively perceived loudness and physiological reactions (e.g., Töpken & van de Par 2021; Marshall & Davies 2012), no studies have yet been conducted to investigate the effect on sleep. There is therefore a need for research to investigate the noise effects of future sonic booms. On behalf of the Federal Environment Agency (UBA), a laboratory study was to be conducted as part of a research project to investigate the effects of sonic booms generated by low-boom aircraft and by the application of the Mach cut-off procedure, in particular on sleep. Based on the results obtained and a literature review, criteria were to be derived to assess the acceptability of sonic booms from future civil supersonic aircraft for the population.

Stimuli and validation

As no recordings of real low sonic booms were available at the start of the project, simulated pressure signatures were used to address the research question. From various options, the C608 signature from the third AIAA Sonic Boom Prediction Workshop was selected as the low-boom pressure signature. This signal is intended to correspond to the NASA X-59 demonstrator and come close to a future civilian supersonic jet. Through an exchange with Pennsylvania State University, the appropriate Mach cut-off simulations, more specifically low-boom signature with application of the Mach cut-off procedure, could be created based on this C608 signature For the presentation of the signatures in the sleep laboratory, the transmission from the outside to the inside was also generically simulated for both signatures using a frequency-independent level reduction and low-pass filtering that corresponds to the mass law for sound transmission for single-walled structures and vertical sound incidence.

The reproduction of the low-boom and Mach cut-off signature in the sleep laboratory was realised using existing subwoofers. Due to the frequency response of the active subwoofers towards very low frequencies and the room situation in the sleep laboratory (larger room volume and permanent ventilation), it was expected that particularly very low frequencies of a few Hertz (Hz) would not be reproduced well. However, a significant proportion of the energy of low-boom signals lies at very low frequencies and it was to be expected that the effect of the sound presentation in the sleep laboratory would be lower than in specialised laboratories.

Accordingly, a comparison of recordings from the sleep laboratory and the original signatures in the pressure chamber at the University of Oldenburg was carried out to validate the sound presentation. In two separate listening experiments, the short-term annoyance was assessed on the one hand and the detection threshold for high-pass filtered signals was determined on the other.

The results for short-term annoyance yielded similar judgements for all three bedrooms of the sleep laboratory, which suggests a uniform sound exposure across all sleeping rooms. Compared to the original signatures, however, the short-term annoyance ratings for the recordings of the C608 signature from the sleep laboratory were higher. Various factors may explain the differences between the original signatures and the respective signatures recorded in the sleep laboratory, but it is difficult to identify the exact causes of these differences in the ratings. Nevertheless, the judgements from the listening experiments are very similar to the short-term annoyance judgements made by awake participants in the sleep study after a night.

The detection threshold for the high-pass filtered signals was on average 60 Hz and, thus, significantly above the lower cut-off frequency of the subwoofers used. A potential influence of the lower limit of the frequency range of the subwoofers used should not have been detectable according to the results of the detection experiment.

Overall, the results of the detection experiment as well as the short-term noise judgements indicate that the low-frequency sound exposure was adequate and comparable for both signatures in all three bedrooms and that the resulting effect of the signatures presented in the sleep laboratory was not underestimated.

Design of the sleep study

Prior to participating in the sleep study, the study applicants underwent a multi-stage selection process (questionnaire, audiometry, sample night) to ensure that the participants did not have any health-related conditions that could impair the evaluation and interpretability of the laboratory results. Applicants with hearing disorders, psychological and physiological illnesses, in particular sleep disorders such as sleep-related breathing disorders (apnoea) or periodic leg movements, as well as those taking certain medications were excluded.

10 days before their participation, the participants were asked to stay in bed for 8 hours and to wear an actometer to record their physical activity. This preparation served the purpose of adaptation and was intended to ensure that all participants had the same initial conditions with regard to sleep pressure and sleep rhythm. The participants spent three consecutive nights in the sleep laboratory, including one quiet control night without any noise playback (control condition) and two nights with 40 played back sonic booms each. During the two noise nights, either low-boom (Low-boom condition) or Mach cut-off signatures (Mach cut-off condition) were played back. While the control condition was always the first night, the order of the noise conditions was randomised and the allocation of participants was counterbalanced. The study was conducted double-blind, i.e. that neither the participants nor the employees and data analysers were given any specific information about the type of noise or the conditions. Polysomnographic measurements were taken during the three nights of the study to analyse objective sleep disturbances. The polysomnography was used to determine whole-night parameters (macroparameters and EEG spectra in non-REM sleep) as well as event-related awakenings, arousals, sleep transitions and changes in the EEG spectrum. To quantify the event-related reactions, the relative percentage rate at which the reaction occurred immediately after a noise event, i. e. within an epoch of 30 seconds, was determined. The rate of spontaneous reactions in the control condition was determined by supposing noise events at the same times as in the two noise conditions. Prediction models were derived for the event-related awakenings and arousals and the noise-induced rates were quantified by calculating the respective rate as the difference to the spontaneous rate in the control condition. In order to record subjective impairments, the participants answered questionnaires on sleep quality, sleepiness and noise-related annoyance after each night. On the third morning physiological responses (heart rate and blood pressure) were also measured while awake over a period of 13.5 minutes in a quiet control condition without playback of noise events and with 5 of each of the two noise signatures (Low-boom and Mach cut-off condition). These data were used to determine the heart rate variability over the three measurement periods and the event-related change in blood pressure and heart rate. For the control condition noise events were also supposed at the same times as in the two noise conditions. For the event-related change in blood pressure, the difference between the diastolic and systolic blood pressure values averaged over 30 seconds

before the noise event and the respective values in the 30 seconds after the noise event was calculated. For the event-related change in heart rate, the difference between the averaged bpm value over the 10 seconds before the noise event and the averaged value over the 10 seconds after the noise event was calculated. For all outcome variables, it was analysed whether there was an effect of the condition (Control, Low-boom, Mach cut-off).

Results of the sleep study

In total, the data from 37 participants (18 women, 19 men) were analysed. The participants were on average around 35 years old (M = 34.54; SD = 12.05) and ranged from 20 to 64 years.

The analysis of the 10 parameters for the sleep macrostructure showed that the condition only had a significant effect on sleep efficiency and total sleep time (TST). While the Low-boom condition did not differ from the control condition, the Low-boom condition showed a significantly lower sleep efficiency of 88.5 % and TST of ~425 minutes than the Mach cut-off condition with a sleep efficiency of 91.4 % and a TST of ~439 minutes. The EEG spectra in non-REM sleep (NREMS) throughout the night did not differ significantly between the three conditions. The event-related analyses showed that the awakening rate was highest in the Low-boom condition at 9 % and differed significantly from the control condition at 2.6 % and from the Mach cut-off condition at 4.3 %. Subtracting the spontaneous awakening rate of the control condition resulted in an awakening rate of 6.4 % for the Low-boom condition and 1.7 % for the Mach cut-off condition. The highest arousal rate of 16.6 % was found for the Low-boom condition and differed significantly from the control condition with 8.9 % and from the Mach cut-off condition with 11.6 %. After subtracting the spontaneous arousal rate of the control condition, the noise-induced arousal rate was 7.8 % for the Low-boom condition and 2.8 % for the Mach cut-off condition. The analysis of lightening of sleep, defined as the change from deep sleep (S4 or S3) to REM sleep or stable sleep (S2), showed no significant difference between the conditions. However, there was a significant effect on the slow-wave activity (SWA) in NREMS in the first minute immediately after a low-boom event: spectral power was significantly lower in the delta frequency band and significantly higher in the beta band than in the control and Mach cut-off condition.

The analyses of the physiological measurements while awake showed no effect of the condition on heart rate variability. While diastolic and systolic blood pressure did not differ between conditions, the low-boom events led to a significant reduction in heart rate of 2 % compared to the control condition with a reduction of 0.3 % and the Mach cut-off condition with 0.2 %.

The analyses of the subjective judgements showed that the annoyance on the scale from 0 to 10 was significantly higher after the night with played back low-boom events with a value of 4.8 than after the Mach cut-off condition with a value of 1.0 and the control condition with a value of 0.8. The annoyance reactions to the nocturnal noise events corresponded approximately to the short-term annoyance judgements of the listening experiments at the University of Oldenburg (Low-Boom = ~5.3; Mach-Cut-off = ~1.4). The assessment of sleep quality on the scale from 0 to 60 did not differ between the Low-boom condition with a value of 31.1 and the control condition with a value of 29.8. However, sleep quality was rated significantly worse after the Low-boom condition than after the Mach cut-off condition with the highest value of 38.5. On the scale of 1 to 9, the assessment of sleepiness was significantly higher for the Low-boom condition with a value of 5.0 than for the control condition with a value of 4.1 and for the Mach cut-off condition with a value of 3.8.

Conclusion based on the results of the sleep study

The electrophysiologically measured sleep quality (e. g. total sleep time, sleep efficiency, wake after sleep onset) showed no clear effect of the low-boom events on the overall night parameters. However, it can be assumed that the use of the Mach cut-off flight procedure can mitigate the negative effects of the sonic booms on sleep quality, at least in terms of sleep duration and sleep efficiency. In contrast, the event-related analyses showed that the low-boom events led to significantly more awakenings and arousals and reduced slow-wave activity (SWA) in NREMS compared to a noise-free night. Accordingly, low-boom aircraft can lead to sleep disturbances despite lower noise emissions than conventional supersonic aircraft. The use of the Mach cut-off procedure can mitigate this effect.

In order to be able to classify the effects of nocturnal sonic booms on sleep, a comparison was made with other conventional modes of transport (rail, air, road). In another laboratory study by Basner, Müller, and Elmenhorst (2011), subsonic aircraft noise and rail and road traffic noise at maximum sound pressure levels ($L_{AS,max}$) between ~55 to 60 dB were found to have a comparable awakening rate of 6.4 % induced by low-boom events. The arousal rate of 7.8 % induced by low-boom events is comparable to the rate caused by conventional traffic noise due to maximum levels of approximately 45 dB(A) (road traffic noise), 50 dB(A) (railway noise) and 55 to 60 dB(A) (aircraft noise). The significantly lower awakening rate of 1.7 % induced by Mach cut-off events was already exceeded by aircraft and road noise at a level of 50 dB(A), while the corresponding level for railway noise was between 50 and 55 dB(A). A corresponding arousal rate of 2.8 % induced by Mach cut-off events was already exceeded by rail and road traffic noise at levels of 45 dB(A), whereas this rate was found for aircraft noise at maximum levels between 45 and 50 dB(A).

Even if the effect of low-boom events on the awakening probability is lower than that of conventional aircraft noise events, the exposure area below the flight trajectory would be larger (~40 km on both sides) and thus also the number of people affected. The noise induced awakening rate of 6.4 % would mean that a noise induced awakening could occur with around 16 overflights by low-boom aircraft at supersonic speed per night. With this assumption, however, it must be considered that the effects found in laboratory studies are somewhat overestimated and can only be transferred to the general population to a limited extent, as only healthy and age-appropriate participants with normal hearing were examined in this study. In addition, the effect of other exposures generated by sonic booms, such as rattling and vibration, which in turn could strengthen the effect, was not considered.

The results of the physiological reactions while awake showed that the low-boom events led to a drop in the heart rate. This suggests that these sonic booms are more likely to be associated with characteristics that do not lead to a startle response when consciously perceived, but to an orientation response that can be triggered by low-intensity noise (Shoushtarian et al. 2019).

Based on the results of the subjective judgements, it can be concluded that although the noise emissions of low-boom aircraft will be lower than those of conventional supersonic aircraft, the night-time sonic booms can still lead to annoyance reactions in the medium range and slightly increased sleepiness. The use of the Mach cut-off flight procedure can mitigate the negative effect of the sonic booms of low-boom aircraft on the perception of annoyance, sleepiness and self-assessed sleep quality.

Development and application of acceptability criteria

To derive suitable criteria for determining the acceptability of future civil supersonic flights, the following steps were carried out:

1. Comprehensive research and evaluation of the relevant national and international literature on the noise impacts of civil supersonic flights;
2. Monitoring ongoing national and international research activities on the topic;
3. Reviewing and summarising the results of the conducted sleep study;
4. Based on this, the development of a proposal for criteria to assess the acceptability of sonic booms from future civil supersonic aircraft for the population in Europe.

The literature analysis was methodologically based on the approach of a scoping review (von Elm, Schreiber & Haupt 2019) with the research questions structured according to the PEOS classification (Freiberg et al. 2019). Inclusion and exclusion criteria were defined, which were used to derive search terms. The literature search was conducted in various databases: PsychINFO, Psyndex, PubMed, BASE, and relevant conference proceedings. The process of literature selection and analysis was aligned with the so-called PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al. 2009).

In addition to the literature search, the work of completed and ongoing relevant research projects was considered: the completed EU Horizon 2020 project RUMBLE (https://rumble-project.eu/i/), ongoing and completed NASA (National Aeronautics and Space Administration) projects, such as the QSF18 study (Quiet Supersonic Flights 2018; Page et al. 2020; Fidell et al. 2020), research activities of the Aviation Sustainable Center (ASCENT; https://ascent.aero) on Mach cut-off flights (e. g. Sparrow & Vigeant 2019), as well as the research activities of the Japanese aerospace research organisation JAXA (Japan Aerospace Exploration Agency).

Results of the literature analysis

The literature search identified 61 relevant publications, including 12 reviews. In addition, 21 otherer publications were considered.

The first studies on sonic booms primarily investigated any direct effect of sonic booms on human health, such as direct impacts on hearing (Maglieri, Huckel & Parrott 1961). Over time, the focus shifted to other potential noise effects, such as noise annoyance, startle effect and sleep disturbance. Aside from the sound of sonic booms, another important phenomenon is the rattling of objects or windows inside a house that accompanies the shock wave. Additionally, at low frequencies, noticeable tactile vibrations can occur. Both the effects of sonic booms and those of rattling and vibrations have been investigated in numerous studies. Earlier studies examined the effects of conventional sonic booms on humans. It was not until the turn of the millennium that studies with simulated “low” sonic booms were conducted, i.e. with sonic booms that had lower amplitudes.

The noise effects are assessed very differently across the various studies, and the sample sizes vary greatly. Overall, sonic booms and low sonic booms are generally perceived as more annoying within a building than outdoors, which can be attributed to accompanying vibrations and rattling that can increase the feeling of annoyance (e.g., Kryter 1966; Miller 2011). Some studies determined dB increases when rattle and vibration were present (e.g., Sullivan et al. 2010). For rattle, dB increment values were found (see also Sullivan et al. 2010) ranging from 0 dB to 20 dB (e. g. Pearsons et al. 1993; Fidell, Silvati & Pearsons 2002; Schomer & Averbuch 1989). For vibrations, two studies reported increase values from 0 dB to 8 dB (Carr & Davies 2015; Rathsam, Klos & Loubeau 2015; Rathsam & Klos 2016). The rise time was also shown to be a relevant factor influencing annoyance and perceived loudness (e. g. May 1972). Therefore, accounting for rattling and vibrations seems relevant when investigating and predicting annoyance from sonic booms and low sonic booms. When comparing different acoustic metrics, PL (perceived level) often emerges as the best predictor for noise annoyance (see McCurdy, Brown & Hilliard 2004; Rathsam, Loubeau & Klos 2012; Rathsam, Loubeau & Klos 2015; Carr & Davies 2015; Carr et al. 2020). Overall, there is still relatively little research on the long-term effects of low sonic booms. Unlike subsonic flights, where residents near airports are exposed to aircraft noise, a large number of people would be exposed to low sonic booms and the associated vibrations and rattling, which can occur throughout the entire flight at supersonic speed.

Summary of the results of the conducted sleep study and literature analysis

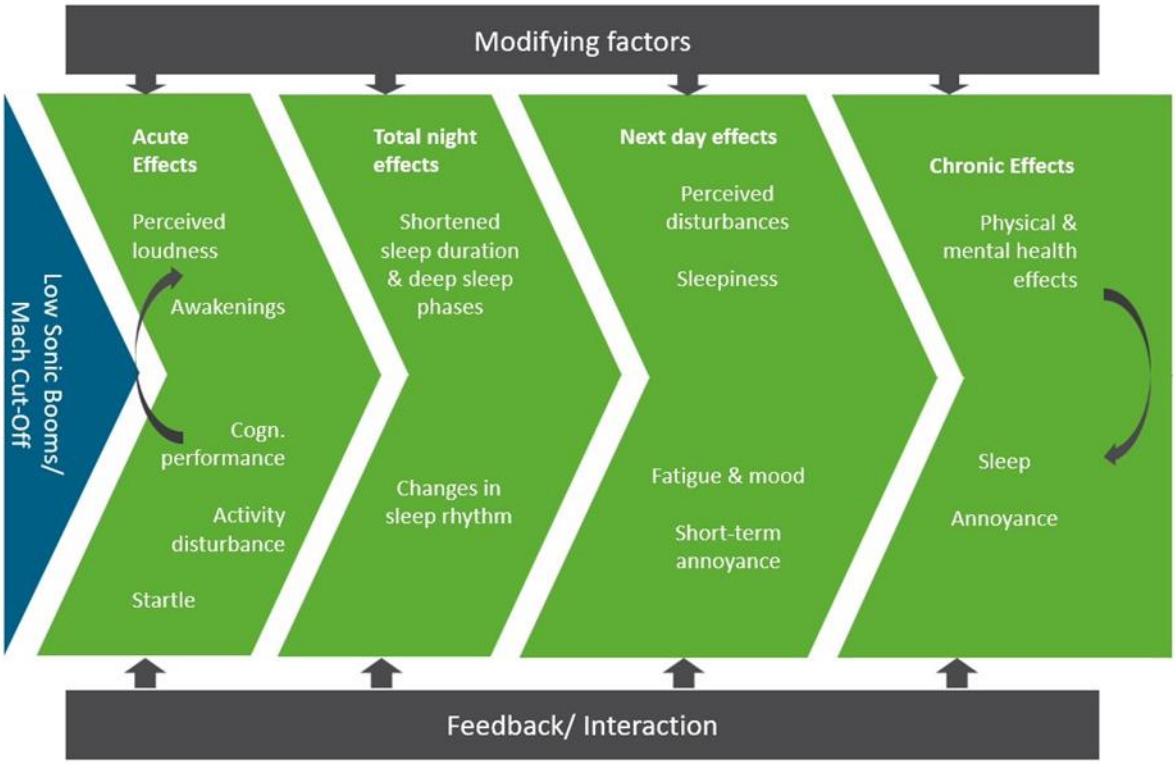
To derive acceptability criteria for low sonic booms and Mach cut-off flights aimed at protecting the population, the results of the sleep study and the literature analysis are discussed in relation to potential acceptability criteria.

In general, the criteria identified from the sleep study and literature can be divided into acoustic parameters and noise effects. Acoustic parameters include various acoustic metrics (e. g. ASEL and PL), the accompanying phenomenon of supersonic flights, rattling and vibrations, as well as the number of noise events.

Noise effects are another important aspect when assessing acceptability. Porter, Kershaw and Ollerhead (2000) developed a model that differentiates various noise effects from nighttime aircraft noise exposure based on their temporal occurrence across four effect levels: Acute effects, total night effects, next day effects, and chronic effects. Acute effects are direct physiological and psychological effects. Total night effects encompass those effects that accumulate over the total night due to acute effects. Next day effects refer to effects that become noticeable the following day and result from the first two effect levels. The final effect level comprises long-term chronic effects that may occur as a result of the first three effect levels. Additionally, the authors note that there are interactions and interdependencies among the noise effects. Furthermore, factors such as attitudes, trust in authorities and individual noise sensitivity also play a role (Porter, Kershaw & Ollerhead 2000).

Based on the noise effects identified in the sleep study and literature analysis, an adapted model was developed that considers both nighttime and daytime exposure. The identified noise effects for low sonic booms and Mach cut-off flights were thus assigned to the four effect levels according to Porter, Kershaw and Ollerhead (2000) (see Figure 1). With regard to low sonic booms and Mach cut-off flights, acute noise effects include, for example, perceived loudness, awakening reactions and startle responses. Total nights effects encompass shortened sleep duration and reduced deep sleep phases as well as changes in sleep rhythm caused by the disturbance. After a noise-disturbed night (next day effects), sleepiness and short-term annoyance may occur. Long-term effects associated with aircraft noise include chronic sleep disturbances, long-term annoyance, and increased physical and mental health risks. These long-term effects could also play a role with low sonic booms and Mach cut-off flights; however, no research results are currently available on the long-term effects of low sonic booms and Mach cut-off flights.

Figure S 1: Adapted model (after Porter, Kershaw & Ollerhead 2000) with relevant noise effects for acceptability criteria



Note: Model adapted from Porter, Kershaw and Ollerhead (2000). Source: own illustration, ZEUS.

Recommendations for deriving acceptability criteria

One of the aims of this research project was to develop suitable acceptability criteria for the assessment of low sonic booms and Mach cut-off flights.

For the evaluation of low sonic booms and Mach cut-off flights, it makes sense to rank the different noise impact. The World Health Organisation (WHO 2018) has already done this for other noise sources, distinguishing between critical, relevant and non-relevant effects. Additionally, for medium- to long-term noise impacts of other environmental noise sources, so-called DALYs (disability adjusted life years) are calculated. These allow for the quantification of noise impacts that differ in severity and could also be useful in future for assessing the effects of low sonic booms and Mach cut-off flights.

At the current state of research, it is not possible to derive concrete recommendations for a ranking of the acceptability criteria or for any thresholds for the acceptability criteria. The sleep study conducted here is an important step towards investigating the noise impact of low sonic booms and Mach cut-off flights, noting that, for instance, the effect of rattling and vibrations could not be examined within the study. Results from the field study on low sonic booms planned by NASA for 2026 to 2028 (NASA's X59 Quesst Community Survey Campaign) can also significantly contribute to the body of knowledge.

Zusammenfassung

Einleitung und Aufgabenstellung

Überschallflugzeuge die mit Überschallgeschwindigkeit fliegen erzeugen eine Druckwelle, die am Erdboden angekommen als lauter Überschallknall wahrgenommen wird. Um negative Auswirkungen wie Schlafstörungen, Schreckreaktionen und Belästigung zu vermeiden, war das Fliegen mit Überschallgeschwindigkeit über Land in Deutschland bis 2015 ausdrücklich verboten. Derzeit strebt die Industrie die Wiedereinführung ziviler Überschallflüge an. Neue Flugzeugkonfigurationen, sogenannte Low-Boom-Designs, und Flugverfahren wie das Mach-Cut-off-Verfahren werden entwickelt, um die Lärmemissionen von Überschallflugzeugen zu reduzieren und eine Zulassung für den zivilen Einsatz zu erreichen. Während es bislang nur wenige Studien zu der Wirkung dieser Low-Boom-Designs auf das Belästigungsempfinden, die subjektiv wahrgenommene Lautheit sowie auf physiologische Reaktionen gibt (z. B. Töpken & van de Par 2021; Marshall & Davies 2012), wurden noch keine Studien durchgeführt, in denen die Wirkung auf den Schlaf untersucht wurde. Daher besteht Forschungsbedarf, um die Lärmwirkung zukünftiger Überschallknalle zu untersuchen. Im Auftrag des Umweltbundesamts (UBA) sollte im Rahmen eines Forschungsprojekts eine Laborstudie durchgeführt werden, in der die Wirkung von durch Low-Boom-Flugzeuge und durch die Anwendung des Mach-Cut-off-Verfahrens erzeugte Überschallknalle, insbesondere auf den Schlaf, untersucht werden. Basierend auf den gewonnenen Ergebnissen und einer Literaturrecherche sollten Kriterien abgeleitet werden, um die Zumutbarkeit von Überschallknallen durch zukünftige zivile Überschallflugzeuge für die Bevölkerung zu beurteilen.

Stimuli und Validierung

Da zum Startzeitpunkt des Projektes keine Aufzeichnungen von realen Low-Boom-Überschallknallen vorhanden waren, wurde zur Bearbeitung der Fragestellung auf simulierte Drucksignaturen zurückgegriffen. Aus verschiedenen Optionen wurde die C608-Signatur aus den Arbeiten des dritten AIAA Sonic Boom Prediction Workshop als Low-Boom-Drucksignatur ausgewählt. Diese soll dem NASA X-59 Demonstrator entsprechen und einem zukünftigen zivilen Überschalljet nahekommen. Durch einen Austausch mit der Pennsylvania State University konnten auf Basis dieser C608-Signatur passende Mach-Cut-off-Simulationen, bzw. Low-Boom-Signatur mit Anwendung des Mach-Cut-off-Verfahrens, erstellt werden.

Für die Darbietung der Signaturen im Schlaflabor wurde zusätzlich für beide Signaturen die Transmission von außen nach innen generisch simuliert durch eine frequenzunabhängige Pegelabsenkung und eine Tiefpassfilterung, die dem Massegesetz für Schalltransmission bei einschaligen Bauteilen und senkrechtem Schalleinfall entspricht.

Die Wiedergabe der Low-Boom- und Mach-Cut-off-Signatur im Schlaflabor wurde über bereits existierende Subwoofer realisiert. Aufgrund des Frequenzganges der aktiven Subwoofer zu sehr tiefen Frequenzen hin und der räumlichen Situation im Schlaflabor (größeres Raumvolumen und dauerhafte Belüftung) war davon auszugehen, dass insbesondere sehr tiefe Frequenzen von wenigen Hertz (Hz) nicht reproduziert werden können. Bei sehr tiefen Frequenzen liegt aber ein maßgeblicher Teil der Energie von Low-Boom-Signalen und es war zu erwarten, dass die Wirkung der Schalldarbietung im Schlaflabor niedriger als in spezialisierten Laboren ausfallen würde.

Entsprechend wurde zur Validierung der Schalldarbietung ein Vergleich von Aufnahmen aus dem Schlaflabor und den Originalsignaturen in der Druckkammer der Universität Oldenburg durchgeführt. In zwei separaten Hörexperimente wurde zum einen die Kurzzeit-Lästigkeit beurteilt und zum anderen die Detektionsschwelle für Hochpass-gefilterte Signale bestimmt.

Die Ergebnisse für die Kurzzeit-Lästigkeit ergaben für alle drei Schlafräume des Schlaflabors ähnliche Urteile, was für eine gleichmäßige Beschallung spricht. Im Vergleich zu den Originalsignaturen lagen die Urteile für die Aufnahmen der C608-Signatur aus dem Schlaflabor jedoch höher. Als mögliche Erklärung für die Unterschiede zwischen den Originalsignaturen und den jeweiligen im Schlaflabor aufgenommenen Signaturen können verschiedene Faktoren in Frage kommen, wobei eine genaue Identifikation der Ursachen für diese Urteilsunterschiede schwierig ist. Die Urteile aus den Hörexperimenten sind dennoch sehr ähnlich zu den Kurzzeit-Lästigkeitsurteilen, die am Morgen nach der letzten Nacht von den Versuchspersonen der Schlafstudie erhoben wurden.

Die Detektionsschwelle für die Hochpass-gefilterten Signale lag im Mittel bei 60 Hz und somit deutlich über der unteren Grenzfrequenz der genutzten Subwoofer. Ein potentieller Einfluss der unteren Grenze des Übertragungsbereiches von den genutzten Subwoofern sollte entsprechend den Ergebnissen des Detektionsexperiments nicht detektierbar gewesen sein.

Insgesamt sprechen die Ergebnisse des Detektionsexperimentes und auch die Kurzzeitlästigkeitsurteile dafür, dass die tieffrequente Schallexposition für beide Signaturen in allen drei Schlafräumen adäquat sowie vergleichbar war und die resultierende Wirkung der im Schlaflabor dargebotenen Signaturen nicht unterschätzt wurde.

Design der Schlafstudie

Vor der Teilnahme an der Schlafstudie durchliefen die Studieninteressierten ein mehrstufiges Auswahlverfahren (Fragebogen, Audiometrie, Probenacht), um sicherzustellen, dass bei den Versuchspersonen keine gesundheitsrelevanten Bedingungen vorlagen, welche die Auswertung und Interpretierbarkeit der Laborergebnisse beeinträchtigen könnten. Studieninteressierte mit Hörstörungen, psychische und physiologische Erkrankungen, insbesondere Schlafstörungen wie schlafbezogene Atemstörungen (Apnoen) oder periodische Beinbewegungen sowie mit bestimmten Medikationen wurden ausgeschlossen.

10 Tage vor ihrer Teilnahme wurden die Versuchspersonen gebeten 8 Stunden Bettzeit einzuhalten und zur Überprüfung ein Aktometer zu tragen, das die körperliche Aktivität aufzeichnet. Diese Vorbereitung diente der Adaptation und sollte sicherstellen, dass bei allen Versuchspersonen die gleichen Ausgangsbedingungen im Hinblick auf den Schlafdruck und den Schlafrhythmus vorlagen. Die Versuchspersonen verbrachten drei aufeinanderfolgende Nächte im Schlaflabor, darunter eine ruhige Kontrollnacht ohne Wiedergabe von Lärmereignissen (Kontrollbedingung) sowie zwei Nächte mit jeweils 40 eingespielten Überschallknallen. Während der beiden Lärmnächte wurden entweder Low-Boom- (Low-Boom-Bedingung) oder Mach-Cut-off-Signaturen (Mach-Cut-off-Bedingung) eingespielt. Während die Kontrollbedingung immer die erste Nacht war, war die Reihenfolge der Lärmbedingungen randomisiert und die Zuteilung der Versuchspersonen erfolgte ausbalanciert. Die Studie wurde doppelblind durchgeführt, d. h. sowohl die Versuchspersonen als auch die Mitarbeitenden und die Datenauswertenden erhielten keine konkreten Informationen über die Art des Lärms oder die Bedingungen. Zur Untersuchung objektiver Schlafbeeinträchtigungen wurden während der drei Studiennächte polysomnographische Messungen vorgenommen. Anhand der Polysomnografie wurden Ganznachtparameter (Makroparameter und EEG-Spektren im Non-REM-Schlaf) sowie ereignisbezogene Aufwachereignisse, Arousals, Schlaf-Enttiefungen und Veränderungen im EEG-Spektrum bestimmt. Zur Quantifizierung der ereignisbezogenen Reaktionen wurde die relative prozentuale Rate bestimmt, mit der die Reaktion unmittelbar nach einem Lärmereignis, d. h. innerhalb einer Epoche von 30 Sekunden, auftrat. Die Rate der spontanen Reaktionen der Kontrollbedingung wurde bestimmt, indem Lärmereignisse zu den gleichen Zeitpunkten wie in den beiden Lärmbedingungen supponiert wurden. Für die ereignisbezogenen Aufwachereignisse und Arousals wurden Vorhersagemodelle abgeleitet und die lärminduzierten

Raten quantifiziert, indem die jeweilige Rate als Differenz zur spontanen Rate in der Kontrollbedingung berechnet wurde. Um subjektive Beeinträchtigungen zu erfassen, beantworten die Versuchspersonen nach jeder Nacht Fragebögen zur Schlafqualität, zur Schläfrigkeit sowie zur lärmbezogenen Belästigung. Am dritten Morgen, wurden zudem in einer ruhigen Kontrollbedingung ohne Wiedergabe von Lärmereignissen und unter Einspielung von jeweils 5 der beiden Lärmsignaturen (Low-Boom- und Mach-Cut-off-Bedingung) physiologische Reaktionen (Herzrate und Blutdruck) im Wachzustand über einen Zeitraum von jeweils 13,5 Minuten gemessen. Anhand dieser Daten wurde die Herzratenvariabilität über die drei Messzeiträume und die ereignisbezogene Veränderung des Blutdrucks und der Herzrate bestimmt. Für die Kontrollbedingung wurden auch hier Lärmereignisse zu den gleichen Zeitpunkten wie in den beiden Lärmbedingungen supponiert. Für die ereignisbezogene Veränderung des Blutdrucks wurde die Differenz zwischen dem diastolischen und systolischen Blutdruck-Wert gemittelt über 30 Sekunden vor dem Lärmereignis und den jeweiligen Werten in den 30 Sekunden nach dem Lärmereignis berechnet. Für die ereignisbezogene Veränderung der Herzrate wurde die Differenz zwischen dem gemittelten bpm-Wert über die 10 Sekunden vor dem Lärmereignis und dem gemittelten Wert über die 10 Sekunden nach dem Lärmereignis berechnet. Für alle Zielvariablen wurde untersucht, ob es einen Effekt der Bedingung (Kontrolle, Low-Boom, Mach-Cut-off) gab.

Ergebnisse der Schlafstudie

Insgesamt wurden die Daten von 37 Versuchspersonen (18 Frauen, 19 Männer) ausgewertet. Die Versuchspersonen waren im Mittel ca. 35 Jahre alt (M = 34,54; SD = 12,05) und lagen zwischen 20 und 64 Jahren.

Die Analyse der 10 Parameter für die Schlaf-Makrostruktur zeigte, dass die Bedingung lediglich auf die Schlafeffizienz und die Gesamtschlafzeit (TST) einen signifikanten Effekt hatte. Während sich die Low-Boom-Bedingung nicht von der Kontrollbedingung unterschied, ergab sich in der Low-Boom-Bedingung eine signifikant niedrigere Schlafeffizienz von 88,5 % und TST von ca. 425 Minuten als in der Mach-Cut-off-Bedingung mit einer Schlafeffizienz von 91,4 % und einer TST von ca. 439 Minuten. Die EEG-Spektren im Non-REM-Schlaf (NREMS) über die ganze Nacht unterschieden sich nicht signifikant zwischen den drei Bedingungen. Die ereignisbezogenen Analysen zeigten, dass die Aufwach-Rate mit 9 % in der Low-Boom-Bedingung am höchsten war und sich signifikant von der Kontrollbedingung mit 2,6 % und von der Mach-Cut-off-Bedingung mit 4,3 % unterschied. Abzüglich der spontanen Aufwach-Rate der Kontrollbedingung ergab sich für die Low-Boom-Bedingung eine lärminduzierte Aufwach-Rate von 6,4 % und für die Mach-Cut-off-Bedingung 1,7 %. Die höchste Arousal-Rate von 16,6 % ergab sich für die Low-Boom-Bedingung und unterschied sich signifikant von der Kontrollbedingung mit 8,9 % und von der Mach-Cut-off-Bedingung mit 11,6 %. Nach Abzug der spontanen Arousal-Rate der Kontrollbedingung ergab sich für die Low-Boom-Bedingung eine lärminduzierte Arousal-Rate von 7,8 % und für die Mach-Cut-off-Bedingung 2,8 %. Die Analyse der Schlaf-Enttiefungen, definiert als Wechsel von Tiefschlaf (S4 oder S3) zu REM-Schlaf oder stabilem Schlaf (S2), zeigte keinen signifikanten Unterschied zwischen den Bedingungen. Jedoch gab es einen deutlichen Effekt auf die langsamwellige Aktivität (LWA) im NREMS in der ersten Minute unmittelbar nach einem Low-Boom-Ereignis: Die spektrale Leistung war im Delta-Frequenzband signifikant niedriger und im Beta-Band signifikant höher als in der Kontroll- und der Mach-Cut-off-Bedingung.

Die Analysen der physiologischen Messungen im Wachzustand zeigten keinen Effekt der Bedingung auf die Herzratenvariabilität. Während sich der diastolische und systolische Blutdruck nicht zwischen den Bedingungen unterschied, führten die Low-Boom-Ereignisse zu einer signifikanten Reduktion der Herzrate von 2 % im Vergleich zur Kontrollbedingung mit einer Reduktion von 0,3 % und zur Mach-Cut-off-Bedingung mit 0,2 %.

Die Analysen der subjektiven Beurteilungen zeigten, dass die Belästigung auf der Skala von 0 bis 10 nach der Nacht mit eingespielten Low-Boom-Ereignissen mit einem Wert von 4,8 signifikant höher war als nach der Mach-Cut-off-Bedingung mit einem Wert von 1,0 und der Kontrollbedingung mit der Bewertung von 0,8. Die Belästigungsreaktionen auf die nächtlichen Lärmereignisse entsprachen in etwa den Kurzzeit-Lästigkeits-Urteilen der Hörexperimente der Universität Oldenburg (Low-Boom = ca. 5,3; Mach-Cut-off = ca. 1,4). Die Einschätzung der Schlafqualität auf der Skala von 0 bis 60 unterschied sich nicht zwischen der Low-Boom-Bedingung mit einem Wert von 31,1 und der Kontrollbedingung mit einem Wert von 29,8. Jedoch wurde die Schlafqualität nach der Low-Boom-Bedingung signifikant schlechter eingeschätzt als nach der Mach-Cut-off-Bedingung mit dem höchsten Wert von 38,5. Auf der Skala von 1 bis 9 ergab sich eine signifikant höhere Einschätzung der Schläfrigkeit für die Low-Boom-Bedingung mit einem Wert von 5,0 als für die Kontrollbedingung mit 4,1 und für die Mach-Cut-off-Bedingung mit einem Wert von 3,8.

Schlussfolgerung anhand der Ergebnisse der Schlafstudie

Die elektrophysiologisch gemessene Schlafqualität (z. B. Gesamtschlafzeit, Schlafeffizienz, Wachliegezeit nach Schlafbeginn) ließ keinen eindeutigen Effekt der Low-Boom-Ereignisse auf die Gesamtnacht-Parameter erkennen. Es kann jedoch vermutet werden, dass die Anwendung des Mach-Cut-off-Flugverfahrens die negativen Auswirkungen der Überschallknalle auf die Schlafqualität zumindest in Bezug auf die Schlafdauer und die Schlafeffizienz abschwächen kann. Im Gegensatz dazu zeigten die ereignisbezogenen Analysen, dass die Low-Boom-Ereignisse im Vergleich zu einer lärmfreien Nacht zu deutlich mehr Aufwachreaktionen und Arousals führten und die LWA im NREMS reduzierten. Demnach können Low-Boom-Flugzeuge, trotz geringerer Lärmemissionen als konventionelle Überschallflugzeuge, zu Schlafstörungen führen. Die Anwendung des Mach-Cut-off-Verfahrens kann diesen Effekt abschwächen.

Um die Auswirkungen von nächtlichen Überschallknallen auf den Schlaf einordnen zu können, wurde ein Vergleich zu anderen konventionellen Verkehrsträgern (Schiene, Luft, Straße) gezogen. In einer anderen Laborstudie von Basner, Müller und Elmenhorst (2011) wurde durch subsonischen Fluglärm sowie durch Bahn- und Straßenverkehrslärm bei Maximalschalldruckpegeln ($L_{AS,max}$) zwischen ca. 55 bis 60 dB eine durch Low-Boom-induzierte vergleichbare Aufwach-Rate von 6,4 % gefunden. Die durch Low-Boom-Ereignisse induzierte Arousal-Rate von 7,8 % ist vergleichbar mit der durch konventionellen Verkehrslärm verursachten Rate durch Maximalpegel von ca. 45 dB(A) (Straßenverkehrslärm), 50 dB(A) (Bahnlärm) und 55 bis 60 dB(A) (Fluglärm). Die deutlich geringere durch Mach-Cut-off-Ereignisse induzierte Aufwach-Rate von 1,7 %, war durch Flug- und Straßenverkehrslärm bei einem Pegel von 50 dB(A) bereits überschritten, für Bahnlärm lag der korrespondierende Pegel zwischen 50 und 55 dB(A). Eine durch Mach-Cut-off-induzierte entsprechende Arousal-Rate von 2,8 % wurde durch Schienen- und Straßenverkehrslärm bei Pegeln von 45 dB(A) bereits überschritten, wohingegen diese Rate durch Fluglärm bei Maximalpegel zwischen 45 und 50 dB(A) gefunden wurde.

Auch wenn der Effekt von Low-Boom-Ereignissen auf die Aufwachwahrscheinlichkeit geringer ist als der von konventionellen Fluglärmereignissen, wäre der Expositionsbereich unterhalb der Flug-Trajektorie größer (ca. 40 km zu beiden Seiten) und damit auch die Anzahl der Betroffenen. Die lärminduzierte Aufwach-Rate von 6,4 % würde bedeuten, dass es bei etwa 16 Überflügen durch Low-Boom-Flugzeuge mit Überschallgeschwindigkeit pro Nacht zu einer lärminduzierten Aufwachreaktion kommen könnte. Bei dieser Annahme ist jedoch zu berücksichtigen, dass die in Laborstudien gefundenen Effekte etwas überschätzt werden und nur bedingt übertragbar sind auf die Allgemeinbevölkerung, da in dieser Studie ausschließlich gesunde und altersentsprechend normal hörende Versuchspersonen untersucht wurden. Zudem wurde die

Wirkung von weiteren durch Überschallknalle erzeugte Expositionen wie Rattle (Deutsch: *Klappern*) und Vibration nicht berücksichtigt, welche den Effekt wiederum verstärken könnten.

Die Ergebnisse zu den physiologischen Reaktionen im Wachzustand zeigten, dass die Low-Boom-Ereignisse zu einem Absinken der Herzrate geführt haben. Das lässt vermuten, dass diese Überschallknalle eher mit Eigenschaften einhergehen, die bei bewusster Wahrnehmung nicht zu einer Schreckreaktionen führen, sondern zu einer Orientierungsreaktion, die durch Lärm geringer Intensität ausgelöst werden kann (Shoushtarian et al. 2019).

Anhand der Ergebnisse zu den subjektiven Beurteilungen kann geschlussfolgert werden, dass obwohl die Lärmemissionen von Low-Boom-Flugzeugen geringer sein werden als die von konventionellen Überschallflugzeugen, die nächtlichen Überschallknalle dennoch zu Belästigungsreaktionen im mittleren Bereich und zu einer leicht erhöhten Schläfrigkeit führen können. Die Anwendung des Mach-Cut-off-Flugverfahrens kann die negative Wirkung der Überschallknalle von Low-Boom-Flugzeugen auf das Belästigungsempfinden, die Schläfrigkeit und die selbst eingeschätzte Schlafqualität abschwächen.

Entwicklung und Anwendung von Zumutbarkeitskriterien

Um geeignete Kriterien zur Bestimmung der Zumutbarkeit von zukünftigen zivilen Überschallflügen abzuleiten, wurden folgende Arbeitsschritte durchgeführt:

1. ausführliche Recherche und -auswertung der nationalen und internationalen, einschlägigen Fachliteratur über die Lärmwirkungen von zivilen Überschallflügen;
2. das Verfolgen laufender nationaler und internationaler Forschungsaktivitäten zu dem Thema;
3. das Aufgreifen und die Zusammenfassung der Ergebnisse der durchgeführten Schlafstudie;
4. daraus ableitend die Erarbeitung eines Vorschlags für Kriterien, um die Zumutbarkeit von Überschallknallen durch zukünftige zivile Überschallflugzeuge für die Bevölkerung in Europa zu beurteilen.

Die Literaturanalyse wurde methodisch an die Vorgehensweise eines ‚Scoping Reviews' angelehnt (von Elm, Schreiber & Haupt 2019) und ihre Fragestellung gliederte sich nach der PEOS-Einteilung (Freiberg et al. 2019). Es wurden Ein- und Ausschlusskriterien festgelegt, anhand derer Suchbegriffe abgeleitet wurden. Die Literatursuche erfolgte in verschiedenen Datenbanken: PsychINFO, Psyndex, PubMed, BASE, relevante Tagungsbände. Der Prozess der Literaturauswahl und -analyse wurde angelehnt an das sogenannte PRISMA-Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses; Moher et al. 2009).

Neben der Literatursuche wurden die Arbeiten von abgeschlossenen und laufenden relevanten Forschungsprojekten berücksichtigt: das abgeschlossene EU-Horizon-2020-Vorhaben RUMBLE (https://rumble-project.eu/i/), laufende und abgeschlossene NASA (National Aeronautics and Space Administration) Projekte, wie die Studie QSF18 (Quiet Supersonic Flights 2018; Page et al. 2020; Fidell et al. 2020), Forschungsaktivitäten des Forschungsverbundes Aviation Sustainable Center (ASCENT; https://ascent.aero) zu Mach-Cut-off Flügen (z. B. Sparrow & Vigeant 2019), sowie die Forschungsaktivitäten der japanischen Luft- und Raumfahrtforschungseinrichtung JAXA (Japan Aerospace Exploration Agency).

Ergebnisse der Literaturanalyse

In der Literatursuche konnten 61 relevante Publikationen identifiziert werden, darunter 12 Reviews. Zusätzlich wurden 21 weitere Publikationen berücksichtigt.

Die ersten Studien zu Überschallknallen untersuchten zunächst eine etwaige direkte Wirkung der Überschallknalle auf die physische Gesundheit von Menschen, z. B. direkte Wirkungen auf das Gehör (Maglieri, Huckel & Parrott 1961). Erst mit der Zeit wurde der Fokus auf weitere mögliche Lärmwirkungen gelegt, wie Lärmbelästigung, Startle-Effekt (Deutsch: *Aufschrecken*) und Schlafstörungen. Neben dem Geräusch der Überschallknalle ist ein weiteres wichtiges Phänomen das mit der Schockwelle einhergehende Rattle (Deutsch: *Klappern*) von Gegenständen oder Fenstern innerhalb eines Hauses. Zusätzlich können bei geringer Frequenz spürbare taktile Vibrationen auftreten. Sowohl die Wirkungen von Überschallknallen als auch die von Rattle und Vibrationen wurden daher in zahlreichen Studien untersucht. Die älteren Studien untersuchten die Wirkungen von herkömmlichen Überschallknallen auf den Menschen. Erst um die Jahrtausendwende wurden erstmals Studien mit simulierten „Low“ Sonic Booms durchgeführt; also mit Überschallknallen, die geringere Amplituden aufwiesen.

Die Lärmwirkungen werden in den verschiedenen Studien teilweise sehr unterschiedlich erfasst und die Stichprobengrößen variieren sehr stark. Insgesamt werden Überschallknalle und auch Low Sonic Booms in der Regel innerhalb eines Gebäudes als belästigender wahrgenommen als im Freien, was unter anderem auf begleitende Vibrationen und Rattle zurückzuführen ist, die das Belästigungsempfinden verstärken können (z. B. Kryter 1966; Miller 2011). Einige Studien ermittelten dB Zuschläge bei Vorhandensein von Rattle und Vibrationen (z. B. Sullivan et al. 2010). Für Rattle fanden sich dB-Zuschlagswerte (vgl. auch Sullivan et al. 2010) von 0 dB bis 20 dB (z. B. Pearsons et al. 1993; Fidell, Silvati & Pearsons 2002; Schomer & Averbuch 1989). Für Vibrationen ergaben zwei Studien Zuschlagswerte von 0 dB bis 8 dB (Carr & Davies 2015; Rathsam, Klos & Loubeau 2015; Rathsam & Klos 2016). Die Anstiegszeit zeigte sich ebenfalls als relevanter Einflussfaktor auf die Belästigung und wahrgenommene Lautheit (z. B. May 1972). Bei der Untersuchung und Vorhersage von Lärmbelästigung durch Überschallknalle und Low Sonic Booms scheint daher die Berücksichtigung von Rattle und Vibrationen relevant zu sein. Beim Vergleich verschiedener akustischer Metriken zeigt sich PL (Perceived Level) häufig als bester Prädiktor für Lärmbelästigung (vgl. McCurdy, Brown & Hilliard 2004; Rathsam, Loubeau & Klos 2012; Rathsam, Loubeau & Klos 2015; Carr & Davies 2015; Carr et al. 2020). Insgesamt liegen noch relativ wenig Forschungsergebnisse, insbesondere zur Langzeitwirkung von Low Sonic Booms vor. Anders als bei Unterschallflügen, bei denen Anwohnende in Flughafennähe Fluglärm ausgesetzt sind, wäre eine breite Masse an Menschen Low Sonic Booms sowie den damit verbundenen Vibrationen und Rattle ausgesetzt, die während des gesamten Fluges mit Überschallgeschwindigkeit auftreten können.

Zusammenfassung der Ergebnisse der durchgeführten Schlafstudie und der Literaturanalyse

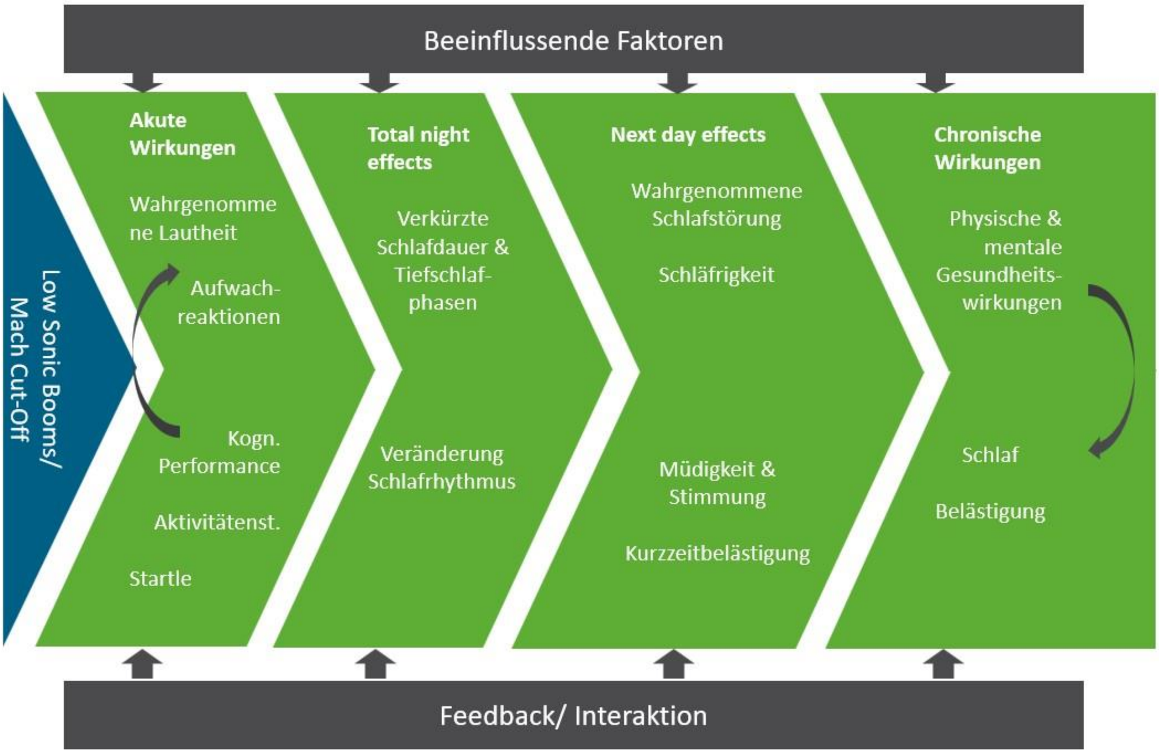
Zur Ableitung von Zumutbarkeitskriterien für Low Sonic Booms und Mach-Cut-off Flüge zum Schutz der Bevölkerung werden die Ergebnisse der durchgeführten Schlafstudie und der Literaturanalyse aufgegriffen und im Hinblick auf etwaige Zumutbarkeitskriterien diskutiert.

Grundsätzlich können die aus der Schlafstudie und Literatur identifizierten Kriterien in akustische Parameter und Lärmwirkungen unterteilt werden. Akustische Parameter beinhalten verschiedene akustische Metriken (z. B. ASEL & PL), die Begleiterscheinung von Überschallflügen Rattle (Deutsch: *Klappern*) und Vibrationen, sowie die Anzahl der Lärmereignisse.

Lärmwirkungen sind ein weiterer wesentlicher Aspekt bei der Beurteilung von Zumutbarkeiten. Porter, Kershaw und Ollerhead (2000) entwickelten ein Modell, welches verschiedene Lärmwirkungen von nächtlicher Fluglärmexposition nach ihrem zeitlichen Auftreten in vier Wirkungslevel differenziert: Akute Wirkungen, Wirkungen über die gesamte Nacht (Total night effects), Wirkungen am darauffolgenden Tag (next day effects) und chronische Wirkungen. Akute Wirkungen sind hierbei direkte physiologische und psychische Wirkungen. Die „Total night effects“ beinhalten Wirkungen, die sich durch die akuten Wirkungen über die gesamte Nachtzeit akkumulieren. „Next day effects“ beziehen sich auf Wirkungen, die am nächsten Tag spürbar werden und durch die ersten beiden Wirkungslevel entstehen. Das letzte Wirkungslevel umfasst langfristige, chronische Wirkungen („chronic effects“), die aufgrund der ersten drei Wirkungslevel auftreten können. Zwischen den Lärmwirkungen kommt es laut Autor*innen zusätzlich zu Interaktionen und Wechselwirkungen. Des Weiteren haben Faktoren, wie Einstellungen, Vertrauen in Verantwortliche oder die individuelle Lärmempfindlichkeit einen Einfluss (Porter, Kershaw & Ollerhead 2000).

Auf Basis der im Rahmen der Schlafstudie verwendeten und der Literaturanalyse identifizierten Lärmwirkungen wurde ein adaptiertes Modell entwickelt, welches neben der nächtlichen Exposition auch die Exposition tagsüber berücksichtigt. Die für Low Sonic Booms und Mach-Cut-off Flüge identifizierten Lärmwirkungen wurden somit den vier Wirkungsleveln nach Porter, Kershaw und Ollerhead (2000) zugeordnet (siehe Abbildung Z 1). In Bezug auf Low Sonic Booms und Mach-Cut-off Flüge beinhalten akute Lärmwirkungen beispielsweise die wahrgenommene Lautheit, Aufwachreaktionen und die Startle-Reaktion (Deutsch: *Aufschrecken*). Die total nights effects umfassen eine verkürzte Schlafdauer und verkürzte Tiefschlafphasen sowie eine durch die Störungen hervorgerufene Änderung des Schlafrhythmus. Nach einer lärmgestörten Nacht (next day effects) kann es unter anderem zu Schläfrigkeit und Belästigung (Kurzzeitbelästigung) kommen. Im Zusammenhang mit Fluglärm fanden sich langfristige Wirkungen wie chronische Schlafstörungen, langfristige Belästigung sowie erhöhte physische und psychische Erkrankungsrisiken. Diese langfristigen Wirkungen könnten auch bei Low Sonic Booms und Mach Cut-Off Flügen eine Rolle spielen, wobei zu den langfristigen Wirkungen von Low Sonic Booms und Mach Cut-Off Flügen noch keine Forschungsergebnisse vorliegen.

Abbildung Z 1: Adaptiertes Modell (nach Porter, Kershaw & Ollerhead 2000) mit relevanten Lärmwirkungen für Zumutbarkeitskriterien



Anmerkung: Angepasstes Modell nach Porter, Kershaw und Ollerhead (2000), Quelle: eigene Darstellung, ZEUS.

Empfehlungen zur Ableitung von Zumutbarkeitskriterien

Ziel dieses Forschungsprojekts war unter anderem die Erarbeitung von geeigneten Zumutbarkeitskriterien für die Beurteilung von Low Sonic Booms und Mach Cut-Off Flügen.

Es bietet sich beispielsweise für die Beurteilung von Low Sonic Booms und Mach-Cut-off Flügen an, die unterschiedlichen Lärmwirkungen einem Ranking zu unterziehen. Die Weltgesundheitsorganisation (WHO 2018) hat dies bereits für andere Lärmquellen getan und diese in entscheidende, relevante und nicht relevante Wirkungen unterschieden. Für mittel- bis langfristige Lärmwirkungen anderer Umgebungslärmquellen werden zudem sogenannte DALYs (disability adjusted life years) berechnet. Diese ermöglichen die Quantifizierung von – auch im Schweregrad – unterschiedlichen Lärmwirkungen und könnten in Zukunft auch für die Wirkungen von Low Sonic Booms und Mach-Cut-off Flügen sinnvoll sein.

Zum jetzigen Forschungsstand können keine konkreten Vorschläge für ein Ranking der Zumutbarkeitskriterien oder für etwaige Grenzwerte für die Zumutbarkeitskriterien abgeleitet werden. Die hier durchgeführte Schlafstudie ist ein wichtiger Schritt zur Untersuchung der Lärmwirkung von Low Sonic Booms und Mach Cut-Off Flügen, wobei anzumerken ist, dass beispielsweise der Effekt von Rattle und Vibrationen im Rahmen der Studie nicht untersucht werden konnte. Ergebnisse der für die Jahre 2026 bis 2028 geplante Feldstudie zu Low Sonic Booms der NASA (NASA’s X59 Quesst Community Survey Campaign) können ebenfalls erheblich zum Wissensstand beitragen.

1 Introduction and task

The era of civil supersonic aircraft ended in 2003 with the last flight of the Franco-British Concorde. One of the emissions produced by a supersonic aircraft is a pressure wave, which is generated as soon as an object travels at supersonic speed (Sparrow & Vigeant 2019). This shock wave spreads behind the aircraft and is perceived as a very loud noise event on the ground. This is known as a sonic boom. Since an aircraft travels continuously at supersonic speed and the pressure wave is produced continuously, the entire area below the aircraft's trajectory (~40 kilometres on both sides) will be affected by the sound propagation.

In order to avoid the effects of the sonic boom on the population (e.g. sleep disturbances, startle reactions, annoyance) and to reduce the impact on the environment, flying at supersonic speeds over land was expressly prohibited in Germany until November 2015 in accordance with §11a of the Air Traffic Regulations (LuftVo). The subsequent version of the LuftVo (2015) was amended as part of the European harmonisation of the air traffic rules (Standardised European Rules of the Air, SERA), thereby removing the previous ban. According to §11 of the LuftVo, the Federal Office of Civil Aviation may grant exemptions for aircraft that cannot comply with the specified speed restrictions (SERA.6001 c-d). §38 of the LuftVo regulates the approval of exemptions for supersonic flights under visual flight rules. This applies both to exemptions (SERA.5005 d, No. 2), provided that no sonic boom is detectable on the ground during supersonic flights, and to exemptions for experimental purposes, if they serve to prove that a sonic boom is not detectable on the ground.

The opportunity to exploit new market potential through optimised, more cost-efficient aircraft and flight procedures is an incentive for the industry to strive for the reintroduction of civil supersonic flights. One advantage is the significant reduction in travel time using supersonic aircraft. The National Aeronautics and Space Administration (NASA) is currently developing designs for quieter supersonic aircraft and flight procedures to enable certification for civil use (Loubeau et al. 2019).

One concept for reducing the exposure of the population to sonic booms on the ground is the so-called "low-boom" design. This involves modifying the aircraft geometry so that the sonic boom generated is less impulsive and softer. The new aircraft designs promise a significant reduction in noise during supersonic flight and the resulting sonic boom – so-called low sonic boom signatures (Maglieri et al. 2014).

In addition to the new aircraft designs, a special flight procedure under certain atmospheric conditions – the so-called Mach cut-off procedure – is also expected to lead to a significant reduction in noise exposure. This involves flying at speeds just above the speed of sound, at around 1.0 to 1.15 Mach in the lower atmosphere (Sparrow & Vigeant 2019). The lower atmosphere refracts the supersonic shock waves upwards. As a result, the central sonic boom does not reach the ground. The pressure wave, which is attenuated in this way, should only be heard on the ground as a rumbling thunder (Loubeau & Page 2018).

Current studies on the effects of low-boom signatures on humans report on the effects on perceived annoyance and subjective loudness, as well as on physiological responses (e.g. Töpken & van de Par 2021; Marshall & Davies 2012). However, to date, there have been no studies on the effects of low sonic boom or Mach cut-off signatures on sleep. These are necessary, however, in order to assess whether flights by quieter supersonic aircraft over populated areas, especially at night, are at all acceptable to the population.

Aircraft are assessed and certified by the International Civil Aviation Organisation (ICAO) according to specific certification criteria. Unlike the noise generated by conventional subsonic flights, the noise emission of a supersonic aircraft is a new type of noise. Therefore, assessment criteria must be established and introduced for the certification of supersonic aircraft. These criteria are based on both the effect of individual noise events and cumulative effects (Loubeau & Page 2018). Not only the noise levels, but also the noise characteristics will differ from those of first-generation supersonic aircraft (Concorde, TU144 and supersonic military aircraft). The human response to these noise immissions, both during sleep and while awake, is also likely to be different. Findings from the literature on the effect of noise from first-generation supersonic aircraft on sleep are not transferable for assessing the effects of low-boom aircraft signatures (Griefahn & Jansen 1975; Rylander, Sörensen & Berglund 1972). Quantifying the effect of aircraft noise on sleep based on exposure-response relationships provides an important basis for the development and introduction of night-time protection concepts, such as those introduced for conventional aircraft at Frankfurt/Main and Zurich airports (Basner, Isermann & Samel 2006; Brink et al. 2010).

In view of the above points, there is a need for research into the relevant noise effects of sonic booms on humans, especially on sleep. The aim is to develop criteria for assessing the acceptability of sonic booms from future civil supersonic aircraft to the population. As part of this research project, a laboratory study was to be designed and conducted under controlled conditions to investigate the effects of sonic booms on sleep. Simulations of sonic booms, as expected from future low-boom aircraft and using the Mach cut-off method at cruising altitude, were to be considered.

Furthermore, a detailed literature review and evaluation of the noise effects of civil supersonic aircraft was to be carried out, including consideration of ongoing national and international research activities. Based on the literature analysis and the results obtained in the sleep study, criteria for assessing the acceptability of sonic booms from future civil supersonic aircraft for the population in Europe should be derived and a recommended level for the noise protection of the population in Germany should be defined. The criteria developed should be used to assess the concepts currently under discussion for the operation of civil supersonic aircraft. The project was carried out in five work packages:

- Work package 1 – Conception of the sleep study,
- Work package 2 – Conduction and evaluation of the sleep study,
- Work package 3 – Development and application of acceptability criteria,
- Work package 4 – Exploitation of the research results,
- Work package 5 – Final report.

2 Work package 1 – Conception of sleep study

The sleep study was designed based on the contractors' experience from previous sleep and noise impact studies and on a literature review of the effects of traffic noise on humans. In particular, current findings and forecasts regarding sonic booms from future civil supersonic aircraft were considered. Initially, hypotheses were derived, subsequently the measurement variables and survey methods were determined and the study design was planned.

Work package 1 included the following steps:

1. Simulation and selection of noise stimuli
2. Test study of achievable overpressures
3. Preparation and validation of sound presentation
4. Literature-based derivation of hypotheses
5. Determination of sample size
6. Conception of the study design

The aim of this research project, commissioned by the Federal Environment Agency, was to examine the effects of sonic boom signatures, as expected from planned civil supersonic aircraft, on sleep. Therefore, a laboratory study was to be designed under controlled conditions and the following specifications were to be implemented:

- Examination of 26 healthy individuals with normal hearing ability according to their age over a period of four days, i.e. a total of 78 nights.
- Inclusion of thirteen female and thirteen male subjects in the study.
- Age of participants between 18 and 65 years.

This research project was intended to answer the following questions:

- Does the sleep rhythm change, and are there changes in sleep depth?
- Are there noise-induced awakenings?
- How is sleep quality assessed by the participants?
- Do noise-related physiological reactions occur while awake?

To answer these questions, sonic booms were to be generated synthetically, with the characteristics of these sounds designed to match those expected on the ground and inside buildings. The effects of sonic booms from future civil supersonic aircraft at cruising altitude were to be examined, as well as sonic booms generated using the Mach cut-off method. Only the effects of single noise events were to be considered.

2.1 Simulation and selection of noise stimuli

Quiet sonic booms essentially consist of an overpressure and a negative pressure wave with predicted amplitudes of around 20 Pascal (Pa) (demonstrator, C25D, Ishikawa et al. 2019) to around 40 Pa (business jet, JAXA S4, Liebhardt et al. 2020). The duration of such a pressure signature depends largely on the length of the aircraft and is in the order of 100 to 150 milliseconds (ms). The signals are spectrally dominated by their low-frequency component with a maximum between 5 and 10 Hz and a decay in intensity towards high frequencies.

Low-boom demonstrators (e.g. NASA X-59, Boom XB-1) are currently under development. These will be significantly smaller than business or passenger jets and will only be able to carry one pilot. As none of these demonstrators are flying yet, only noise simulations of potential future low-booms are available. The simulations are mainly of demonstrator aircraft. Only one published simulation of a future business jet has been found in the literature so far (JAXA S4, Liebhardt et al. 2020). There are also attempts to generate low-booms through special flight manoeuvres. There was already a major field study on this by NASA in Galveston in 2018 (Page et al. 2018). The extent to which the sounds generated by flight manoeuvres actually correspond to those of future low-boom jets is still unclear.

The noise signatures of Mach cut-off flights have often been compared with fighter jet flights (Cliatt et al. 2016; Sparrow & Vigeant 2019). Mach cut-off noises consist of pressure fluctuations with an amplitude of around 2 Pa to 4 Pa over a duration of 2 to 4 seconds. There are initial approaches to simulating the ground noise of Mach cut-off flights, but to the contractor's current knowledge there are no publications on this in the scientific literature, neither for conventional supersonic aircraft/fighter jets nor for future low-boom configurations.

Several sources are available as stimuli for the reproduction of low-boom signals and Mach cut-off signals, which were identified during the design of the laboratory study. There was also an internal exchange regarding usable signatures within DLR (e.g. EU project [European Union] "noiSe and EmissioNs of supErsoniC Aircraft" [SENECA]). The final selection of noise stimuli was then made in consultation with the client.

The following sources for a low-boom signature were generally considered:

a) The ground signature of a JAXA (Japan Aerospace Exploration Agency) S4 business jet simulation scaled to a maximum overpressure of 43 pascals (Pa) (Liebhardt 2020).

b) The ground signature of a simulation of the NASA (National Aeronautics and Space Administration) C25D demonstrator. This originates from the work of the project "RegUlation and norM for low sonic Boom Levels" (RUMBLE)/ Sonic Boom Prediction Workshop 2 of the American Institute of Aeronautics and Astronautics (AIAA) (NASA 2017; Park & Nemec 2017; Ishikawa et al. 2019).

c) The ground signature of a simulation of the NASA C608 demonstrator. This originates from the work of the AIAA Sonic Boom Prediction Workshop 3 (NASA 2020). The simulation is intended to match the X-59 demonstrator and come close to a future civilian supersonic jet.

The following sources for a Mach cut-off signature are possible:

d) The image of an F18 military jet in Mach cut-off flight from the NASA study "FArfield Investigation of No boom Threshold" (Cliatt et al. 2016; Sparrow & Vigeant 2019). A request for the signatures was made to NASA in mid-2021 and access was granted in mid-2022.

Flying a supersonic aircraft using the Mach cut-off flight procedure results in the supersonic pressure waves being deflected upwards from a certain line, preventing the central sonic boom from reaching the ground. This line is the so-called caustic line. At this line, there is a very strong pressure focussing with pressure maxima of up to more than 100 Pa. The caustic line can be regarded as a worst-case scenario, which must be avoided at all costs. In the range from z = -100 to z = -500 metres below the caustic line, there are very different noise signatures. The maximum overpressure generally decreases with increasing distance from the caustic line, i.e. which noise is perceived by a person depends on the distance of the person (height above the ground) to the caustic line. From a distance of z = -400 metres, (almost) no noise is to be expected below the caustic line. Due to terrain formation and buildings, the relative height to the caustic line can be less than z = -400 metres.

e) Simulation of a Mach cut-off flight at Pennsylvania State University. A data set (Case A) with signatures for five different distances from the caustic line (z = -100 metres to z = -500 metres) was supplied by Pennsylvania State University.

f) Self-synthesised signals: Construction of a time signal by reading the figures from the ASCENT (Aviation Sustainability Center)-042 report (Sparrow & Vigeant 2019). From the perspective of the contracting institutions (AN), synthesisation is associated with very high uncertainties, especially in the high-frequency range.

Due to an exchange with Pennsylvania State University, the possibility of a low-boom Mach cut-off simulation also arose:

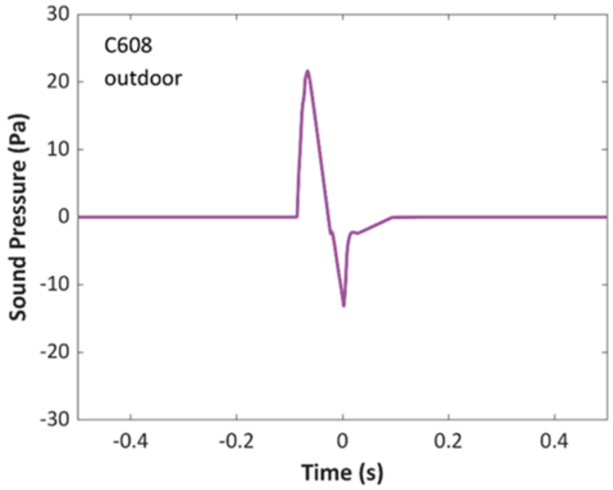
g) simulation of a Mach cut-off flight based on the C608 outdoor signature. A data set with signatures for five different distances from the so-called "caustic line", where pressure focussing occurs, was supplied by Pennsylvania State University.

This option g) for the Mach cut-off signal together with option c) for the low-boom signal best address the questions of the primary and secondary hypotheses (difference between low-boom and Mach cut-off) and were pursued accordingly.

2.1.1 Low-boom simulation

The low-boom simulation (c) corresponds to a signature from the AIAA Sonic Boom Prediction Workshop 3 (NASA, 2020). The signature (Figure 1) originates from the data set "c608groundKirzc608viscmixed064MaTRe", in which a pressure curve and a time vector are given. The original signature has a sampling rate of around 146.52 kilohertz and a duration of around 0.26 seconds. Due to the very high sampling rate, the signature was interpolated and downsampled to a sampling rate of 48 kilohertz (kHz). The signatures were exported as a wave file (.wav) for playback in the simulator.

Figure 1: Sound pressure of the low-boom simulation



Note: Option (c) or signature C608 from the AIAA Sonic Boom Prediction Workshop 3 (NASA 2020) shown as sound pressure over time. Source: own visualisation, UOL.

2.1.2 Low-boom Mach cut-off simulations (Mach cut-off simulations)

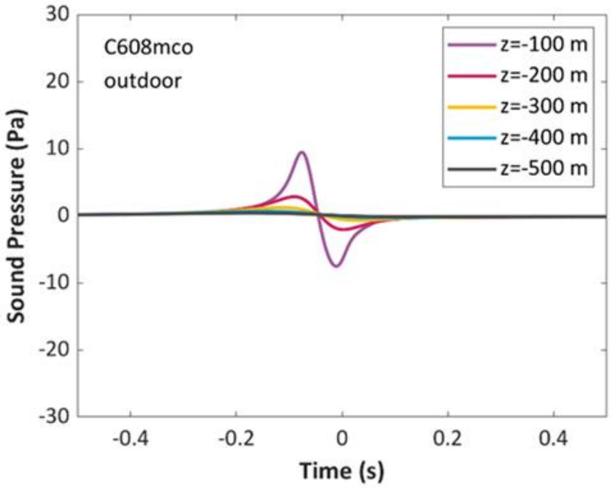
The low-boom Mach cut-off simulations of option (g) were supplied by Pennsylvania State University as a MATLAB file. The signal of the low-boom simulation from option (c) served as the basis for the simulation. The initial ground signature (C608) was supplied to Pennsylvania

State University by UOL. The resulting Mach cut-off simulations again contained signatures at different distances from the caustic line (Figure 2).

Option (g) allowed a direct comparison of the additional effect of a (simulated) Mach cut-off procedure for a simulated low-boom configuration. Since the overpressures in case (g) are very low overall, a distance of z=-100 metres below the "caustic line" can be included in the study as a "worst case".

The signatures supplied by Pennsylvania State University were exported as wave files for playback in the simulator. (.wav) files for playback in the simulator.

Figure 2: Sound pressure of the Mach cut-off simulations based on the C608 low-boom simulation für five distances below the „caustic line“



Note: Option (g) based on the C608 low-boom simulation from Pennsylvania State University. Shown is the sound pressure over time for five distances z below the so-called "caustic line". Source: own illustration, UOL

In the following sections, only the term Mach cut-off simulation is used to differentiate between the two signatures (low-boom signature and low-boom Mach cut-off signature).

2.1.3 Outdoor-indoor simulation

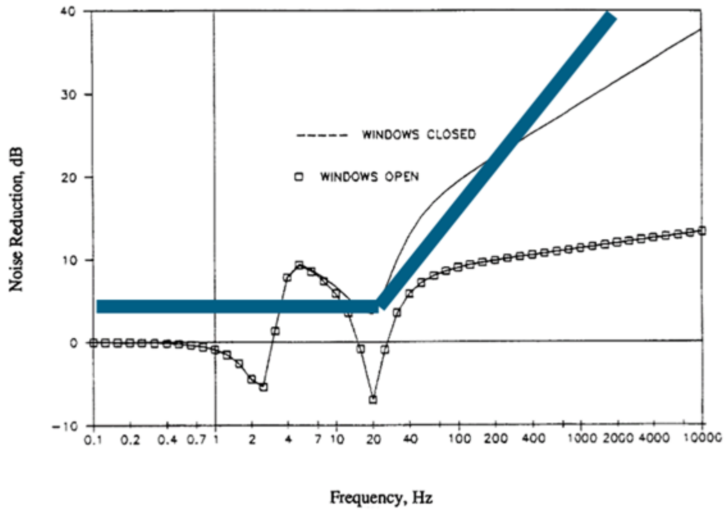
For a reproduction of the signals in the sleep laboratory, a transmission of the outdoor ground signatures from outside to inside a building was simulated. In the literature, measured transmission losses for sound transmission in buildings from the outside to the inside, even for very low frequencies, were found.

In Brown and Sutherland (1992), a model for typical residential buildings was used to predict the sound transmission for reduced sonic booms in the building. Figure 3 shows the sound pressure level reduction for open and closed windows from Brown and Sutherland (1992).

Sparrow and Vigeant (2019) used a model to simulate sound transmission from the outside to the inside based on a timber construction (purple curve in Figure 4). Comparisons with measurements of typical buildings showed that the real transmission losses achieved were almost frequency-independent at around 20 decibels (dB), especially for frequencies above 500 Hz (yellow curve in Figure 4). This frequency independence at higher frequencies was also adopted for their investigations (black curve in Figure 4).

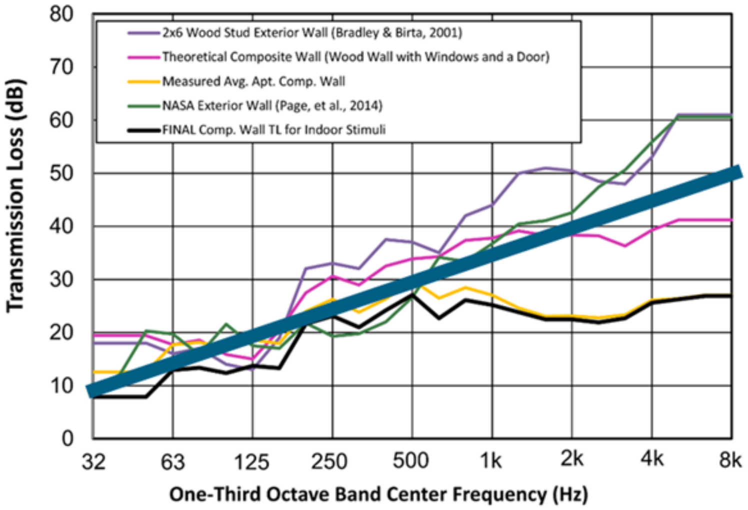
In Keränen et al. (2019), measurements of the level reduction for transmission from the outside to the inside can be found for 13 different houses in Finland with a total of 26 different exterior wall constructions. For the measurements, loudspeakers were placed outside of buildings and sound pressure levels were measured in front of the façade and inside the building. Figure 5 shows different percentiles of the transmission loss for measurement positions in the centre of a room.

Figure 3: **Transmission loss for sound transmission from outside to inside as level reduction over frequency and simple approximation**



Note: The blue line represents the simple approximation. Source: Brown and Sutherland (1992), adapted.

Figure 4: **Transmission loss for sound transmission from outside to inside as level reduction over frequency and simple approximation**

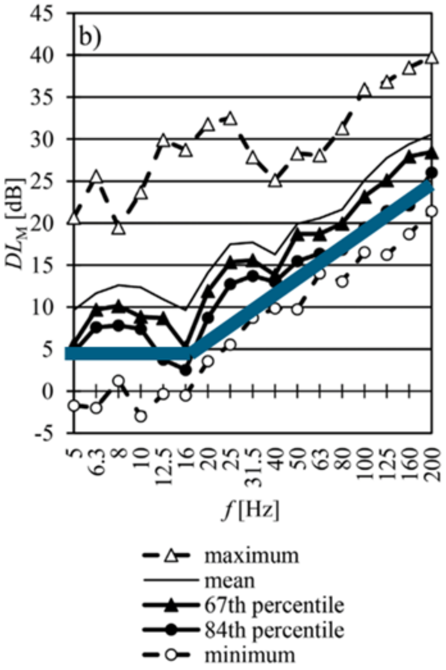


Note: The blue line represents the simple approximation. Source: Sparrow and Vigeant (2019), adapted.

In general, the data from the literature show local minima of the transmission loss at around 3 Hz (Brown & Sutherland 1992) and 5 Hz (Keränen et al. 2019) and at 20 Hz (Brown & Sutherland 1992) and 16 Hz (Keränen et al. 2019) with a local maximum of around 10 dB in between. The reduced transmission loss for the frequencies is probably due to track matching effects at the coincidence frequencies, which depend on the respective wall construction. In contrast to the modelling by Brown and Sutherland (1992), the measurements by Keränen et al. (2019) only show truly negative transmission losses in the local minima for the lowest percentile curve. From the 67 per cent percentile, the minima are still at least 5 dB in terms of transmission loss. For higher frequencies, all studies show a level reduction that increases with frequency from around 20 Hz. The increase is stronger for the buildings of European design (Keränen et al. 2019) than for the buildings of the American studies and their models (Brown & Sutherland, 1992, Sparrow & Vigeant 2019).

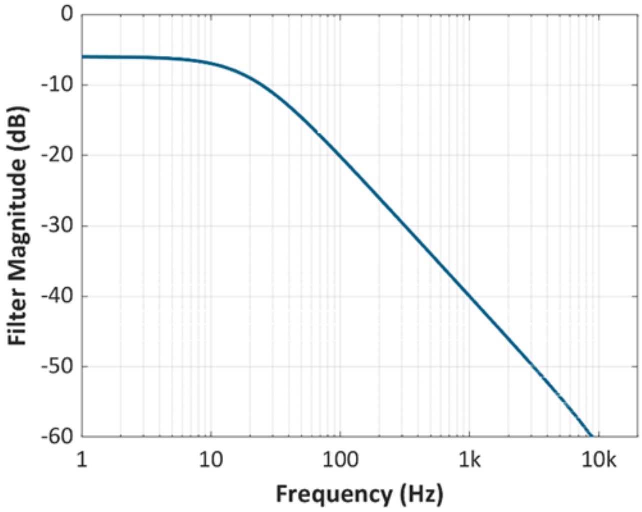
A generic, conservative approximation of the transmission loss is a low-pass filter with a decay of -6 decibels/octave (dB/oct.) and a cut-off frequency of around 20 Hz together with an additional frequency-independent level reduction of 6 dB (Figure 6). This approximation corresponds approximately to the 84 per cent percentile of the study by Keränen et al. It is shown as a blue line for comparison with the literature data in Figure 3 to Figure 5. A decay of -6 dB/oct. also corresponds to the so-called mass law for sound transmission for single-shell walls and vertical sound incidence (Kuttruff 2004). As a rough approximation, the frequency range up to the coincidence frequency is considered constant and a fixed reduction of 6 dB is applied, which comes close to the measurements of Keränen et al. (2019).

Figure 5: **Percentiles of measured transmission losses for sound transmission from outside to inside as level reduction DL_M over frequency and simple approximation**



Note: The blue line represents the simple approximation. Source: Keränen et al. (2019), adapted.

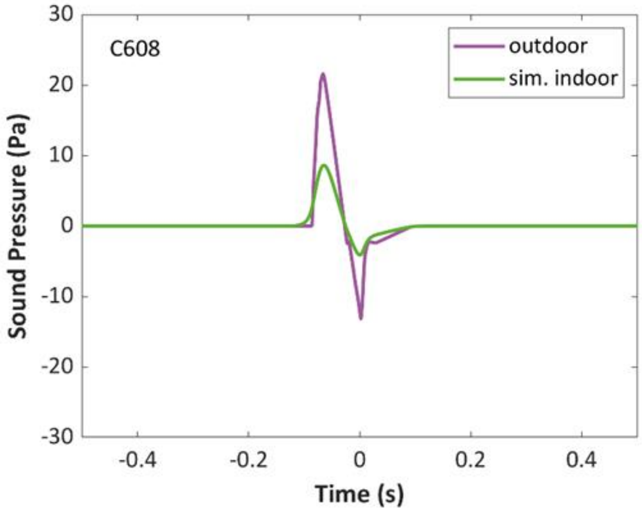
Figure 6: **Amplitude transfer function of the low-pass filter for simulating the outdoor-indoor transfer function**



Note: Source: own illustration, UOL.

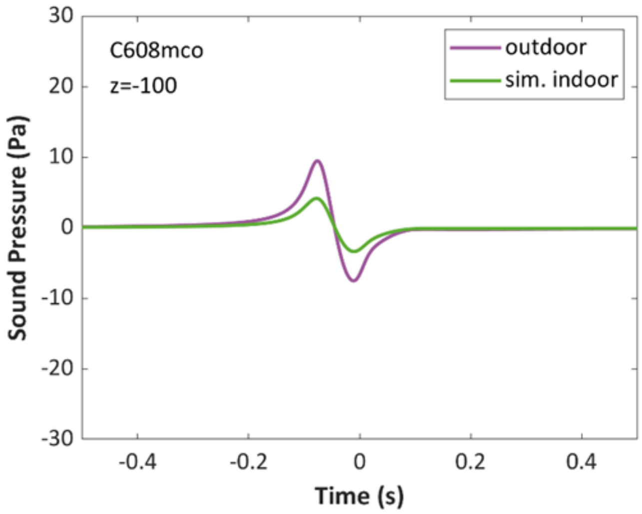
Figure 7 shows the low-boom signature (option c) and Figure 8 shows the Mach cut-off simulation (option g) as indoor signatures to be used in the sleep study, together with the underlying outdoor signature in each case.

Figure 7: **Sound pressure of the low-boom simulation C608 as outdoor signal and simulated indoor signal**



Note: Low-boom signature (option c) as an outdoor signal (blue line) and simulated indoor signal (orange line). Shown is the sound pressure over time. Source: own illustration, UOL.

Figure 8: **Sound pressure of the Mach cut-off simulations as outdoor signal and simulated indoor signal for a distance of 100 metres below the "caustic line"**



Note: Mach cut-off simulations (option g based on the C608 low-boom simulation, Pennsylvania State University) as outdoor signal (blue line) and simulated indoor signal (orange line). Shown is the sound pressure over time for a distance of z = -100 m below the so-called "caustic line". Source: own illustration, UOL.

2.2 Test study of achievable overpressures

A presentation of high sound pressures at low frequencies is often realised in the laboratory in a so-called pressure chamber, i.e. a small, airtight room in which the air volume in the room is compressed, e.g. by loudspeaker chassis embedded in the wall. As the rooms for the sleep study had a significantly larger floor area than such a pressure chamber and constant ventilation had to be ensured, it was initially unclear what overpressure values could be achieved with conventional subwoofer loudspeakers. In a test study in June 2022, the achievable overpressures in a typical sleep laboratory room with the existing subwoofer loudspeakers were therefore tested in the bedrooms of the AMSAN (Occupational Medical Simulation Facility) of the DLR in Cologne.

The tested AMSAN sleep room C (Figure 9) has a floor area of ~5.5 square metres (~2.6 metres x 2.4 metres with the door positioned diagonally in the corner) and a ceiling height of 2.6 metres, resulting in a room volume of ~14 cubic metres. The room has a simple single-leaf door with a single seal and ventilation slots at the bottom.

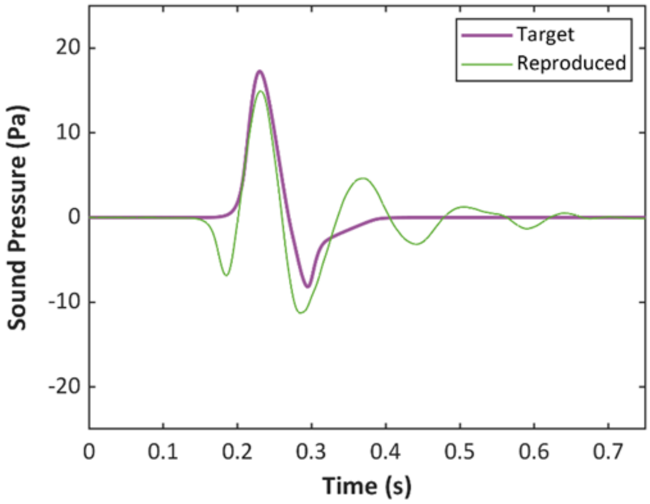
In the room, three existing subwoofers (type SVSound SB-2000) were placed one above the other in the rear right-hand corner of the room at a distance of around 20 centimetres from the walls (Figure 9). The settings of the subwoofers were as follows: Volume: maximum, Phase: 0, Low Pass Filter: 50 Hz. The technical measurement setup corresponds to the block diagram shown in Figure 15, except for the number of speakers and their distribution across rooms. The reproduction of various low-boom signatures was measured at the listening position above the pillow. In principle, overpressures of up to around 15 Pa could be achieved with various low-boom signatures. There was no audible rattling noise from lamps, ventilation grilles or similar.

However, there were deviations from the target signature with an undershoot before the maximum overpressure and some aftershocks, which can be caused by the loudspeaker systems used (in particular their integrated high-pass and low-pass filters) and the room influence (Figure 10). The deviations could not be compensated for by digital pre-filtering of the signatures, so this was not used in the following.

Figure 9: **Measurement setup in AMSAN bedroom**

Note: Three stacked subwoofers in the corner of the room and measurement microphone at the listening position. Source: own illustration, UOL.

Figure 10: **Target signal and reproduction of the low-boom signature C608 (indoor, +6dB) in AMSAN bedroom**



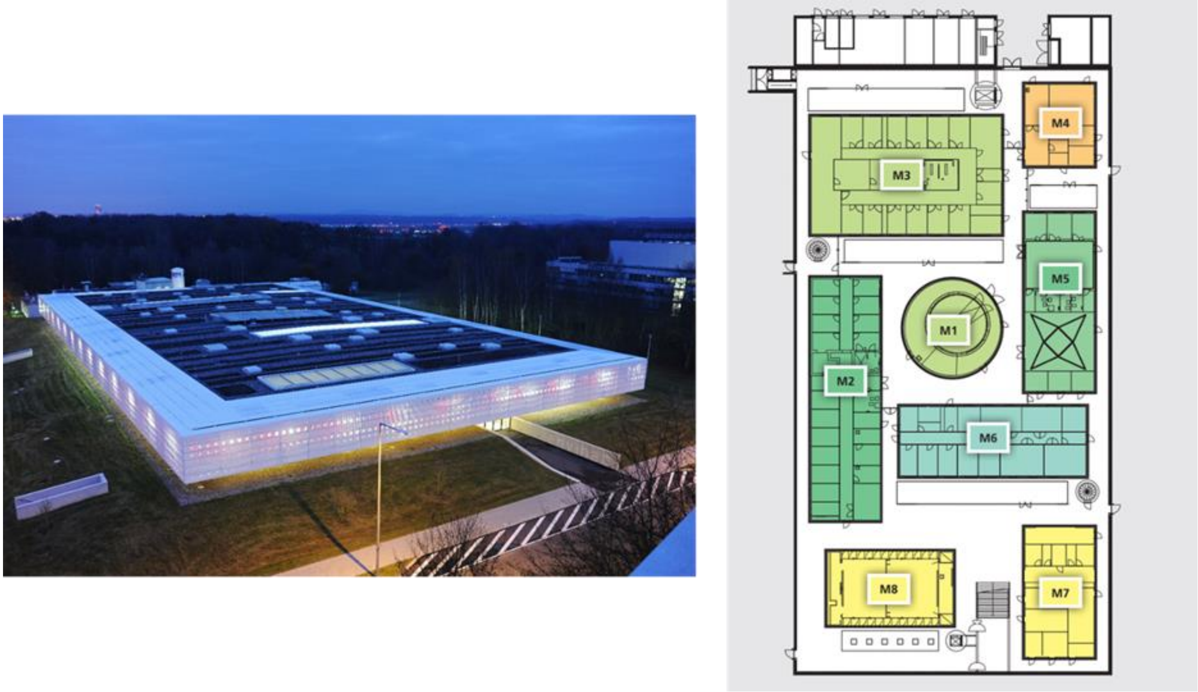
Note: The target signal (blue) and its reproduction in room C (red) are shown as sound pressure over time. Source: own illustration, UOL.

2.3 Preparation and validation of the sound presentation in module 5 (M5) of the :envihab (August 2022)

The sleep study was to take place in Module 5 (M5, psychology laboratory) of the aerospace medicine research facility :envihab ("environment" = environment and "habitat" = living space) of the DLR in Cologne (Figure 11). The psychology laboratory is a 130 square metre section of the :envihab for human studies. Three participants can be accommodated there for several days or even weeks under controlled environmental conditions. It is a closed, fully air-conditioned and soundproofed system. The participant area consists of a lounge, three bedrooms, a kitchen and three bathrooms.

For the presentation of the signatures in the sleep study, the three bedrooms (hereafter A, B and C) in M5 were equipped with loudspeakers. The signatures were played back in the bedrooms and recorded at the listening position. The recorded signals were used to validate the sound presentation in further listening experiments in the laboratory at the University of Oldenburg.

Figure 11: Aerospace medicine research facility :envihab of the DLR in Cologne



Note: Exterior view (left) and floor plan (right) of the :envihab (left). M1 = DLR short-arm centrifuge, M2 = prevention and rehabilitation laboratory, M3 = sleep and physiology laboratory, M4 = PET-MRI, M5 = psychology laboratory, M6 = biology laboratory, M7 = infrastructure, M8 = auditorium, source: own illustration, DLR (CC BY-NC-ND 3.0).

The dormitories in M5 are each slightly more than twice as large as those in the AMSAN. They each have a floor area of 12.6 square metres (~3.3 metres x 3.8 metres) and a ceiling height of 2.8 metres, which results in a room volume of ~35 cubic metres each. Each room has a double-leaf soundproof door with double door and floor seals.

2.3.1 Background level and reverberation times in the bedrooms in M5

The background level was measured in all three bedrooms using a hand-held sound level meter (Norsonic, Nor 140) at the listening position above the pillow in the bed over a period of 10 seconds. In all rooms, there was an A-weighted sound pressure level of about 30 dB(A) with differences of about 3 dB between the rooms due to the permanently running ventilation and air conditioning system (Table 1). The unweighted sound pressure level was higher than the A-weighted sound pressure level, which suggests that the background noise was characterised in particular by low-frequency components, which is typical of air-conditioning noise.

Table 1: **Background sound pressure level in the bedrooms of the M5**

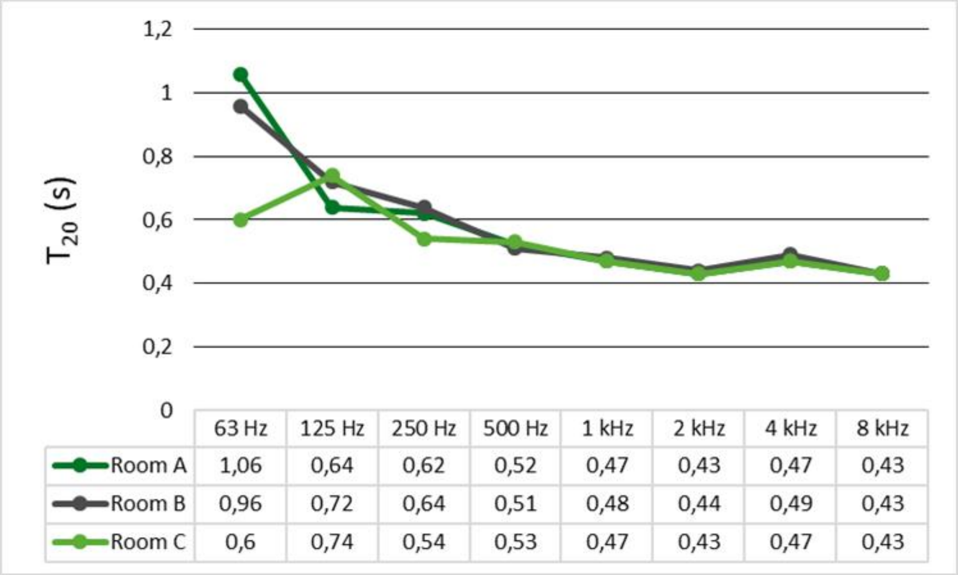
Sleeping room	$L_{Z,eq}$	L_{Aeq}
Room A	43,2 dB	33,2 dB(A)
Room B	40,4 dB	29,9 dB(A)
Room C	53,0 dB	27,4 dB(A)

Note: Average of two measurements over 10 seconds each, unweighted (Z) and including an A-weighting.

An orientating measurement of the reverberation times was carried out with a hand-held sound level meter (Norsonic, Nor 140) and an impulsive excitation (hand clap). The reverberation times of the three bedrooms are shown in Figure 12 over the octave frequencies from 63 Hz to 8 kHz. The measurement position in each case was on a tripod at approximately ear height at the foot of the bed. The reverberation time for 500 Hz and higher octave frequencies is between 0.4 seconds and 0.5 seconds. For lower octave frequencies, the reverberation time for all three rooms increases to up to 1 second at 63 Hz. The relatively low reverberation time at 63 Hz in room C could be due to limited excitation of low frequencies during impulse excitation.

Due to the relatively high reverberation time, especially at low frequencies below 250 Hz, an effect on the reproduction of the signatures can be assumed. A reduction of the reverberation time at such low frequencies could only be realised with very high structural effort. For this reason and on the basis of the test study, further optimisation of the performance through filtering was discarded and the limited reproduction accuracy was documented in measurements.

Figure 12: **Reverberation times (T_{20}) of the three bedrooms for octave frequencies from 63 Hz to 8 kHz**



	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz
Room A	1,06	0,64	0,62	0,52	0,47	0,43	0,47	0,43
Room B	0,96	0,72	0,64	0,51	0,48	0,44	0,49	0,43
Room C	0,6	0,74	0,54	0,53	0,47	0,43	0,47	0,43

Note: Source: own visualisation, UOL.

2.3.2 Laboratory set-up in the M5

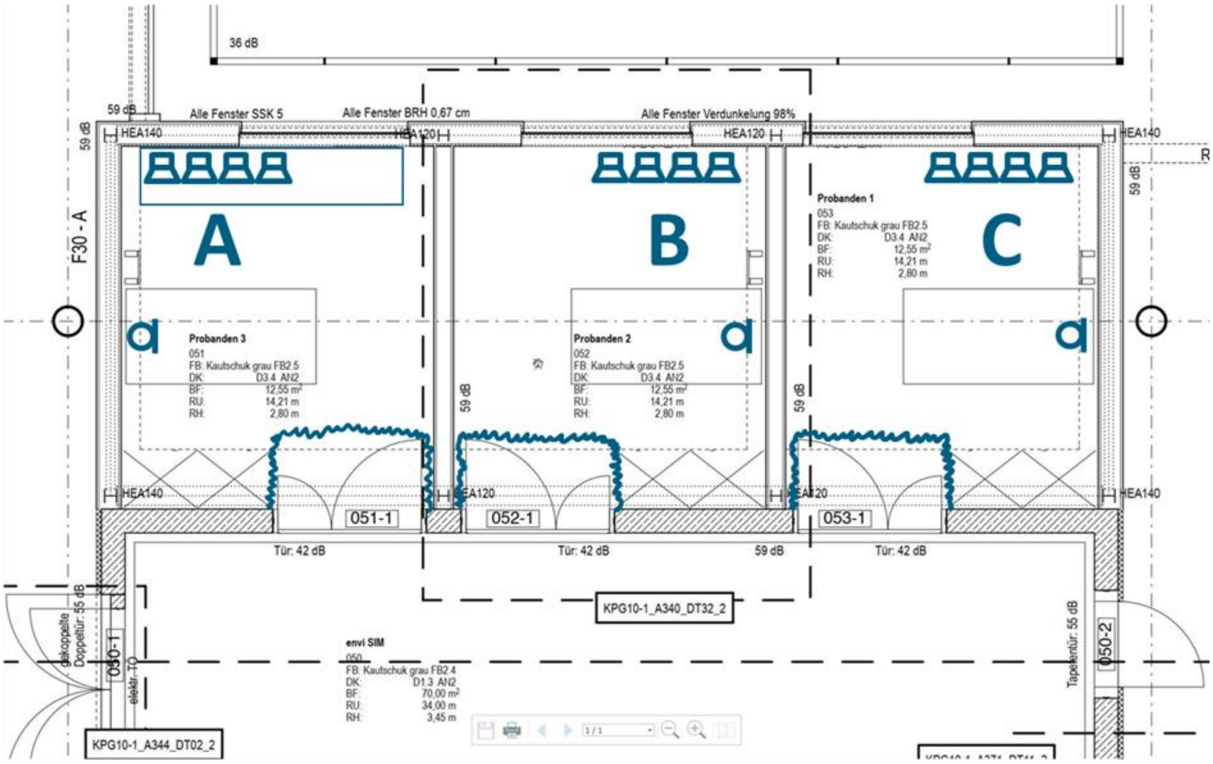
Each of the three bedrooms in the M5 (A, B and C) was equipped with 4 subwoofers (type SVSound SB-2000) for the presentation of the signatures. The subwoofers were placed on the floor parallel to the bed at a distance of around 17 centimetres from the outer wall (Figure 13) in order to minimise the visual impact. Figure 14 shows an example of the setup in room A with the loudspeakers and the measurement microphone positioned at the ear position above the bed. Figure 15 shows a block diagram of the electro-acoustic components used.

The signals were fed to the subwoofers via the main audio interface (RME, Digiface USB) and the digital-to-analogue converter (Ferrofish, Pulse 16 CV). The signal source was either the DLR computer or the UOL computer, which could be digitally connected to the main interface via an audio interface (RME, Fireface UFX+) using ADAT. Each subwoofer was fed into the LFE input from a separate output of the digital-to-analogue converter.

The settings for each subwoofer were: Volume: maximum, Phase: 0, Low Pass Filter: 50 Hz. Measurements showed no clear effect of the low-pass filter on the reproduction of the signatures, as the majority of the energy for the low-boom signatures is in the range below 10 Hz. To suppress any high-frequency interference components, the low-pass filter was set to a minimum value of 50 Hz.

The recordings were made with a ½" infrasonic microphone (GRAS, 47 AC), which was digitally connected via an ICP power supply (UOL 127/09) and an AD converter (RME, ADI-8 QS) and from there to the audio interface (RME, Fireface UFX+) via Multi Channel Audio Digital Interface (MDAI). The measurements were carried out with a single measurement microphone in the three rooms one after the other, with the same signature being played synchronously in all rooms.

Figure 13: Sketch of the laboratory setup during the measurements in the M5

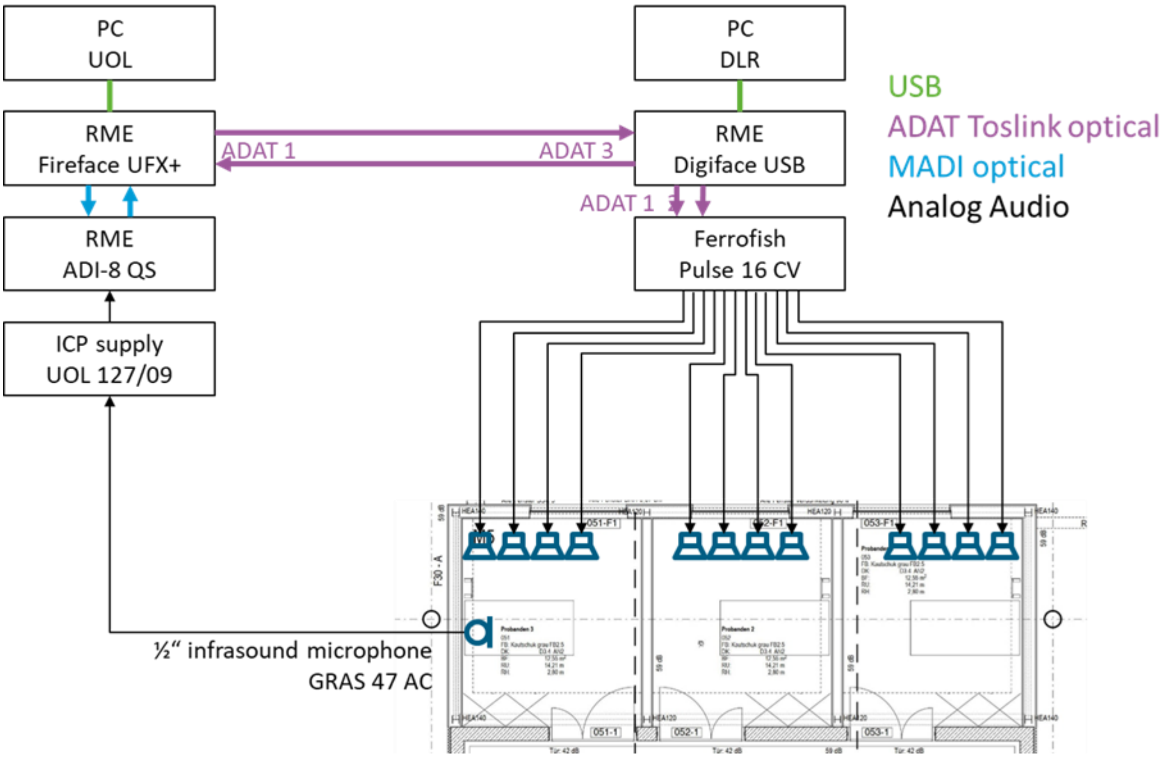


Note: Floor plan with speaker and microphone positions in the three bedrooms A, B and C. The rooms were each equipped with a heavy curtain in the door area. Source: own illustration, DLR/UOL.

Figure 14: Laboratory setup during the measurement in M5

Note: Room A is shown as an example. Source: own illustration, UOL.

Figure 15: Block diagram of the electro-acoustic components for the measurements



Source: own illustration, DLR/UOL.

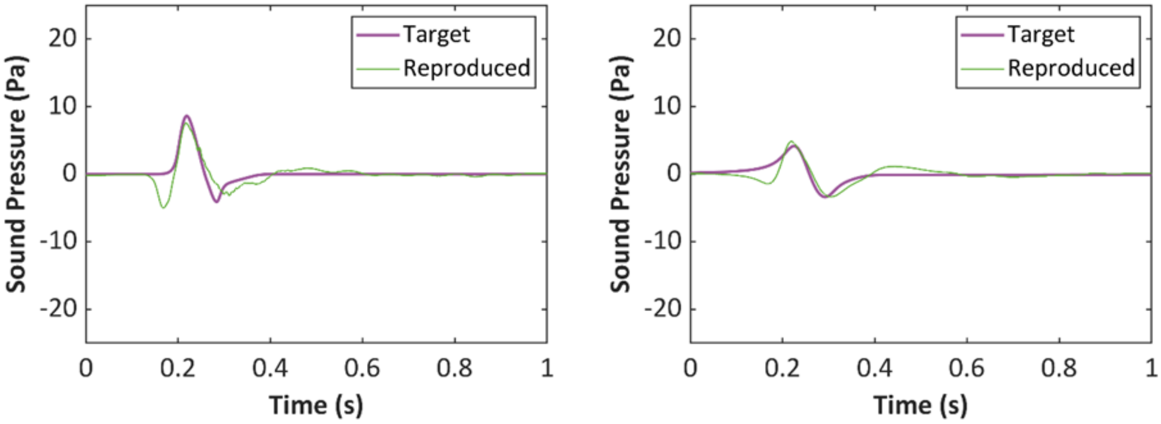
2.3.3 Reproduction of the signatures in the bedrooms

Due to the limited number of available loudspeakers and an unknown signal processing chain in the active subwoofers used (e.g. high and low pass filters) as well as an unknown influence of the room in terms of larger room volume and reverberation time, limitations in the reproduction accuracy for the pressure signatures were to be expected.

The measurements in Figure 16 show that the peak overpressure for the two signatures intended for the sleep study was approximately achieved. There is also a clear deviation in the signal (negative pressure before peak), which may originate from the loudspeaker system used.

Low-frequency resonances, as they occurred in the AMSAN test measurement, are not seen here. Due to the influence of the room with a relatively long reverberation time at low frequencies, it can be assumed that the pressure signatures reverberate accordingly. However, due to the linear representation of the sound pressure, the reverberation can only be recognised to a limited extent in Figure 16. In the bedrooms, there was also quiet rattling noise from the ceiling lamps, which could be partially reduced by fixing loose parts.

Figure 16: Target signal and reproduction of the low-boom signature C608 (indoor) and Mach cut-off signature (indoor) simulated for a distance of 100 metres below the "caustic line"



Note: Indoor low-boom signature C608 (left) and indoor Mach cut-off signature simulated for a distance of 100 metres below the caustic line (right). Target signal (blue) and reproduction in room A (red). Source: own illustration, UOL.

2.3.4 Validation of the signal presentation: Short-term annoyance ratings and determination of the detection threshold for high-pass filtering of the signatures in the simulator at the University of Oldenburg

When reproducing the low-boom and Mach cut-off signatures in the sleep laboratory, it was assumed that very low frequencies in the frequency range of a few Hz, in which most of the energy of the low-boom signatures lies, could no longer be adequately reproduced due to the structural situation of the room and the playback system used, which was based on commercial subwoofers. In addition to the limited number of subwoofers and thus limited cone area, the exact signal processing in the subwoofers was not known and high-pass filtering in the electrical signal path could not be ruled out. It was unclear whether this limitation of the playback system would even be detectable in the sleep laboratory and whether the evaluation of the sounds would potentially be lower than in a simulator.

The aim of this validation experiment was to collect short-term noise annoyance ratings and to determine the detection threshold for high-pass filtering of the signatures in the simulator in Oldenburg, as this can reproduce the signatures down to 2 Hz.

Stimuli: Short-term noise

A total of 16 signals were rated in terms of short-term noise annoyance in listening experiments. An overview of all signals can be found in Table 2. The signals contained the C608 signature (C608) and a Mach cut-off simulation based on it (C608_MCO100, supplied by Pennsylvania State University). In addition, level variations of the C608 signature by plus 3 decibels (dB) (C608_p3dB) and minus 3 dB (C608_m3dB) were analysed. Recordings of the signatures reproduced in the M5 sleep laboratory were also analysed. For each sleep room (A, B and C) there was one recording of the reproduced C608 signature and one of the C608-Mach cut-off signature.

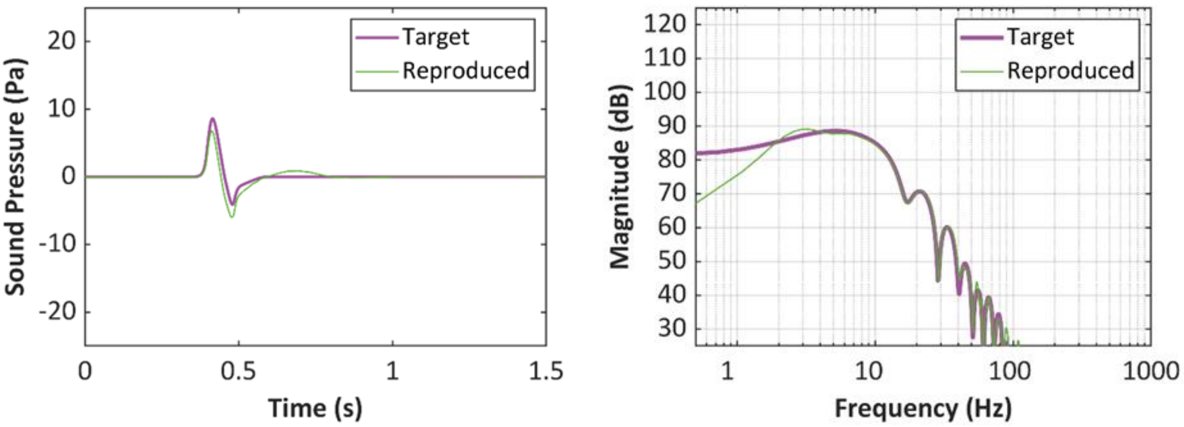
Both the original signals and recordings of the signatures played back in the sleep laboratory were reproduced in a pressure chamber in the laboratory in Oldenburg. As examples, Figure 17 shows the original C608 signature, Figure 18 the Mach cut-off simulation and Figure 19 and Figure 20 the respective recordings from a laboratory room in the sleep laboratory. In each case, the desired target signal (Target) and the reproduction achieved in the pressure chamber (Reproduced) are shown as a time signal and spectrum. Both the original C608 signature (Figure 17) and its Mach cut-off simulation (Figure 18) and the exemplary recordings from room A of the sleep laboratory (Figure 19 and Figure 20) could be accurately reproduced in the pressure chamber and thus used for the listening experiments. The reproduction for the other bedrooms B and C is similar to that of room A and is therefore not shown here.

A comparison of the original C608 signature (Figure 17, blue curve) and the recording from the sleep laboratory (Figure 19, blue curve) shows some differences both in the time signal and in the spectral representation. The signature played back in the sleep laboratory contains less energy at very low frequencies below 5 Hz, which may be due to high-pass filters already expected to be in the signal path and limitations of the subwoofers. There are also additional frequency components in the range from 50 Hz to around 150 Hz. Possible causes for this could be the influence of the room (excited room modes), external background noise, excitation and rattling of components in the room (suspended ceiling, lamps) and potential distortion of the signal by the speakers used.

Table 2 shows the values calculated from the signals for the A-weighted sound exposure level (ASEL) and the maximum overpressure as well as the values achieved in the reproduction in the pressure chamber.

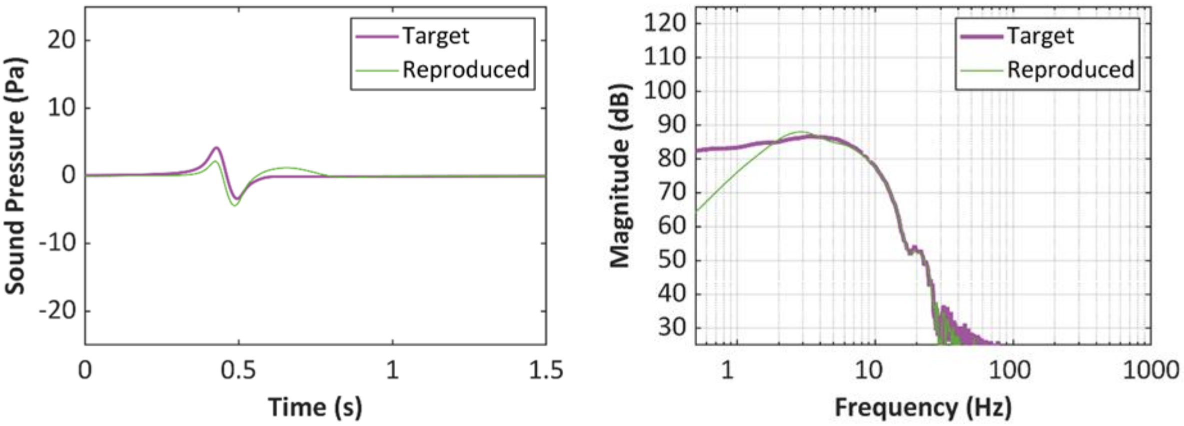
In addition, six signals were taken from the Farfield Investigation of No boom Threshold (FaINT) database, which were also used in the Aviation Sustainability Center (ASCENT) Project 42 in listening experiments (Sparrow & Vigeant 2019). These signatures are recordings of Mach cut-off flights of an F-18 in parallel to a linear microphone array on the ground. The maximum overpressures of these original signatures did not exceed 4 Pascal (Pa) and were significantly lower after the outdoor indoor filtering. Details on the flight altitude and speed from the FaINT-Ground reports (Cliatt et al. 2013) and the respective flight information for these 6 signatures can be found in Table 3.

Figure 17: **Target signal and reproduction of the low-boom signature C608 with indoor filtering**



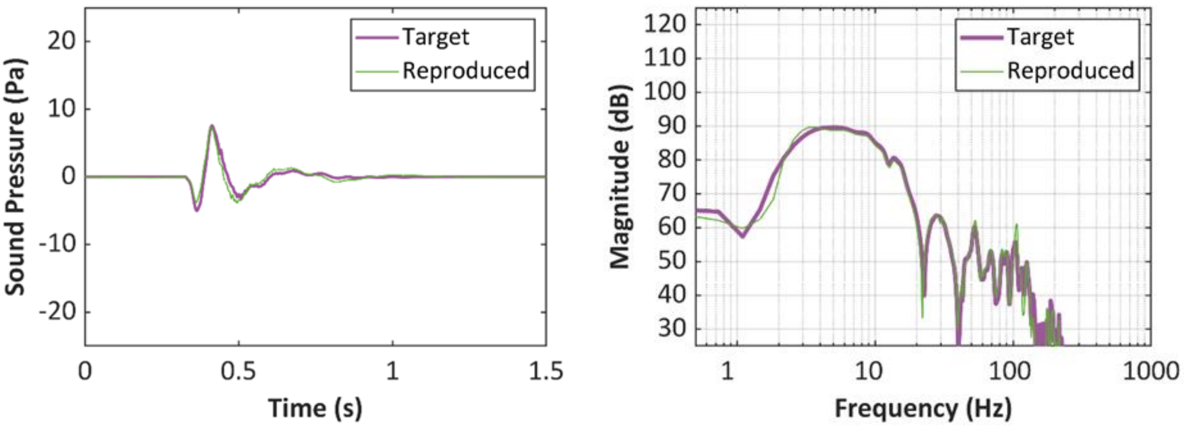
Note: Shown is the target signal of the low-boom signature C608 (AIAA Sonic Boom Prediction Workshop 3, NASA, 2020) with indoor filtering and its reproduction as sound pressure over time (left) and spectrum (right). Source: own illustration, UOL.

Figure 18: **Target signal and reproduction of the Mach cut-off simulation of the low-boom signature C608 with indoor filtering**



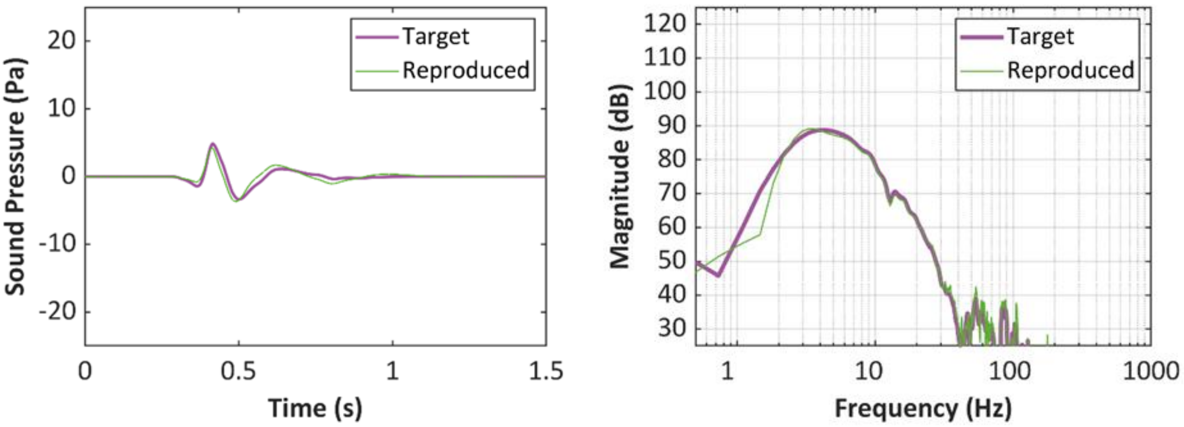
Note: The target signal of the Mach cut-off simulation of the low-boom signature C608 with indoor filtering and its reproduction as sound pressure over time (left) and spectrum (right) are shown. Source: own illustration, UOL.

Figure 19: Target signal and reproduction of the low-boom signature C608 with indoor filtering recorded in the sleep laboratory



Note: The target signal and its reproduction of the low-boom signature C608 with indoor filtering recorded in the sleep laboratory (M5, room A) are shown as sound pressure over time (left) and spectrum (right). Source: own illustration, UOL.

Figure 20: Target signal and reproduction of the Mach cut-off simulation of the low-boom signature C608 with indoor filtering recorded in the sleep laboratory



Note: The target signal and its reproduction of the Mach cut-off simulation of the low-boom signature C608 with indoor filtering recorded in the sleep laboratory (M5, room A) are shown as sound pressure over time (left) and spectrum (right). Source: own illustration, UOL

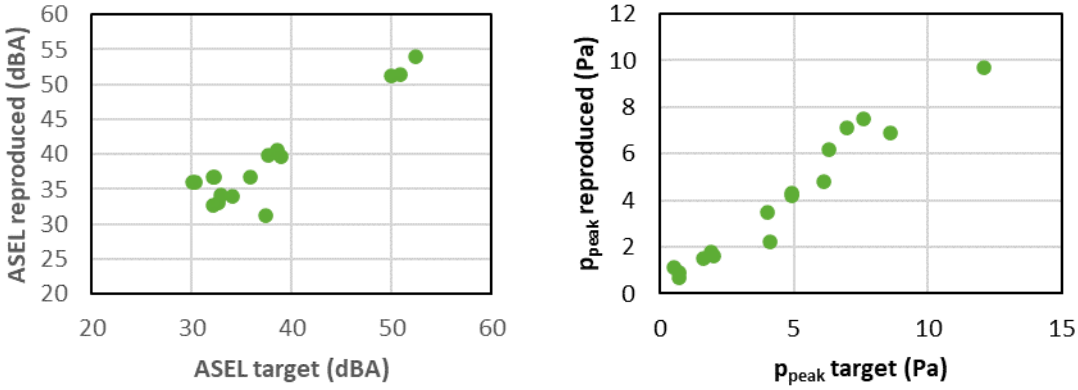
All 16 signatures included a generic simulation of the transmission from outside to inside in the form of a level reduction of 6 dB and low-pass filtering with a decay of -6 dB/octave above a cut-off frequency of 20 Hz. Figure 21 shows the values reproduced in the pressure chamber for the A-weighted exposure level (ASEL) and the maximum overpressure (p_{peak}) above the target values.

Table 2: A-weighted exposure level and maximum overpressure for the signals used in the listening experiment calculated from the signals and their reproduction in the pressure chamber

Number	Signature	ASEL-value (dB) from signal	Maximum overpressure p_{peak} (Pa) from signal	ASEL-value (dB) from re-production	Maximum overpressure p_{peak} (Pa) from reproduction
1	C608_p3dB	38.9	12.1	39.7	9.7
2	C608	35.9	8.6	36.7	6.9
3	C608_m3dB	32.9	6.1	34.1	4.8
4	C608_MCO100	37.4	4.1	31.2	2.2
5	C608_recM5A	50.0	7.6	51.3	7.5
6	C608_MCO100_recM5A	34.1	4.9	34.0	4.3
7	C608_recM5B	50.8	6.3	51.4	6.2
8	C608_MCO100_recM5B	32.1	4.0	32.6	3.5
9	C608_recM5C	52.4	7.0	53.9	7.1
10	C608_MCO100_recM5C	32.6	4.9	33.1	4.2
11	Soft1	30.1	0.7	35.9	0.7
12	Soft2	30.3	0.7	36.0	0.9
13	Loud1	37.6	1.9	39.8	1.8
14	Loud2	38.6	1.6	40.6	1.5
15	Highfreq1	32.2	2.0	36.7	1.6
16	Highfreq2	32.3	0.5	36.8	1.1

Note: Signals 1 to 4 are the low-boom signature, the low-boom signature with level variation of +3 dB and -3 dB, and the Mach cut-off signature with indoor filtering. Signals 5 to 10 are recordings of signals 2 and 4 played back in rooms A, B and C of the sleep laboratory. Signals 11 to 16 are recordings of Mach cut-off flights of an F-18 from the FaINT data set / ASCENT Project 42 with indoor filtering.

Figure 21: **Illustration of the ASEL and overpressure values achieved in the reproduction in the pressure chamber over the values calculated from the signals**



Note: ASEL (dBA) = A-weighted exposure level (left), p_{peak} (Pa) = maximum overpressure in pascals (right), source: own illustration, UOL.

Table 3: **Details of the six overflight recordings of the Mach cut-off flights of an F-18 from the FaINT database**

Label (Sparrow & Vigeant 2019)	**Flight Number** (Cliatt et al. 2016)	**Project Flight**	**DFRC Flight**	**Pass**	**Mic. Chan.**	**Speed (Mach)**	**Goal**	**Description by field personnel**
Soft1	5	12	1392	3	46	1.137	Mach Cut-off 10000, 7500, 3300 ft AGL	Whoosh, Low Rumble
Soft2	2	9	1389	4	32	1.154	Mach Cut-off altitudes of 7300 and 9800 ft AGL	Distant Thunder
Loud1	2	9	1389	1	6	1.154	Mach Cut-off altitudes of 7300 and 9800 ft AGL	Rumble, Distant Thunder
Loud2	6	13	1393	3	37	1.149	Mach Cut-off at 8300 ft AGL	Rumble, Distant Thunder
Highf1	2	9	1389	5	26	1.157	Mach Cut-off altitudes of 7300 and 9800 ft AGL	Whoosh, Distant Thunder
Highf2	3	10	1390	4	43	1.154	Mach Cut-off altitude at 5000 ft AGL	Whoosh, Rumble > Distant Thunder

Note: Assignment to flight numbers in Cliatt et al. 2016 and original information from FaINT Ground Reports (Cliatt et al. 2013), Mic. Chan. = Microphone Channel, ft = feet, AGL = Above Ground Level.

Stimuli: Detection threshold

To determine the detection threshold, the level variations of the C608 signal (signals 1-3 in Table 1) were used as base signals for the adaptive filtering.

Procedure

The listening experiments were carried out by individuals and the procedure was the same for all participants. After a general introduction and written consent, the two experiments took place one after the other in the pressure chamber. The first experiment was always the rating of short-term annoyance and the second experiment was always the determination of the detection threshold. Before each experiment, the participants were given uniform written instructions. After completing the assessment of short-term noise, there was a short break during which initial impressions and annoyance/unpleasantness-relevant aspects of the sounds were openly requested. The participants were also asked how familiar the sounds were to them and how acceptable the sounds would be in general if they were heard several times a day. After the break, the detection threshold for high-pass filtering of the low-boom signals was determined in the second experiment. At the end of the experiment, an open questionnaire was again used to gather initial impressions. In total, one test session lasted about one hour, with each of the two experiments taking about 10 minutes.

Method: short-term blindness

The experiment always started with an orientation phase in which all 16 signals were presented and heard by the participant. The short-term annoyance of the 16 signals was then assessed using an 11-point categorical scale from 0 to 10. The end points of the scale were labelled and the question to the participants was: "How annoying was the noise on a scale from 0 (not annoying at all) to 10 (extremely annoying)". The order of the 16 signals was individually randomised in the orientation phase and in the evaluation.

Method: Detection threshold

The detection threshold for high-pass filtering was determined for each of the three output signals using a separate 3-interval, 3-AFC (Adaptive Forced Choice) procedure. The participants were presented with three intervals in succession, two of which contained the unfiltered signal as a reference and one interval contained the high-pass filtered target signal to be detected. The cut-off frequency of the high-pass filter was varied depending on the participant’s response using a 1-up, 2-down rule. If an incorrect decision was made, the cut-off frequency was increased and after two consecutive correct decisions, the cut-off frequency was reduced. The cut-off frequency of the high-pass filter was 100 Hz at the beginning of the adaptive procedure and the starting step size was 40 Hz. The step size was halved after each upper reversal point of the adaptive track until a final step width of 10 Hz was reached. The procedure was completed after six reversal points with the final step size and the individual detection threshold is calculated as the mean value over the last six reversal points. The adaptive tracks of the measurements for the three output signals were interleaved within the experiment.

Participants

A total of 19 volunteers (10 female, 9 male) took part in the listening test. The mean age was 25.5 years (SD = 3.6 years) and 15 participants already had experience with other listening experiments. All participants were students or employees of the University of Oldenburg. All participants self-reported normal hearing.

For the validation experiments in Oldenburg, an ethics vote was obtained from the Commission for Research Assessment and Ethics at the University of Oldenburg.

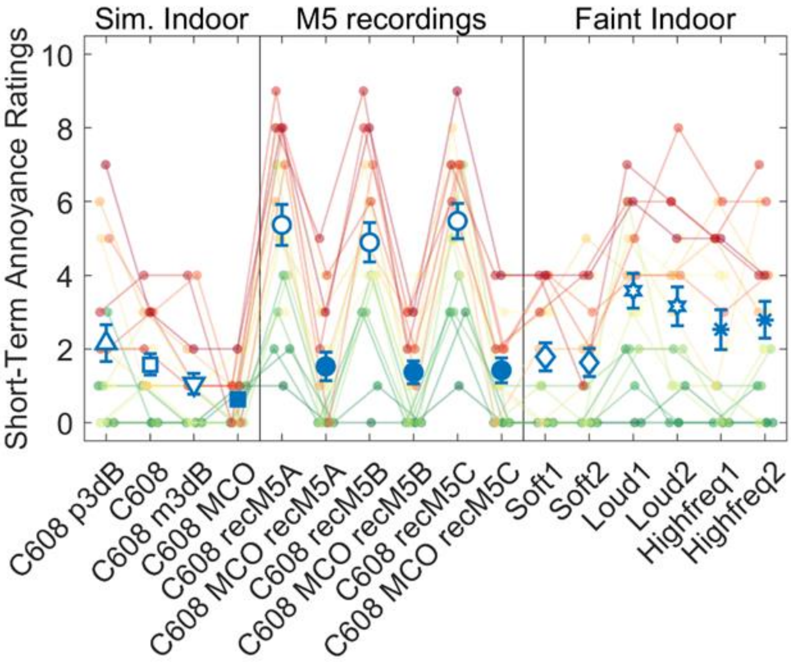
Results: Short-term annoyance

Figure 22 shows the results of the short-term annoyance ratings for the 16 signatures tested. In addition to the mean values and standard errors (blue symbols), the individual data of the 19 participants are also shown in the background. The individual data are colour-coded from red (high mean rating) to green (low mean rating) based on the mean judgement. The results were analysed using a repeated measures analysis of variance (RM-ANOVA). Overall, there was a significant effect of the stimulus on the rated short-term annoyance ($F(5.3; 95.4) = 29.3$, $p<0.05$,

ε_{GG} = 0.35, η^2=0.40). The individual signal conditions were compared using a Tukey HSD post-hoc test.

The C608 signature was judged to be less annoying on average (M = 1.6; SE = 0.3). The level increase by 3 dB led to a slightly higher judgement (M = 2.1; SE = 0.5), the level reduction by 3 dB led to a slightly lower judgement (M = 1.1; SE = 0.3). The Mach cut-off simulation for the C608 signature, with even lower maximum overpressure, also achieved slightly lower annoyance judgements (M = 0.6; SE = 0.2). However, the differences between these signal conditions were not statistically significant (p>0.05).

Figure 22: Mean values and standard errors of the short-term annoyance judgements for the 16 signatures (with outdoor-indoor filtering)



Note: Individual data with small symbols in the background (red: people with a high mean value across all sounds, green: people with a low mean value across all sounds), standard error in blue, N = 19, source: own presentation, UOL.

The signatures recorded in the M5 sleep laboratory were rated on average as more annoying overall than the original signatures. The judgements for the C608 recordings were around 5.3 on the scale and thus 3.7 categories above the original signature. The difference between the original C608 signature and the M5 recordings was statistically significant for all three rooms (A, B and C) (p<0.05). The judgements for the C608-Mach cut-off simulation recordings were ~1.4 and 0.8 categories above the original. The difference compared to the original was not statistically significant for all three rooms (A, B and C) (p>0.05).

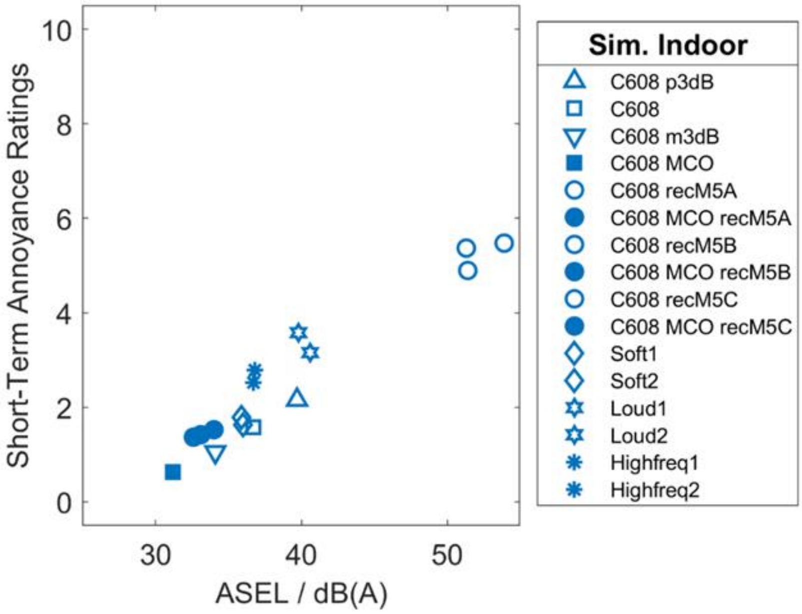
The M5 recordings in the three bedrooms (A, B and C) led to very similar short-term annoyance judgements for each of the two signals. These differences between the rooms were not statistically significant (p>0.05) for the C608 signal and also the C60 make-cut-off signal, indicating comparable sound exposure in the three bedrooms.

The judgements for the signals from the FaINT database were between 1.6 and 3.6 on the 11-point annoyance scale from 0 to 10. The six FaINT signals were therefore slightly more annoying on average than the original C608 signature and the C608 Mach cut-off signature (each with outdoor/indoor filter). Two signatures (Loud1, Loud2) each differed significantly from the 3 dB lowered C608 signature and the C608 Mach cut-off signature. The "Highfreq2" signal also differed significantly from the C608 Mach cut-off signature. The FaINT signatures all had a significantly longer signal duration of several seconds, were similar to thunder during a thunderstorm and in some cases also contained quiet vegetation noises (birds, insects) in the background after the actual thunder, which made these noises sound more familiar and "natural" than the synthetic C608 pressure signatures.

Despite the orientation phase before the actual ratings, the scale was used to varying degrees by the participants. Some of the participants (green individual data in Figure 22) rated all sounds on average as very little annoying and some sounds as not annoying at all (scale value 0). Only the lower part of the scale was used by these participants. Participants who gave higher average ratings (red individual data in Figure 22) also used the scale more.

Figure 23 shows the mean short-term annoyance ratings plotted against the A-weighted sound exposure level (ASEL). The correlation coefficient between the short-term annoyance judgements and the ASEL was r = 0.96.

Figure 23: **Mean values of the short-term annoyance judgements for the 16 signatures (with outdoor-indoor filtering) above the A-weighted exposure level (ASEL)**



Note: Source: own visualisation, UOL.

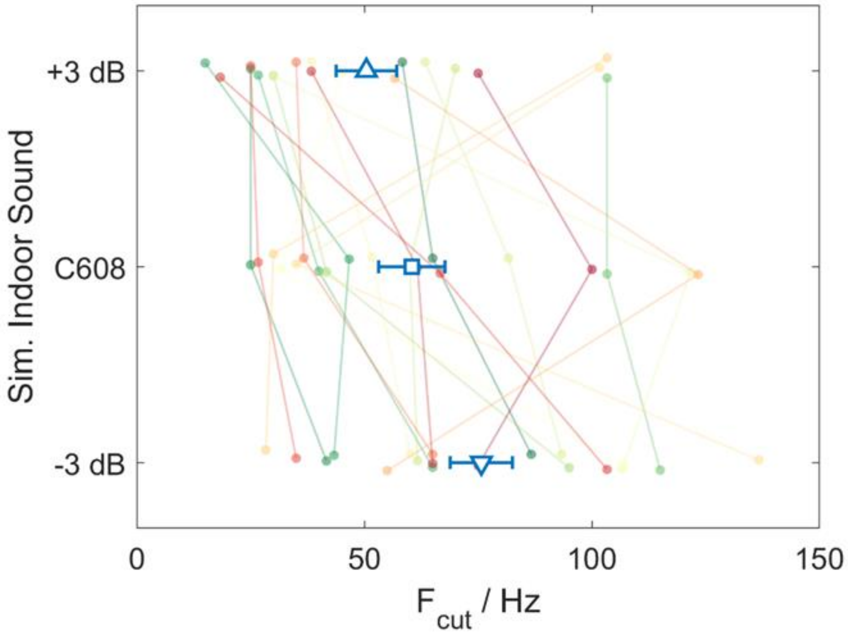
Results: Detection threshold

Figure 24 shows the mean values of the detection threshold for high-pass filtering of the C608 signature and the variants with a level increased by 3 dB and reduced by 3 dB. The figure also contains the individual data in the background in the same colour coding as in Figure 22.

For the C608 signature, the detection threshold for high-pass filtering was on average 60.4 Hz (SE =7.3). For the C608 signature increased by 3 dB, the mean threshold was 50.4 Hz (SE = 6.6); for the C608 signature reduced by 3 dB, the mean threshold was 75.7 Hz (SE = 6.9). The effect of high-pass filtering was statistically significant (F(2,36) = 4.563; $p<0.05$; $\eta^2 = 0.11$). Post-hoc comparisons (Tukey HSD) showed a significant difference between the condition with a level increased by 3 dB and the condition with a level reduced by 3 dB ($p<0.05$). The remaining comparisons were not statistically significant ($p>0.05$).

Towards low frequencies, the hearing threshold and the curves of equal loudness increase sharply and the increase also becomes steeper for lower levels. Accordingly, lower frequencies were easier to detect at higher levels. The increase in the detection threshold with decreasing signal level corresponds qualitatively to the curve of equal loudness and the hearing threshold at low frequencies.

Figure 24: Mean values and standard errors of the detection threshold of the cut-off frequency of a high-pass filter for the three levels of the low-boom signature C608 (signals no. 1, 2 and 3 from Table 2) and the individual data



Note: Standard error in blue, Fcut = cut-off frequency of the high-pass filter, small symbols in the background = individual data (colour assignment as in Figure 22), N = 19, source: own visualisation, UOL.

Conclusion: Validation of the sound presentation

For the reproduction of low-boom and Mach cut-off signatures in the sleep laboratory, existing SVSound, SB-2000 subwoofers with a frequency response of 19 to 220 Hz were used (SVSound 2014). Due to the limitations of the loudspeakers used towards very low frequencies and the spatial situation in the sleep laboratory (larger room volume and permanent ventilation), a lower exposure of the participants to low-frequency sound compared to simulations in a pressure chamber were expected. Accordingly, lower short-term annoyance ratings were also expected for the reproduction of the recordings from the sleep laboratory compared to the original signatures in the pressure chamber in Oldenburg.

Contrary to this expectation, the short-term annoyance ratings for the recordings of the C608 signature from the sleep laboratory were higher than for the "dry" original signals. A possible explanation for the differences between the original signatures and the respective signatures recorded in the sleep laboratory may lie in changes to the signals caused by the presentation in the sleep laboratory (e.g. distortion and excitation of rattling parts), the recording of the signatures using a low-frequency microphone at the listening position (e.g. background noise in the laboratory and recording noise) and the playback chain in the pressure chamber. The differences were evident in an increase in the ASEL for the recorded signals compared to the original signature, whereas the maximum overpressure of the signatures in the original and recording were almost identical. Taken together, this indicates differences rather in the high-frequency range, for which the A-weighting is designed. Corresponding to the higher ASEL values, the higher short term annoyance ratings also appear plausible. Due to the nominal upper cut-off frequency of 220 Hz of the subwoofers used, excessive radiation of high frequencies cannot be assumed, apart from minimal distortion products. However, it is difficult to precisely identify the causes of these differences.

For the subwoofers used for sound reinforcement in the sleep laboratory, it was assumed that very low frequencies of a few Hz in particular could not be reproduced due to the frequency response of the active subwoofers. However, the experimentally determined detection threshold for high-pass filtered signals for the C608 signal was on average 60 Hz and therefore significantly above the lower cut-off frequency of the subwoofers used. A potential influence of the lower limit of the transmission range of the subwoofers used should not have been detectable according to the results of the detection experiment.

Overall, the results of the detection experiment in particular, as well as the short-term noise annoyance ratings, indicate that the low-frequency sound exposure for the C608 signature and the C608-MCO signature in the sleep laboratory was adequate and that the resulting effect of the signatures presented in the sleep laboratory was not underestimated.

2.4 Literature-based derivation of hypotheses

Based on the results of previous aircraft noise studies, according to which reactions during sleep can be observed even at very low maximum levels starting at ~33 dB(A) (Basner, Isermann, Samel 2006), it was assumed that low-boom and Mach cut-off signals (low-boom Mach cut-off signals) could impair sleep compared to a quiet control condition. It was also expected that low-boom signals would disturb sleep more than Mach cut-off signals.

Likewise, it was assumed that – while awake - stronger cardiovascular responses would be observed during the exposure with low-boom or Mach cut-off signals than during a quiet control period. Furthermore, it was expected that low-boom signals would elicit stronger cardiovascular responses than Mach cut-off signals.

The planned laboratory study aimed at testing the following hyptheses:

- ► Primary hypothesis:
  - a) The awakening rate in the Low-boom condition is greater than the spontaneous awakening rate in the quiet control condition.

    The following applies:

    - ▪ awakening rate $_{\text{Low-boom}}$ > awakening rate $_{\text{Control}}$
- ► Secondary hypotheses:
  - b) The awakening rate in the Low-boom condition is greater than the awakening rate in the Mach cut-off condition.

    The following applies:

    - ▪ awakening rate $_{\text{Low-boom}}$ > awakening rate $_{\text{Mach cut-off}}$
  - c) The rate of EEG arousals in the Low-boom condition is greater than the rate of spontaneous EEG arousals in the quiet control condition. In addition, the arousal rate in the Low-boom condition is greater than the arousal rate in the Mach cut-off condition.

    The following applies:

    - ▪ arousal rate $_{\text{Low-boom}}$ > arousal rate $_{\text{Control}}$
    - ▪ arousal rate $_{\text{Low-boom}}$ > arousal rate $_{\text{Mach cut-off}}$

d) The rate of transitions from deep sleep (slow wave sleep) to S2 or REM sleep (lightening of sleep), i.e. the transitions from S4 to S3, S2 or REM sleep and from S3 to S2 or REM sleep, in the Low-boom condition is greater than the rate of spontaneous lightening of sleep in the quiet control condition. Furthermore, the rate of lightening of sleep in the Low-boom condition is greater than in the Mach cut-off condition.

The following applies:

- rate of lightning of sleep $_{\text{Low-boom}}$ > rate of lightening of sleep $_{\text{Control}}$
- rate of lightening of sleep $_{\text{Low-boom}}$ > rate of lightening of sleep $_{\text{Mach cut-off}}$

e) The slow wave activity (SWA) in the EEG of non-REM sleep (NREMS) immediately, i.e. within the first minute after a low-boom event is lower than the SWA in a 1-minute quiet period in the control condition. In addition, the SWA in the EEG of NREMS 1 minute after a low-boom event is lower than after a Mach cut-off event.

The following applies:

- SWA of NREMS$_{\text{1 min after Low-boom}}$ < SWA of NREMS$_{\text{1 min after Control}}$
- SWA of NREMS$_{\text{1 min after Low-boom}}$ < SWA of NREMS$_{\text{1 min after Mach cut-off}}$

f) The electrophysiologically measured sleep quality over the total night, expressed in terms of the parameters a) sleep efficiency, b) sleep onset latency, c) proportion of deep sleep, d) proportion of being awake, e) number of awakenings, is lower in the Low-boom condition than in the quiet control condition. Furthermore, the sleep quality during the Low-boom condition is lower than during the Mach cut-off condition.

The following applies:

- physiological sleep quality $_{\text{Low-boom}}$ > physiological sleep quality $_{\text{Control}}$
- physiological sleep quality $_{\text{Low-boom}}$ > physiological sleep quality $_{\text{Mach cut-off}}$

g) The SWA in the EEG of NREMS in the Low-boom condition is lower than the SWA in the quiet control condition. In addition, the SWA in the EEG of NREMS in the Low-boom condition is lower than in the Mach cut-off condition.

The following applies:

- SWA of NREMS $_{\text{Low-boom}}$ < SWA of NREMS $_{\text{Control}}$
- SWA of NREMS $_{\text{Low-boom}}$ < SWA of NREMS $_{\text{Mach cut-off}}$

h) The heart rate variability (HRV) while awake is lower when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the heart rate variability while awake is lower during the playback of low-boom signals than during the playback of Mach cut-off signals.

The following applies:

- HRV $_{\text{Low-boom}}$ < HRV $_{\text{Control}}$
- HRV $_{\text{Low-boom}}$ < HRV $_{\text{Mach cut-off}}$

i) The heart rate while awake is higher when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the heart rate while awake is higher during the playback of low-boom signals than during the playback of Mach cut-off signals.

The following applies:

- heart rate $_{\text{Low-boom}}$ > heart rate $_{\text{Control}}$
- heart rate $_{\text{Low-boom}}$ > heart rate $_{\text{Mach cut-off}}$

j) The blood pressure while awake is higher when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the blood pressure while awake is higher during the playback of low-boom signals than during the playback of Mach cut-off signals.

The following applies:

- blood pressure $_{\text{Low-boom}}$ > blood pressure $_{\text{Control}}$
- blood pressure $_{\text{Low-boom}}$ > blood pressure $_{\text{Mach cut-off}}$

k) Participants' self-assessed sleep quality is lower in the Low-boom condition than in the quiet control condition. Furthermore, participants' self-assessed sleep quality is lower in the Low-boom condition than in the Mach cut-off condition.

The following applies:

- self-assessed sleep quality $_{\text{Low-boom}}$ > self-assessed sleep quality $_{\text{Control}}$
- self-assessed sleep quality $_{\text{Low-boom}}$ > self-assessed sleep quality $_{\text{Mach cut-off}}$

l) Participants' self-assessed morning sleepiness is higher after the Low-boom condition than after the quiet control condition. Furthermore, participants' self-assessed morning sleepiness is higher after the Low-boom condition than after the Mach cut-off condition.

The following applies:

- self-assessed sleepiness $_{\text{Low-boom}}$ > self-assessed sleepiness $_{\text{Control}}$
- self-assessed sleepiness $_{\text{Low-boom}}$ > self-assessed sleepiness $_{\text{Mach cut-off}}$

m) The noise-induced short-term annoyance is higher after the Low-boom condition than after the quiet control condition. Furthermore, short-term annoyance is higher after the Low-boom condition than after the Mach cut-off condition.

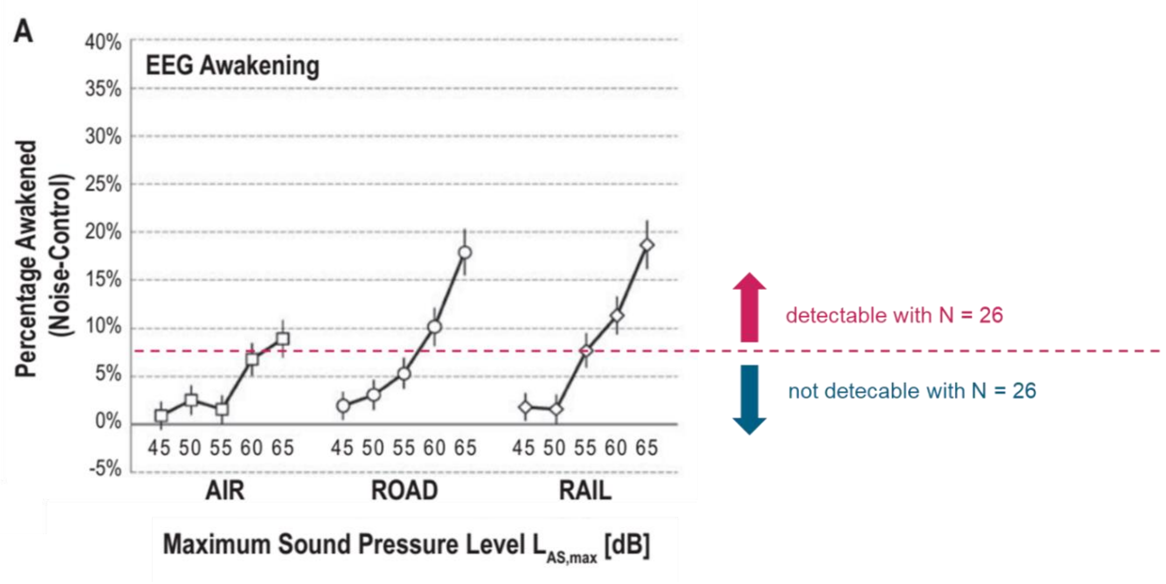
The following applies:

- annoyance $_{\text{Low-boom}}$ > annoyance $_{\text{Control}}$
- annoyance $_{\text{Low-boom}}$ > annoyance $_{\text{Mach cut-off}}$

2.5 Determination of sample size

The starting point for a priori analysis of power and the corresponding sample size calculation was the primary research question regarding the awakening rate due to low-boom events compared to the spontaneous awakening rate during a quiet control night. Since the number of participants was initially set at 26 by the Federal Environment Agency, the power analysis was based on this number to determine the extent to which the planned study design would be able to detect any effect that might be present. For this purpose, the minimum detectable difference in the awakening rate between the night with recorded low boom events and the quiet control night was estimated. The analysis revealed a detectable difference of 7.56 %. Based on experience from previous noise impact studies, this difference appeared to be very high. Comparing this with the effect of conventional aircraft noise (Basner, Müller, Elmenhorst 2011), an increase in the awakening rate of ~7.5 % would only be expected for very high indoor noise levels (> 60 dB[A]) (Figure 25).

Figure 25: Relationship between the maximum level (LAS,max) of a traffic noise event and the awakening rate



Note: Distinction between aircraft (AIR), road (ROAD) and rail traffic noise (RAIL). The area above the red dotted line indicates the awakening rate as a function of the maximum level that would be detectable with a number of 26 participants (N), while the area below would not be detectable with the same number of participants. Source: Basner, Müller and Elmenhorst (2011), adapted.

When calculating the power, it was necessary to take into account that the number of noise events should not be set too high, as this could lead to interaction effects, e.g. because the person might not fall asleep between events. For this reason, the number of noise events presented per night was limited to 40 for the planned experiment.

As described above, an increase in the awakening rate of 7.56 % due to a noise event would have been comparatively high compared to the spontaneous awakening rate in the control condition. In order to be able to detect even smaller increases in the awakening rate, the number of participants could be increased (Table 4). From a medical point of view, however, it seemed reasonable that increases of 6 %, corresponding to the effect of medium to high sound pressure levels, should already be detectable. In order to measure a 6 % increase in the awakening rate, the power analysis indicated an increase of the necessary sample size to at least 41 participants.

Table 4: **Increase in the awakening rate depending on the number of participants and noise events**

Detectable effect: Increase in the awakening rate by ...%	Alpha level (5 %)	Power (%)	Required number of participants (N)	Number of noise events required per night
7.56	5	80	26	29
7.00	5	80	30	30
6.00	5	80	41	32
5.00	5	80	57	35

Note: Null hypothesis: The awakening rate due to low-boom events is the same as the spontaneous awakening rate during a quiet control night. Alternative hypothesis: The awakening rate due to low-boom events compared to the spontaneous awakening rate on a quiet control night is different. Probability of a false positive result: Alpha error = 5 %. Probability of a false negative result: Power = 80 %.

Due to the study design (balancing the order of noise nights and equal distribution of male and female participants), complete data sets of a total of 42 participants were needed.

2.6 Concept of the study design

This section summarizes the requirements that were supposed to be realized via the study design:

The sleep study examines 21 female and 21 male participants in the age of 18 to 65 who are healthy, in particular with healthy sleep and normal hearing ability according to their age. All participants undergo three study nights. These are to include one quiet control night without playback of any noise signature and two noise nights with a playback of 40 noise events in each night. Only one type of signature is played back in each of the noise nights, i.e. either low-boom signatures or Mach cut-off signatures (or low-boom Mach cut-off signatures). The two sonic boom signatures are presented with the same exposure number and in separated nights, as not only the event-related effect (e.g. awakenings) is supposed to be investigated, but also the effect on the total night (e.g. sleep macro parameters). In addition, investigating the combined effect of both noise signatures in one night would have required an additional study night or an increase in the number of noise events per night. While the order of the noise conditions has to be randomised to minimise order effects, the control condition without playback of a noise signature is always set to be the first study night. This decision is based on recent research showing that the night after a night of sleep disturbance may be subject to a rebound effect, reflecting the sleep deprivation of the previous night (Wick, Combertaldi & Rasch 2024). The control condition represents an unaffected night, as this night aimed as reference to quantify noise-induced awakenings. Since the effect of these novel sonic boom events on sleep was unknown, it was important to avoid a significant impairment of sleep in a noise condition influencing the subsequent control condition. This results in the following study night procedures:

- Study group A: control condition, Low-boom condition, Mach cut-off condition
- Study group B: control condition, Mach cut-off condition, Low-boom condition

The allocation of participants to the study groups has to be conducted in a balanced way. The participants in group A undergo the control condition on the first night, the Low-boom condition on the second night and then the Mach cut-off condition on the third night. For participants in group B, the sequence of nights with the two noise conditions is reversed.

In addition, the study is conducted as a double-blind trial. Accordingly, the participants and all investigators who may have direct contact with the participants are not informed that there will be different study groups (group A or B) and when, what kind of or how many noise events will be played. They are only informed that this is a study to investigate the effects of environmental noise. Similarly, the evaluation of the electrophysiological sleep signals, i.e. the decision about a specific sleep stage at a specific point in time during the night, is carried out blinded and without any knowledge of the occurrence, type and intensity of any noise event at that point in time.

To investigate objective sleep disturbances, polysomnographic measurements need to be performed on all participants during all three study nights. These include the recording of brain activity (electroencephalogram, EEG), eye movements (electrooculogram, EOG), muscle tone (electromyogram, EMG) and cardiac activity (electrocardiogram, ECG).

In order to investigate the subjective sleep disturbances resulting from exposure to supersonic signals, the participants are asked every morning after a study night to assess their sleep quality during the previous night using a standardised questionnaire (Griefahn, Marks & Robens 2006), their current sleepiness using the Karolinska Sleepiness Scale (Akerstedt & Gillberg 1990) and their noise-induced annoyance during the previous night.

The measurements of physiological reactions while awake are planned for the third morning so as not to unblind the participants to the type of noise and the conditions before they had completed the three study nights. For this purpose, the participants are to be presented with the three conditions (Control, Low-boom, Mach cut-off) after getting up and cardiovascular parameters (blood pressure, heart rate variability) are to be recorded during this time.

The sleep study design as described above was reviewed and approved by the Ethics Committee of the North Rhine Medical Association. It was also registered with the German Clinical Trials Register (DRKS) (DRKS ID: 00028595).

3 Work package 2 – Conducting and evaluating the sleep study

The following steps of work package 2 are described here:

1. Recruitment and selection of participants
2. Study protocol
3. Method for the playback of the signatures
4. Method for measuring physiological reactions during sleep
5. Method for measuring physiological reactions while awake
6. Method for measuring subjective assessment
7. Description of the study sample
8. Results of physiological measurements during sleep
9. Conclusion based on the results of physiological measurements during sleep
10. Results of physiological measurements while awake
11. Conclusion based on the results of physiological measurements while awake
12. Results of the subjective assessment
13. Conclusion based on the results of the subjective assessment

3.1 Recruitment and selection of participants

Before recruiting and selecting the participants, inclusion and exclusion criteria were first defined to ensure that the participants did not have any health-related conditions that could interfere with the evaluation and interpretability of the laboratory results. Such health-related conditions included hearing impairments, mental and physiological disorders, in particular sleep disorders such as sleep-related breathing disorders (apnoea) or periodic limb movements, as well as certain medications.

The following criteria were defined for inclusion:

- 18 - 65 years
- (sleep)-healthy
- male or female
- age-appropriate normal hearing ability
- signed declaration of consent to data protection, the participant contract, the data protection declaration for the conduct of the study and the participant consent form
- sufficient knowledge of the German language
- recovered from coronavirus disease 2019 (COVID-19) (recovery status not older than 3 months) or fully vaccinated, including booster vaccination (2GPlus rule) or a status in accordance with the currently valid DLR coronavirus protection measures
- willingness to wear a particle-filtering respirator mask of protection class 2 (FFP2) while outside the participant rooms and during close contact with study personnel (e.g. when attaching electrodes) in accordance with the currently valid coronavirus protection measures of the DLR

The following criteria have been defined for exclusion:

- any medication/illness or disorder/medical treatment/surgery that, in the opinion of the physicians examining for the study, could significantly distort the study parameters (in particular intrinsic sleep disorders such as restless legs syndrome, periodic limb movement disorder or obstructive sleep apnoea syndrome)
- obesity and overweight with a body mass index > 30 kilograms/square metre
- pregnancy
- general consumption of soft and hard drugs
- general consumption of nicotine
- caffeine consumption > 450 milligrams per day
- alcohol consumption > 14 units per week
- hearing disorders (tinnitus, sudden hearing loss) or poor hearing, i.e. the hearing thresholds in an audiometric screening for the ear with the poorer hearing are higher than the 10th Percentile of the gender- and age-specific hearing thresholds according to ISO 7029 (2017), an additional penalty of 10 dB is taken into account due to the fact that the audiometry does not take place in a soundproof room. Since the presented supersonic booms have a very low frequency range, only frequencies between 125 and 1000 Hz are considered in the audiometric screening
- atypical sleeping habits:
    a) regular sleep duration < 6 and > 9 hours (night-time sleep)
    b) sleep times on working days: going to bed before 9 p.m. or after midnight, getting up before 5 a.m. or after 8:30 a.m.
- not proficient in the German language
- acute infection with COVID-19
- any other condition that, in the opinion of the examining physicians, makes the participant unsuitable (e.g. claustrophobia, presence of or increased risk of developing a depressive episode due to sleep impairment)

These inclusion and exclusion criteria were checked using a multi-stage selection process. The stages of the selection process and the time frame for the acquisition and selection steps are shown in Table 5. Potential participants were made aware of the study via the internal participant database of the DLR Institute of Aerospace Medicine or via announcements on relevant internet portals.

Candidates who were interested in participating received a link to a website containing a detailed description of the study. Once they had declared their consent to the protection and use of the data collected by the DLR, they were redirected to the pre-selection questionnaire. This pre-selection questionnaire asked about the health-related inclusion and exclusion criteria (see above).

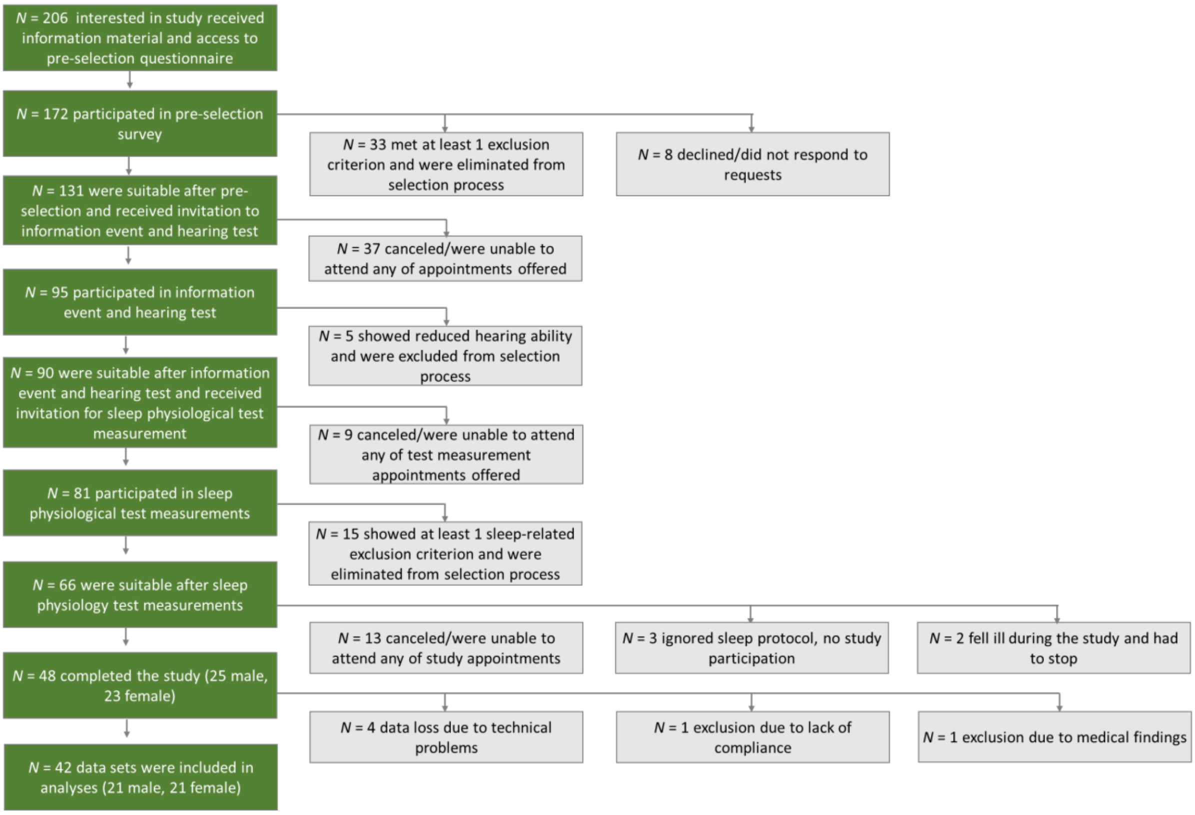
Table 5: Stages of the recruitment and selection process of the participants

Acquisition/selection stage	Verified inclusion and exclusion criteria	Time
• recruitment of participants by contacting individuals from the participants database, advertising on the DLR internet portal and on social media (Twitter, Instagram, Facebook) • information about inclusion and exclusion criteria for study participation	• none	May – September 2022
• questionnaire-based pre-selection via online questionnaire	• age and gender • sleep health and habits, any sleep disorder that may indicate apnoea and periodic limb movements • hearing ability • consent to data protection declaration • sufficient knowledge of the German language • willingness to wear class 2 particle-filtering respiratory protection (FFP2 mask), any discomfort when wearing it • timely availability • consumption of alcohol, caffeine, nicotine and drugs • Body mass index (BMI) • illnesses, medication and other conditions which, in the opinion of the examining physicians, make the participant not illegible	June - September 2022
• information session with hearing test	• signed participant contract and the participants' signed declaration of consent to participate in the test measurement • hearing ability assessed with audiometric screening • risk of obstructive sleep apnoea syndrome by measuring neck circumference in addition to the screening in the pre-selection questionnaire	June - September 2022
• sleep physiology test measurement in the DLR laboratories	• apnoea and hypopnoea • Periodic limb movements	August – October 2022
• approval as a participant, taking into account a balanced gender ratio and 10	• signed participant contract and the participants' signed	September 2022 – January 2023

Acquisition/selection stage	Verified inclusion and exclusion criteria	Time
days of compliance with a sleep protocol with no or limited consumption of alcohol and caffeine - conduction of the main study	declaration of consent to participate in the study - compliance with the via a sleep protocol prescribed bed times - acute infection/illness - evidence of consumption of nicotine and drugs	

The results of the participant acquisition and selection process are shown in Figure 26. The chart shows a relatively high proportion of candidates who were already excluded in the questionnaire-based pre-selection process. The main reasons for exclusion were predominantly drug consumption and medication that could have an impact on the study parameters. The reasons for exclusion based on the questionnaire and their frequency are listed in Table 6.

Figure 26: Results of the recruitment and selection process of the participants



Note: *N* refers to the number of candidates. Source: own visualisation, DLR.

Table 6: Questionnaire-based reasons and frequencies for exclusion of participants from the study

Reason for exclusion	Frequency
Drug comsumption	10
Medication	7
Mental disorders	4
Overweight (BMI > 30)	3
Sleeping habits/sleep problems/shift work	3
Sudden hearing loss/hearing problems	4
Caffeine consumption	2
Insufficient German language knowledge	2
Regular tobacco/ nicotine consumption	2
Physical illness	2
Age	1
Unwillingness to wear particle-filtering respiratory protection of class 2 (FFP2 mask)	1
Problems in confined spaces	1
Teeth grinding	1

Note: Multiple answers are possible.

If the candidates successfully passed the questionnaire-based pre-selection process, they received an invitation to an information session including a medical consultation with the examining physician. After the candidates signed a declaration of consent to participate in the test measurement (in accordance with the Declaration of Helsinki) and a participant contract, a hearing screening was carried out using an audiometer. In addition, the neck circumference was measured, which can be an indicator of sleep-related breathing disorders.

The following selection step was a test measurement in the sleep laboratory using polysomnography. The measurement was intended to detect any previously undetected sleep disorders, in particular apnoea/hypopnoea and periodic limb movements. The night also served as an opportunity to familiarise participants with the electrophysiological measuring instruments and the study protocol. Candidates were reimbursed for participating in the test measurement.

The number of information sessions and test measurements carried out was based on the target of a total of 42 participants with complete data sets. Based on experience from previous studies, a dropout rate of up to 25 % was expected for each selection stage and a correspondingly higher number of people were selected for the next selection step. Figure 26 illustrates that a large proportion of candidates who participated in the test measurement had to be excluded due to apnoea (AHI > 15) and periodic leg movements (PLMI > 20) (a comorbidity of apnoea and periodic leg movements was possible). Candidates suffering from apnoea and/or periodic leg movements had to be excluded from the study because EEG arousals resulting from apnoea and the associated oxygen desaturation or periodic leg movements are almost indistinguishable in an electroencephalogram from arousals induced by a noise event.

After determining the eligibility of the participants on the basis of the test measurement, they were randomly assigned to one of two study conditions (group A or group B) in the main study, taking into account a balanced gender ratio.

Ten days before the start of the main study, the finally selected participants were asked to protocol and to comply a prescribed eight hours of bedtime, which were also applied to during the study nights. To make it easier for the participants to integrate the bedtimes into their everyday lives, they were given the option of choosing between early bedtimes (10 p.m. to 6 a.m.) and late bedtimes (11 p.m. to 7 a.m.). Sleeping during the day was not permitted. Compliance with bedtimes during the preparation period was monitored using activity data recordings (actigraphy). During the preparation period, the participants were asked to avoid alcohol and to limit their caffeine consumption to a maximum of 2 cups of coffee or tea (~200 milligrams of caffeine) in the morning (until noon). This preparation period served to adapt to the respective bedtimes in the sleep laboratory and was intended to ensure that all participants had the same starting conditions in terms of sleep pressure and sleep rhythm.

During the study, every evening after the participants' arrival at the sleep laboratory, a coronavirus test, a drug screening and, in the case of female participants, an additional pregnancy test were carried out. Actigraphy data were reviewed and compliance with the agreed bedtimes during the 10-day preparation period was assessed. Participants who did not follow the sleep protocol could not be admitted to the study. The same applied if there was evidence of acute coronavirus infection (COVID-19), pregnancy or the consumption of drugs and nicotine, as determined by rapid tests or urine tests. Prior to study participation, a signed declaration of consent from the participants (taking into account the Declaration of Helsinki) and a participant contract, which included information on expense allowances, were obtained.

Data collection took place from September 2022 to February 2023. Replacement participants were considered in addition to the intended number of three participants per session to compensate for dropouts due to sudden cancellations by participants (illness, scheduling conflicts, and others) and lack of compliance (non-adherence to the sleep protocol). Furthermore, data losses occurred due to technical problems (loss of data recording) and medical reasons (increased PLM index). Ultimately, data from 42 participants were analysed, but five of them were excluded from the subsequent analyses due to low sleep efficiency.

3.2 Study protocol

On the first evening, the participants were given information about the study procedure and were instructed not to talk about noise in general or the noise played back during the study nights. They were also asked to complete the initial questionnaire (details in 3.6.1.1).

Every evening, trained DLR personnel placed the polysomnography attachments on the participants' body. Shortly before going to bed, the participants were asked to complete the evening questionnaire (details in 3.6.1.2). Afterwards, the participants went to bed at the prescribed time and the noise condition was played back.

Each morning, after the participants were awakened at the prescribed time, participants were given a 30-minute wake-up phase before they completed the morning questionnaire (details under 3.6.1.3). During this wake-up phase, the participants left their beds to counteract sleep inertia. Sleep inertia is a physiological state of impaired cognitive and sensorimotor performance that occurs immediately after waking up. In most cases, morning sleep inertia vanishes 15 to 30 minutes after waking up. After the morning questionnaire, cardiovascular responses were measured while awake. For this purpose, in the morning after the first and second night, a non-invasive measurement of blood pressure, an electrocardiogram, an electroencephalogram and finger pulse amplitude were recorded over a period of 13.5-minute in a quiet control condition.

On the last morning, in addition to measuring cardiovascular responses while awake over a period of 13.5-minute in a quiet control condition, the same measurements were also taken once while playing low-boom events back and once while playing Mach cut-off events back. Measurements were first taken under the control condition, followed by the two noise conditions in randomised order. Accordingly, three 13.5-minute measurements were conducted on the last morning. Finally, the participants were asked to complete the closing questionnaire (details under 3.6.1.4).

3.3 Method for the play back of the signatures

To ensure that all measurements were synchronised in terms of time, only participants with the same prescribed bedtime were in the sleep laboratory at the same time. To minimise sequence effects, the order of the noise nights between the study groups (study group A or B) was randomised, while the quiet control night was always the first study night. On each of the noisy nights, only one type of signature was played back, i.e. either the low-boom signatures or the Mach cut-off signatures, but not a mix of them. For each of the three study nights, an 8-hour acoustic file was created and played back by using a computer. Since both the participants and the DLR personnel were blinded to the type of noise events and the different conditions, a pseudo-acoustic file without any noise events was also created for the first night, which always corresponded to the control condition. The acoustic file for the Low-boom condition contained 40 noise events of the low-boom signature and the acoustic file for the Mach cut-off condition contained 40 noise events of the Mach cut-off signature. The noise events occurred at randomised intervals between 3 and 21 minutes. The points in time for the presentation and intervals between the Low-boom and Mach cut-off conditions were kept constant. To enable event-related evaluation of the data, the computer was timely synchronised with all data recording devices, the acoustic file was always started to the full minute and the exact start time was recorded. Thereby, the exact points in time of the noise events were known and the noise events were always played back to the full minute.

For the measurements in the morning while awake, three acoustic files were created over 13.5 minutes, which were also played back to the full minute by using the computer. Even here, to maintain the blinding to the type of noise events and conditions, again a pseudo-file without any noise event was created, which was played back on the first and second morning. For the third and final morning, two files were created - one with five noise events of the low-boom signature and one with five noise events of the Mach cut-off signature. The noise events were played back at the following points in time after the start of the measurement: 1) after 30 seconds, 2) after 3 minutes, 3) after 6.5 minutes, 4) after 8.5 minutes and 5) after 11.5 minutes. The order of the conditions corresponded to the order of the study nights, to which the participants were randomly assigned at the beginning of the study (study group A or B).

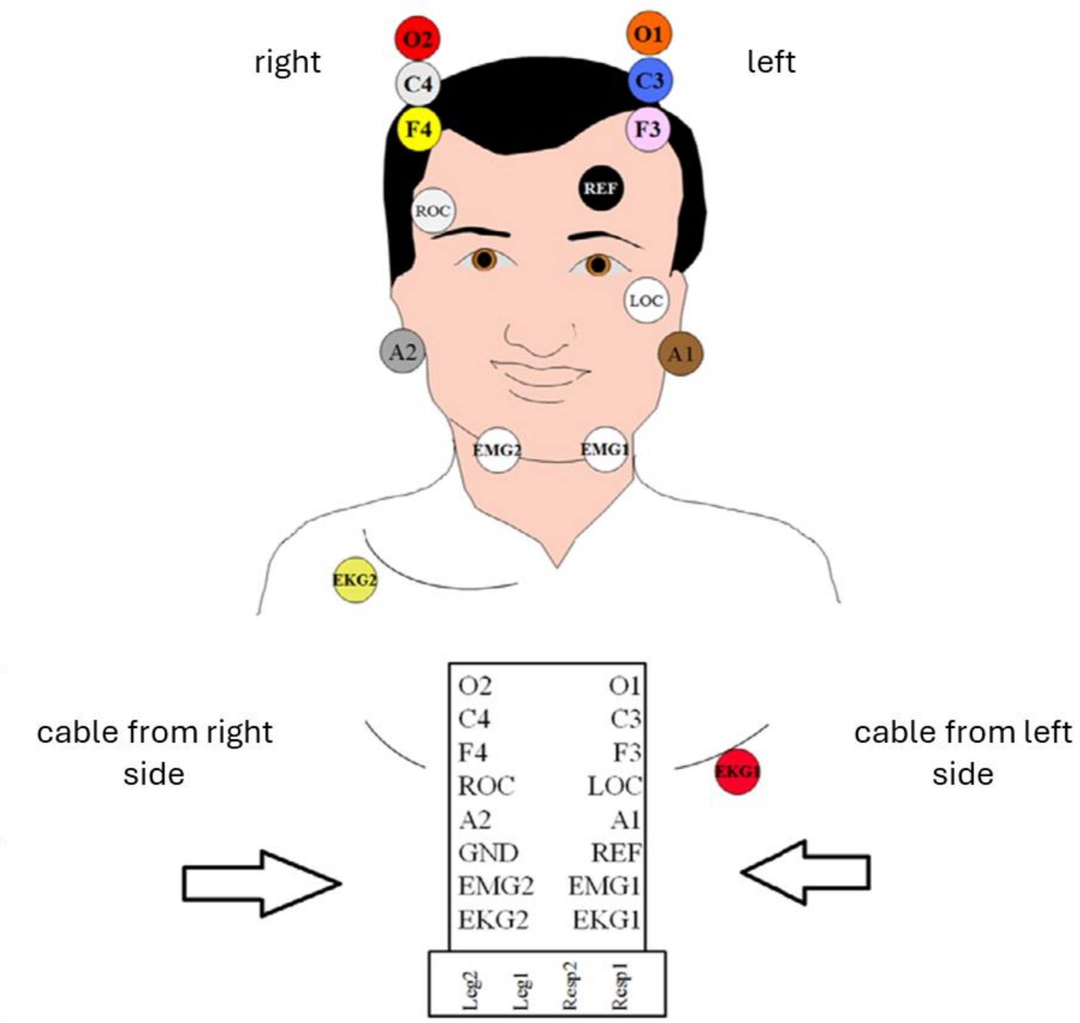
3.4 Method for measuring physiological reactions during sleep

To investigate the effects of supersonic boom signatures on sleep, the physiological sleep quality of the participants was measured using polysomnography during all three study nights. Polysomnography remains the gold standard for measuring sleep (Basner 2021). This involves the simultaneous recording of brain activity (electroencephalogram, EEG), eye movements (electrooculogram, EOG), muscle tone (electromyogram, EMG) and heart activity (electrocardiogram, ECG).

The EEG electrodes were attached to the participants` scalps in accordance with the international 10/20 system (Figure 27). The polysomnographic signals were recorded by digital recording devices developed and regularly used at the DLR. To ensure event-related evaluation of the data, the time on the recording devices was synchronised with the time on the computer for acoustic playback every evening. The analogue signals were high-pass filtered (time constant 2.2 seconds for EEG and EOG, 0.04 seconds for EMG), low-pass filtered (Butterworth, 12 dB/octave; -6 dB at 70 Hz for EEG, EOG and EMG) and digitised (resolution 12 bits; sampling rate 1024 Hz; storage rate 256 Hz). The raw signals were stored on digital memory cards (1 gigabyte SanDisk) and downloaded offline to a computer as part of data backup. The electrophysiological data were reviewed and backed up in the morning after each study night by trained personnel.

EEG, EMG and EOG recordings were performed in accordance with AASM criteria (EEG recordings: F3/A2, F4/A1, C3/A2, C4/A1, O1/A2, O2/A1, see Figure 27). The sleep-wake stages were evaluated according to the criteria of Rechtschaffen and Kales (1968) using visual scoring. The total night was divided into 30-second epochs and assigned to a specific sleep stage based on EEG frequency and amplitude, certain patterns in the EEG, muscle tone in the EMG and the occurrence of slow and rapid eye movements in the EOG. All nights were evaluated by a specially trained medical technical assistant (MTA) who was blinded to the conditions.

Figure 27: **Electrode positions**



Note: Source: own visualisation, DLR.

Based on the electrophysiological signals, polysomnograms with the following sleep stages could be identified using an internationally standardised procedure (Rechtschaffen & Kales 1968): wake, rapid eye movement sleep (REM sleep) and non-REM sleep (NREMS), divided into sleep stages 1–4 (S1–S4), where S1 describes non-regenerative, light sleep; S2 describes stable sleep; and S3 and S4 describe deep sleep or slow wave sleep (SWS). While SWS and REM sleep are important for recovery and memory formation (Di et al. 1990), wake and S1 are typical indicators of disturbed and fragmented sleep (Maschke 1992). A sleeping person typically cycle through these sleep phases several times per night, with deep sleep predominating in the first hours of a sleep period and REM sleep and S2 predominating in the later hours. Figure 28 shows a graphical representation of the different sleep phases (hypnogram) of a participant over one night under the control condition.

Figure 28: Example hypnogram of a participant from the control condition

Note: Source: own visualisation, DLR.

3.4.1 Macro parameters of sleep

In a first step, objective sleep quality was determined using macro parameters derived from sleep stage scoring on a 30-second epoch basis. The following macro parameters were determined in the period between the start of the measurement (first epoch considered after lights out) and the end of the measurement (last epoch considered before lights on):

- Stage 1 (S1): light sleep or the transition between awake and sleep
- Stage 2 (S2): stable sleep
- Slow wave sleep (SWS): deep sleep consisting of stage 3 (S3) and stage 4 (S4)
- Rapid eye movement sleep (REMS): sleep phase characterised by rapid eye movements
- Time in bed (TIB): the period between the first considered epoch and the last considered epoch, i.e. the total time the participant spent in bed and during which sleep was measured. Due to the study design and the specified sleep times from 6 a.m. to 10 p.m. and 7 a.m. to 11 p.m., the TIB for all participant was exactly 8 hours or 480 minutes
- Total Sleep Time (TST): the actual time spent asleep or the time in S1, S2, S3, S4 and REMS between the first and last considered epoch of the TIB
- Sleep Efficiency: the ratio of TST to total TIB in %
- Sleep Onset Latency (SOL): the time until sleep onset, i.e. the time between the first considered epoch and the first epoch in at least stage S2
- WASO (Wake After Sleep Onset): the time spent awake between sleep onset and lights on
- Number of awakenings: the number of transitions from S2, SWS and REMS to S1 or wake
- Number of arousals: number of abrupt changes in the EEG and EMG lasting between 3 and 15 seconds in S1, S2, SWS and REMS

The sleep data were analysed using linear mixed models for repeated measurements (LMM) with random intercepts. An LMM allows the combination of fixed and random effects and is often used when, as in this case, multiple repeated measurements are available for all participants. In such cases, the assumption of independence of the measurements is usually violated, as repeated values for a person are usually similar (smaller or larger than the mean). First, raw models were calculated for each sleep parameter and condition (Control, Low-boom, Mach cut-off) as fixed factor. Robust standard errors were calculated for parameters whose residuals were not completely normally distributed. Robust standard errors can always be used when there is uncertainty about the distribution of the residuals. If the non-normal distribution of the residuals is not too severe or if the sample size is large, they can still provide reliable results because they are less susceptible to outliers and violations of the normal distribution assumption. The control condition was used as a reference for the two noise conditions. If one of the two noise conditions differed significantly from the control condition, pairwise post-hoc comparisons with Bonferroni-Holm correction for multiple testing were calculated. In a further step, additional potential non-acoustical covariates were included into the models to explore potential correlations with the respective criterion and determine if they account for a significant proportion of the variance: gender, age, study group (A: Control/Low-boom/Mach cut-off vs. B: Control/Mach cut-off/Low-boom), bedtime (early: 10 p.m. to 6 a.m. vs. late: 11 p.m. to 7 a.m.) and self-assessed difficulties falling asleep and maintain sleep due to the polysomnography and/or the laboratory environment (*sleep disturbance due to setting:* yes vs. no). If there was a significant correlation ($p < 0.05$) between the predictor variable and the criterion variable and a reduction in the Akaike Information Criterion (AIC), it was assumed that the added factors improved the model quality because they had incremental validity (Fabozzi et al. 2014). The AIC does not say anything about the absolute quality of a model, but rather about its quality in relation to other models. Since the AIC estimates the amount of information lost, a lower value compared to the previous value indicates better model quality. A reduction of two points in the AIC was interpreted as the model with the better model quality, based on the guidelines of Fabozzi et al. (2014).

In order to check whether the sleep parameters changed with increasing duration in the laboratory, LMMs were also created with the study days (1 to 3) instead of the condition as the independent variable.

In addition, Pearson's correlation was used to investigate the following potential associations of objective and subjective sleep parameters:

- Sleep efficiency and self-assessed sleep quality
- SOL and self-assessed sleep onset latency

3.4.2 EEG spectral analysis

The EEGs of the C3/A2 and C4/A1 derivations were subjected to spectral analysis based on a fast Fourier transform (FFT) routine. The aim of this quantitative analysis was to test whether the sonic boom signatures cause changes in the sleep EEG that could possibly remain undetected by the less sensitive method of sleep stage analysis (macro parameters). It is possible that the sonic boom signatures do not significantly reduce the duration of deep sleep (SWS), but lower the spectral power density of the EEG in the frequency range of delta waves (~0.75-4.0 Hz) in NREMS, thus causing a slight "lightening" of sleep.

EEG power density spectra were calculated for 4-second segments (subepochs), each offset by 3 seconds, using a Hanning window. High- and low-frequency artefacts were automatically excluded on the basis of a moving average. The remaining 4-second subepochs were averaged to produce mean 30-second power density spectra with a frequency resolution of 0.5 Hz, which corresponded to the sleep stage epochs. Finally, all NREMS epochs per night were averaged and differential spectra were calculated, with the spectral power density per 0.5 Hz bin in each of the two sonic boom conditions presented as a percentage of the control condition. Log transformed absolute power densities were subjected to an LMM with the factors *condition* and *EEG frequency bin.*

3.4.3 Event-related analyses

The playback of the acoustic files to the full minute and the synchronous recording of the electrophysiological data enabled the establishment of a temporal relationship between a noise event and the response of a participant during sleep. Since the control condition was intended to serve as a reference, noise events were supposed for the analyses at the same time points as those played back in the two noise conditions. I.e. the analyses of the control condition refer to the spontaneous reactions (awakenings, arousals, lightening of sleep, changes in the EEG spectrum) that occurred after the supposed noise events.

3.4.3.1 Awakenings

The sleep study focused on the event-related analysis of awakenings and the quantification of the noise-induced awakening rate. For the event-related analysis of awakenings, the rate was quantified at which an awakening, i.e. a transition from a sleep stage to stage wake or S1, occurred immediately after a noise event. In the event-related analysis, each noise event was screened for an associated awakening within the SPT. A noise-associated awakening was defined as a change from stage S2, S3, S4 or REM to S1 or wake within a specific time window (screening window) after the onset of a noise event. The advantage of laboratory studies over field studies is the controlled presentation of noise events. Since the noise events were only 0.26 seconds long and were always played back to the full minute and thus at the beginning of an epoch, an analysis approach was chosen, in which the screening window consisted of the 30 seconds-epoch immediately after the noise event.

The following rules were applied for the event-related analysis of awakenings:

- For each noise event, it was recorded whether a transition to stage S1 or wake occurred in the subsequent epoch (1) or not (0).
- The awakenings were considered from sleep onset (first occurrence of S2, S3, S4 or REM).
- Noise events were excluded if the reference epoch (epoch before the noise event) was scored as "wake", "S1" or "movement" or if no information on the sleep stage was available, i.e. noise events were included if the reference epoch was scored as "S2", "S3", "S4" or "REM".

For the event-related analysis of awakenings, the relative percentage rate for noise-associated awakenings for each participant for each of the three conditions was determined, i.e. the awakening rate was calculated in relation to the noise events, which occurred while the respective participant was in stage S2, S3, S4 or REM. The data were analysed using LMM with random intercept. Due to the lack of normal distribution in the residuals, robust standard errors were calculated. The model included noise-associated awakenings as the criterion and the condition as a fixed factor. Subsequently, pairwise comparisons (post-hoc t-tests with Bonferroni-Holm correction) were performed for this raw model if one of the two noise conditions differed significantly from the control condition.

A prediction model was derived using generalised linear mixed models (GLMM) with binary outcome, logit link function and random intercept. The binary outcome variable of the model was assigned a value of 1 if an awakening occurred after a noise event, and a value of 0 if no awakening occurred. The final predictors were determined using a stepwise forward selection process based on the Akaike Information Criterion (AIC). The AIC was used to assess whether the model improved by adding further factors. As there was strong collinearity (Pearson correlation > 0.7) between the elapsed sleep time and the number of noise events prior to the respective noise event, it was considered that these two potential predictors were not included in the same model. The following potential variance-explaining predictors were considered for model selection: (1) condition, (2) the number of noise events that occurred between sleep onset and the respective noise event, (3) the sleep stage in the (reference) epoch prior to the respective noise event (stages S3 and S4 were combined as SWS; stage S2 as the predominant sleep stage during the night was defined as the reference group), (4) the elapsed sleep time between sleep onset and the respective noise event, excluding wake, (5) the age of the participants, (6) the gender of the participants. Given the significant role of the sleep stage in the (reference) epoch prior to the respective noise event in previous studies on noise impact (Basner, Isermann & Samel 2006; Bartels et al. 2021), it was decided to include this predictor into the model in addition to the condition. The sleep stage in the (reference) epoch prior to the noise event was defined as an indicator variable, with sleep stage S2 as the reference. The p-values were not considered in the traditional context of hypothesis testing, but as indicators of relative importance (Harrell 2015; Hosmer Lemeshow, Sturdivant 2013). Nevertheless, care was taken to prevent the exclusion of significant predictors. To supplement the interpretation of the results, odds ratios (OR) were calculated as a measure of effect size. Prior to the stepwise analysis, the presence of nonlinear effects was verified. Therefore, separate univariate models containing nonlinear terms from the group of fractional polynomials of degree 1 and 2 were calculated. For each predictor, the model with the lowest AIC was selected. Based on the results, the simple linear function was selected for all variables and included in the stepwise selection process. In order to consider potential interactions between predictors, a final analysis was conducted to determine if the inclusion of two-way interactions could significantly enhance the model's performance.

Since awakenings can result from direct responses to noise or can occur spontaneously multiple times throughout the night (Basner, Griefahn & van den Berg 2010), a differentiation is made between noise-associated awakenings and noise-induced awakenings. The rate for noise-associated awakenings was derived from the awakenings that occurred within the first epoch after a noise event and was initially calculated for each participant and subsequently accumulated across all participants. The rate of noise-induced awakenings resulting from the noise conditions was initially calculated for each participant by subtracting the rate of spontaneous awakenings resulting from the control condition and subsequently accumulated across all participants.

3.4.3.2 Arousals

Since the extent of potential sleep disturbances caused by these novel sonic boom events was unknown, a quantification of arousals was performed to detect low-threshold sleep disturbances. They occur spontaneously 3 to 4 times more frequently than awakenings. Arousals are short activations (> 3 and < 15 seconds) in the EEG and EMG that are not classified as awakenings (≥ 15 seconds). Arousals are scored according to standardised criteria: An arousal during sleep stages S1, S2, SWS or REM is to be scored if there is a sudden change in EEG frequency (alpha, theta and/or frequencies faster than 16 Hz, but no spindles) lasting a minimum of 3 seconds, following a preceding period of at least 10 seconds of uninterrupted sleep. An arousal during REM sleep is to be scored if an increase in muscle tone lasting at least 1 second is detectable in the submental EEG (Berry et al. 2020). For arousals that occur as a result of a noise event, it is assumed that the associated cardiac activations can increase the risk of cardiovascular disease in the case of long-term noise exposure (Muzet 2007; Babisch 2006).

Arousals are a disturbance of sleep that does not necessarily lead to awakenings, but can nevertheless reduce the restorative effect of sleep.

The following rules were applied for the event-related analysis of arousals:

- For each noise event, it was recorded whether an arousal occurred in the following epoch (1) or not (0).
- Arousals were considered from sleep onset (first occurrence of S2, S3, S4 or REM).
- Noise events were excluded if the reference epoch was scored as "wake", “S1” or "movement" or if no information on the sleep stage was available, i.e. noise events were included if the reference epoch was scored as "S2", "S3", "S4" or "REM".

As well as the awakenings, the relative percentage rate for noise-associated arousals for each participant was initially determined for each of the three conditions, i.e. the arousal rate was calculated in relation to the noise events that occurred after sleep onset in stage S2, S3, S4 or REM. The data were also analysed using LMM with random intercept and robust standard errors. Pairwise post-hoc comparisons with Bonferroni-Holm correction for multiple testing were calculated, if one of the two noise conditions differed significantly from the control condition.

Subsequently, a prediction model was derived using the same method of GLMM as for the awakenings (details in section 3.4.3.1). Initially, the rate of noise-induced arousals resulting from the noise conditions was determined for each participant by subtracting the rate of spontaneous arousals resulting from the control condition. Subsequently, it was accumulated across all participants.

3.4.3.3 Lightening of sleep

Equally to the awakenings and arousals, event-related analysis was performed for the lightening of sleep. For this purpose, the transitions from deeper (SWS) to more superficial sleep stages (S2 or REM) were analysed and the following rules were applied:

- For each noise event, it was recorded whether a transition from S4 to S3, S2 or REM or from S3 to S2 or REM occurred in the following epoch (1) or not (0).
- Lightening of sleep was considered from sleep onset (first occurrence of S2, S3, S4 or REM).
- Noise events were excluded if the reference epoch was scored as "REM", "S2", "S1", "wake" or movement, or if no information on the sleep stage was available, i.e. noise events were only included if the reference epoch was scored as S3 or S4.

The relative percentage rate for noise-associated lightening of sleep for each participant was determined for each of the three conditions, i.e. the rate was calculated in relation to the noise events that occurred while the respective participant was in stage S3 or S4. The data were analysed using LMM with random intercept and robust standard errors. In addition, the rate of noise-induced lighting of sleep was determined.

3.4.3.4 Changes in the EEG spectrum

To further investigate whether the sonic boom signatures lead to a short-term lightening of NREMS, the EEG power density spectra were used. It was assumed that an immediate (instantaneous) disturbance of NREMS would lead to a decrease in EEG power density in the delta range (0.75-4.0 Hz) and an increase in the beta range (16.25-25.0 Hz). To test this, the power density spectra within one minute after a noise event were expressed as deviations (%)

from the spectrum within one minute before the noise event. In the control condition, time points corresponding to the noise events were selected. A GLMM with identity link function was used to analyse the relative change in spectral power density after the noise events. The dependent variable was the percentage change after a noise event. Pairwise comparisons for the three conditions were performed using estimated marginal means for the delta band and beta band, and the p-values were FDR-corrected (Benjamini-Hochberg adjustment).

3.5 Method for measuring physiological responses while awake

Startle responses to intense external stimuli such as a sonic boom manifest themselves in cardiovascular responses such as heart rate acceleration, heart rate variability or blood pressure. To examine potential startle responses in the participants, non-invasive measurements of blood pressure, as well as recordings of electrocardiogram, electroencephalogram, and finger pulse amplitude, were conducted each morning. The necessary electrodes and devices were kept on from the previous night's polysomnography. In addition, continuous blood pressure was measured using Finapres NOVA in a randomly selected subsample. In order to enable an event-related evaluation of the data, the time on these devices was synchronised with that of the computer used for acoustic playback. The measurement was taken every morning 30 minutes after waking up for 13.5 minutes in a quiet control condition. The participants were asked to sit quietly on their beds during this time and not to engage in any activity. On the third morning, the measurement was additionally carried out for 13.5 minutes under supersonic boom conditions (Low-boom, Mach cut-off).

3.5.1.1 Heart rate variability

Heart rate variability (HRV) describes changes in the time intervals between successive heartbeats, known as interbeat intervals (IBIs). HRV is part of interdependent regulatory systems that help the body adapt to environmental and psychological challenges. It is essentially driven by the autonomic nervous system. The sympathetic (SNS) and parasympathetic nervous systems (PNS) regulate the heart rate as antagonists. While PNS activity typically lowers the heart rate and increases HRV, SNS activity tends to increase the heart rate and decrease HRV. Thus, the heart rate is lowest during rest and recovery phases and HRV is highest when parasympathetic activation is strongest. Conversely, under stress, when SNS activity is increased, the heart rate rises and HRV decreases (Kubios 2025). This regulation enables the body to adapt quickly to changing environmental conditions. High HRV is therefore associated with health, self-regulation, adaptability and resilience (Shaffer & Ginsberg 2017), while low or unusually high HRV is associated with some cardiovascular diseases (Thayer, Yamamoto, Brosschot 2010). A measurement of at least 5 minutes is required to derive some of the HRV parameters which was ensured by a continuous measurement of the ECG using polysomnography over 13.5 minutes. The Kubios HRV Premium software (version 4.1.2.1) was used to derive the HRV parameters for this measurement period.

Based on previous studies (e.g. Cai et al. 2022, Veternik et al. 2018, Manohare et al. 2022) investigating the effect of noise on HRV, the following parameters were selected:

Time-related parameters

- Averaged RR interval or interbeat interval (IBI) = mean value of the time intervals between two heartbeats or between two R waves in the ECG (positive deflections representing the depolarisation of the ventricles) in ms
- SDNN = standard deviations of NN intervals (N = normal intervals or RR intervals adjusted for abnormal beats, respectively) in ms; reflects the general (both short-term and long-term)

variability within the RR intervals; a low value means that heart rate variability is low (Shaffer & Ginsberg 2017)

- RMSSD = square root of the mean squared differences between consecutive RR intervals in milliseconds; measure of short-term variability within RR intervals; a low value means that heart rate variability is low

Frequency-related parameters

Measurements in the frequency range are used to estimate the distribution of absolute or relative power (Shaffer & Ginsberg 2017).

- VLF = Absolute power in the very low frequency band (0 - 0.04 Hz) in ms^2; reflects sympathetic activity; a low value may indicate stress
- LF = Absolute power in the low frequency band (0.04 - 0.15 Hz) in ms^2; indicator of baroreceptor activity (regulation of blood pressure) under resting conditions; reflects parasympathetic and sympathetic activity, with the sympathetic nervous system predominating; a high value may indicate stress
- HF = Absolute power in the high frequency band (0.15 - 0.4 Hz) in ms^2; reflects parasympathetic activity; a low value may indicate stress
- LF/HF ratio = ratio between LF and HF in %; a low value reflects parasympathetic dominance and corresponds to relaxation, a high value reflects sympathetic dominance and may indicate stress

To correct artefacts, the automatic correction function of the Kubios software was used, which detects artefacts from a time series containing differences between successive RR intervals. The data quality allowed for the evaluation of a total of 36 participants. Since there was no normal distribution of the residuals for all parameters except for the averaged RR interval, LMM with robust standard errors were used to identify and quantify a potential effect of the condition on the HRV parameters. As sensitivity analyses, models were re-computed using mathematically transformed parameters (Table 7) and corresponding normal distribution of the residuals.

Table 7: Mathematical transformations of the HRV parameters

HRV parameter	Type of transformation
Averaged RR interval	No transformation
SDNN VLF LF HF LF/HF ratio	Transformation using natural logarithm ln x
RMSSD	Transformation using root function $\sqrt{x}$

3.5.1.2 Heart rate

Beside the investigation of HRV as a macro parameter across the whole morning measurement, an event-related analysis of heart rate was performed. The data was processed using a programme developed by DLR that also allows deriving the heart rate for shorter intervals (< 20 seconds). According to Eder, Elam and Wallin (2009), stimuli shorter than 250 ms lead to an immediate acceleration and subsequent deceleration of the heart rate, which subsides within 10 seconds. Therefore, the difference between the averaged heart rate in the period of 10 seconds prior to and 10 seconds after the noise event was calculated. To correct for artefacts, bpm values < 30 bpm and > 120 bpm were excluded (Basner, Müller & Elmenhorst 2011). The averaged heart rate over the 10-second interval prior to the noise event was used as the baseline. Since it was expected that the heart rate would increase with a noise event, the baseline heart rate was subtracted from the averaged heart rate over the period of 10 seconds after the noise event to calculate the relative percentage differences. Positive difference values therefore correspond to an increase in heart rate due to a noise event compared to the baseline, while negative values mean that the heart rate was higher in the baseline. Subsequently, an LMM with random intercept and the condition as a factor was calculated. Since the residuals of the relative differences were only approximately normally distributed, an LMM with robust standard errors was calculated. The mathematical transformations applied (square root, natural logarithm, Box-Cox) did not result in a normal distribution of the residuals. Subsequently, pairwise post-hoc comparisons with Bonferroni-Holm correction for multiple testing were calculated whenever heart rate in one of the two noise conditions differed significantly from the heart rate in the control condition.

3.5.1.3 Blood pressure

The Finapres NOVA (Finapres Medical Systems) was used to measure blood pressure, which enabled continuous non-invasive measurement using a finger cuff (Figure 29). This is a haemodynamic system that measures blood flow and pressure with each heartbeat, enabling the calculation of the vascular resistance in the blood vessels. The measurement was performed automatically after the device was started manually until the measurement was stopped manually. The subsample consisted of a total of 22 participants. The data quality allowed the evaluation of data from 21 participants. Using DLR's own software (PhysioPy), the blood pressure data was processed and artefacts were removed. As a first step, the mean value over the time interval of 30 seconds before each noise event was computed for each participant. In a second step, values were aggregated across all participants for each condition. These values are referred to as pre-measurement. Then, each measured value within 30 seconds after the respective noise event was used to calculate the relative percentage difference, again first for each participant and then aggregated for each condition. A LMM with random intercept and the condition as a factor was calculated. The residuals of the relative differences were normally distributed.

Figure 29: Continuous non-invasive blood pressure measurement using the Finapres NOVA

Note: Source: own visualisation, DLR.

3.6 Method for measuring subjective assessment

3.6.1 Questionnaires

Table 8 provides an overview of all questionnaires and scales used in the sleep study.

Table 8: Questionnaires and scales

Initial questionnaire on the first evening after moving into the laboratory	**Evening questionnaire** every evening 20 minutes before bedtime	**Morning questionnaire** every morning 30 minutes after getting up	**Closing questionnaire** on the last morning before leaving the laboratory
Subjective sleep quality over the last 4 weeks (PSQI)	Current sleepiness (KSS)	KSS	Sociodemographic data
Chronotype	Current feelings and emotions (PANAS)	PANAS	Noise sensitivity (LEF-K)
General capacity to adapt to noise	Mental, temporal and physical stress as well as restfulness, concentration and performance throughout the preceding day	Subjective sleep quality during the previous night	Noise sensitivity to impulsive noises (LFN)
Capacity to cope with noise and perceived control over noise	Stressful events	Time to fall asleep	Sensitivity to low-frequency noise (IN)
		Difficulties falling asleep and maintaining sleep	Evaluation of the study (experimenters' care of participants, time management and scheduling, etc.)
		Short-term annoyance and disturbance during the previous night	Assumptions about the type of noise
		Sleep disturbance due to laboratory setting and noise	Debriefing
			Attitude towards civil supersonic aircraft

3.6.1.1 Initial questionnaire

The initial questionnaire was completed by the participants on the first evening shortly after arriving at the sleep laboratory. This questionnaire contained the Pittsburgh Sleep Quality Index (PSQI, Buysse et al. 1989) to retrospectively assess sleep quality, the frequency of sleep-disturbing events, usual sleep times, sleep onset latency and sleep duration, the use of sleep medication, and daytime sleepiness over the previous four weeks. A total of 18 items are assigned to seven components, each of which can take a value from 0 to 3. The component values were added up and subtracted from 21 (maximum total value). A low score thus corresponds to reduced sleep quality and a high score to high sleep quality. A cut-off value was used to classify participants in those with “good" and those with "poor" sleep quality, with a score of ≤ 5 representing a "good" sleep quality.

To determine their chronotype, participants received an example description of the evening type and the morning chronotype and were asked to classify themselves as an extreme morning chronotype, moderate morning chronotype, slight morning chronotype, normal chronotype/intermediate chronotype, slight evening chronotype, moderate evening chronotype or extreme evening chronotype. This item was modified according to Roenneberg et al. (2003). Furthermore, the participants were asked on a 5-point scale (1 = "not" to 5 = "very much") to estimate their general capacity to adapt to environmental noise. Six items according to Guski et al. (1978) were adapted to measure self-reported general control and coping capacity in relation to environmental noise using 5-point scales (1 = "not true" to 5 = "very true"). The items refer to individual cognitive and behavioural strategies and capacities for coping with noise situations. The values of the six items were added up to an index with a possible value range from 6 to 60. Low values therefore correspond to a low ability and high values to a high ability to cope with noise situations.

3.6.1.2 Evening questionnaire

The evening questionnaire was administered every evening to the participants 20 minutes before they went to bed. The Karolinska Sleepiness Scale (KSS, Akerstedt & Gillberg 1990) was used to assess the perceived current sleepiness on a 9-point scale ranging from 1 = "extremely alert" to 9 = "extremely sleepy – fighting sleep". The KSS is interpreted using the response value with values > 7 indicating high sleepiness and values < 4 indicating low sleepiness.

The evening questionnaire also obtained current mood and emotions using the German version of the Positive and Negative Affect Schedule (PANAS, Krohne et al. 1996). The questionnaire consists of 20 adjectives, 10 of which cover the dimensions of positive affect (PA) and negative affect (NA), each. Each item is assessed on a 5-point scale (1 = "not at all" to 5 = "extremely"). Mean values were computed for each of the two dimensions. Higher values on the PA dimension represent a greater degree of positive affect. Higher values on the NA dimension represent a greater degree of negative affect. The two dimensions are not considered to be opposite poles, but rather as distinguishable dimensions of the same construct. While the PA dimension refers to an enthusiastic, active and alert state, the NA dimension describes the extent of negative tension caused by despondency, anger and anxiety (Watson, Clark, & Tellegen 1988). While correlations between PA and social activity, satisfaction and the number of pleasant events were found, NA was associated with stress, health problems and the number of unpleasant events (Watson, Clark, & Tellegen 1988).

The mental, temporal and physical stress experienced throughout the day was also assessed by the participants using three 11-point rating scales (0 = "low stress" to 10 = "high stress") as part of the evening questionnaire. The following question was used to identify any stressful events: "Was there anything today or is there anything coming up in the near future that is currently concerning, stressing or particularly preoccupying you?". Via a 5-point scale (1 = "not at all" to 5 = "very much"), the participants rated on a 5-point scale to what extend this event was preoccupying them at that moment. Both the mental, temporal and physical stress throughout the day and any stressful events were obtained for a potential consideration as covariates for the prediction of subjective sleep assessments. In addition, two items assessed concentration and performance (0 = "good" to 10 = "impaired") and another item was used to ask how rested the participants felt during the past day (0 = "very" to 10 = "not at all"). These items served as supplementary variables to test whether and to what extent noise pollution and self-assessed sleep quality affected subjective performance during the day.

3.6.1.3 Morning questionnaire

Every morning, 30 minutes after getting up, the participants completed the morning questionnaire. A 30-minute waiting period was applied to avoid the effect of sleep inertia, which can lead to drowsiness, reduced cognition and motor impairments. The KSS and PANAS were also administered in the framework of the morning questionnaire. Subjective sleep quality was assessed using six 11-point rating scales developed by Griefahn, Marks and Robens (2006), which refer to difficulties falling asleep, sleep tranquillity, sleep depth, sleep duration, sleep recuperation and movement frequency. The answers are coded from 0 to 10. The values of the individual scales are added up and subtracted from 60 (maximum total value) resulting in a potential value range from 0 to 60, with low values corresponding to low sleep quality and high values to high sleep quality. Participants also estimated how long they needed to fall asleep and whether they had difficulties falling asleep. Finally, the participants also rated their short-term annoyance by environmental noise during the previous night on an 11-point scale (0 = "not at all" to 10 = "extremely") (Fields et al., 2001). The participants were also asked to estimate whether and why they woke up during the previous night using a multiple-choice list: environmental noise, urge to urinate, heat/cold, worries/nightmares, physical discomfort, electrodes/cables, don't know, other causes. The *"other causes"* option provided a free-field text entry for potential other reasons. The answers relating to electrodes/cables or the situation in the unfamiliar laboratory environment were subsumed under the variable *"sleep disturbance due to setting*". Similarly, the answers relating to environmental noise were subsumed under the variable *"sleep disturbance due to noise"*.

3.6.1.4 Closing questionnaire

On the last morning before leaving the sleep laboratory, the participants completed the closing questionnaire. This questionnaire was used to collect the following socio-demographic data from the participants: age, gender, nationality and socio-economic status. To assess general sensitivity to noise, a short questionnaire with nine items (LEF-K, Zimmer & Ellermeier 1998) was used. This questionnaire covers perceptual, affective, cognitive and behavioural reactions in various situations in the areas of performance, general attitude, sleep and social context. There are four response options for each item: strongly agree, somewhat agree, somewhat disagree, strongly disagree. For data evaluation, the response options of 4 items are coded from 0 to 3 and the response options of 5 items were recoded. The items were combined into an index using the sum value resulting in a potential value range from 0 to 27. High values indicate high noise sensitivity. While the LEF-K is supposed to have moderate internal consistency according to Zimmer and Ellermeier (1998), the consistency in our sample was low (Table 10). Studies show that general noise sensitivity is not necessarily related to sensitivity to low-frequency noise (Persson Waye et al. 2001; Pawlaczyk-Luszczynska et al. 2005). Therefore, three items for measuring sensitivity to low-frequency noise according to Pawlaczyk-Luszczynska et al. (2005) were adapted, plus two additional newly developed items using the same response options as for the LEF-K. Three items were recoded and an index was formed based on the sum of the five items (low-frequency noise, LFN). High values corresponded to a high sensitivity to low-frequency noise. In addition, four items with the same response options to measure sensitivity to impulsive noise were developed. Two of them were recoded before adding up to an index based on the sum value (Impulsive Noise, IN). High values correspond to high sensitivity to impulsive noise. Table 9 lists the items used to measure noise sensitivity to low-frequency and impulsive noise. The internal consistency of the IN index improved significantly from 0.530 to 0.712 after omitting the item "When I am asleep, even a loud clap of thunder cannot wake me up". Both the LFN index and the IN index achieved acceptable internal consistency (Table 10).

Table 9: Items for assessing noise sensitivity to low-frequency (LFN) and impulsive noises (IN)

Item	Construct	Source	Recoding
Low-frequency noises frighten me.	LFN	DLR	R
I find it unpleasant when the bass is turned up so high at concerts/in nightclubs that one can feel it with your whole body.	LFN	DLR	R
I am not sensitive to noise with low tones.	LFN	Pawlaczyk-Luszczynska et al., 2005	
I find even quiet monotonous humming (e.g. from a transformer) unpleasant.	LFN	Pawlaczyk-Luszczynska et al., 2005	R
I like listening to music with the bass turned up.	LFN	Pawlaczyk-Luszczynska et al., 2005	
Even a loud bang cannot disturb my peace of mind.	IN	DLR	
I am easily startled by sudden noises.	IN	DLR	R
When I'm asleep, even a loud clap of thunder can't wake me up.	IN	DLR	
I startle awake when I hear doors slam, even if they are far away.	IN	DLR	R

Note: R = recoding, LFN = low frequency noise, IN = impulsive noise.

The participants also evaluated the study. They were asked about their satisfaction with the time management and scheduling, the support and care provided by the experimenter, the test procedure, the appropriateness of the questions asked and the expense allowance, as well as the strain from study participation. The participants answered these items using a 5-point response scale ranging from "not" to "very much". Two yes/no questions were used to determine whether they found the information provided prior to the study sufficient and whether they understood all the questions asked. Suggestions for improvement were collected via open questions. Finally, they were asked how they had become aware of the study.

Before unblinding the participants to the type of noise events, which also took place as part of the closing questionnaire through a written debriefing, they were asked in another open question whether they had any idea what kind of noise they were exposed to. This was followed by a short text explaining the origin of the noise events and a yes/no question asking whether they had heard or read anything about the research and development of modern civil supersonic aircraft in the recent past. To assess attitudes towards supersonic aircraft, participants were asked to rate the following attributes of civil supersonic aircraft on a 5-point scale from "disagree" to "strongly agree": necessary, unsafe, convenient, harmful to the environment, avoidable, bad for air quality, technically advanced, economically significant, harmful to the climate and harmful to building structures. The responses were coded from 1 to 5, partially recoded and added up to form an index, resulting in a value range from 10 to 50, with high values corresponding to a positive attitude towards supersonic aircraft. The index achieved good internal consistency (Cronbach's alpha = 0.861).

3.6.2 Statistical evaluation of the questionnaires

3.6.2.1 Annoyance

To test the secondary hypotheses on short-term annoyance, LMM with random intercepts were calculated. First, a raw model was derived that included the criterion variable *short-term annoyance* and the condition as a fixed factor. If one of the two noise conditions differed significantly from the control condition, pairwise post-hoc comparisons with Bonferroni-Holm correction for multiple testing were performed. The residuals were normally distributed. Since annoyance is influenced by both acoustical and non-acoustical factors (e.g. personal and situational factors), the initial raw model was expanded by additional potential predictors that were systematically included through forward selection. This was done to examine whether there are additional predictors, that contribute incremental validity to the model and explain a portion of the variance of the criterion. The inclusion of the following variables was tested because they could have a relevant influence on acute annoyance: age; gender; adaptation capacity; control and coping capacity; noise sensitivity (LEF-K, LFN and IN); mental, temporal and physical stress on the previous day; stressful events on the previous day; situational sleepiness (KSS) in the evening and in the morning; self-assessed sleep quality of the previous night; time taken to fall asleep and difficulties falling and maintain sleep; self-assessed difficulties falling and maintain sleep due to polysomnography and/or the laboratory environment (*sleep disturbance due to setting)* and self-assessed difficulties falling and maintain sleep due to noise (*sleep disturbance due to noise)*. Unlike the prediction model for physiologically measured awakenings and arousals, the p-values were considered in the traditional context of hypothesis testing. When the predictor variable correlated significantly ($p < 0.05$) with the criterion variable, the variable was considered for the variable selection process. In addition, the AIC was used to determine whether the model was improved by including further factors. A reduction of the AIC by two points was determined as the model with the better model quality (Fabozzi et al. 2014) and resulted in the variable remaining in the model. Multiple regression analyses were conducted to detect any collinearities. The existence of critical intercorrelations could be excluded, if the variance inflation factor (VIF) for the covariates was < 10. In order to examine whether the discomfort of the participants increased with increasing duration in the laboratory and thus increasing duration of noise exposure, an LMM was calculated with the study days (1 to 3) as the independent variable instead of the condition.

3.6.2.2 Self-assessed sleep quality and morning sleepiness

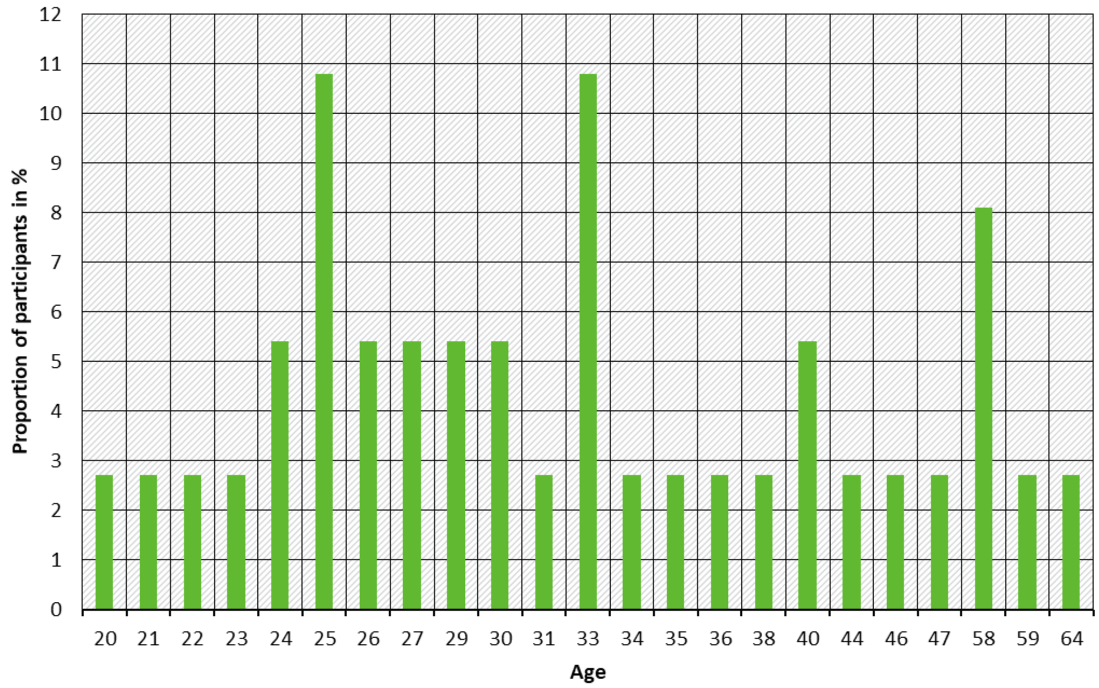
LMM with random intercepts were calculated. Raw models were first derived, which contained either the criterion variable self-assessed sleep quality or morning sleepiness and the condition as a fixed factor. Subsequently, pairwise post-hoc comparisons with Bonferroni-Holm correction were performed. The residuals were normally distributed. In a further step, based on these two raw models, the following potential non-acoustical predictors were added iteratively using forward selection to test whether they had a relevant influence on self-assessed sleep quality or morning sleepiness: age; gender; chronotype; adaptation capacity; control and coping capacity;

noise sensitivity (LEF-K, LFN and IN); mental, temporal and physical stress; stressful events; sleepiness (KSS) on the previous evening; sleep disturbance due to setting and noise. A significant correlation ($p < 0.05$) between the predictor variable and the criterion variable led to a consideration of the variable for the variable selection process. The variable remained in the model if the AIC improved. The existence of critical intercorrelations between covariates could be excluded. For self-assessed sleep quality, an additional LMM was calculated with the study days (1 to 3) as the independent variable instead of the condition.

3.7 Description of the sample

During the conduction of the study, four data sets had to be excluded due to technical problems and one data set due to lack of compliance (mobile phone use during the measurements while awake, no disclosure of existing cold symptoms). One participant was mistakenly included in the study despite already showing a periodic leg movement index > 20 in the test measurement. Since this finding was also evident in the sleep data from the study nights, this data set was also excluded. Since the control condition was used to quantify the noise-induced awakening rate in the noise conditions, only the data from participants whose electrophysiologically measured sleep quality in the control condition met a minimum criterion were analysed. Sleep efficiency was used as an indicator of sleep quality. According to expert consensus (Ohayon, Wickwire & Hirshkowitz 2017), sleep efficiency with a value < 75% is not considered adequate to be used as an indicator of good/adequate sleep quality. Accordingly, this cut-off value was applied and the data from five participants with a sleep efficiency of < 75% were excluded. As a result, from a total of 48 participants (23 women, 25 men) who completed the study entirely, the data of 37 participants (18 women, 19 men) were included in the analysis (Figure 26, graph). The 37 participants were on average ~35 years old (M = 34.54; SD = 12.05) and ranged in age from 20 to 64 years (Figure 30). For the randomised allocation to the study groups (order of conditions), 25 participants went through the order of conditions in group A (Control, Low-boom, Mach cut-off) and 17 participants in group B (Control, Mach cut-off, Low-boom).

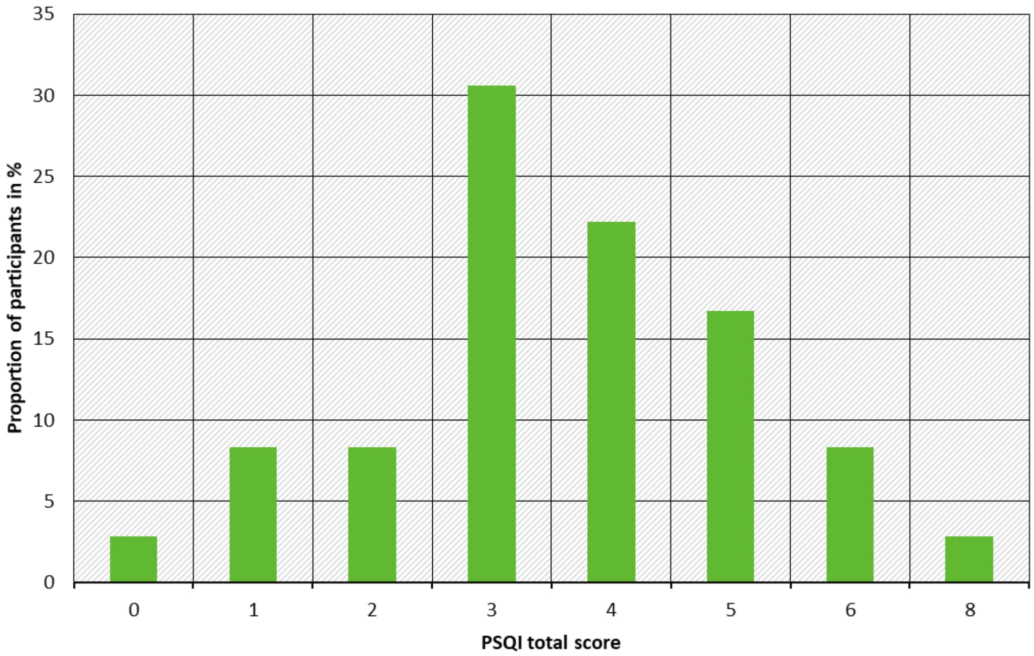
Figure 30: Distribution of the age of the study sample



Note: N = 37, source: own visualisation, DLR.

The majority of the participants (35) were German citizens, one participant was Italian and another participant was Indian. The evaluation of the PSQI showed that 10.8% of the participants had "poor" and 86.5% had "good" sleep quality over the last four weeks (1 data set with missing information, Figure 31). The participants rated their sleep quality on average as 4 (M = 3.61; SD = 1.64) with ratings ranging from 0 to 8 out of a possible range of 0 to 21.

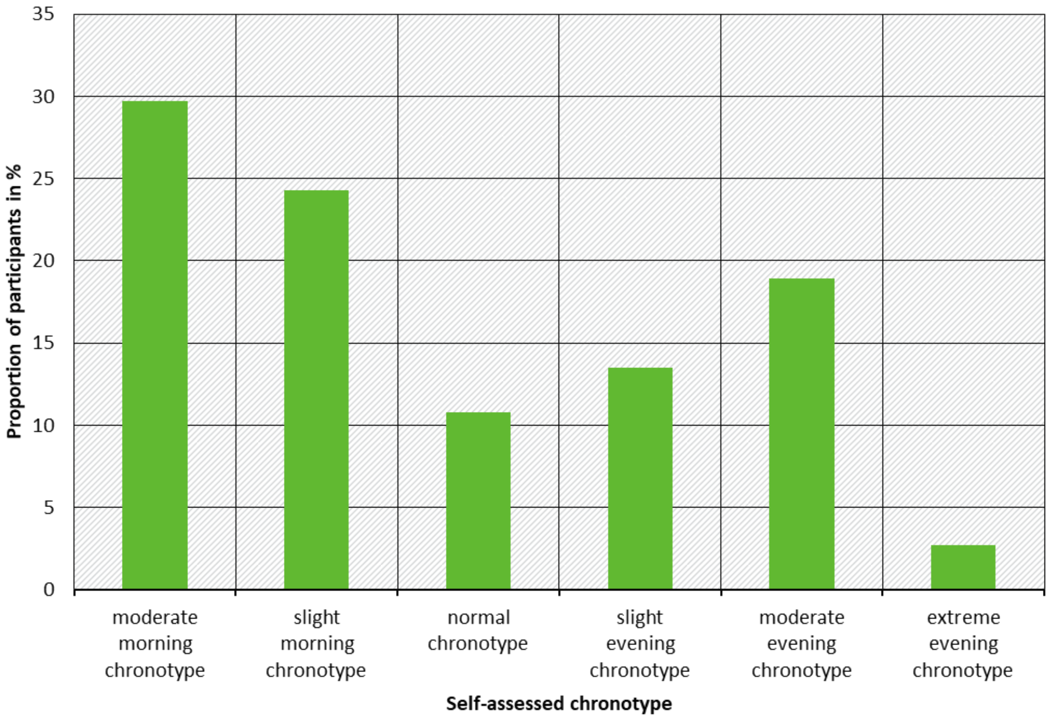
Figure 31: Frequency distribution of self-assessed sleep quality over the last four weeks



Note: N = 37, source: own visualisation, DLR.

The majority of participants classified themselves as either moderate morning chronotype or moderate evening chronotype (29.7% moderate morning chronotype, 24.3% slight morning chronotype, 10.8% normal chronotype, 13.5% slight evening chronotype, 18.9% moderate evening chronotype, Figure 32). Only one participant described themselves as an extreme evening chronotype.

Figure 32: Frequency distribution of self-assessed chronotype



Note: N = 37, Source: own visualisation, DLR.

Table 10 provides an overview of the variables that describe how people cope with noise. The table lists the descriptive data on noise sensitivity (LEF-K, LFN and IN), control and coping capacity in relation to noise, and general capacity to adapt to noise.

Table 10: Descriptive data for variables relating to coping with noise

Variable	M (SD)	Minimum	Maximum	Internal consistency (Cronbach's alpha)
Noise sensitivity LEF-K (9 items, value range 0–27)	13.16 (3.64)	7	22	0.558
Noise sensitivity LFN (low frequency noise, 5 items, value range 0–15)	6.03 (3.33)	0	13	0.73
Noise sensitivity IN (impulsive noise, 3 items, value range 0–9)	4.27 (2.09)	0	8	0.712
Control and coping capacity (6 items, value range 6–30)	19.97 (4.53)	9	28	0.792
Adaptation capacity (1 item, score range 1–5)	3.46 (0.69)	2	5	-

Note: N = 37.

After the participants were informed about the origin of the noise events on the last morning, they showed a mixed attitude towards the civil operation of supersonic aircraft, ranging from 32.22 (SE = 1.19) on the index scale from 10 to 50. High values corresponded to a positive attitude and low values to a negative attitude towards supersonic aircraft. While civil supersonic aircraft were rated as rather technically advanced (M = 4.35, SE = 0.14), convenient (M = 3.95, SE = 0.16) and economically significant (M = 3.73, SE = 0.18), they were also rated as rather harmful to the climate (M = 2.24, SE = 0.18), harmful to the environment (M = 2.32, SE = 0.18) and bad for air quality (M = 2.57, SE = 0.19).

3.8 Results of physiological measurements during sleep

3.8.1 Macro parameters of sleep

Table 11 contains the descriptive statistical data for the global sleep parameters as well as for the number of awakenings, number of noise-associated awakenings, number of arousals and number of noise-associated arousals for the three conditions (Control, Low-boom, Mach cut-off), averaged across the sample of 37 participants. The analyses revealed a significant effect of the condition on sleep efficiency and TST. The subsequent pairwise comparisons showed that the Low-boom condition did not differ from the control condition. However, statistically significant differences consistent with the hypothesis were found between the Low-boom and the Mach cut-off condition: Sleep efficiency (MDiff = 2.888; 95% CI [-0.002; 5.780]; $p = 0.033$) and TST (MDiff = 13.865; 95% CI [-0.008; 27.700]; $p = 0.033$) were lower in the Low-boom condition than in the Mach cut-off condition. Surprisingly, sleep efficiency (MDiff = 2.392; 95% CI [0.627; 4.160]; $p = 0.004$) and TST (MDiff = 11.486; 95% CI [3.014; 20.000]; $p = 0.004$) were significantly higher in the Mach cut-off condition than in the control condition.

While no difference was found between the three conditions in terms of the total number of awakenings and arousals, event-related analysis of the two noise conditions revealed a significantly higher number of noise-associated awakenings (MDiff = 1.541; 95% CI [0.976; 2.110]; $p < 0.001$) and arousals (MDiff = 1.541; 95% CI [0.397; 2.680]; $p = 0.010$) in the Low-boom condition compared to the Mach cut-off condition. The averaged total number of awakenings over the total night of the three conditions ranged between ~22 and 24. Approximately 3 noise-associated awakenings were observed in the Low-boom condition, i.e. they occurred immediately after a low-boom event. In the Mach cut-off condition ~1.5 noise-associated awakenings were observed. The total number of arousals of the three conditions ranged between ~90 and 94, of which ~6 occurred immediately after a low-boom event and approximately 4 after a Mach cut-off event.

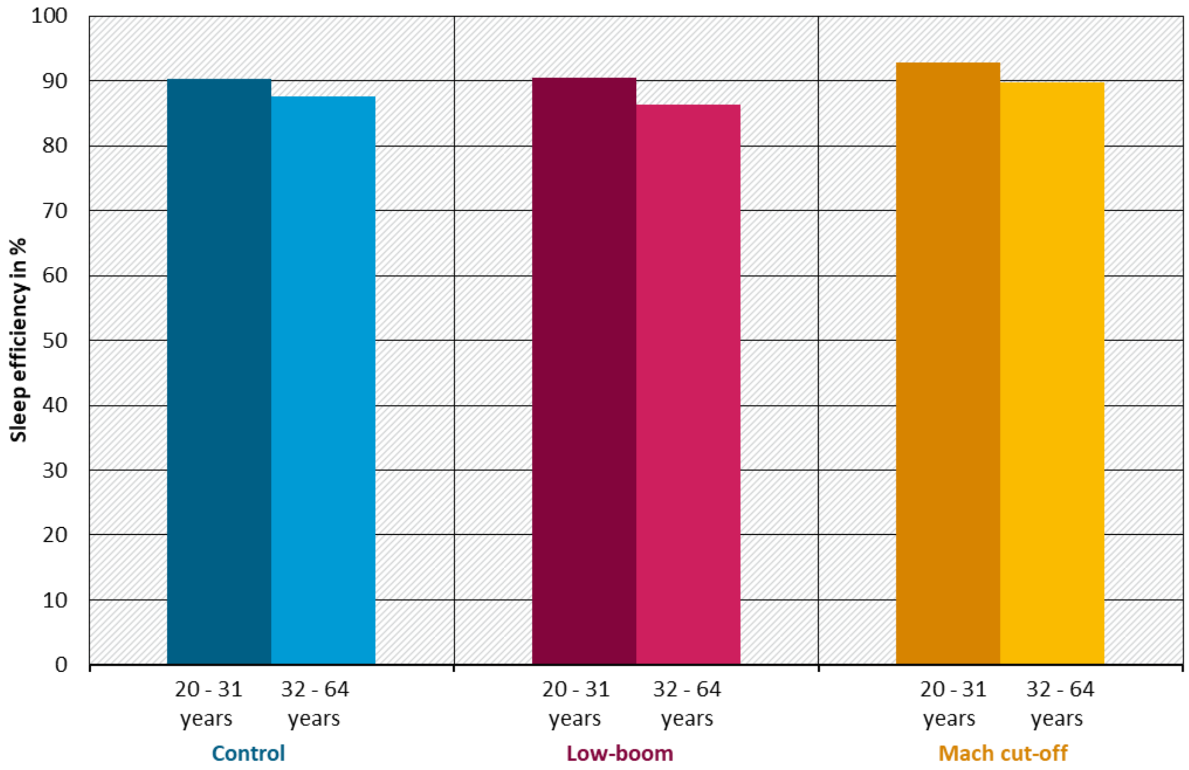
Table 11: Mean and standard error of sleep parameters for the three conditions

Sleep parameter	**Control** **M** **(SE)**	**Low-boom** **M** **(SE)**	**Mach cut-off** **M** **(SE)**
TST (min)	427.15 (4.01)	424.77 (5.37)	438.64^{*+} (3.70)
Sleep efficiency (%)	88.99 (0.84)	88.49 (1.12)	91.38^{*+} (0.77)
SOL (min)	20.05 (1.72)	21.24 (2.36)	16.96 (1.54)
WASO (min)	35.78 (3.44)	36.50 (4.87)	26.87 (3.24)
S1 (min)	20.77 (1.71)	21.61 (1.55)	22.19 (1.60)
S2 (min)	236.82 (6.49)	229.0 (6.34)	230.96 (6.35)
SWS (min)	83.16 (5.72)	83.69 (5.00)	90.32 (5.45)
REMS (min)	86.39 (2.94)	90.47 (3.60)	95.16 (3.94)
Number of awakenings	21.68 (1.01)	22.59 (1.12)	23.46 (1.05)
Number of noise-associated awakenings	-	3.05 (0.30)	1.51*** (0.20)
Number of arousals	90.11 (5.73)	94.05 (6.72)	92.46 (6.97)
Number of noise-associated arousals	-	5.65 (0.50)	4.11* (0.38)

Note: N = 37, M = mean, SE = standard error, TST = total sleep time, SOL = sleep onset latency, WASO = wake after sleep onset, S1 = stage 1, S2 = stage 2, SWS = slow wave sleep, REMS = REM sleep, ***$p < 0.001$, *$p < 0.05$ = difference between the Mach cut-off and the Low-boom condition (post-hoc t-test with Bonferroni-Holm correction), +$p < 0,05$ = difference between the Mach cut-off and the control condition (post-hoc t-test with Bonferroni-Holm correction). No significant differences were found between the Low-boom and the control condition.

Of the selected potential covariates, only the age correlated with sleep efficiency ($\beta = -0.126$; 95% CI [-0.239; -0.012]; $p = 0.031$). Higher age was associated with lower sleep efficiency. However, the model's fit improved only slightly from the raw model (AIC = 680) to the model that included the age (AIC = 679). Accordingly, the age of the participants was not able to explain any additional variance in sleep efficiency. Furthermore, there were no significant differences for the interactions between the conditions and age. To illustrate the age effect, a median split for age was performed exploratively and the mean values of sleep efficiency across the conditions for two age groups (20–31 years vs. 32–64 years) were presented (Figure 33). The figure shows that the younger participants achieved higher sleep efficiency than the older participants in all three conditions. There was no obvious difference in sleep efficiency between the conditions.

Figure 33: **Sleep efficiency of the three conditions for two different age groups**



Note: Age groups (20–31 years, N = 19 vs. 32–64 years, N = 18) based on a median split. N = 37, source: own visualisation, DLR

Additional analyses using LMM with the study days (1 to 3) instead of the condition as the independent variable showed only a significant increase in REMS on the third night compared to the first night (MDiff = 11.338; 95% CI [1.660; 21.000]; $p = 0.016$).

The correlation analyses revealed a significant positive moderate correlation between electrophysiologically measured sleep efficiency and the sleep quality self-assessed by the participants ($r = 0.393$, $p < 0.001$) across all conditions.

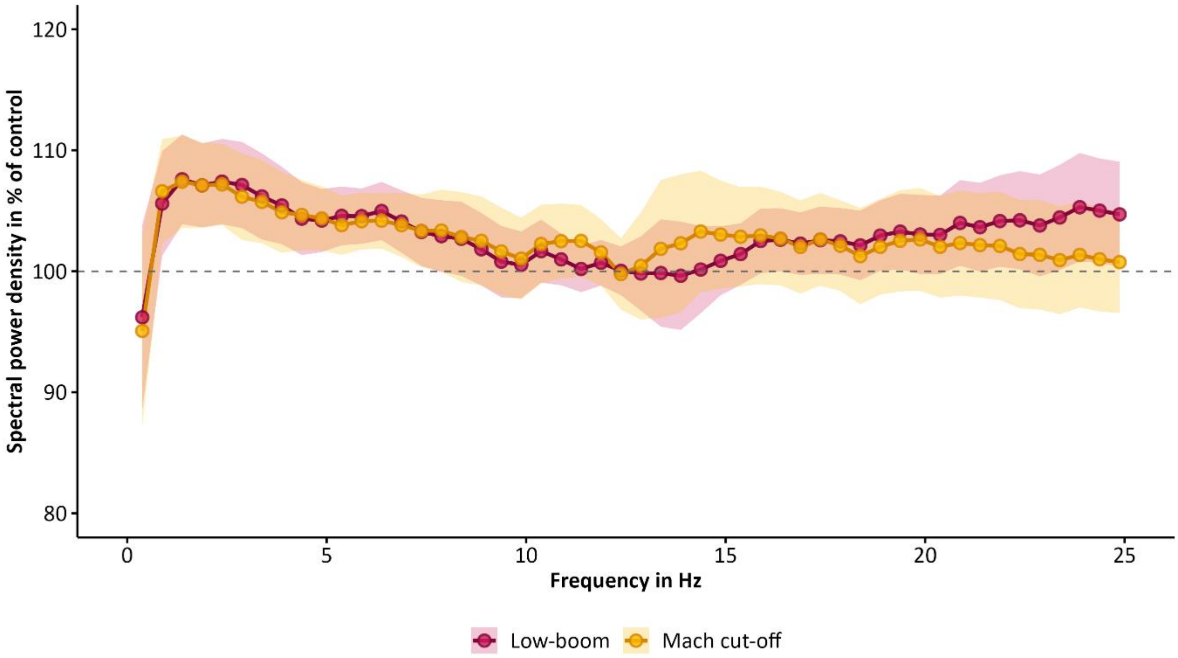
The analyses of the correlation between the electrophysiologically measured sleep onset latency (SOL) and the sleep onset latency self-assessed by the participants revealed a significant positive moderate correlation ($r = 0.265$, $p = 0.005$) across all conditions.

In addition, for the first study night, it was investigated whether the elapsed time since the test measurement of the participant selection process correlated with sleep quality. The averaged time in between was ~70 days (minimum = 15 days, maximum = 141 days). However, there was no significant correlation between the sleep parameters and the elapsed time between the night of the test measurement and the first study night.

3.8.2 EEG spectra in non-REM sleep

The analysis of the EEG spectra in non-REM sleep over the total night showed no significant differences among the three conditions (Figure 34). Neither the factor *condition* nor the interaction between *condition* and *EEG frequency* had an influence on the averaged spectral power density.

Figure 34: EEG spectra during non-REM sleep during the Low-boom and Mach cut-off condition, averaged over the total night and shown as a percentage of the control condition



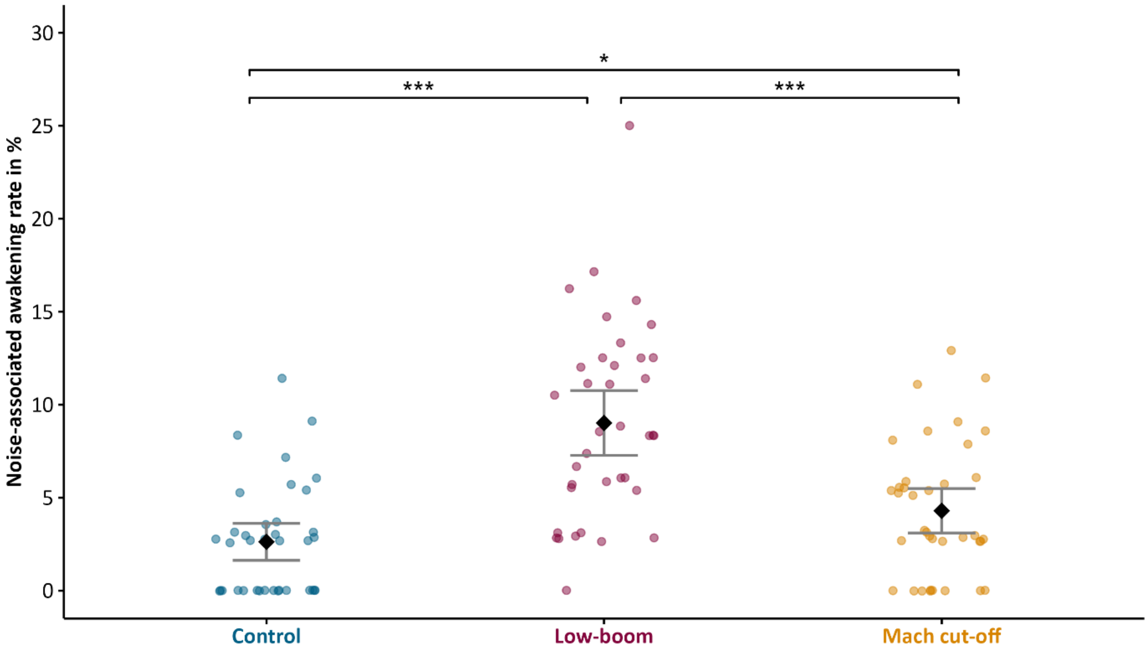
Note: Mean values for the Low-boom (dark red line) and Mach cut-off condition (dark orange line) and ± standard errors for the Low-boom (light red area) and Mach cut-off condition (light orange area) over the total night are shown. The grey dashed line represents the spectral power density of the control condition. Due to deviating values from one participant, whose data was excluded according to Tukey's outlier rules (1.5 * IQR rule), the results were from N = 36 for the Mach cut-off condition and N = 37 for the control and Low-boom condition. Source: own visualisation, DLR.

3.8.3 Event-related analyses

3.8.3.1 Awakening events

On average, ~34 noise events (SD = 2.82) were considered for the event-related analysis of awakenings (Control: M = 33.89; SD = 2.97; Mode = 35; Low-boom: M = 33.84; SD = 2.85; Mode = 36; Mach cut-off: M = 35.30; SD = 2.44; Mode = 35). The number ranged from 25 to 39 noise events (Control: 27 – 39; Low-boom: 25 – 38; Mach cut-off: 27 – 39). Figure 35 shows the relative percentage rate for noise-associated awakenings for each participant across the three conditions. The awakening rate was highest in the Low-boom condition at 9% (SE = 0.86) and differed significantly from the control condition (MDiff = 6.393; 95% CI [4.723; 8.064]; $p < 0.001$) with 2.6% (SE = 0.49) and from the Mach cut-off condition (MDiff = 4.721; 95% CI [3.051; 6.391]; $p < 0.001$) with 4.3% (SE = 0.59). The difference between the Mach cut-off condition and the control condition was also significant (MDiff = 1.632; 95% CI [0.002; 3.343]; $p = 0.00497$). While in the control and Mach cut-off condition, several participants did not show any noise-associated awakening, there was only one participant in the Low-boom condition who did not wake up due to one of the sonic boom events.

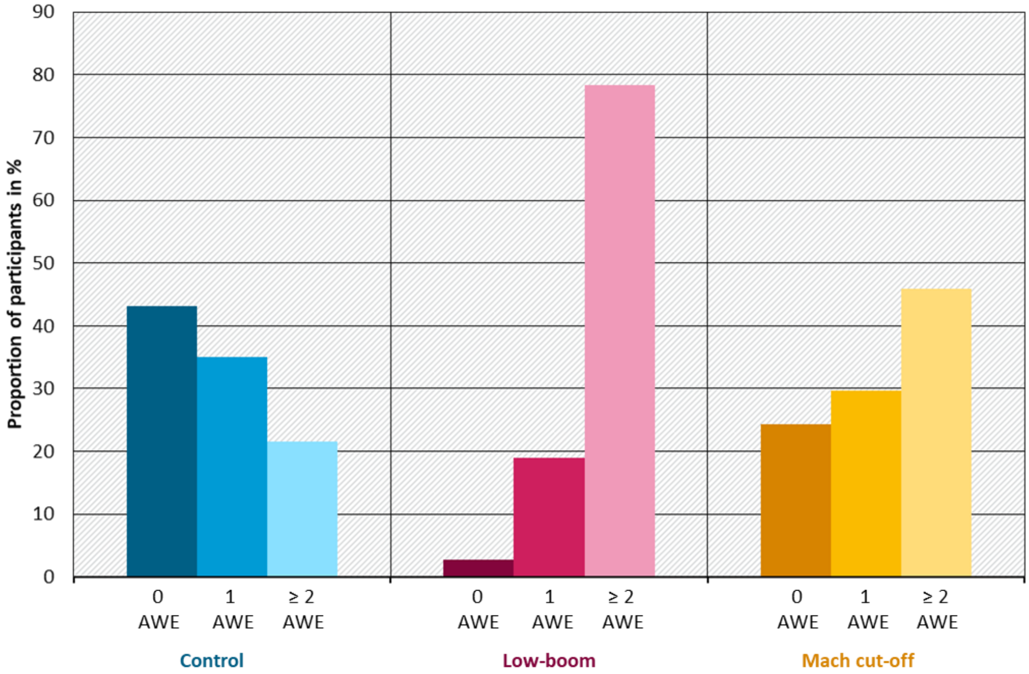
Figure 35: Relative rate of noise-associated awakenings for each condition



Note: The diamonds represent the averaged awakening rate across all participants, and the error bars indicate the 95% confidence interval. The dots represent the awakening rate for each participant. ***p < 0.001, *p < 0.05, N = 37, source: own visualisation, DLR.

To illustrate the variations in the distribution of noise-associated awakenings, Figure 36 depicts the proportion of participants with and without noise-associated awakenings – i.e. awakenings that occurred immediately after a noise event and, in the control condition, after a supposed noise event. In the Low-boom condition, only one participant did not show any noise-associated awakening, compared to a higher proportion in the control (16 participants, 43.2%) and the Mach cut-off condition (9 participants, 24.3%). In the control condition, 35.1% of participants showed one noise-associated awakening, followed by the Mach cut-off condition with 29.7% and the lowest proportion of 18.9% in the Low-boom condition. The highest proportion of participants who experienced two or more noise-associated awakenings was observed in the Low-boom condition at 78.3%, followed by the Mach cut-off condition at 45.9% and the lowest proportion in the control condition at 21.6%. The maximum number of four noise-associated awakenings was experienced by one participant in the control condition and by three participants in the Mach cut-off condition. In the Low-boom condition, nine participants woke up four times immediately after a noise event and one participant showed the maximum number of nine noise-associated awakenings.

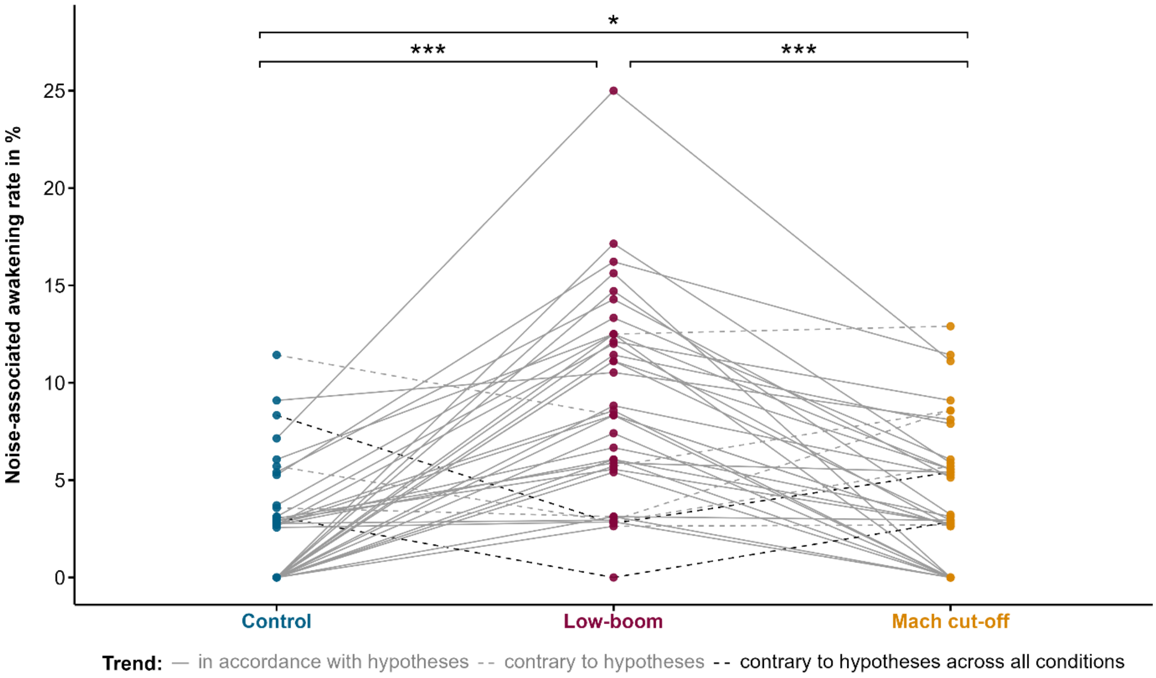
Figure 36: Proportion of participants with and without noise-associated awakenings



Note: N = 37, AWE = awakening event, source: own visualisation, DLR.

Figure 37 illustrates how many participants showed awakening rates in accordance with hypotheses (Low-boom > Mach cut-off > Control), awakening rates contrary to hypotheses between two conditions, and awakening rates contrary to hypotheses across all three conditions. Only two participants showed awakening rates that were contrary to the hypotheses across all conditions.

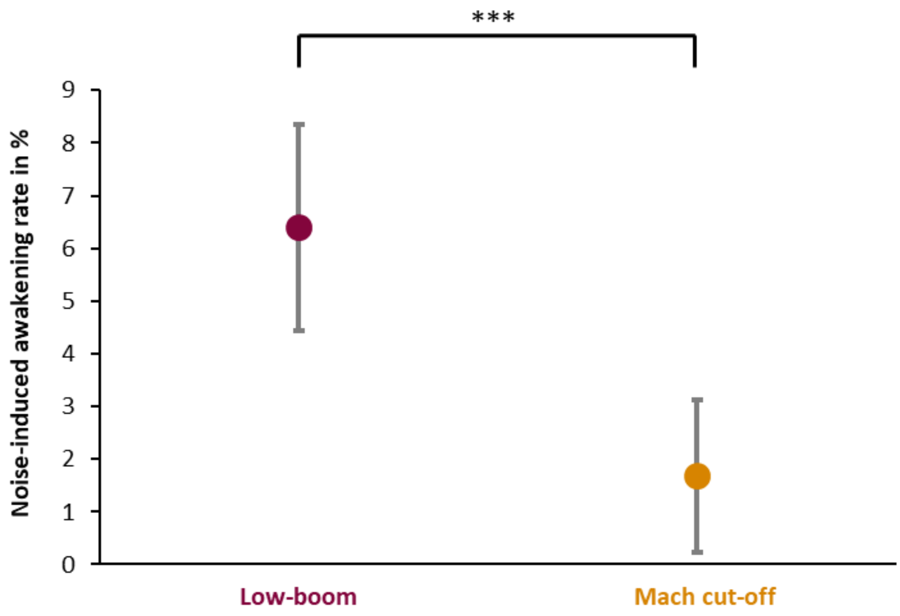
Figure 37: Trends in awakening rate for each participant and each condition



Note: The dots represent the awakening rate for each participant. ***p < 0.001, *p < 0.05, N = 37, source: own visualisation, DLR.

The noise-induced awakening rate for the two noise conditions is shown in Figure 38. After subtracting the spontaneous awakening rate of the control condition from those of the noise conditions, the averaged awakening rate for the Low-boom condition was 6.4% (SE = 0.96) and for the Mach cut-off condition 1.7% (SE = 0.71) (MDiff = 4.721; 95% CI [3.052; 6.390]; $p < 0.001$).

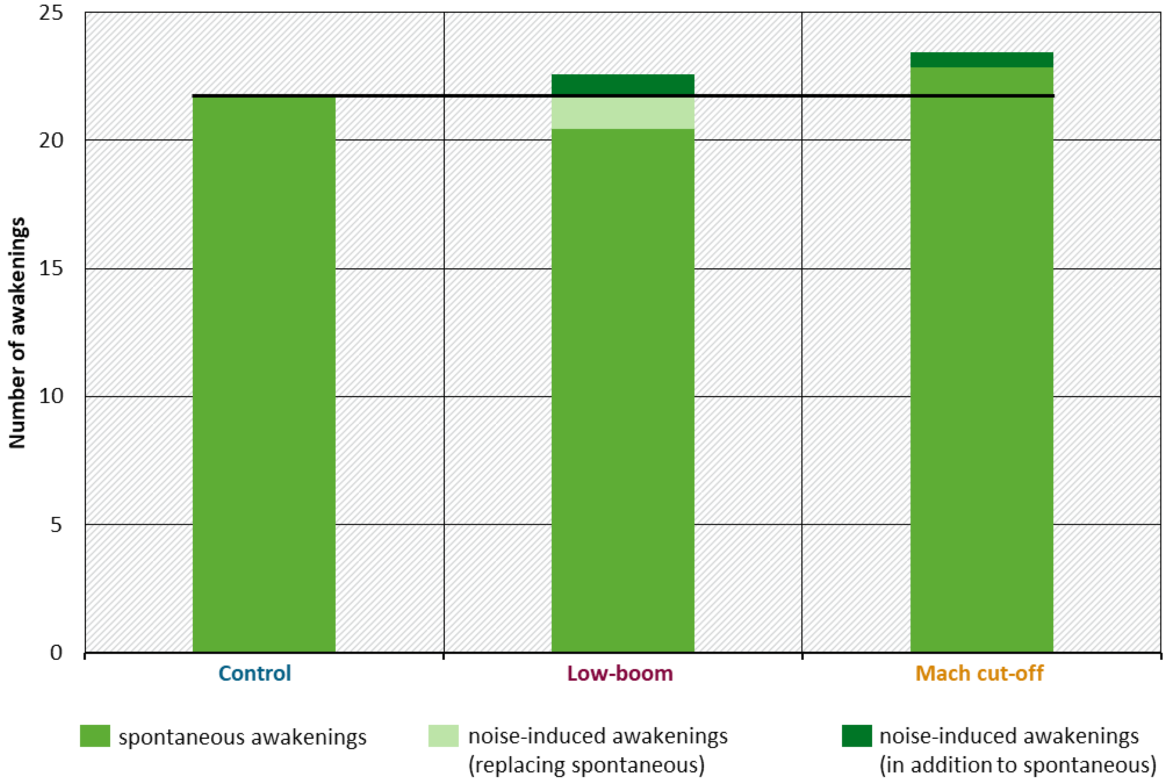
Figure 38: Noise-induced awakening rate in the Low-boom and Mach cut-off condition



Note: Difference between the awakening rate in the control condition and those in the noise conditions, first calculated for each participant and subsequently accumulated across all participants. The dots represent the averaged awakening rate across all participants and the error bars represent the 95% confidence interval. N = 37, ***$p < 0.001$, source: own visualisation, DLR.

In the Low-boom condition, an average of 2.16 awakenings out of the total number of awakenings (22.59) were noise-induced. In the Mach cut-off condition, 0.62 of all awakenings (23.46) were induced by noise events. Since Basner, Müller and Elmenhorst (2011) assume that noise-induced awakenings not only occur in addition to spontaneous awakenings but also replace them, the noise-induced awakenings were divided into awakenings that replaced spontaneous awakenings and awakenings that occurred in addition to the spontaneous awakenings. It was assumed that the number of awakenings in the control condition (21.68) corresponded to the spontaneous awakenings. Figure 39 illustrates that in the Low-boom condition, slightly more than half (58%) of the noise-induced awakenings "replaced" awakenings that would presumably have occurred spontaneously. In the Mach cut-off condition, the noise-induced awakenings occurred in addition to the spontaneous awakenings and do not appear to have replaced any spontaneous awakenings.

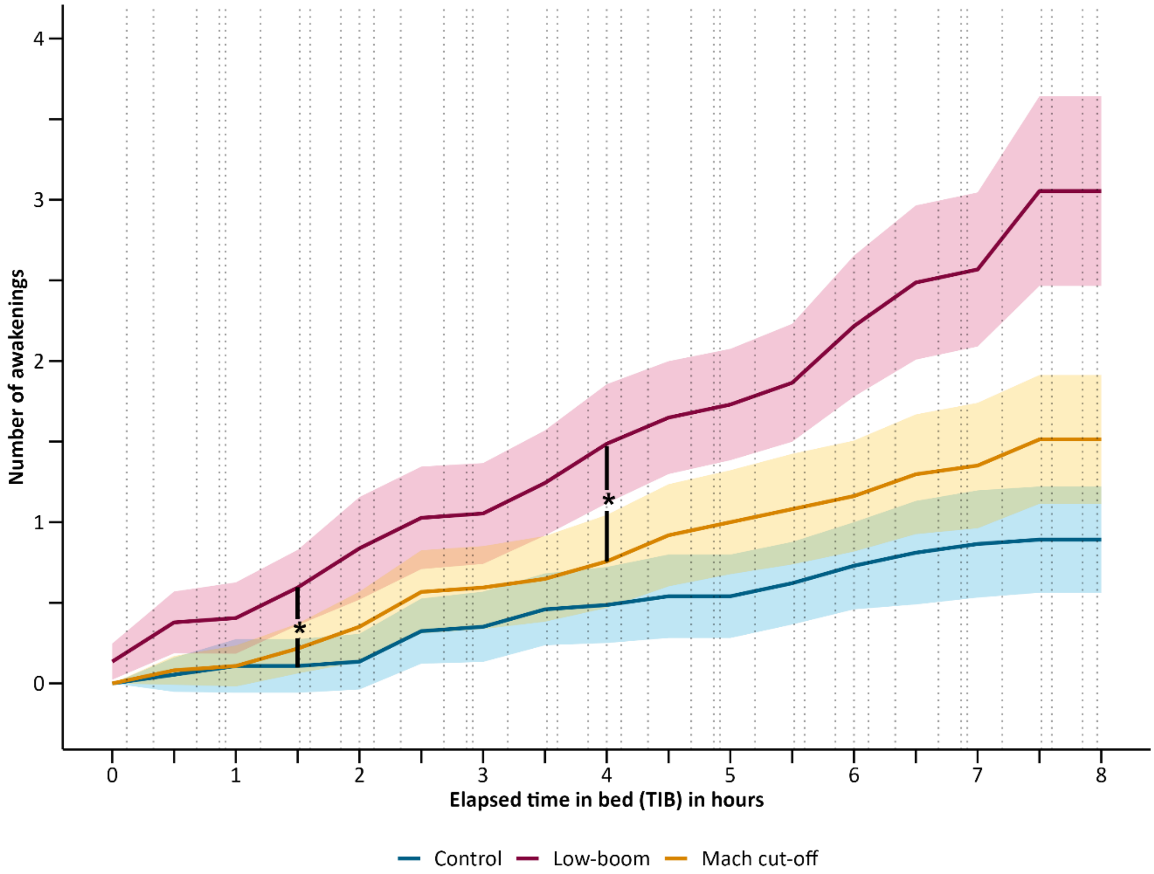
Figure 39: Averaged number of awakenings for the three conditions



Note: The black line represents the averaged number of awakenings during the noise-free control night. N = 37, source: own visualisation, DLR.

Figure 40 shows the cumulative number of noise-associated awakenings in the two noise conditions and the number of awakenings due to the supposed noise events in the control condition over the elapsed time in bed (TIB = 8 hours). In addition, the time points of the 40 (supposed) noise events are shown over the TIB. After 1.5 hours TIB and 6 noise events, the number of awakenings in the Low-boom condition was significantly higher until the end of the TIB ($p < 0.05$) than in the control condition. Compared to the Mach cut-off condition, the number of awakenings in the Low-boom condition was significantly higher after 4 hours TIB and 19 noise events until the end of TIB ($p < 0.05$). Figure 40 shows that towards the end of the TIB, the number of awakenings remains constant in all conditions, as some participants were already awake at that point.

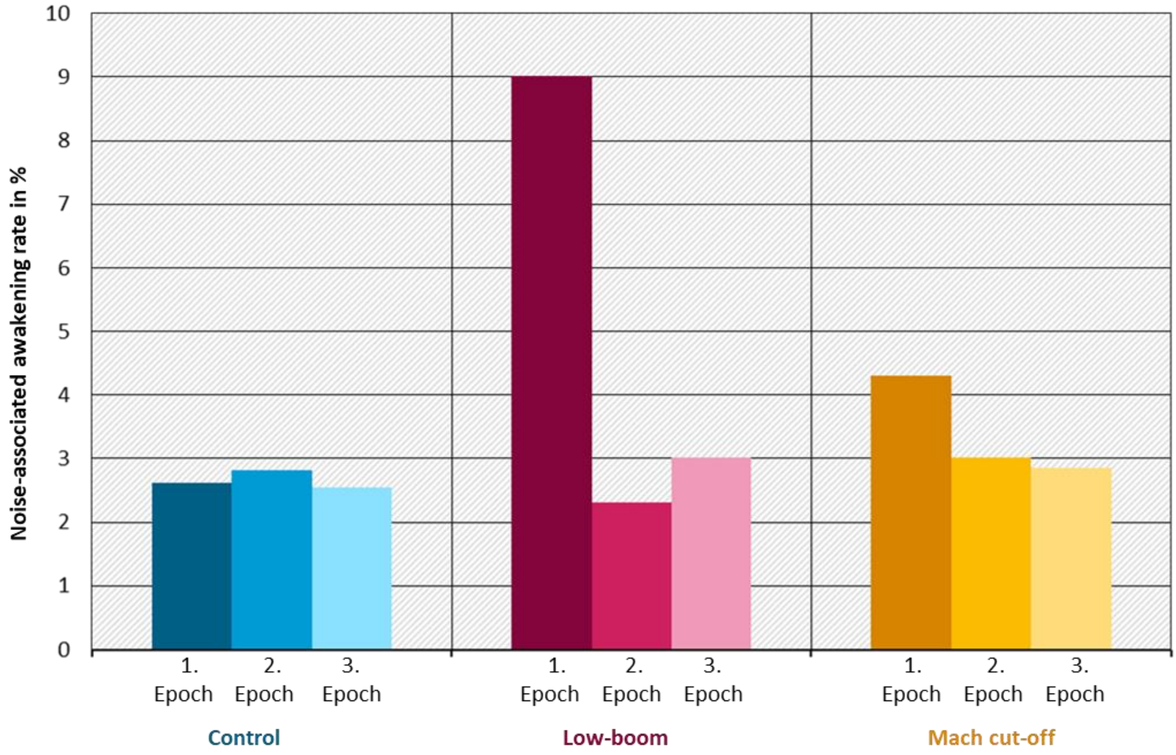
Figure 40: Cumulative number of awakenings



Note: For each 30-minute interval, a distribution of cumulative awakenings was calculated for each participant and subsequently across all participants. The conditions were compared for each 30-minute time point during the time in bed (TIB). The cumulative number of awakenings for the control (dark blue line), Low-boom (dark red line) and Mach cut-off condition (dark orange line) and the 95% confidence intervals for the control (light blue area), Low-boom (light red area) and Mach cut-off condition (light orange area) are shown. The grey dotted lines represent the time points of the noise events in the two noise conditions and those of the supposed noise events in the control condition. *$p < 0.05$, N = 37, source: own visualisation, DLR.

In order to verify whether the first epoch after the noise event was actually appropriate for determining the noise-associated awakening rate for sonic booms, an additional analysis was performed in which the awakenings in the second and third epochs after the noise event were considered. Figure 41 shows that the supposed noise-associated awakening rate in the control condition hardly differs between the three epochs (1st epoch: M = 2.6%, SE = 0.49; 2nd epoch: M = 2.8%, SE = 0.43; 3rd epoch: M = 2.6%, SE = 0.51). Since this is the control condition, it can be assumed that the awakening rate of 2.6% to 2.8% corresponds to the spontaneous awakening rate. The awakening rate in the second and third epoch did not differ between conditions ($p > 0.05$). In the Low-boom and Mach cut-off condition, the highest awakening rate occurred in the first epoch (Low-boom: M = 9.0%, SE = 0.86; Mach cut-off: M = 4.3%, SE = 0.59). The second (Low-boom: M = 2.3%, SE = 0.40; Mach cut-off: M = 3.0%, SE = 0.41) and third epoch (Low-boom: M = 3.0%, SE = 0.48; Mach cut-off: M = 2.9%, SE = 0.50) corresponded to the level of the control condition and thus to the spontaneous awakening rate.

Figure 41: **Comparison of the noise-associated awakening rate in the 1st, 2nd and 3rd epoch after the noise event**



Note: N = 37, source: own visualisation, DLR.

The results of the prediction model using logistic regression analysis are shown in Table 12. The model showed a significantly higher awakening probability for the Low-boom condition and the Mach cut-off condition compared to the control condition. When considering the sleep stage in the (reference) epoch prior to the noise event, the probability to wake up from SWS or REM was lower compared to the probability to wake up from S2. Based on the performed forward selection process, the elapsed sleep time was selected from the potential predictors due to its enhancement of the model fit and significant impact on the awakening probability. The awakening probability increased with the increase in elapsed sleep time. In addition, a significant interaction was selected between the sleep stage in the (reference) epoch prior to the respective noise event and the elapsed sleep time between the sleep onset and the respective noise event, excluding the time spent awake. The effect of elapsed sleep time depended on the previous sleep stage: the protective effect of SWS and REM sleep decreased with increasing elapsed sleep time. The age of participants as an additional predictor did not correlate with the awakening probability and did not improve the model fit.

Table 12: Prediction model for the awakening probability

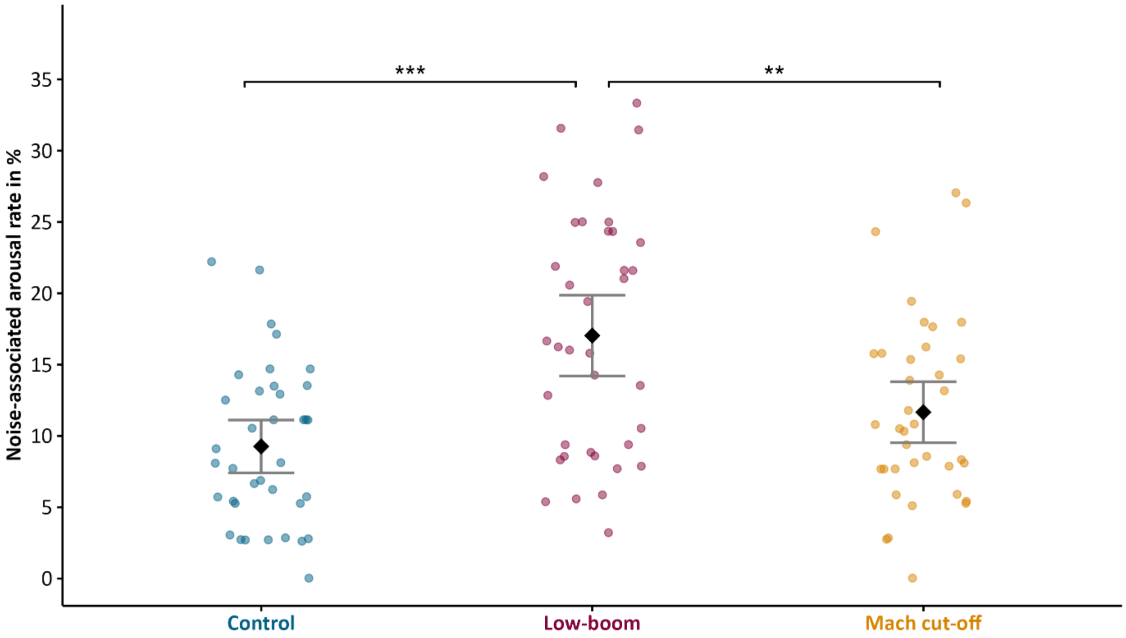
Parameter	Regression coefficient	Odds ratio (OR)	OR 95% CI (below - above)	p-value
Intercept	-3.712	0.024	0.015 - 0.041	<0.001***
Condition: Control	Reference	Reference	Reference	Reference
Condition: Low-boom	1.311	3.711	2,497 - 5,516	<0.001***
Condition: Mach cut-off	0.507	1.660	1.072 - 2.569	0.023
Sleep stage prior to noise event: S2	Reference	Reference	Reference	Reference
Sleep stage prior to noise event: SWS	-0.718	0.488	0.240 - 0.993	0.048*
Sleep stage prior to noise event: REMS	-0.4438	0.642	0.239 - 1.720	0.378
Elapsed sleep time	0.031	1.032	0.941 - 1.131	0.508
Sleep stage prior to noise event: S2 x elapsed sleep time	Reference	Reference	Reference	Reference
Sleep stage prior to noise event: SWS x elapsed sleep time	0.249	1.283	1.049 - 1.569	0.015
Sleep stage prior to noise event: REMS x elapsed sleep time	0.058	1.059	0.869 - 1.292	0.568

Note: Logistic regression model with random intercept, ***$p < 0.001$, *$p < 0.05$, REMS = REM sleep; SWS = deep sleep (S3 and S4), N = 37.

3.8.3.2 Arousals

For the event-related analysis of arousals, the same number of noise events (M = 34.34; SD = 2.82) as for the analysis of awakenings were considered. Figure 42 shows the relative percentage rate for noise-associated arousals for each participant across the three conditions. The Low-boom condition showed the highest arousal rate of 16.6% (SE = 1.42) and differed significantly from the control condition with 8.9% (SE = 0.89) (MDiff = 7.749; 95% CI [4.674; 10.825]; $p < 0.001$) and from the Mach cut-off condition with 11.6% (SE = 1.08) (MDiff = 4.998; 95 % CI [1.922; 8.074]; $p = 0.004$). In the control and Mach cut-off condition one participant did not show any noise-associated arousal. Conversely, in the Low-boom condition, every participant responded with at least one arousal to the sonic boom events.

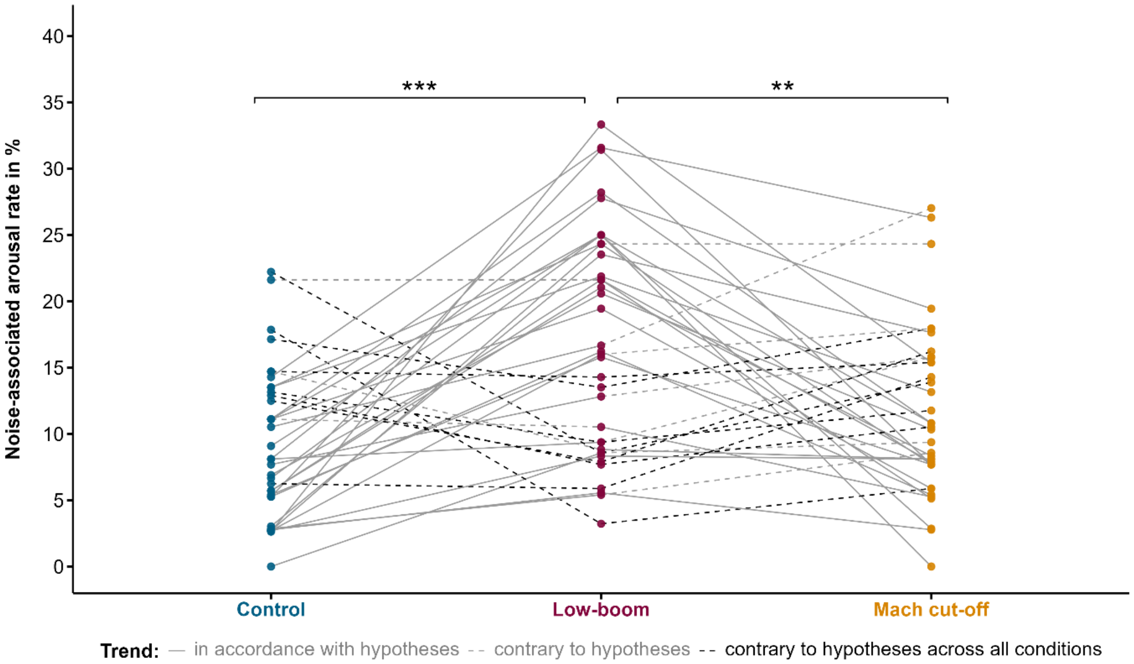
Figure 42: Relative rate of noise-associated arousals for each condition



Note: The diamonds represent the averaged arousal rate across all participants, and the error bars represent the 95% confidence interval. The dots represent the arousal rate for each participant. N = 37, ***p < 0.001, **p < 0.01, source: own visualisation, DLR.

Figure 43 shows how many participants exhibited arousal rates in accordance with hypotheses (Low-boom > Mach cut-off > Control), arousal rates contrary to hypotheses between two conditions, and arousal rates contrary to hypotheses across all conditions. Nine participants showed arousal rates contrary to hypotheses across all conditions.

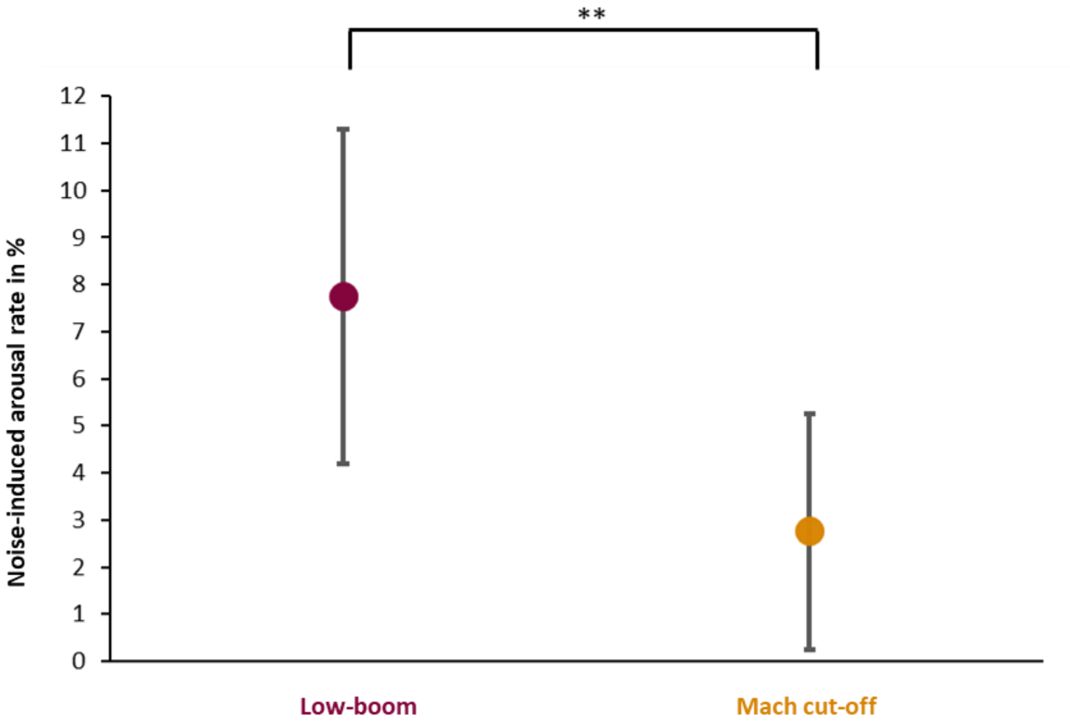
Figure 43: Trends in arousal rate for each participant and each condition



Note: The dots represent the arousal rate for each participant. N = 37, ***p < 0.001, **p < 0.01, source: own visualisation, DLR.

After subtracting the spontaneous arousal rate of the control condition from those of the noise conditions, the noise-induced arousal rate was 7.8% (SE = 1.75) for the Low-boom condition and 2.8% (SE = 1.23) for the Mach cut-off condition (MDiff = 4.998; 95% CI [1.759; 8.238]; p = 0.003; Figure 44).

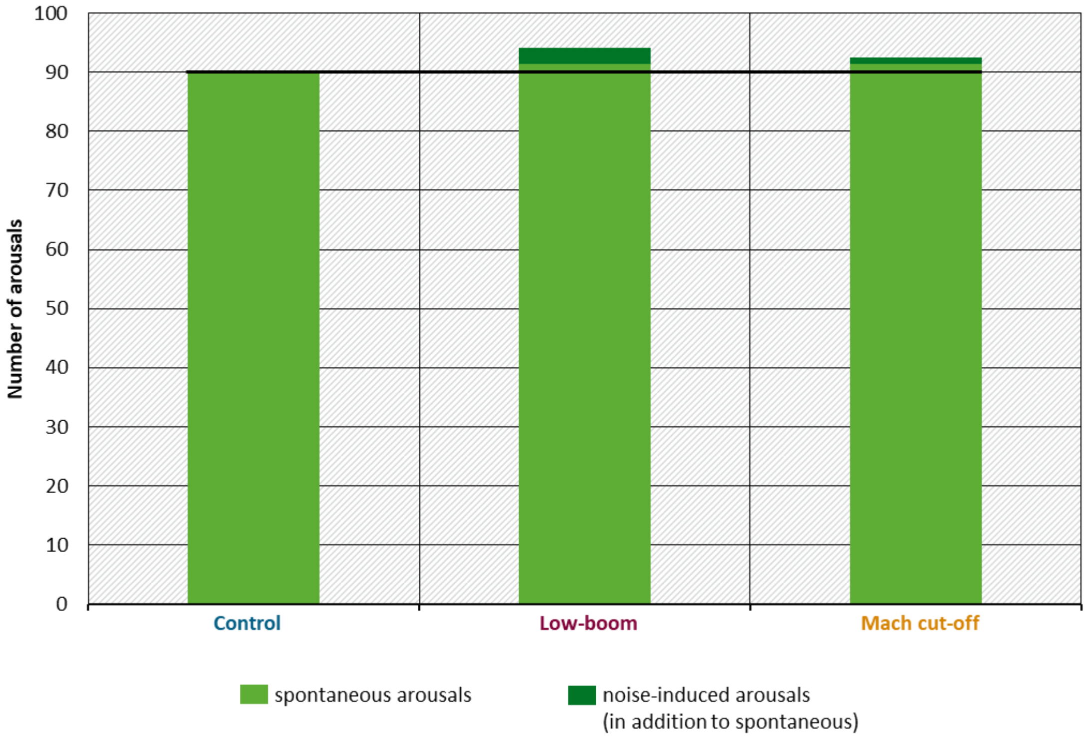
Figure 44: Noise-induced arousal rate in the Low-boom and Mach cut-off condition



Note: Difference between the arousal rate in the control condition and those in the noise conditions, first calculated for each participant and subsequently accumulated across all participants. The dots represent the averaged arousal rate across all participants and the error bars represent the 95% confidence interval. N = 37, **p < 0.01, source: own visualisation, DLR.

Out of the total number of arousals in the noise conditions (Low-boom: 94.05; Mach cut-off: 92.46), an average of 2.65 were induced by low-boom events and 1.11 by Mach cut-off events. In the control condition, an average of 90.11 spontaneous arousals occurred. Figure 45 illustrates that in both noise conditions, the noise-induced arousals occurred additionally and do not appear to have replaced any spontaneous arousals.

Figure 45: **Averaged number of arousals for the three conditions**



Note: The black line represents the averaged number of arousals in the noise-free control night. N = 37, source: own visualisation, DLR.

Table 13 shows the results of the logistic regression analysis. The prediction model shows a significantly higher arousal probability for the Low-boom condition compared to the control condition. Similar to the awakenings, the sleep stage in the epoch prior to the respective noise event was selected as an additional predictor. Compared to S2, arousals occurred less frequently when the sleep stage in the (reference) epoch prior to the noise event was SWS, but more frequently when it was REM sleep. A significant interaction between the condition and sleep stage prior to the noise event highlighted that the effect of the preceding sleep stage differs between conditions. All effects are interpreted relative to the reference combination of control x S2. For the Low-boom condition, it was observed that SWS was less protective compared to S2 than in the control condition. This indicates that the expected decrease in the probability of arousals during SWS is attenuated in the Low-boom condition. In contrast, the increase in the probability of arousals during REM sleep in the Low-boom condition was lower than in the control condition, suggesting that REM sleep in the Low-boom condition was less susceptible to arousals than expected. There were no significant interactions between sleep stage and the Mach Cut-off condition. The inclusion of age as additional predictor did not correlate with the arousal probability and did not improve the model fit.

Table 13: Prediction model for the arousal probability

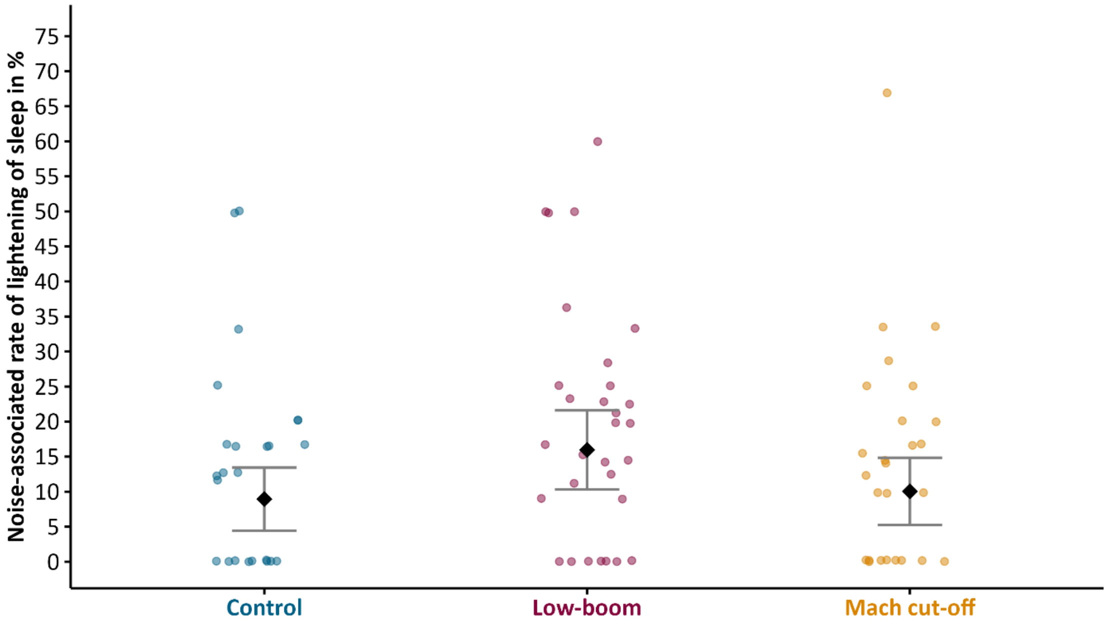
Parameter	Regression coefficient	Odds ratio (OR)	OR 95% KI (below - above)	p-value
Intercept	-2.425	0.088	0.067 – 0.117	< 0.001***
Condition: Control	Reference	Reference	Reference	Reference
Condition: Low-boom	0.799	2.223	1.599 – 3.090	< 0.001***
Condition: Mach cut-off	0.310	1.363	0.964 – 1.928	0.080
Sleep stage prior to noise event: S2	Reference	Reference	Reference	Reference
Sleep stage prior to noise event: SWS	-1.346	0.260	0.111 – 0.609	0.002**
Sleep stage prior to noise event: REMS	0.759	2.137	1.405 – 3.250	< 0.001***
Condition: Control x Sleep stage prior to noise event: S2	Reference	Reference	Reference	Reference
Condition: Low-boom x Sleep stage prior to noise event: SWS	1.578	4.844	1.929 – 12.162	0.001**
Condition: Mach cut-off x Sleep stage prior to noise event: SWS	0.778	2.178	0.800 – 5.924	0.127
Condition: Low-boom x Sleep stage prior to noise event: REMS	-1.080	0.340	0.190 – 0.607	<0.001***
Condition: Mach cut-off x Sleep stage prior to noise event: REMS	-0.201	0.818	0.464 – 1.440	0.486

Note: Logistic regression model with random intercept, REMS = REM sleep; SWS = deep sleep (S3 and S4), ***p < 0.001, **p < 0.01, N = 37.

3.8.3.3 Lightening of sleep

The number of noise events considered for the event-related analyses of lightening sleep was lower compared to those of the analysis of awakenings and arousals, since participants had to be in sleep stage S3 or S4 in the epoch prior to the noise event. On average, ~7 noise events (SD = 23.07) were included in the analysis (Control: M = 6.92; SD = 3.17; Mode = 6; Low-boom: M = 7.70; SD = 3.36; Mode = 7; Mach cut-off: M = 7.43; SD = 2.69; Mode = 10). The number ranged from 1 to 17 noise events (Control: 1 – 17; Low-boom: 1 – 14; Mach cut-off: 3 – 13). The relative percentage rate of lightening of sleep determined by the transitions from deep sleep (S3 or S4) to REM or S2 for each participant in the three conditions is shown in Figure 46. The analyses showed the lowest rate of 8.9% (SE = 2.22) for the control condition, followed by the Mach cut-off condition with 10% (SE = 2.37) and the Low-boom condition with the highest rate of 16% (SE = 2.79). However, the difference between the conditions was not statistically significant.

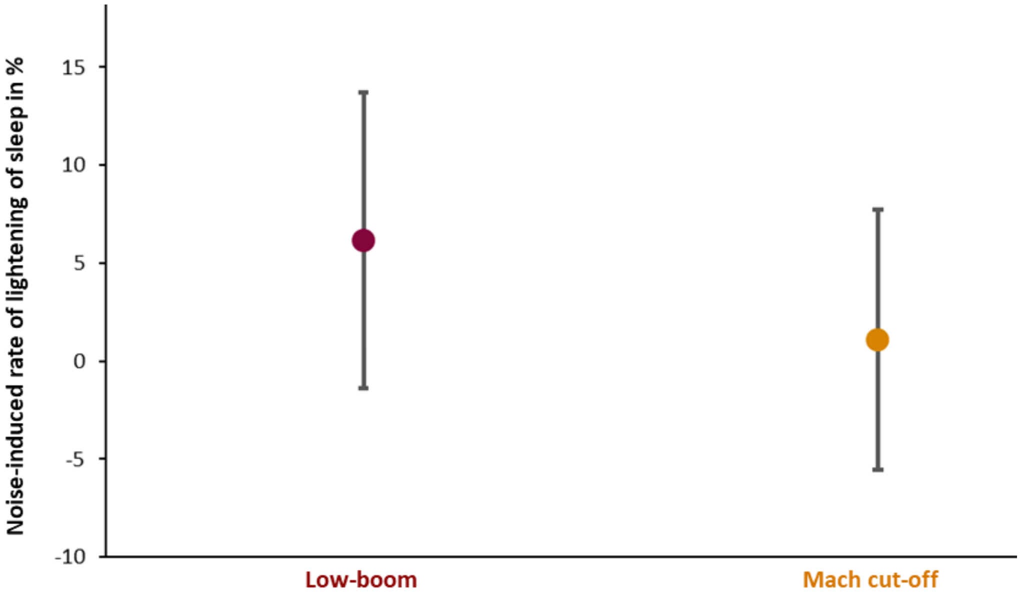
Figure 46: Relative rate of noise-associated lightening of sleep for each condition



Note: The diamonds represent the averaged rate of lightening of sleep across all participants, and the error bars represent the 95% confidence interval. The dots represent the rate of sleep lightening for each participant. N = 37, source: own visualisation, DLR.

Figure 47 illustrates the results for noise-induced lightening of sleep by subtracting the spontaneous lightening of sleep of the control condition. The Low-boom condition resulted in a mean noise-induced rate of 6.2% (SE = 3.71) and the Mach cut-off condition resulted in a rate of 1.1% (3.26). The difference was not significant.

Figure 47: Noise-induced rate of lightening of sleep in the Low-boom and Mach cut-off condition

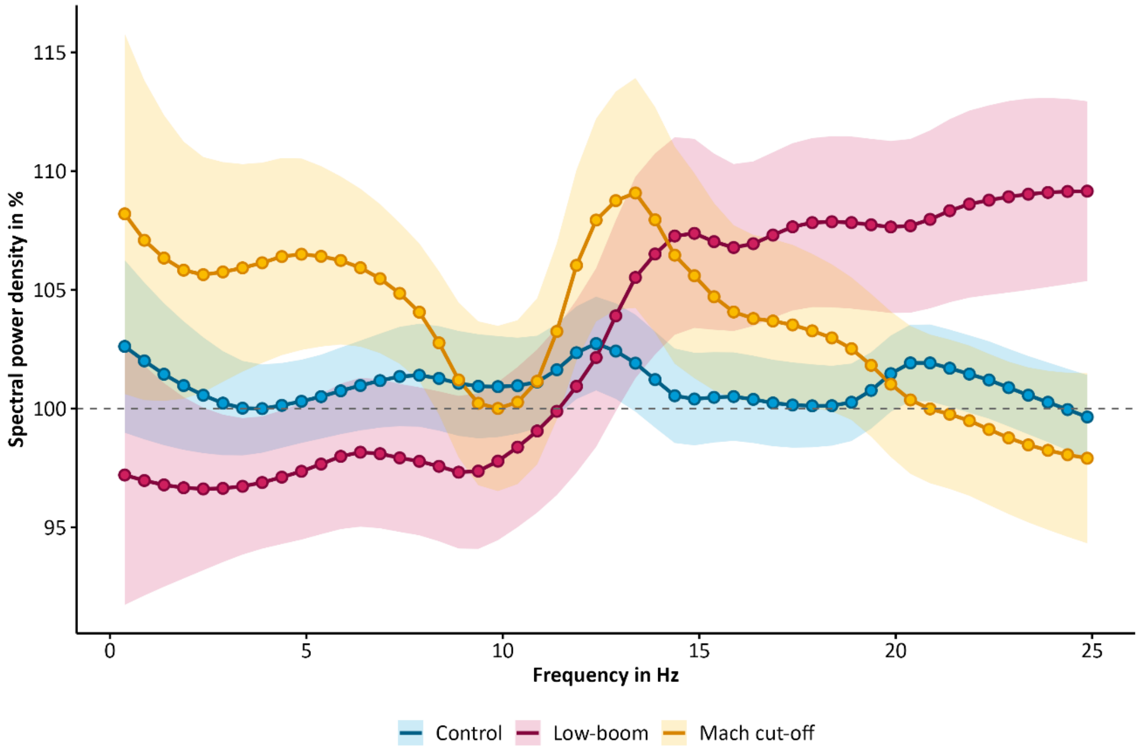


Note: Difference between the rate of lightening of sleep in the control condition and those in the noise conditions, first calculated for each participant and subsequently accumulated across all participants. The dots represent the averaged rate of lightening of sleep across all participants and the error bars represent the 95% confidence interval. N = 37, source: own visualisation, DLR.

3.8.3.4 Changes in the EEG spectrum

The lightening of NREMS within the first minute immediately after a low-boom event was more pronounced in the EEG spectrum (Figure 48). In the Low-boom condition, the spectral power density in the delta frequency band (0.5–4 Hz) was reduced in comparison to the control condition ($p < 0.05$) and to the Mach cut-off condition ($p < 0.001$). The difference between Mach cut-off and control condition was also significant ($p < 0.02$). A loss of power in the delta range indicates that sleep was less deep. In contrast, the beta band (16–25 Hz) showed an increase in the Low-boom condition compared to the control ($p < 0.001$) and the Mach cut-off condition ($p < 0.001$), while there was no difference between the control and the Mach cut-off condition. An increase of power in the beta range is indicative of disturbed sleep.

Figure 48: EEG power density spectra during non-REM sleep in the first minute after a noise event



Note: Mean values per 0.5 Hz bin are shown for the control (dark blue line), Low-boom (dark red line) and Mach cut-off condition (dark orange line) and ± standard error for the control (light blue area), Low-boom (light red area) and Mach cut-off condition (light orange area). The spectral power density values are shown in each condition as a percentage of the respective values in the last minute before the noise event (grey dotted line), N = 37, source: own visualisation, DLR.

3.9 Conclusion based on the results of physiological measurements during sleep

3.9.1 Macroparameters and EEG spectra in non-REM sleep

The present results provide initial insights into the effects of sonic booms from modern civil supersonic aircraft on electrophysiologically measured sleep quality.

Based on the hypotheses established, it would have been expected that the electrophysiologically measured sleep quality in the Low-boom condition would have been lower than in the control condition. Instead, the sleep quality in the Low-boom condition did not differ from the control condition.

Therefore, the following secondary sub-hypothesis for assessing global changes in sleep architecture (as a secondary outcome measure) due to the exposure to the low-boom signals could not be confirmed:

- The sleep quality over the total night, expressed in terms of the parameters a) sleep efficiency, b) sleep onset latency, c) proportion of deep sleep, d) proportion of being awake, e) number of awakenings, is lower in the Low-boom condition than in the quiet control condition.

With regard to the Mach cut-off condition, the following secondary sub-hypothesis could only be partially confirmed:

- The sleep quality over the total night, expressed in terms of the parameters a) sleep efficiency, b) sleep onset latency, c) proportion of deep sleep, d) proportion of being awake, e) number of awakenings, is lower in the Low-boom condition than in the Mach cut-off condition.

Based on the results, it can be concluded that, with regard to the total night, the use of the Mach cut-off flight procedure slightly mitigated the negative effects of sonic booms from future supersonic aircraft only in terms of total sleep time (TST) and sleep efficiency.

The results show that sleep efficiency decreases with age. Younger participants achieved higher sleep efficiency than older participants in all three conditions. Since no interaction was found, it can be concluded that the results found for sleep efficiency apply to all age groups.

The analyses of the effect of the elapsed days in the study on sleep parameters showed a significant increase from the first to the third night (~11 minutes) only for REMS, which can be classified as minor.

The moderate correlation found between self-assessed and electrophysiologically measured sleep quality is consistent with previous findings. Electrophysiologically measured sleep quality cannot be fully reflected by self-assessed sleep quality (e.g. Akerstedt et al. 2002; Edinger et al. 2000; Croy et al. 2017; Griefahn et al. 2006).

There was also no significant effect of the conditions on the EEG spectra in NREMS. Thus, the following secondary hypothesis for assessing the EEG spectra over the total night could not be confirmed:

- The slow-wave activity (SWA) in the EEG of NREMS in the Low-boom condition is lower than the SWA in the quiet control condition. In addition, the SWA in the EEG of NREMS in the Low-boom condition is lower than in the Mach cut-off condition.

This non-sensitivity of the macro parameters and EEG spectra throughout the night is comparable to the previous findings on the effect of conventional traffic noise (aircraft, road, rail) on sleep (e.g. Basner, Müller & Elmenhorst 2011).

3.9.2 Noise-associated awakenings, arousals, lightening of sleep and changes in the EEG spectrum

For some time now, sleep researchers have been reporting that only a few of the symptoms caused by sleep disorders can be explained by changes in the macrostructure and have been discussing the independence of changes in the macro- and microstructure. It is assumed that sleep is fragmented by many short awakenings and arousals, leading to reduced sleep recuperation without any relevant changes in the macrostructure (Bonnet 1985; Bonnet 1986; Guilleminault et al. 1993).

In contrast to the non-sensitivity of the macro parameters to sonic booms, the event-related analysis awakenings and arousals showed clear differences between the conditions. Both the primary hypothesis for assessing awakenings and the following secondary hypotheses could therefore be confirmed.

Primary hypothesis:

- The awakening rate in the Low-boom condition is greater than the spontaneous awakening rate in the quiet control condition.

Secondary hypotheses:

- The awakening rate in the Low-boom condition is greater than the awakening rate in the Mach cut-off condition.
- The arousal rate in the Low-boom condition is greater than the spontaneous arousal rate in the quiet control condition. In addition, the arousal rate in the Low-boom condition is greater than the arousal rate in the Mach cut-off condition.
- The slow wave activity (SWA) in the EEG of NREMS immediately, i.e. within the first minute, after a low-boom event is lower than the SWA in a 1-minute quiet period in the control condition. In addition, the SWA in the EEG of NREMS within the first minute after a low-boom event is lower than after a Mach cut-off event.

The results suggest that low-boom aircraft, despite lower noise emissions than conventional supersonic aircraft, can cause sleep disturbances. The application of the Mach cut-off procedure can mitigate the negative impact.

The results show that noise events are more likely to wake participants from sleep stage S2 than from deep sleep (SWS), and that more arousals occur in S2. The picture for REM sleep was mixed: an increased occurrence of awakenings compared to S2, but a lower occurrence of arousals was found. As an explanation, Buxton et al. (2012) explain suggest that the probability of such reactions appears to vary across the phasic and tonic components of this sleep stage and depends on the type of stimulus. Since REM sleep and S2 predominate in the later hours, the probability of an awakening is higher in the second half of the night than in the first. In addition, the results showed that noise-induced awakenings replaced spontaneous awakenings, but this does not apply to arousals.

In contrast to the event-related lightening of NREMS in the EEG spectrum, the lightening of sleep caused by transitions from deeper (SWS) to more superficial sleep stages (S2 or REM) showed no differences between the conditions. Therefore, the following secondary hypothesis could not be confirmed:

- The rate of lightening of sleep (i.e. the transition from S4 to S3, S2 or REM sleep and from S3 to S2 or REM sleep) in the Low-boom condition is greater than the rate of spontaneous lightening of sleep in the quiet control condition. Furthermore, the rate of lightening of sleep in the Low-boom condition is greater than in the Mach cut-off condition.

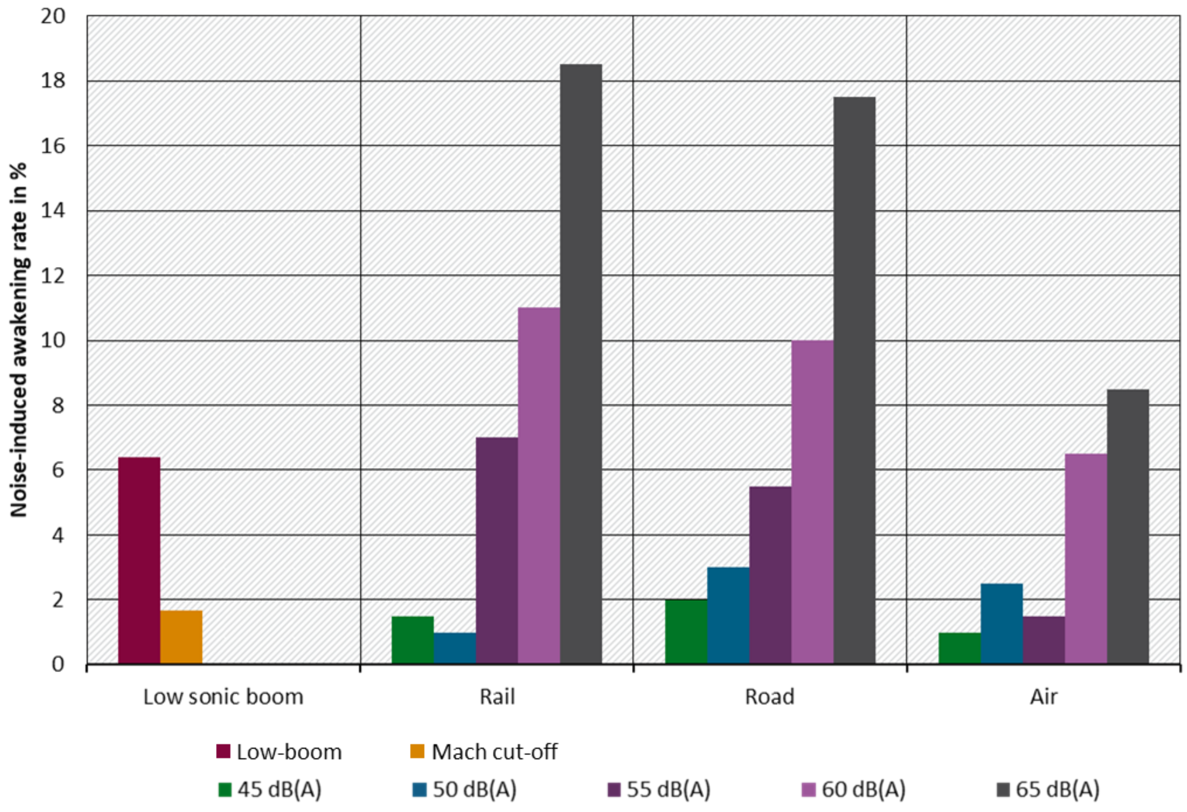
For the frequency of awakening following a sonic boom event, the noise-induced awakening rate (= noise-associated awakening rate – spontaneous awakening rate) was considered. Noise-induced awakenings can either replace the corresponding spontaneous changes of sleep that would have occurred at the same time or slightly later, or lead to an increase in their total number over the total night (i.e. lead to additional reactions). A higher total number of these activations leads to a general increase in the level of arousal and can thus disrupt the natural course of deep sleep (SWS, deep sleep) and/or REM sleep (Basner, Griefahn, van den Berg 2010).

In order to classify the effects of nocturnal sonic booms on sleep, a comparison was made with the effects of other transport modes. As in the present study, the participants in the comparative studies likewise were healthy adults with normal hearing ability according to their age. The age range of the participants included in the laboratory and field studies ranged from 18-61 years with M= 29.1 and SD = 11.7 (Sanok et al. 2022) to 18-77 years with M = 44.1 and SD = 16.1 (Elmenhorst et al. 2024).

The mean noise-induced awakening rate for low-boom events was 6.4%. In order to achieve a similarly high awakening rate for subsonic, conventional aircraft noise in laboratory studies, a maximum sound pressure level ($L_{AS,max}$) of ~60 dB is required , whereby the maximum level refers to the level close to the ear of the participant lying in bed. For rail noise, the corresponding level was around 55 dB(A) and for road noise between 55 and 60 dB(A) (Basner, Müller & Elmenhorst 2011).

For a rough classification, Figure 49 shows the noise-induced awakening rates of low-boom and Mach cut-off events in comparison to conventional transport modes (rail, road, air). The awakening rates identified in the study by Basner, Müller and Elmenhorst (2011) at sound pressure levels of 45 and 65 dB(A) serve as comparative values. As no continuous exposure-response curve was published in the study by Basner, Müller and Elmenhorst (2011), only level ranges could be estimated.

Figure 49: Comparison of awakening rates caused by sonic booms with noise from conventional transport modes



Note: The figure shows a comparison of the awakening rate caused by low-boom and Mach cut-off events with the awakening rate caused by rail, road and air traffic, based on a laboratory study by Basner, Müller and Elmenhorst (2011). Own visualisation, DLR.

Field studies show a trend for higher maximum levels needed to evoke awakenings, i.e. participants in the field tended to be slightly less sensitive to traffic noise in their home environment. For aircraft noise, field studies found levels between 60 (Basner & McGuire 2018) and 63 dB(A) (Elmenhorst et al. 2024; Müller 2021) and for rail noise 58 dB(A) (Basner & McGuire 2018). For road traffic noise, the required level varied between 58 dB(A) (Basner & McGuire 2018) and no longer detectable (Sanok et al. 2022).

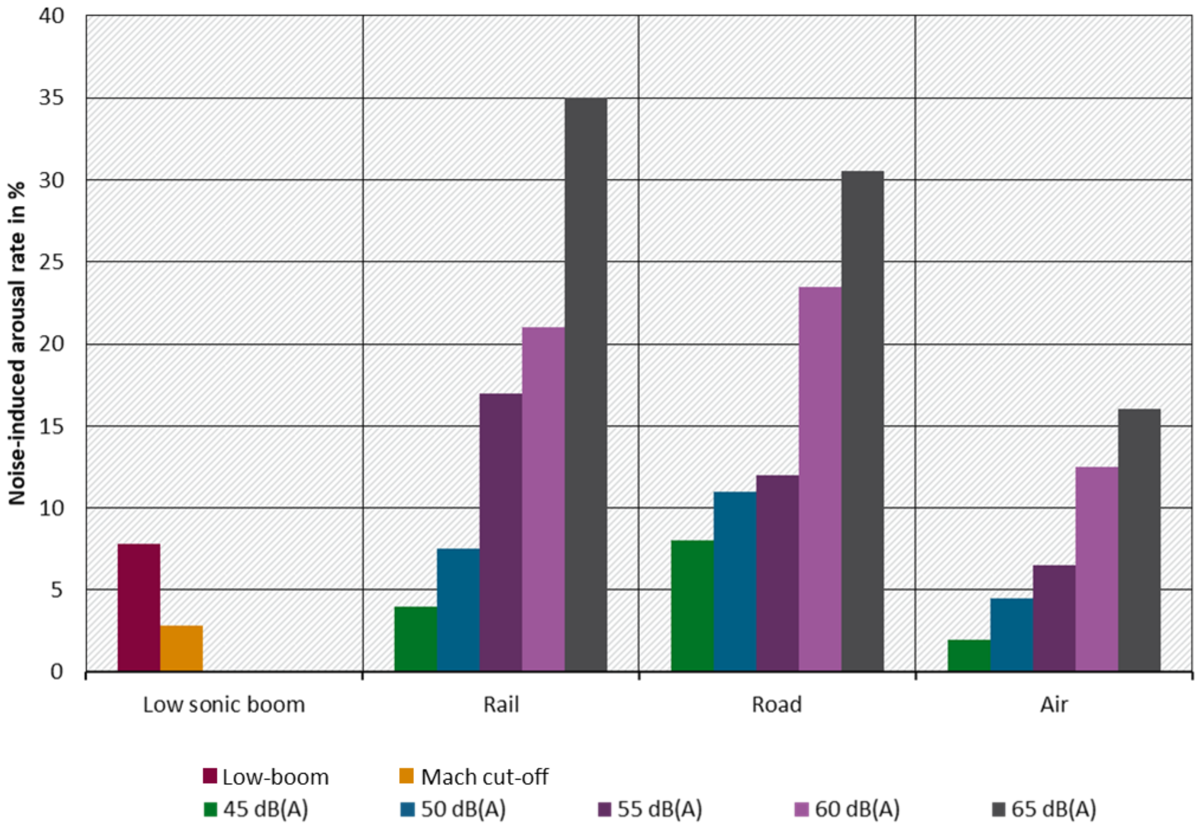
The noise-induced awakening rate was significantly lower at 1.7% for Mach cut-off events, which is reflected in the maximum levels of conventional transport modes required for a similarly high awakening rate. In a laboratory study, the awakening rate of 1.7% was already exceeded for aircraft and road noise at a level of 50 dB, while for rail noise the corresponding level was between 50 and 55 dB(A) (Basner, Müller and Elmenhorst 2011). In field studies, a comparably high noise-induced awakening rate was found for aircraft noise levels between 40 (Elmenhorst et al. 2024) and 45 dB(A) (Basner & McGuire 2018), 41 dB(A) for rail noise and between 44 (Basner & McGuire 2018) and 64 dB(A) (Sanok et al. 2022) for road traffic noise.

In addition to noise-induced awakenings, arousals are considered as a second parameter of sleep fragmentation. The laboratory study by Basner, Müller and Elmenhorst (2011) was used as a basis for comparison. In this study, just like in the present study, the effects of individual traffic noise events on the frequency of arousals were quantified. Taking into account the spontaneous arousal rate in the control condition, the present study found a mean noise-induced arousal rate of 7.8% for the Low-boom condition. In the laboratory study by Basner, Müller and Elmenhorst (2011), comparable rates occurred for railway noise at maximum levels of 50 dB(A). For road traffic noise, the arousal rate of 7.8% was already reached at a maximum level of 45 dB(A) whilst for aircraft noise, the maximum levels required for a comparable rate were between 55 and 60 dB(A).

The arousal rate in the Mach cut-off condition was 2.8% in the present study. A corresponding rate was exceeded in the laboratory study by Basner, Müller and Elmenhorst (2011) for rail and road traffic noise even at the lowest levels of 45 dB(A), whereas for aircraft noise, maximum levels between 45 and 50 dB(A) were required.

Figure 50 shows a rough classification of the noise-induced arousal rates of low-boom and Mach cut-off events compared to conventional transport modes (Basner, Müller and Elmenhorst 2011).

Figure 50: Comparison of the arousal rate caused by sonic booms with noise from conventional transport modes



Note: The figure shows a comparison of the arousal rate caused by low-boom and Mach cut-off events with the arousal rate caused by rail, road and air traffic based on a laboratory study by Basner, Müller and Elmenhorst (2011). Own visualisation, DLR.

Noise protection concepts for Frankfurt, Leipzig/Halle and Zurich airports have already been derived on the basis of event-related awakening probabilities (Basner, Isermann & Samel 2006; Brink et al. 2010). These are based on probabilities of awakenings up due to single noise events, as also applied in the present study for low-boom events. The effect of low-boom events on the awakening probability is comparatively lower than that of conventional aircraft noise events. However, the number of people affected would be greater, as the sonic boom would occur throughout the entire flight at supersonic speed and would expose a large area (~40 km on both sides) below the flight path. Noise exposure from conventional aircraft affects people living near airports since aircraft fly at low altitude in these areas and the highest noise emissions are generated during take-off and landing. The noise-induced awakening rate of 6.4% found in this study would mean that approximately 16 flyovers by low-boom aircraft travelling at supersonic speeds per night could evoke one noise-induced awakening. However, it must be taken into account that the effects found in laboratory studies are somewhat overestimated due to poorer sleep quality compared to field studies. In addition, the results are only partially transferable to the general population, as only healthy participants with normal hearing ability according to their age were examined in this study. The influence of age and gender was considered as covariates, but did not show any effect. The present study did not take into account additional exposures caused by sonic booms, such as rattle and vibration, which are very likely to have greater effects than noise exposure alone.

3.10 Results of physiological measurements while awake

3.10.1 Heart rate variability

An overview of the descriptive statistics of the individual HRV parameters in the three conditions can be found in Table 14. The analyses using LLM showed no significant effect of the condition on the HRV parameters (all p > 0.05).

Table 14: Mean and standard error of heart rate variability (HRV) for the three conditions

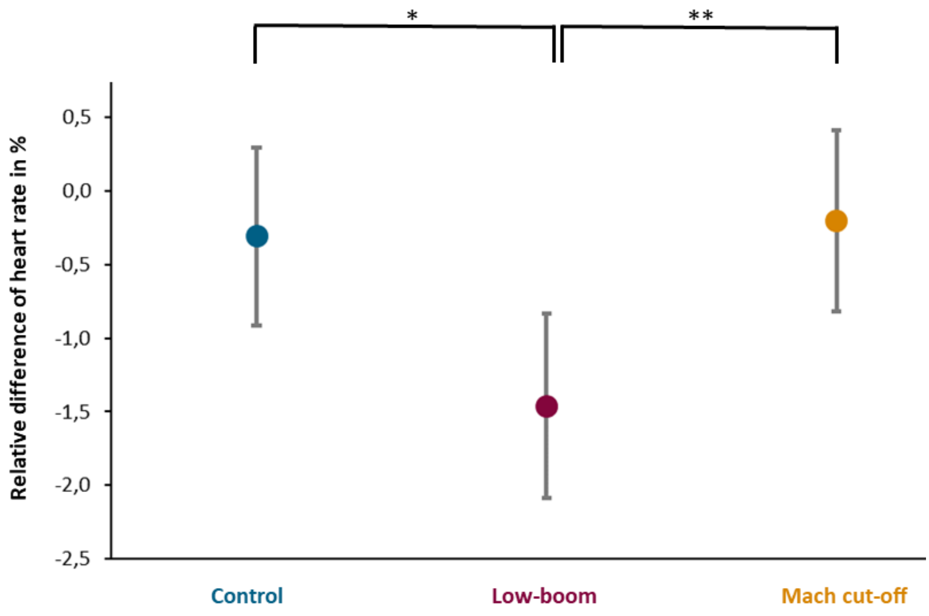
HRV parameter	Control M (SE)	Low-boom M (SE)	Mach cut-off M (SE)
Averaged RR interval (ms)	910,89 (18,08)	914,96 (19,15)	907,90 (17,45)
SDNN (ms)	44,17 (2,86)	46,62 (2,71)	46,26 (2,66)
RMSSD (ms)	40,58 (3,08)	41,32 (2,95)	40,10 (2,76)
VLF (ms^2)	162,88 (21,93)	208,88 (31,48)	196,43 (22,30)
LF (ms^2)	1146,60 (181,04)	1256,38 (203,42)	1292,65 (218,67)
HF (ms^2)	807,85 (141,67)	821,75 (123,70)	773,14 (126,13)
LF/HF ratio (%)	2,03 (0,24)	2,41 (0,35)	2,44 (0,29)

Note: N = 36.

3.10.2 Heart rate

Surprisingly, the analyses of heart rate showed negative relative difference values for all conditions. Negative difference values indicate that the heart rate was higher prior to the noise events than after the noise events. Figure 51 displays the percentage change in heart rate, determined by the difference between the 10-second averaged heart rate prior to the noise events and the 10-second averaged heart rate after the noise events. The LMM and subsequent pairwise comparisons showed a significantly higher difference for the Low-boom condition compared to the control (MDiff = 1.666; 95% CI [0.026; 3.307]; p = 0.030) and Mach cut-off condition (MDiff = 1.736; 95% CI [0.352; 3.119]; p = 0.008). Compared to the control condition with a reduction of 0.3% (SE = 0.41) and the Mach cut-off condition with 0.2% (SE = 0.44), the heart rate decreased by an average of ~2% (SE = 0.45) immediately after a low boom event. In the Low-boom condition, the heart rate averaged over 10 seconds was 67.42 bpm and decreased to a heart rate of 65.96 bpm averaged over the 10 seconds after the noise event.

Figure 51: Percentage change in heart rate after the noise events for each condition

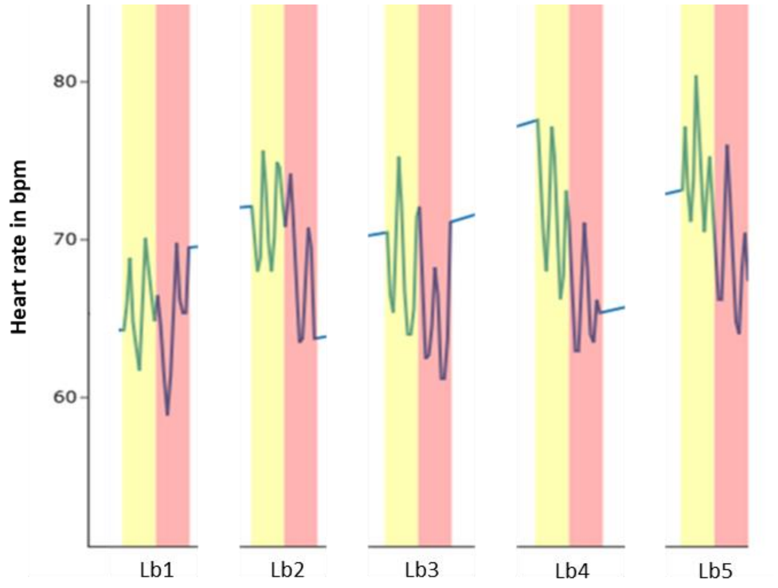


Note: Difference between the heart rate averaged over 10 seconds prior to the noise events and the averaged heart rate over the 10 seconds after the noise events. The dots represent the averaged difference in heart rate across all participants, and the error bars represent the 95% confidence interval. Missing values for one participant resulted in N = 36 for the Mach cut-off condition and N = 37 for the control and Low-boom condition, **p < 0.01, *p < 0.05, source: own visualisation, DLR.

Figure 52 shows a representative heart rate curve for a participant in the Low-boom condition, showing a decrease in heart rate immediately after the noise events.

The inclusion of additional factors (age, gender, order of conditions, position of noise events) to the raw model did not improve the AIC and showed no significant correlation with the heart rate (p > 0.05).

Figure 52: Example of the heart rate curve during the playback of low-boom events

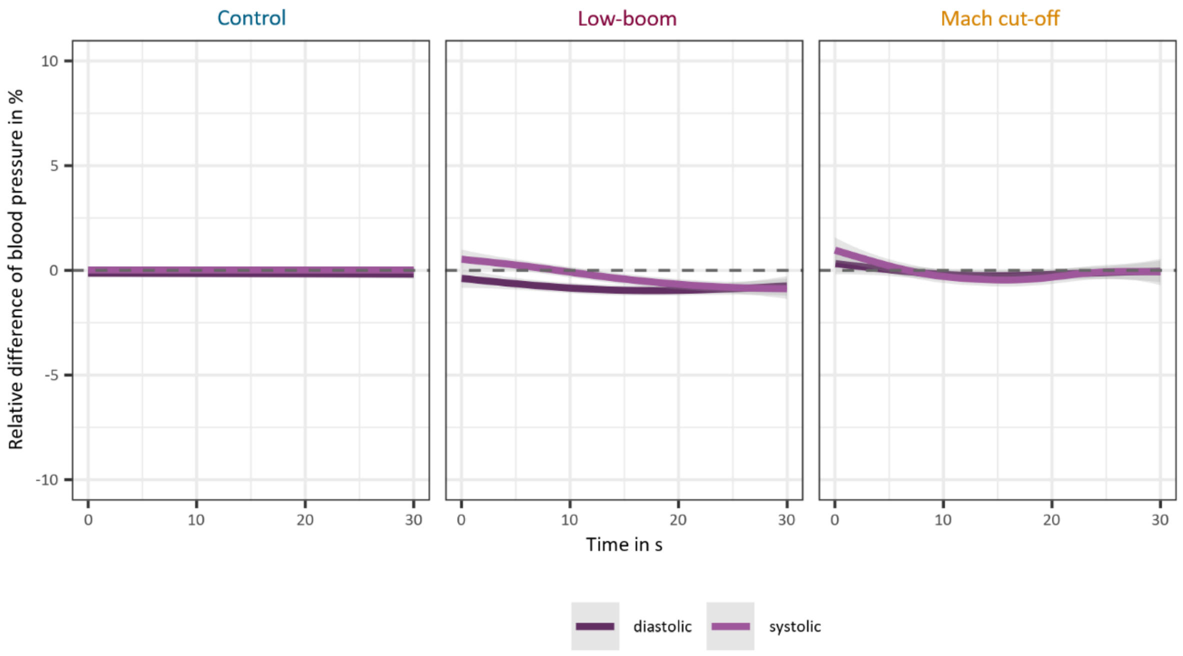


Note: Lb1 to Lb5 represent the five low-boom events played back. The yellow area represents the heart rate 10 seconds prior to the noise event and the red area represents the heart rate 10 seconds after the noise event. Source: own visualisation, DLR.

3.10.3 Blood pressure

The analysis showed that the relative differences between the conditions did not differ significantly ($p > 0.05$). Figure 53 shows the percentage change in diastolic and systolic blood pressure as the difference between the blood pressure averaged over 30 seconds prior to the noise events and the blood pressure values in the 30 seconds after the noise events.

Figure 53: Percentage change in blood pressure after the noise events for each condition



Note: Difference between the blood pressure averaged over 30 seconds prior to the noise events and the blood pressure values in the 30 seconds after the noise events. The black line represents the blood pressure averaged over 30 seconds prior to the noise events. The grey area represents the 95% confidence interval. N = 21, s = seconds, source: own visualisation, DLR.

3.11 Conclusion based on the results of physiological measurements while awake

The examination of HRV makes it possible to determine whether and how the autonomic nervous system is affected by noise. Even in healthy people, there are large interindividual differences and gender-specific differences in HRV, which also change with age (Nunan, Sanderock & Brodie 2010; Bonnemeier et al. 2003). HRV is also influenced by breathing, the baroreceptor reflex, changes in vascular tone and the endocrine system (Shaffer & Ginsberg 2017). Normal values for healthy individuals therefore vary widely. Based on a systematic review, Nunan, Sanderock and Brodie (2010) provided standard values for some HRV parameters from short-term measurements (measurements over ~5 min.) (mean values, range min - max: IBI (ms) 926, 785 – 1160; SDNN (ms) 50, 32–93; RMSSD (ms), 42, 19–75; LF (ms2) 519, 193–1009; HF (ms2) 657, 83–3630; LF/HF ratio 2.8, 1.1 – 11.6). In the present study, with the exception of the LF values, which exceeded the specified range in all conditions, all HRV values were within the normal range. None of the HRV parameters showed significant differences between conditions. Some other studies investigating the effect of noise on HRV also found no significant effects (e.g. Manohare et al. 2022; Veternik et al. 2018; Stockfelt et al. 2022; Alves et al. 2018).

The results of the heart rate analysis were surprising. While the heart rate did not change prior and after a (supposed) noise event in the control and in the Mach cut-off condition, the heart rate initially decreased after a low-boom event. Although these results were unexpected, they can be explained. Noise triggers both a direct (i.e. via subcortical connections in the brain) and an indirect (i.e. via transmission of sensory information from the auditory thalamus to the auditory cortex) stress response. This disrupts the balance of the autonomic nervous system (ANS) due to increased activity in the sympathetic nervous system branch and decreased activity in the parasympathetic nervous system branch, both of which control everyday fluctuations in heart rate (Eriksson, Pershagen & Nilsson 2019). Increased sympathetic control leads to a slow (~5 s delay) increase in heart rate (Draghici & Taylor 2016), while increased parasympathetic control leads to a rapid (within milliseconds) decrease in heart rate (Glick, Braunwald & Lewis 1965). In a laboratory study, Shoushtarian et al. (2019) investigated the relationship between short-term noise exposure and acute cardiovascular responses. They found that short noise events (18 s) at 15 and 40 dB(A) led to a reduction in heart rate compared to baseline, while noise events at 65 and 90 dB(A) led to a significant increase in heart rate. Similarly to the present study, the mean heart rate decreased by 1.6% from baseline at a noise level of 15 dBA. Shoushtarian et al. (2019) interpreted this as a consequence of a rapid orientation response triggered by the onset of low-intensity noise (Graham & Clifton 1966). While defensive and startle responses occur in response to intense stimuli and are a protective reflex associated with pain sensations, the orientation response increases sensitivity when listening and facilitates the absorption of sensory information. The latter has been shown to occur in response to any detectable change, including the onset or end of a stimulus (Smith & Strawbridge 1969). The results suggest that, due to their characteristics, the low-boom events did not lead to startle and defence responses while the participants were awake, but rather to an activation of attention. In addition, participants were aware that the study focused on the impacts of environmental noise and anticipated hearing noise events.

With regard to systolic and diastolic blood pressure, the present study showed no significant differences between the conditions while participants were awake. The results of a study by Manohare et al. (2022) suggest that startle responses and thus a decrease in heart rate variability and an increase in heart rate are more likely to be associated with loud stimuli such as loud, abrupt honking. The sonic booms played in the present study are more comparable to the dull slamming of a door and do not appear to have caused any detectable startle responses.

Based on the present results, the following secondary hypotheses could not be confirmed:

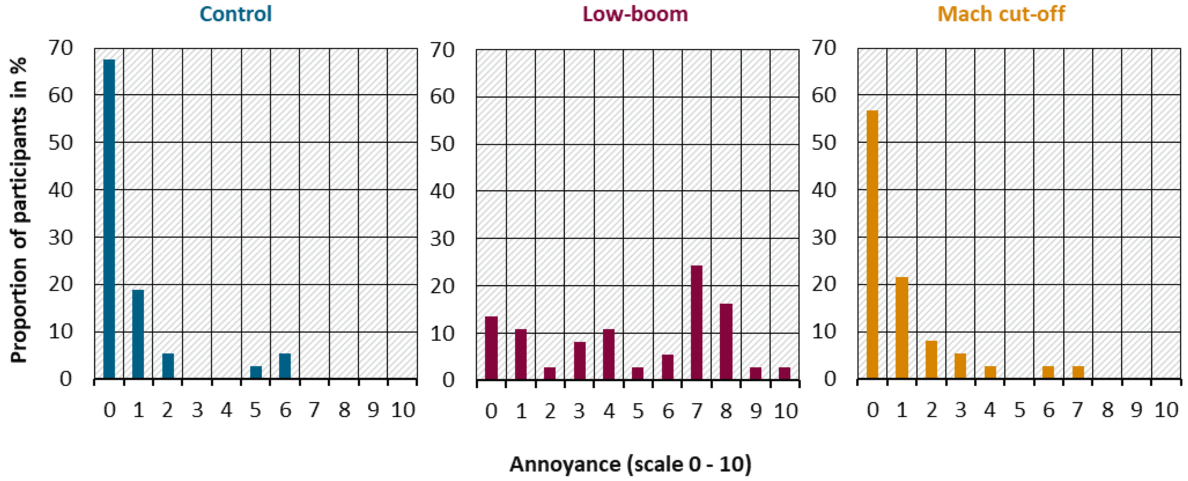
- The heart rate variability while awake is lower when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the heart rate variability while awake is lower during the playback of low-boom signals than during the playback of Mach cut-off signals.
- The heart rate while awake is higher when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the heart rate while awake is higher during the playback of low-boom signals than during the playback of Mach cut-off signals.
- The blood pressure while awake is higher when low-boom signals are played back than in a control period of equal length without noise. Furthermore, the blood pressure while awake is higher during the playback of low-boom signals than during the playback of Mach cut-off signals.

3.12 Results of subjective assessment

3.12.1 Short-term annoyance

Figure 54 shows the distribution of the short-term annoyance rate for the three different conditions. While in the control and Mach cut-off conditions the majority of participants stated that they were not annoyed (0) and the maximum values were 6 (Control) and 7 (Mach cut-off) on the scale from 0 to 10, the responses in the Low-boom condition were distributed across the entire scale.

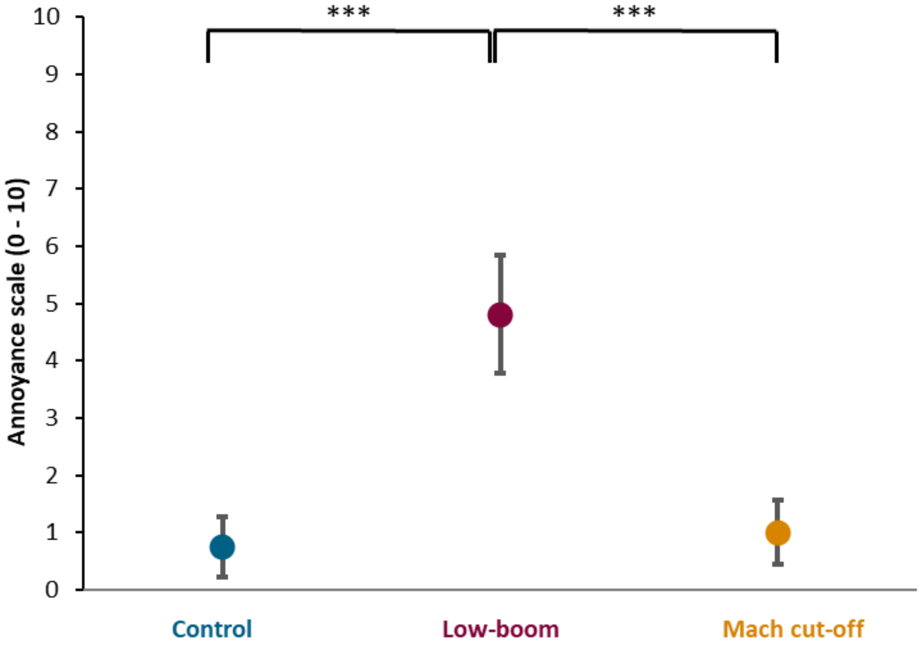
Figure 54: Percentage distribution of short-term annoyance for the three conditions



Note: N = 37, source: own visualisation, DLR.

Figure 55 illustrates the effect of the condition on short-term annoyance and shows the mean values for each condition. Averaged across the sample, the highest annoyance was caused by the Low-boom condition with a value of 4.8 (SE = 0.51) on the scale from 0 to 10, followed by the Mach cut-off condition with 1.0 (SE = 0.28) and the control condition with a rating of 0.8 (SE = 0.26). The LLM and subsequent pairwise comparisons showed that the Low-boom condition differed significantly from the control (MDiff = 4.054; 95% CI [2.974; 5.134]) and the Mach cut-off condition (MDiff = 3.811; 95% CI [2.803; 4.819]) (both $p < 0.001$).

Figure 55: Effect of condition on short-term annoyance



Note: The dots represent the averaged annoyance across all participants and error bars represent the 95% confidence interval, N = 37, ***p < 0.001, source: own visualisation, DLR.

Based on the raw model, the best model fit was obtained by adding control and coping capacity (capacity to cope with noise and perceived control over noise) and adaptation capacity (general capacity to adapt to noise) as relevant factors alongside the condition to explain the variance in annoyance ratings (Table 15). A low self-assessed ability to cope with noise and to habituate to noise was associated with higher annoyance. Although subjective sleep quality correlated significantly with short-term annoyance, it did not contribute to improving the model quality.

Table 15: Linear mixed model for short-term annoyance depending on condition

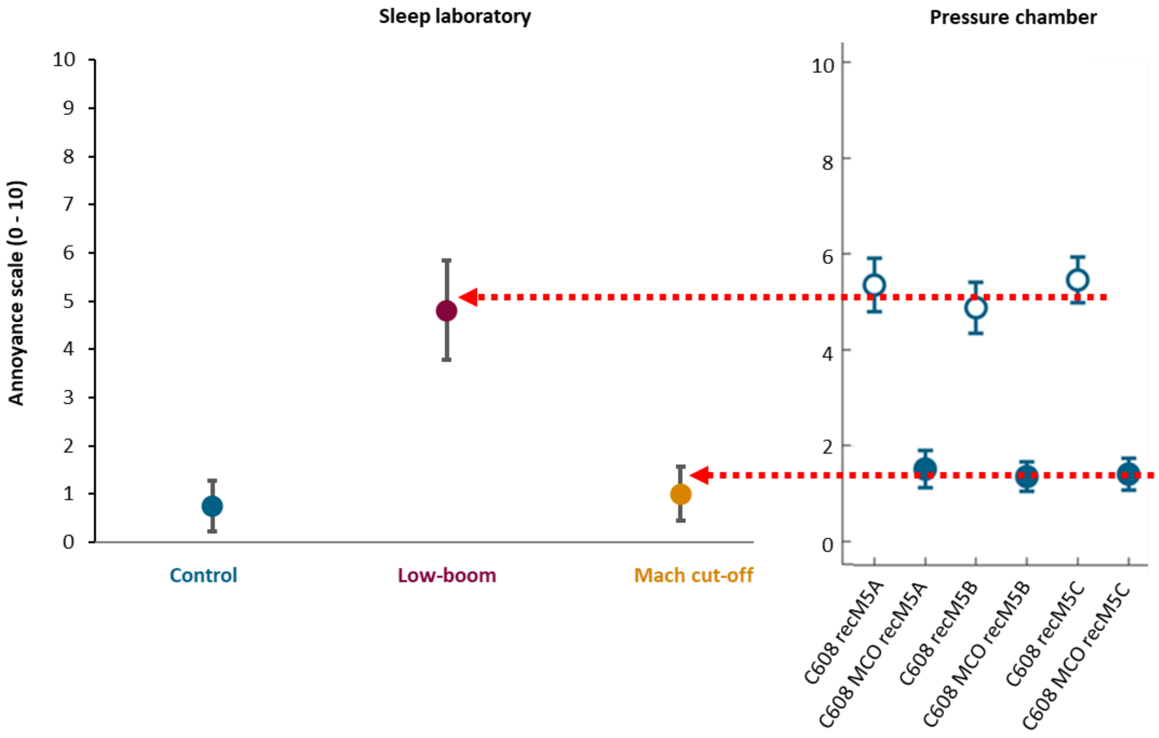
Parameter	Estimator (SE)	p-value	AIC after addition
Intercept	5.779 (1.285)	<0.001***	
Condition: Control	Reference	Reference	489
Condition: Low-boom	4.054 (0.450)	<0.001***	
Condition: Mach cut-off	0.243 (0.450)	0.590	
Control and coping capacity	-0.147 (0.053)	0.010	481
Adaptation capacity	-0.605 (0.350)	0.092	478

Note: Linear mixed model with random intercept, ***p < 0.001, *p < 0.05, SE = standard error, N = 37.

An LMM with the elapsed days in the study (study days 1 to 3) as the independent variable showed that annoyance after the first night was significantly lower in comparison to the second night (MDiff = 2.108; 95% CI (0.683; 3.533) and the third night (MDiff = 2.189; 95% CI (0.662; 3.715)) (both p = 0.003). There was no difference in annoyance between the second and third night. Since the first night was the control condition, these results are consistent with our expectations. The results suggest that the randomisation of the two noise conditions (Low-boom, Mach cut-off) was successful and thus avoided a sequence effect. Noise annoyance did not increase with increasing duration of noise exposure.

In the listening experiment at the University of Oldenburg, just like in the sleep study, the short-term annoyance of the 16 signals was assessed using an 11-point categorical scale from 0 to 10 (0 = "not at all" to 10 = "extremely", Fields et al. 2001). Figure 56 shows the mean values of the annoyance ratings for the 40 Low-boom (C608) and Mach cut-off signatures (C608 MCO) played back during the night in the sleep laboratory of the German Aerospace Center (left) and the mean values of the annoyance ratings for the recordings of the signatures played back in the three rooms of the sleep laboratory (A, B, C) collected in the pressure chamber of the University of Oldenburg (right). A direct comparison shows that, despite the different laboratory settings (sleep laboratory versus pressure chamber), the mean values were similar: the annoyance rating for the Low-boom condition in the sleep laboratory was on average around 4.8 and the annoyance rating for the C608 recordings was around 5.3; the annoyance rating for the Mach cut-off condition in the sleep laboratory was 1.0 and the annoyance rating for the C608 Mach cut-off recording was around 1.4.

Figure 56: Comparison of the short-term annoyance mean values for the low-boom and Mach cut-off signatures in the sleep laboratory and in the pressure chamber



Note: left: short-term annoyance for the low-boom (C608) and Mach cut-off signatures (C608 MCO) played back in the sleep laboratory of the German Aerospace Center. The dots represent the averaged annoyance across all participants and the error bars represent the 95% confidence interval, ***p < 0.001, N = 37; right: short-term annoyance ratings for the recordings (recM5) of the three rooms of the sleep laboratory (A, B, C) played back in the pressure chamber at the University of Oldenburg. The dots represent the averaged annoyance across all participants and the error bars represent the standard error, N = 19; source: own visualisation, DLR.

3.12.2 Self-assessed sleep quality and morning sleepiness

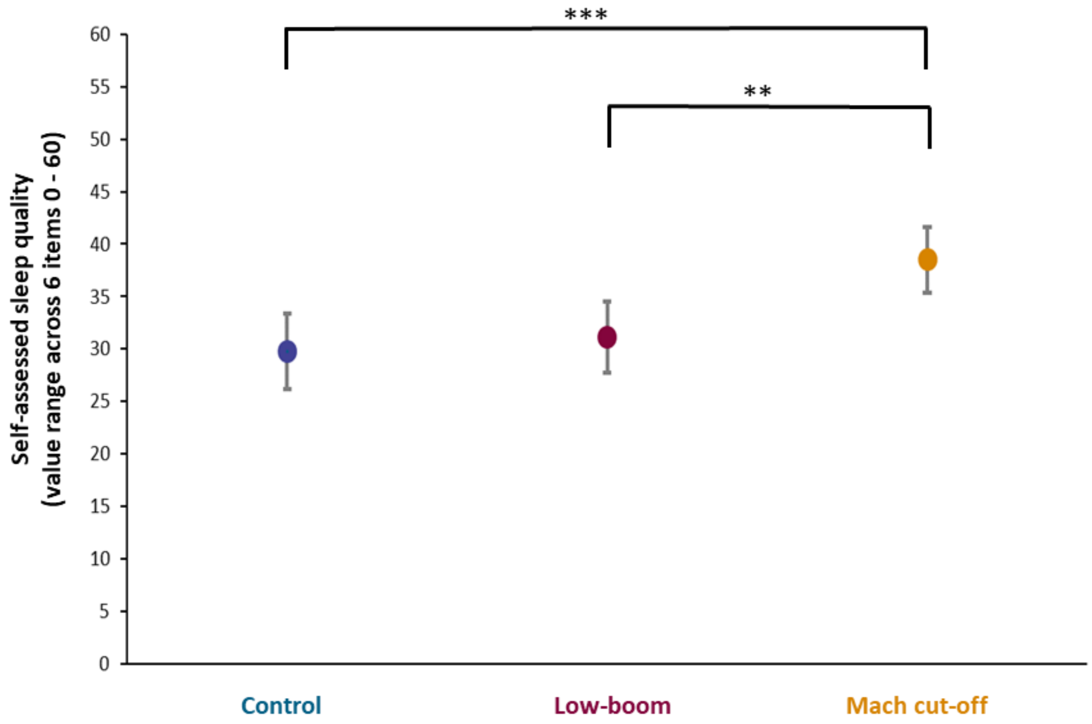
To provide a clearer visualisation of the distribution of self-assessed sleep quality for the three conditions, the data was divided into three percentiles: poor (6–29), moderate (30–38) and good (39–58) sleep quality (Figure 57). A larger proportion of 43.2% of participants reported poor sleep quality after the Low-boom condition. After the Mach cut-off condition, sleep quality was predominantly rated as good by 48.7%. Surprisingly, within the control condition and across the three conditions, the highest proportion of participants (48.7%) rated their sleep as poor.

Figure 57: Percentage distribution of self-assessed sleep quality divided into three percentiles for the three conditions

Note: N = 37, SQ = sleep quality, source: own visualisation, DLR.

Figure 58 shows the effect of the condition on self-assessed sleep quality and the mean values. Averaged across the sample, the control condition yielded the lowest value of 29.8 (SE = 1.77) on a scale from 0 to 60, surprisingly indicating the poorest assessment of sleep quality. This was followed by the Low-boom condition with a value of 31.1 (SE = 1.68) and the Mach-off condition with the highest value of 38.5 (SE = 1.54). Deriving the raw model by using LMM, no significant difference was observed between the Low-boom and control condition. However, a significant difference was detected between the Mach cut-off and control condition. Additionally, there was a significant difference between the Low-boom and Mach cut-off condition. The pairwise comparisons to the Mach cut-off condition showed that sleep quality was significantly worse after the control condition (MDiff = 8.730; 95% CI (3.726; 13.734); $p < 0.001$) and the Low-boom condition (MDiff = 7.351; 95% CI (2.681; 12.021); $p = 0.002$).

Figure 58: Effect of condition on self-assessed sleep quality



Note: The dots represent the averaged self-assessed sleep quality across all participants and the error bars represent the 95% confidence interval. N = 37, *** = p < 0.001, ** = p < 0.01, source: own visualisation, DLR.

The best model fit was achieved by adding self-assessed difficulties falling asleep and maintain sleep due to polysomnography and/or the laboratory environment (*sleep disturbance due to setting*) (Table 16). Poor sleep quality correlated with reports of feeling disturbed by polysomnography and/or the laboratory setting.

Table 16: Linear mixed linear model for self-assessed sleep quality depending on condition

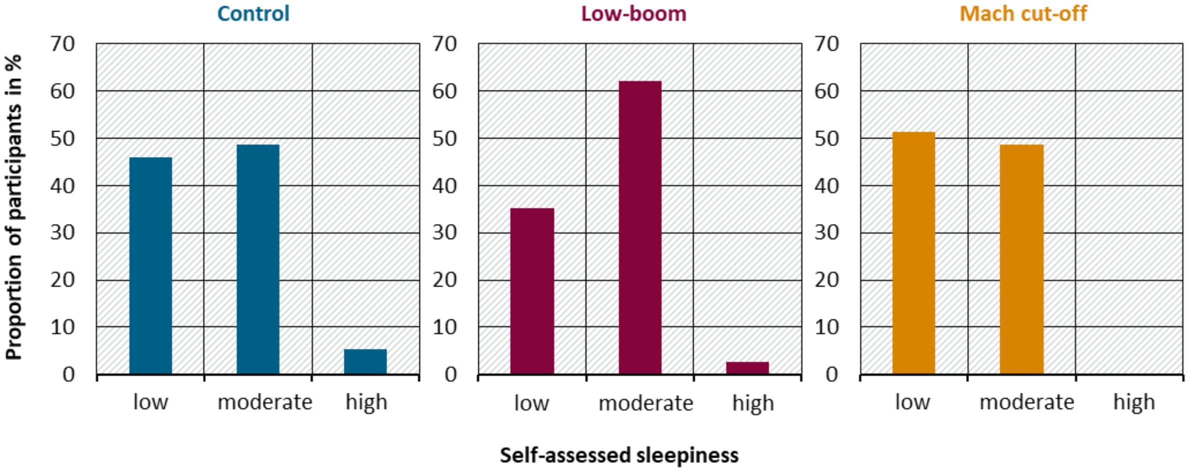
Parameter	Estimator (SE)	p-value	AIC after addition
Intercept	31.131 (1.720)	<0.001***	
Condition: Control	Reference	Reference	817
Condition: Low-boom	1.226 (2.058)	0.553	
Condition: Mach cut-off	8.577 (2.058)	<0.001***	
Sleep disturbance due to setting: no	Reference	Reference	808
Sleep disturbance due to setting: yes	-5.649 (2.343)	0.018	

Note: Linear mixed model with random intercept, N = 37, *** = p < 0.001, * = p < 0.05, SE = standard error.

An LMM with the elapsed days in the study (study days 1 to 3) as the independent variable showed that showed that sleep quality after the first night was rated significantly worse than after the third night (MDiff = 6.351; 95% CI (0.982; 11.720); p = 0.018). However, there was no difference in the assessment of sleep quality between the second and third nights (p > 0.05).

According to Akerstedt and Gillberg (1990), KSS values > 7 indicate high sleepiness and values < 4 indicate low sleepiness. Therefore, the data on self-assessed morning sleepiness were divided into three groups: low (1–3), moderate (4–7) and high (8–9) sleepiness. Figure 59 shows that, after the control condition, sleepiness was rated as low (46%) and moderate (48.7%) in almost equal proportions and as high in a proportion of 5.1%. After the Low-boom condition, the majority of participants (62.2%) rated their sleepiness as moderate and a proportion of 2.7% as high. After the Mach cut-off condition, none of the participants rated their sleepiness as high, but in almost equal proportions (51.4%) as low and moderate (48,7%).

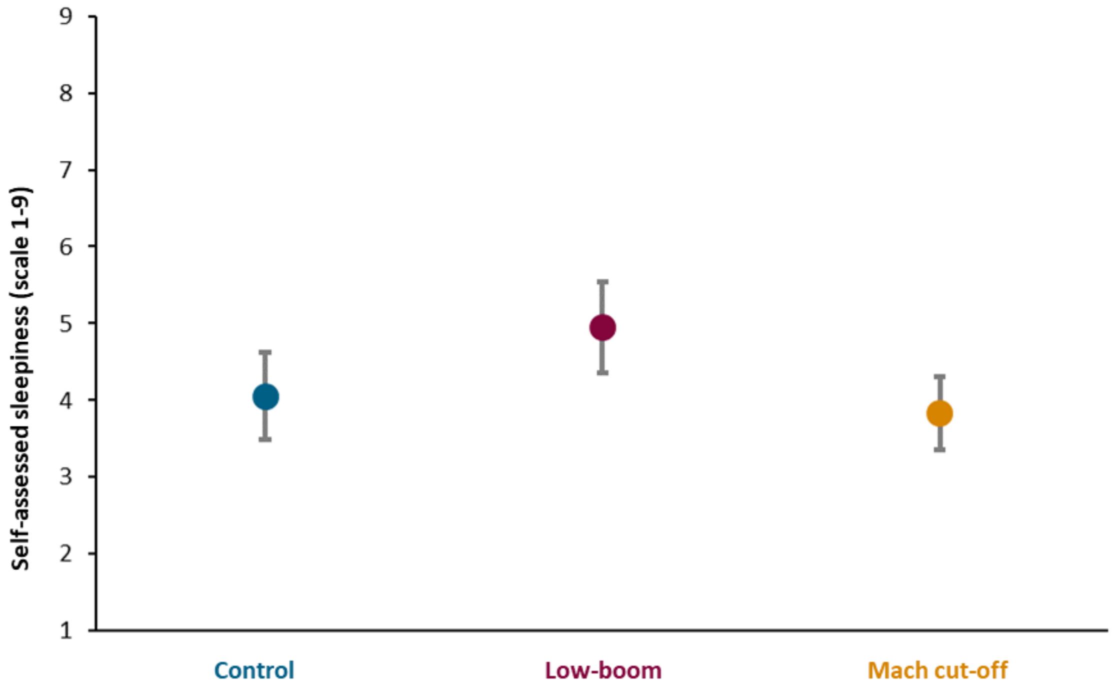
Figure 59: Percentage distribution of self-assessed sleepiness (KSS) divided into three groups for the three conditions



Note: N = 37, SQ = sleep quality, source: own visualisation, DLR.

Figure 60 shows the mean values for the three conditions. On a scale from 1 to 9, the highest self-assessed sleepiness was found for the Low-boom condition with a value of 5.0 (SE = 0.29), followed by the control condition with 4.1 (SE = 0.28) and the Mach cut-off condition with a value of 3.8 (SE = 0.23). The raw model and pairwise comparisons showed a significantly higher assessment of sleepiness after the Low-boom condition compared to the control (MDiff = 0.892; 95% CI [0.211; 1.573]; p = 0.008) and Mach cut-off condition (MDiff = 1.108; 95% CI [0.378; 1.838]; p = 0.003).

Figure 60: Effect of condition on self-assessed morning sleepiness (KSS)



Note: The dots represent the averaged self-assessed sleepiness across all participants and the error bars represent the 95% confidence interval. N = 37, ** = p < 0.01, source: own visualisation, DLR.

Based on the raw model, the iterative inclusion of the same potential predictors was tested as for the model for self-assessed sleep quality. Since self-assessed sleep quality showed a moderate correlation with sleepiness (r = 0.36, p < 0.001), it was also tested as a covariate and resulted in the highest model fit (Table 17). The poorer the participants' assessment of their sleep quality, the higher they rated their sleepiness. Although self-assessed sleep quality also correlated with the condition (see Table 16), critical collinearity could be ruled out (VIF < 10).

Table 17: Linear mixed model for self-assessed sleepiness (KSS) depending on the condition

Parameter	Estimator (SE)	p-value	AIC after addition
Intercept	5.749 (0.483)	<0.001***	
Condition: Control	Reference	Reference	415
Condition: Low-boom	0.970 (0.280)	0.001	
Condition: Mach cut-off	0.281 (0.304)	0.359	
Self-assessed sleep quality	-0.057 (0.014)	<0.001***	406

Note: Linear mixed model with random intercept, *** = p < 0.001, ** = p < 0.01, SE = standard error, N = 37.

3.13 Conclusion based on the results of the subjective assessment

The present results provide initial insights into the effects of sonic booms from future civil supersonic aircraft on short-term annoyance. In addition, the importance of non-acoustical factors in the assessment of annoyance is also highlighted in these new types of sonic booms. In this study, the self-assessed capacity to cope with noise and get adapted to it was found to be relevant to annoyance. These results are consistent with those from studies on other conventional traffic noise sources (Weidenfeld et al. 2021; Bartels et al. 2022; Guski 1999).

The following secondary hypothesis was confirmed by the results:

- The noise-induced short-term annoyance is higher after the Low-boom condition than after the quiet control condition. Furthermore, short-term annoyance is higher after the Low-boom condition than after the Mach cut-off condition.

Accordingly, the noise emissions of low-boom aircraft can cause moderate annoyance reactions, even if they are lower than those of conventional supersonic aircraft. The use of the noise-reducing Mach cut-off flight procedure during a flight over populated areas with a low-boom aircraft could, however, reduce annoyance reactions.

In addition, the results provide initial insights into the effects of low sonic booms on self-assessed sleep quality and sleepiness in the morning. Based on the results for short-term annoyance and the hypotheses established, it was expected that self-assessed sleep quality would be poorer following exposure to low-boom signals compared to the control condition and with no significant difference between the control and Mach cut-off condition. Instead, sleep quality was assessed to be similar after the Low-boom and the control condition, while a comparatively higher quality was stated after the Mach cut-off condition. A sequence effect may have contributed to the comparatively poor sleep quality in the control condition. While the two noise conditions were randomised, the control condition was always the first study night to avoid possible carry-over effects due to the noise effects on the following nights. Despite an adaptation night (test night) in the laboratory prior to the study nights, a sequence effect in terms of subjective sleep quality could not be completely ruled out. The present results are comparable to those of earlier studies (e.g. Akerstedt et al. 2002, Edinger et al. 2000), according to the difference between the objectively measured sleep quality and subjective assessment.

However, the results for the assessment of sleepiness did not reflect the results for self-assessed sleep quality. The Low-boom condition caused slightly increased sleepiness compared to the control and Mach cut-off condition. The addition of self-assessed sleep quality improved the model fit.

Based on the results, the following secondary sub-hypothesis could not be confirmed:

- Participants' self-assessed sleep quality is lower in the Low-boom condition than in the quiet control condition.

However, the following secondary sub-hypotheses could be confirmed:

- Participants' self-assessed sleep quality is lower in the Low-boom condition than in the Mach cut-off condition.
- Participants' self-assessed morning sleepiness is higher after the Low-boom condition than after the quiet control condition.
- Participants' self-assessed morning sleepiness is higher after the Low-boom condition than after the Mach cut-off condition.

It can be concluded that although noise emissions from low-boom aircraft will be lower than those from conventional supersonic aircraft, they still appear to cause slightly increased sleepiness in the morning. The use of the Mach cut-off flight procedure can mitigate the negative effect of sonic booms from future supersonic aircraft on self-assessed sleep quality.

4 Work package 3 – Development and application of acceptability criteria

The development and application of acceptability criteria involved the following steps:

1. Detailed research and evaluation of relevant national and international literature on noise impacts of civil supersonic flights;
2. monitoring ongoing national and international research activities on the topic;
3. Review and summarisation of the results of the sleep study (Chapters 3.7 to 3.12);
4. Based on this, the development of a proposal for criteria to assess the acceptability of sonic booms from future civil supersonic aircraft for the population in Europe.

4.1 Literature analysis

4.1.1 Literature analysis based on the concept of 'scoping reviews'

The planned detailed literature analysis was methodologically based on the approach of a 'scoping review' (von Elm, Schreiber & Haupt 2019). The steps involved in a scoping review are as follows (von Elm, Schreiber & Haupt 2019):

1. Objective, question(s) of the review;
2. Inclusion and exclusion criteria for literature selection;
3. Procedure for literature search (specialist databases, search strings);
4. Presentation of results:
    a) Literature selection: number/type of literature included, number of literature records excluded and reasons for exclusion,
    b) Information extracted from the included literature;
7. Summary of and conclusions drawn from the results.

4.1.2 Objective and research question of the literature analysis

The research question for the literature analysis in this project was formulated using the PEOS system (population, exposure, *outcomes* [effect target variables/results], study design) (Freiberg et al. 2019), which in turn is based on the PECO system (population, exposure, *comparator* [control condition], *outcomes)* (Morgan et al. 2018). In other words, the research question relates to the population to be studied, the exposure (type, intensity, characteristics, etc.), the effects to be considered and, finally, the study design and, where applicable, related minimum requirements.

The question, as classified by the PEOS, which guided the literature search in this project, is presented in Table 18.

Table 18: Question for the literature analysis broken down according to the PEOS classification (Freiberg et al. 2019)

Population	For which population (e.g., students, general population, employees/associates of [military] airfields) ...
Exposure	... does supersonic noise of future civil supersonic aircraft (low sonic booms) and the noise of supersonic overflights according to the Mach cut-off procedure ...
Outcome	... have which relevant noise effects at daytime and night-time ...
Study design	... and what study design (laboratory study, field experiment, simulation, etc.) was used to investigate this?

4.1.3 Inclusion and exclusion criteria for literature selection

In the next step, inclusion and exclusion criteria were defined for selecting the literature (see Table 19).

Table 19: Inclusion and exclusion criteria for literature selection

	Inclusion criteria	Exclusion criteria
Population	Humans (population, residents, students or university members, members of the army/aviation, military facilities, airfields)	Animals, buildings
Exposure	Low sonic boom signatures, (conventional) sonic boom signatures (so-called N-wave signatures), insofar as they are used (adapted) with regard to low sonic boom issues; Mach cut-off signatures, en-route supersonic flight noise	Other exposures, e.g., aircraft noise from aircraft flying at subsonic speeds, noise from LTO flights (LTO = landing, take-off operations), other noise sources, air pollutant emissions from supersonic aircraft
Outcomes	Sleep disturbances (self-reported, physiological), noise annoyance, activity disturbances, cognitive performance, physiological and psychological acute reactions (stress reactions, startle reactions), other noise effects relevant to supersonic noise	Building damage, monetary effects
Study design	Longitudinal study, cross-sectional study, laboratory study, laboratory experiment, field experiment, simulation study, review	

4.1.4 Literature search procedure (specialist databases, search strings)

For the literature analysis, the relevant literature was systematically researched in relevant bibliographic databases. The search focused on the topic of sonic booms and low sonic booms, as well as their effects, on the one hand, and on literature regarding the noise impact of Mach cut-off flights on the other. Searches were conducted for German and English literature using the following search terms:

- German: (Überschall **OR** Schall **OR** Mach **OR** X-59 **OR** LBFD[1]) **AND** (Flug **OR** Knall **OR** Betrieb **OR** Spur) **AND** (Belästigung **OR** Schlaf **OR** Störung **OR** kardio **OR** Herzkreislauf **OR** psychisch **OR** kognitiv **OR** Hör **OR** Reaktion **OR** Gesundheit **OR** Wahrnehmung **OR** Empfindung **OR** erschrecken)

- English: (low-sonic **OR** sonic **OR** supersonic **OR** low-boom **OR** Mach-Cut **OR** Mach cut **OR** X-59 **OR** LBFD) **AND** (flight **OR** boom **OR** thump **OR** operation **OR** aircraft **OR** signature) **AND** (annoyance **OR** sleep **OR** disturbance **OR** cardiovascular **OR** mental **OR** cognitive **OR** hearing **OR** reaction **OR** response **OR** health **OR** perception **OR** startle)

The search was conducted in the databases PsychINFO, Psyndex, and PubMed. In addition, the search was conducted in BASE (Bielefeld Academic Search Engine), which allows searching for "grey" literature (dissertations, research reports, conference proceedings).

The literature search also included reviewing conference proceedings from relevant scientific conferences (e.g., the American Sociological Association Annual Meetings, Euronoise, Forum Acusticum, International Congress on Acoustics, Congress of International Commission on Biological Effects of Noise, Inter-Noise). Another source of literature was the team's own extensive literature collection, which was built up in the course of working on relevant research projects (including the H2020 project RUMBLE; RegUlation and norM for low sonic Boom LEvels).

4.1.5 Literature selection and information extraction

The process of literature selection and analysis was based on relevant recommendations for conducting and documenting systematic reviews and meta-analyses. The PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) proved helpful in this regard (Moher et al. 2009). Figure 61 provides an overview of the literature identified according to the PRISMA statement.

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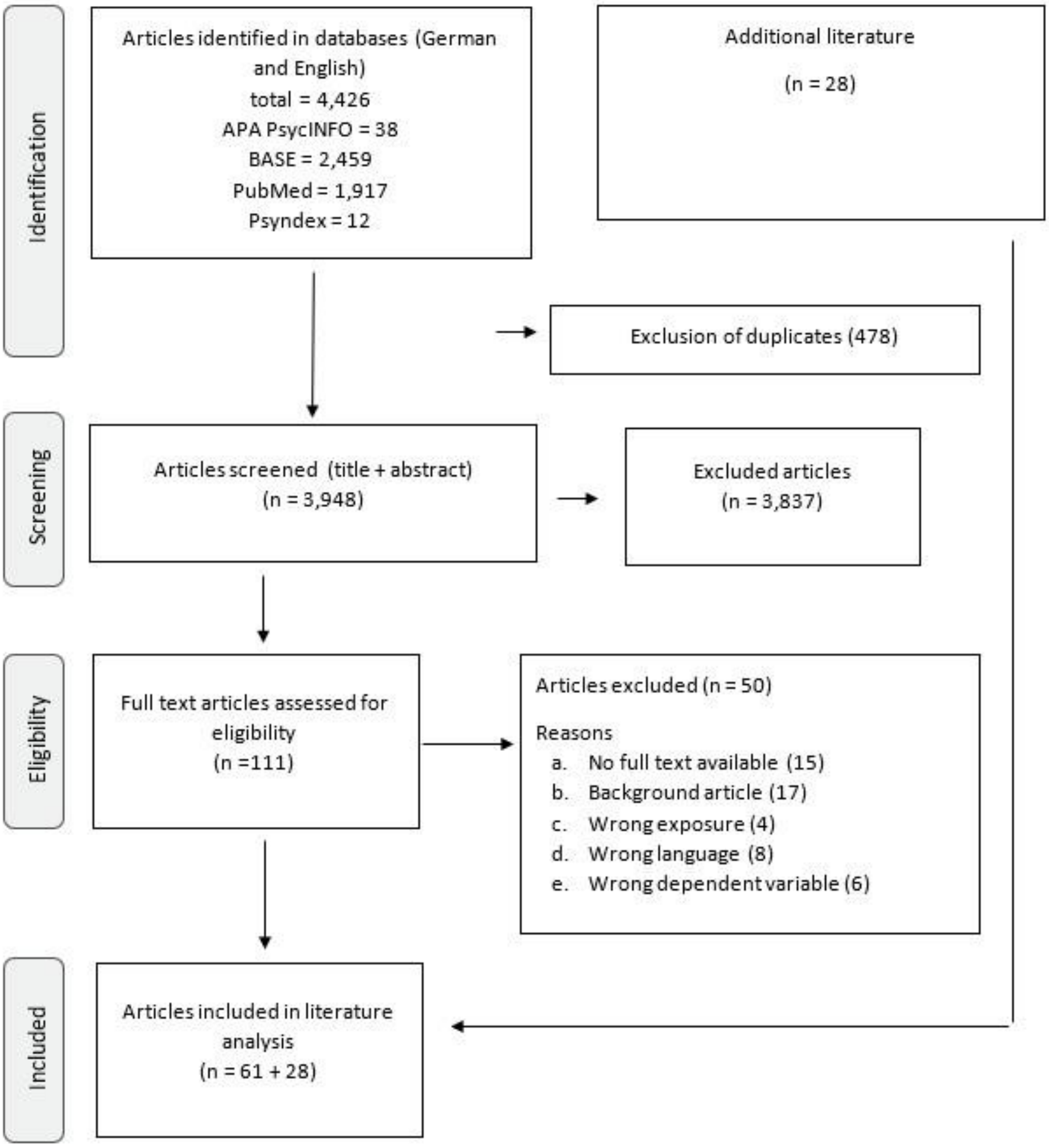
[1] LBFD = Low Boom Flight Demonstrator

Figure 61: Flow chart of the procedure for selecting literature in systematic literature searches according to PRISMA (Moher et al. 2009)



Note: Source: visualisation according to Moher et al. 2009

4.2 Consideration of recently completed and ongoing research

Internationally, various research groups are currently active in ongoing research projects or have recently completed research projects (see, among others, Etter & Coen 2016; Page & Loubeau 2019 for an overview). These include, among others:

- the 3-year EU Horizon 2020 project RUMBLE (https://rumble-project.eu/i/), completed in December 2020;
- the NASA (National Aeronautics and Space Administration) project QSF18 (Quiet Supersonic Flights 2018), published in 2020: a field study on the effect of low sonic boom noise generated by special flight manoeuvres of military jets on the population of Galveston, Texas, in the USA (Page et al. 2020; Fidell et al. 2020);

- NASA's ongoing research activities to develop and test the X59 low sonic boom demonstrator (https://www.nasa.gov/X59) and the planned future impact study (Community Response Survey);
- Research activities of the Aviation Sustainable Center (ASCENT) research consortium, also known as the Federal Aviation Administration Center of Excellence for Alternative Jet Fuels & Environment (https://ascent.aero) on Mach cut-off flights, their acoustic modelling and the perception of noise from Mach cut-off flights (https://ascent.aero/project/acoustical-model-of-mach-cut-off/; e.g., Sparrow & Vigeant 2019);
- the research activities of the Japanese aerospace research institution JAXA (Japan Aerospace Exploration Agency) on shaped booms (modified sonic booms) and the perception of and annoyance caused by these noises in laboratory studies (e.g., Veggeberg 2012; Naka 2013).

4.3 Results of the literature analysis

In 1947, the first human flew at supersonic speed (Maglieri et al. 2014). When military aircraft in the USA began flying at supersonic speeds more frequently, some residents reported hearing a loud bang. Although it was known that supersonic flights generate a shock wave, it was unexpected that this shock wave would reach the ground and produce an audible noise, known as a *sonic boom (*cf. von Gierke 1966).

Initial studies on the phenomenon of sonic booms investigated the direct effects of sonic booms on human physical health, such as their impact on hearing (Maglieri, Huckel, & Parrott, 1961). Only gradually were other possible effects of sonic booms investigated, such as noise annoyance, the startle effect and sleep disturbances. In addition to the noise of sonic booms, another important phenomenon is the rattling of objects or windows inside a house caused by the shock wave. In addition, noticeable tactile vibrations can occur at low frequencies. The effects of sonic booms, rattling and vibrations have therefore been investigated in numerous studies. For example, it was found that people who were inside a building during sonic booms were more annoyed than people who were outside (Nixon & Borsky 1966). One explanation for this is that the sound pressure wave causes rattling inside the house; this correlation was also observed with explosive noises (Schomer & Averbuch 1989). Due to rattling and vibrations, as well as the fact that sonic booms sound different outside a building than inside, a distinction is often made between sonic booms as heard inside a house or indoors and those heard outside a house or outdoors. Similarly, the effect can also be determined for both outdoor and indoor settings.

Earlier studies examined the effects of conventional sonic booms on humans. It was not until the turn of the millennium that studies were first conducted with simulated "low" sonic booms, i.e., sonic booms with lower amplitudes. Low sonic booms were intended to solve the problem of loud sonic booms. The International Civil Aviation Organisation (ICAO), affiliated with the United Nations (UN), pursues the goal of sustainably promoting international civil aviation and avoiding "unacceptable situations for the population caused by sonic booms from civil supersonic aircraft" (ICAO 2022, I-76).

It should be noted that in earlier studies, pressure levels were given in units such as pounds per square foot (psf, lb/sq ft) or millibars (mbar). For better comparability, these were converted to dB Sound Pressure Level (SPL) in this project. A total of 61 relevant publications were identified in the literature search, including 12 reviews. First, the reviews identified in the literature analysis are summarised, followed by individual publications on studies on noise annoyance, startle response and sleep disturbance. Finally, the results of other publications not found in the literature search but relevant to the research topic are also included and presented.

4.3.1 Reviews

At the Sonic Boom Symposium, von Gierke (1966) provided an overview of the studies conducted to date on the effects of sonic booms on humans. Early studies initially focused in particular on the direct physical effects of sonic booms on humans (e.g., Maglieri, Huckel & Parrott 1961; Guild 1962). In the "Little Boom" study, for example, 50 participants were exposed to supersonic flights of approximately 169 dB SPL (120 lb/sq ft) without experiencing any negative physical effects (Maglieri, Huckel, & Parrott 1961).

Another review provides an overview of laboratory studies on the psychological and physiological effects of sonic booms on humans (Kryter 1966). Kryter included laboratory studies on the loudness of sonic booms with different waveforms, the perception of sonic booms in comparison to other noise sources, startle responses and sleep. In summary, Kryter (1966) reports that the rise time of sonic booms influences the perceived loudness of the sonic boom: sonic booms with a shorter rise time are perceived as louder than sonic booms with a longer rise time; the duration of the sonic boom, on the other hand, appears to have no effect on the perception of loudness. Filtering out low frequencies below 40 Hz also had no effect on perceived loudness. Compared to noise from aircraft flying at subsonic speeds, sonic booms are perceived as less disturbing outdoors and more disturbing when the person is indoors, which can be explained by rattling and vibrations inside the house. Furthermore, evidence from the literature reviewed suggests that startle responses may decrease with repeated exposure to sonic booms (Kryter, 1966).

In a review published in 1972, Borsky summarised studies on the annoyance effect of sonic booms. The first major field study was conducted in St. Louis, USA, in 1961, involving the survey of approximately 1,300 people (see also Section 4.3.2). Another major noise impact study was conducted in Oklahoma City, USA, over a period of six months in 1964 (Borsky 1965). The study area was exposed to 1,253 sonic booms during the day (M = 129.17 dB SPL outdoor) during the study period, and surveys were conducted before, during and after the flight movements. During the course of the study, the overpressure of the sonic booms was increased: while the SPL averaged 128.64 dB during the first 11 weeks, it rose to 129.38 dB SPL during the following 8 weeks and to 131.66 dB SPL during the last 7 weeks. A total of 2,852 participants took part in all three surveys. Almost all participants reported disturbances due to vibrations and rattling caused by the sonic boom. Sonic booms-related startle reactions and anxiety were reported by 40% of participants living closer to the flight path (0 to ~13 km) and by 30% of participants living further away. In the third survey, i.e., after six months of exposure to sonic booms, 56% of participants reported high levels of annoyance, and 27% stated that they could not accept being exposed to sonic booms indefinitely. About one-fifth of the participants reported sleep disturbances caused by the sonic booms. It should be noted here that the noise exposure only took place during the day, so that the participants probably experienced sleep disturbance as difficulties falling asleep and/or maintain sleep. Vibrations and rattling were the most frequently mentioned undesirable side effects of sonic booms (94%). Due to the gradual increase in overpressure of the sonic booms, it was not possible to investigate any separate effects of the number and overpressure of the sonic booms (Borsky 1972). In France, a study involving 3,900 participants was conducted in 1970 (Brémond, 1971). Similarly, a study with approximately 3,000 participants was conducted in the United Kingdom in the same year (McKennell, 1971). In the French study, 5% of participants reported that sonic booms disturbed their sleep. Sixty-five per cent found night-time sonic booms unacceptable, and around 50% felt annoyed by them. As in the Oklahoma City study, French participants also cited rattling and vibrations as undesirable effects of sonic booms (72%). In the British study, about one-third of respondents reported being annoyed by sonic booms.

Von Gierke and Nixon (1972) identified various laboratory and field studies and summarised the results in a review published in 1972. In particular, peak pressure and rise time were found to be associated with annoyance and the perceived loudness of sonic booms (e.g., Shepherd & Sutherland 1967). Sonic booms with a shorter rise time are more annoying and are perceived as louder (see also Kryter 1966). Furthermore, higher peak overpressures are associated with higher perceived loudness. Sonic booms are generally perceived as more annoying inside the home, which may be related to the vibrations and rattling they cause. Vibrations and rattling caused by a sonic boom reduce acceptance. Sonic booms can be accompanied by startle responses, and sleep disturbances were observed in the studies considered at levels above 127.6 dB SPL. Peak overpressures of 107 dB SPL (0.1 psf) to 125 dB SPL (0.75 psf) are suggested as acceptable levels by Gierke and Nixon (1972). The authors conclude that the use of commercial supersonic aircraft would expose a large number of people to sonic booms. Since levels above 127 dB SPL (1 psf) are considered unacceptable, the authors consider the decision to allow supersonic flights only over water to be reasonable (von Gierke & Nixon 1972).

Rice (1972) and Pearson and colleagues (1989) each published a review summarising the current state of knowledge on the effects of sonic booms on sleep. Among other things, they found that middle-aged adults wake up in 30% of cases when exposed to sonic booms between 121.94 dB SPL and 143.5 dB SPL (Rice 1972). Zepler and colleagues (1973) summarised, among other things, the study results of May (1971a, 1971b, 1971c). May (1971a, 1971b, 1971c) utilised several studies to develop a function that predicts startle responses to sonic booms when the overpressure and rise time are known. However, the function is based on data from people who had already experienced sonic booms before. Background noise also had an influence on startle responses (Zepler et al. 1973).

Another review concluded that the degree of startle responses to a sonic boom in individuals is not associated with the intensity of the sonic boom, but that such a correlation could be observed in groups of people (Rylander 1974). The publications reviewed also pointed to a habituation effect at 10 or more sonic booms and showed negative effects of sonic booms on sleep (Rylander 1974).

At the beginning of the 2000s, Darden stated that, based on the published studies, it was not possible to define overpressure thresholds below which sonic booms would be unquestionably acceptable (Darden 2002). Other relevant acoustical factors would need to be taken into account, such as the number and timing (daytime or night-time) of the event(s), the intermittency, and the individual signatures (Darden 2002).

Three publications (Shepherd et al. 1995; Leatherwood et al. 2002; Sullivan 2006) summarised NASA studies on the effects of sonic booms. Shaped (modified) sonic boom signatures are associated with lower perceived loudness and annoyance (Leatherwood et al. 2002). Comparisons between symmetrical and asymmetrical signatures showed that asymmetrical signatures are perceived as less loud than symmetrical signatures. Stevens' Perceived Level (PL) proved to be the best predictor of self-reported sonic boom effects (see, e.g., McCurdy, Brown & Hilliard 1995, 2004).

4.3.2 Studies on noise annoyance, sleep disturbances and startle responses caused by sonic booms

The following two sections (Sections 4.3.2 and 4.3.3) describe the publications identified in the literature search as well as additional relevant literature that was found. Appendix A.1, Table 20, briefly presents all the studies identified in the literature analysis according to PEOS, along with the most important information.

One of the first major studies on sonic booms was conducted in 1961 and 1962 in the St. Louis area in the USA (Nixon & Hubbard 1965). Over a period of seven months, residents were exposed to 79 supersonic flights. There were two surveys, in which a total of 1,043 people from the study area and just under 300 people from a control group took part. The sonic booms generated by the aircraft were measured and then correlated with the reported disturbances, noise annoyance and complaints received. The sonic booms reached an average SPL of 132.69 dB (1.8 psf). 90% of the sample reported disturbances caused by the sonic booms: the most common disturbances were building vibrations and startle reactions. 35% of participants felt annoyed by the sonic booms, and 10% considered filing a complaint, of which 1% actually did so during the study period. However, in the three months following the completion of the main study, a total of 74 additional overflights with sonic booms occurred, resulting in significantly more complaints. 42% of participants also reported sleep disturbances caused by sonic booms. The sonic booms were rated as less acceptable by participants who were indoors during the flyover (Nixon & Borsky 1966). Furthermore, acceptance of night-time flyovers and the associated night-time exposure to sonic booms was lower than for daytime flyovers. A similar picture emerged when comparing military and commercial overflights: acceptance was lower for the latter. According to the authors, a single overpressure value may not be sufficient to adequately reflect the effect of sonic booms (Nixon & Borsky 1966).

A study on the acceptance of sonic booms was conducted in the vicinity of Edwards Air Force Base in the United States (Kryter, Johnson & Young 1967, 1968). Those who had been regularly exposed to sonic booms for several years demonstrated a higher tolerance to sonic booms than participants with no previous experience. Sonic booms at 132.19 dB SPL were just as unacceptable to participants who were already regularly exposed to sonic booms as noises from subsonic aircraft with peak levels of 109– Perceived Noise Level (PNL) dB. The frequency range from 20 to 500 Hz, in particular, was associated with the reactions and effects.

In 1968, Nixon et al. investigated the effect of sonic booms on ground personnel and the population (here: self-reported physiological symptoms). Although the personnel showed startle reactions, there was no interruption in the task performance, and no physiological symptoms were reported in the population survey.

In a smaller study, 39 residents living near the military airfield in Meppen, Germany, were asked about the annoyance effect of sonic booms (May 1972). Over a period of 10 days, participants were exposed to 53 sonic booms with an average SPL of 131 dB and a rise time between 2 ms (milliseconds) and 39 ms. Only sonic booms perceived outdoors were taken into account, not those perceived indoors. The results showed that a shorter rise time at the same level was associated with greater annoyance than longer rise times.

Thackray et al. had 40 students perform a 30-minute tracking task while 4 simulated sonic booms, as they would be heard outside, were played between 127.6 dB SPL and 139.6 dB SPL with a rise time of 295 ms (Thackray, Touchstone & Jones 1971). Skin conductance and heart rate were measured as effects. It was found that the students performed the task better after a sonic boom. Furthermore, skin conductance increased and heart rate slowed down. The authors concluded that the sonic booms investigated here triggered a kind of orientation or alarm reaction rather than a startle reaction. However, only a constant rise time was used in the study, and different rise times could have influenced the effects investigated (Thackray, Touchstone, & Jones 1971).

The possible effects of night-time exposure to sonic booms on mood as a proxy for sleep effects were investigated in a laboratory study by Smith and Hutto (1972) with 24 participants. The participants slept in the sleep laboratory for a total of 21 consecutive nights, during which they were exposed to simulated sonic booms (107.58 dB SPL in the bedrooms) every hour on nights 6 to 17. No significant effect of the sonic booms on the participants' mood was found, from which the authors concluded that the sonic booms used had no significant effect on the participants' sleep, as otherwise mood effects would have been evident (Smith & Hutto 1972). However, the extent to which mood effects allow actual conclusions to be drawn about sleep was not investigated.

In Sweden, Rylander and colleagues conducted two studies on the effects of sonic booms (Rylander, Sörensen, Berglund & Brodin 1972; Rylander, Sörensen & Berglund 1972). One study took place in Nausta with 165 soldiers and 33 civilian participants (Rylander, Sörensen, Berglund & Brodin 1972). During the study period, there were 42 sonic booms with maximum levels of up to 142 dB SPL. Both groups provided information on activities at the time of the flyover and on the effects of sonic booms. The 33 participants also performed a visual performance task and a tracking task. Higher levels were associated with a higher percentage of highly annoyed people. At a level of 133 dB SPL, 50% of participants reported annoyance, and at a level of 132 dB SPL, 8% reported being highly annoyed. The participating soldiers showed greater annoyance from the sonic booms than the civilian participants. The sonic booms had a significant negative impact on the performance test and reduced accuracy in the tracking task, regardless of the level. The proportion of people annoyed is slightly higher in the study by Rylander and colleagues at a level of 130.8 dB SPL (60%) than, for example, in the Oklahoma study (56%). Rylander et al. also conducted a sleep study on sonic booms (Rylander, Sörensen & Berglund 1972). In the study, 189 soldiers and 212 civilian participants were exposed to a total of 7 sonic booms over a 3-month period, each occurring at 4:25 a.m. The remaining nights served as control nights. The sonic booms reached levels of 109.5 dB SPL to 130.1 dB SPL. Both groups of participants took part in a survey that asked questions about annoyance and awakening reactions to sonic booms, as well as comparisons with other types of noise (e.g. traffic noise and gunfire/artillery fire) and personality. Civilian participants were also asked how many sonic booms they had heard and whether they had woken up and had difficulty falling back asleep. Sleep disturbances among the soldiers were measured using a motion sensor placed under their beds. They were also asked to press a button at the head of the bed when they woke up. Louder sonic booms were associated with more sleep disturbances. At an SPL of 129.5 dB, soldiers woke up 10% more often. The rise time, overpressure and sleep disturbances were not related to each other. Overall, soldiers who woke up due to sonic booms scored higher on neuroticism. 21% of soldiers rated the sonic booms as annoying, and 3% as very annoying. Two per cent reported difficulty falling back asleep after a sonic boom. At an SPL of 109.5 dB, there were no significant effects on sleep. Fifty-six per cent of civilian participants reported sleep disturbances. Older age was associated with greater sleep disturbance, indicating that the elderly population may be a vulnerable group. However, the number of 7 sonic booms over a period of 3 months is relatively low.

In another Swedish study, the startle responses to supersonic flights and conventional overflights (129.5-146.4 dB SPL outdoor level) were investigated in 60 participants (Thackray, Rylander & Touchstone 1973). As a reference noise, a starting shot was fired daily after the last overflight (107 dB SPL). The startle response was measured using an arm-hand stability apparatus. Louder sonic booms elicited more startle responses, with older participants showing fewer startle responses overall. At sonic booms of 143.5 dB SPL (outdoor), a startle response was observed in 75% of participants and in 10% at levels between 130.8 dB and 135.5 dB SPL. Thackray et al. suggest a threshold for startle responses of 127.95 dB SPL or less. Overall, there was no evidence of habituation to the sonic booms.

Twelve families participated in a study in which a community noise simulation system was set up in their homes to play simulated sonic booms during the day (Mabry & Oncley 1973). From the results, Mabry and Oncley derived an acceptable threshold for sonic booms of 87 dB

(Stevens' Mark VI) for indoor living and a maximum number of 15 sonic booms per day and no sonic booms at night.

Leatherwood and Sullivan (1993) showed in a laboratory study that the annoyance levels for the indoor noise of sonic booms were significantly higher than the loudness levels for this type of noise. The results also led to the recommendation to use the PL as a predictor of the effect of sonic booms. In a series of experiments by the same authors (Leatherwood & Sullivan 1994), possible differences in annoyance were investigated using various noise metrics (Stevens' Perceived Level, PL; PNL; C-weighted SEL, CSEL; A-weighted SEL, ASEL) and rise times (1 ms and 3 ms) of symmetrical N-wave sonic booms and regular overflight noise. The results show that, for the same level of annoyance, the C-weighted SEL is almost 10 dB to 15 dB higher than the A-weighted SEL. According to the authors, however, this difference could also be due to inaccuracies in the calculations and measurements. Furthermore, with the exception of the A-weighted SEL, the levels of the various noise metrics were higher for sonic booms than for regular overflight noise at the same noise level. Another study showed that the loudness of asymmetric N-wave sonic boom signatures is perceived as lower than that of symmetric N-wave sonic boom signatures at the same PL: the higher the asymmetry of the sonic boom signature, the lower the perceived loudness (Leatherwood & Sullivan 1992).

A 1997 study using pair comparisons found that sonic booms are perceived as more annoying than explosive noises at the same CSEL (Schomer, Sias & Maglieri 1997). In addition, outdoor CSEL correlates better with indoor annoyance than indoor CSEL. Fidell and colleagues (2002) also used pair comparisons to investigate annoyance from simulated indoor sonic booms and recorded regular overflight noise. The higher the noise level, the higher the annoyance. Sonic booms with rattle were perceived as more annoying. This effect was stronger at lower levels than at higher levels. For the same level of annoyance, the average dB values of non-impulsive variables were 5 dB higher for sonic booms with rattle compared to sonic booms without rattle.

Griefahn (1975a, 1975b) investigated the effect of nocturnal sonic booms on sleep in a sleep laboratory study using pulse rate and EEG (electroencephalogram) measurements. Two participants were exposed to 2 to 16 sonic booms with an average of 83.5 dB(A) (A-weighted decibel; 80-89 dB(A); 137.6-137.2 dB SPL) for 19 and 53 nights, respectively. Exposure to sonic booms during sleep was associated with a significant reduction in pulse rate. However, no correlation was found between pulse rate and the intensity of the sonic booms. There was no adaptation to the noise, but rather a form of compensation, and night-time exposure to sonic booms significantly shortened the deep sleep phases (Griefahn & Jansen 1975).

In two experiments, Ludlow and Morgan (1972) investigated the effect of sonic booms of varying loudness on sleep. Eight participants took part in each experiment. In the first experiment, simulated sonic booms with levels of 71.2 dB(A), 74.2 dB(A) and 77.6 dB(A) were used, and in the second experiment, 69 dB(A), 79 dB(A) and 84.5 dB(A) were used. Sleep disturbances and other relevant variables were recorded as follows: Subjective Stress Scale, Subjective Fatigue Scale, Clyde Mood Scale, personality test, sleep questionnaire and waking up by pressing a button. In the first experiment, no significant effect of sonic booms on the frequency of waking up was found; however, the sonic booms had a significant effect on self-reported fatigue (Subjective Fatigue Scale). In the second experiment, significantly more awakening reactions were found at higher noise levels, and the other measuring instruments also showed a negative influence of sonic booms.

Two experiments compared the effect of sonic booms and subsonic flyovers on sleep (measured using EEG) between different age groups (Lukas & Kryter 1970; Lukas, Dobbs & Kryter 1971). It was found that older people in particular showed significantly more frequent awakening reactions to both sonic booms and subsonic flights than middle-aged people. Children aged 7 to

8 showed little to no reaction to either type of noise in both experiments (Lukas & Kryter 1970; Lukas, Dobbs & Kryter 1971). However, the sample sizes in both studies were quite small for each age group, which means that no generalisable conclusions can be drawn.

Fields (1997) investigated the annoyance effect of sonic booms in two regions (region A near Las Vegas and region B near Los Angeles) in the western United States. Both regions had already been exposed to sonic booms for several years. In the highly exposed communities, the noise levels over the six-month period were 55 dB CSEL and 40 dB ASEL, respectively, and in the least exposed communities, 40 dB CSEL and 25 dB ASEL, respectively. Startle responses, rattling and vibrations, and concern about possible damage from sonic booms were cited as particularly disturbing. Of the participants who showed startle responses, most reported that they did not observe any habituation effect in themselves. The effects of sonic booms differed between the two regions: for example, in the Las Vegas region, 35% of people were very annoyed (4-point scale) at 30 to 40 dB(A), compared to 5% in the Los Angeles region at the same dB(A) value. At the same level, sonic booms were perceived as more annoying than aircraft noise. Fields concluded that this difference could amount to 10 dB, but that higher dB values (20 to 40) were also possible and could not be ruled out (Fields 1997).

In a recent publication, Schomer et al. (2023) reanalysed existing data on the effect of sonic booms and rattle (including data from the St. Louis and Oklahoma City studies). Rattle emerged as the most important predictor of annoyance from sonic booms. The relationship between rattle and perceived annoyance was non-linear (Schomer, Naidu & Naidu 2023).

4.3.3 Studies on low sonic booms

Studies from the last 20 years have primarily focused on the effect of low sonic booms on humans. Unlike conventional sonic booms, low sonic booms are much quieter and are therefore thought to have less of a negative impact on humans. However, audible noise, vibrations and rattle remain. Until now, studies on low sonic booms have been laboratory studies, as there was no aircraft demonstrator capable of producing low sonic booms.

McCurdy and colleagues (2004) investigated the annoyance effect of various simulated sonic booms in an 8-week field experiment. For this purpose, a system was set up in the homes of 33 participants that generated 4 to 63 sonic booms (N-Wave sonic booms outside and inside and shaped sonic booms outside) with 66 dB ASEL, 70 dB ASEL or 74 dB ASEL during the day. The more sonic booms a participant was exposed to, the more annoyed they were. There was no difference in annoyance between the different waveforms. Participants who showed a startle response were more annoyed. The study also compared different noise metrics, and PL proved to be the best predictor of noise annoyance. During recreational activities such as sleeping, annoyance increased by 1.5 dB PL per hour. During conversations with other people or listening to music, however, annoyance decreased by an equivalent of 0.75 dB PL and 0.5 dB PL per hour. Annoyance increased by an equivalent of 0.25 dB PL per year of age.

In 2006, Sullivan et al. conducted a 3-week study on the effects of low sonic booms (Sullivan et al. 2010). During this period, 77 participants rated the annoyance caused by real low sonic booms and synthetic low sonic booms while they were both outside and inside a building. The low sonic booms reached levels between 107.58 dB SPL and 123.15 dB SPL. An F18 flew over the building and produced low sonic booms using a specific flight procedure. The annoyance caused by a low sonic boom was higher for the same level when participants were inside the building compared to outside. However, the annoyance caused by a specific low sonic boom did not differ significantly between outdoor and indoor locations. In a post-assessment, most participants rated the indoor low sonic booms as more annoying overall than the outdoor low sonic booms, which contrasts with the rating of the individual low sonic booms. One explanation offered by the authors is that all sounds used may be perceived as more annoying inside the building, possibly due to different expectations of noise sources inside and outside a building. The authors also assume that rattle has a lesser effect on annoyance than other studies suggest, as doors and windows in the building used rattled, but the degree of annoyance caused by individual low sonic booms did not differ between indoors and outdoors. It should be noted, however, that the presence and intensity of rattle was not controlled for in this study and was not part of the study design.

In her dissertation, Miller investigated, among other things, the influence of different listening environments on the perception of annoyance caused by recorded indoor and outdoor low sonic booms (2011). Participants listened to the low sonic booms through headphones both in an office environment and on an outdoor terrace. The same low sonic booms were perceived as more annoying when participants were indoors, and the recorded indoor low sonic booms were associated with higher annoyance than the recorded outdoor low sonic booms. When comparing different characteristics of rooms that could influence the perception of annoyance caused by low sonic booms, such as size and shape, it was found that low sonic booms are perceived as most annoying in small, square rooms and rooms with a longer reverberation time for low sonic booms (Giacomoni & Davies 2013).

Two further NASA studies investigated the effect of rattle on annoyance, among other things (Loubeau et al. 2013; Rathsam, Loubeau & Klos 2013). Overall, the authors found a penalty of 3 to 9 dB for the presence of rattle. Rattle from small objects such as glasses or pictures was perceived as less annoying than rattle from windows and doors, even though all rattle noises were set to the same dB PL (Loubeau et al. 2013). In addition, low sonic booms combined with rattle were perceived as more annoying than low sonic booms alone. The Moore and Glasberg Stationary Loudness (MGSL) proved to be the best predictor of annoyance for low sonic booms in combination with rattle. However, other studies point to PL as the best predictor of annoyance (e.g., Rathsam, Loubeau & Klos 2012). Studies showed values between 0 and 8 dB for the dB penalty for the effect of vibrations (Carr & Davies 2015; Rathsam, Loubeau & Klos 2015; Rathsam & Klos 2016).

Another study investigated the relationship between short-term and long-term annoyance caused by low sonic booms (Fidell 2013). Forty-nine participants were exposed to supersonic flights producing low sonic booms in their homes over a period of two weeks. The study recorded both short-term annoyance after each low sonic boom event and long-term annoyance at the end of each day. The single low sonic boom event perceived as most annoying was particularly useful as a predictor of long-term annoyance. In addition, the number of startle responses in a day and the highest annoyance caused by rattle were significant predictors of long-term annoyance (Fidell 2013).

The studies conducted by NASA on low sonic booms focused in particular on the effect inside a building and the influence of different waveforms on annoyance and the suitability of different acoustic metrics (Loubeau, Rathsam & Klos 2013; Page & Loubeau 2019). Rathsam and colleagues (Rathsam, Loubeau & Klos 2015) used four low sonic booms with PL levels of 65 dB, 73 dB and 81 dB without rattle, combined these with rattle noises also with different PL levels (53 dB, 61 dB, 69 dB) and played these noises to 33 participants. The annoyance was recorded on a continuous scale, with the data subsequently converted into a numerical expression. In addition, the metrics PL, CSEL and ASEL were compared with each other in terms of their suitability for predicting annoyance. The authors found that PL (indoor) is a good predictor of annoyance inside the house; this applies to low sonic booms with and without rattle. Low sonic booms with rattle, as heard outside, are suitable for predicting annoyance in the population.

In two studies – one at NASA research facilities and one at Purdue University's laboratory – various types of noise (low sonic booms, doors slamming, explosions, gunshots) and noise metrics (PL, PNL, ASEL, BSEL, CSEL, ESEL, time-dependent loudness (Glasberg & Moore 2002), Zwicker loudness, duration, heaviness (H; difference between CSEL-ASEL)) were compared (Carr & Davies 2015; Carr et al. 2020). The Purdue study took place in a laboratory setting and the noises were played through headphones. The NASA study was conducted in a simulator (see also Klos, Sullivan & Shepherd 2013) and also investigated the effect of vibrations, with participants sitting on an isolated chair (no vibration) for part of the study and on a non-isolated chair for the other part of the study, thus being exposed to vibrations. Both studies examined the effect of noise on annoyance, but used two different approaches: Purdue used the ICBEN (International Commission on Biological Effects of Noise) 5-point scale to measure noise annoyance (Fields et al. 2001), and NASA used a 5-point scale with the same values, but it was possible to click between the given scale values, i.e., to select decimal numbers. Loud, synthetic sonic booms without a 50 Hz high-pass filter were perceived as the most annoying. A reduced low frequency was associated with less annoyance, and additional low frequencies (25-50 Hz) can lead to greater annoyance. In addition, louder sonic booms were more annoying. Differences between the two studies were evident in the annoyance values: the mean annoyance value for values below 5 is higher in the Purdue study than in the NASA study. The models with the highest variance explanation ($R^2 > 0.89$), in which several metrics were taken into account, included H, PL, duration and loudness. All four variables achieved significance. Both indoor and outdoor metrics are suitable predictors of annoyance from indoor noise. According to the results, loudness and annoyance capture different constructs, and lower frequencies had a different influence on the perception of annoyance compared to loudness. The NASA study also showed a small effect of vibrations on noise annoyance (Rathsam, Klos & Loubeau 2015).

In 2011, the pilot project "Waveforms and Sonic Boom Perception and Response (WSPR)" was conducted at Edwards Air Force Base in California, USA, to test the applicability and efficiency of various study designs for collecting data on the noise impact of low sonic booms (Page et al. 2014). Fifty-one participants took part in the two-week study, during which 110 low sonic booms were generated simultaneously by an F18 aircraft. However, the area around the Air Force Base is regularly exposed to sonic booms, even before the study. The survey consisted of the evaluation of individual events and a questionnaire at the end of each day. Results showed that the perception of annoyance was particularly related to the disturbances experienced from low sonic booms.

In NASA's QSF18 study, the community of Galveston, Texas, in the USA was exposed to 52 real low sonic booms over a period of two weeks in November 2018 (Page et al. 2020). An F18 aircraft flew over the community using a special flight procedure, generating low sonic booms with a level between 56 dB SPL and 90 dB PL (Lee, Rathsam & Wilson 2020). Most low sonic booms were no louder than 73.7 dB PL (Page et al. 2020). This study recorded the effect of individual low sonic booms and an overall assessment of the disturbance for each day. A total of 476 participants took part in the study (Page et al. 2020). 1% of the sample was highly annoyed by the low sonic booms (1% HA). The low sonic boom sound levels were positively associated with %HA for the individual event assessment. For the overall assessment of low sonic booms at the end of each day, however, there was no significant relationship between the sound level and %HA, which could be due to the relatively small number of highly annoyed individuals. Two different regressions were calculated using data from 371 individuals: a multilevel logistic regression and a multilevel ordinal regression (Lee, Rathsam & Wilson 2020). According to the authors, the two models differed by 2.5 dB at a fixed %HA, which is still within the confidence intervals (CI; Lee, Rathsam & Wilson 2020). The annoyance results are similar to those of the WSPR study, although participants in the latter study were already regularly exposed to sonic booms prior to the study.

Töpken and van de Par compared the loudness and short-term annoyance effect, measured on an 11-point scale, of conventional outdoor N-Wave sonic booms with outdoor low sonic booms (EU project RUMBLE, 2020; 2021). In total, they used 24 different sonic booms and low sonic booms with dB values between 55.5 dB ASEL and 69.8 dB ASEL. The results showed a significant difference between the different signatures and sound levels (Töpken & van de Par 2020). In addition, the loudness and annoyance of the different signatures were rated differently depending on the sound level. Annoyance and loudness are particularly attributable to medium and higher frequencies (> 1000 Hz) and less to frequencies below 1000 Hz. A higher dB value was associated with higher annoyance and higher loudness (Töpken & van de Par 2020). For annoyance and loudness, an increase of 6 dB was associated with a 2-to-3-point increase on the respective scale. In another study from the EU project RUMBLE, 41 participants were exposed to low sonic booms in a specially prepared building located on the campus of Sorbonne University in France (Marmel et al. 2024; 2025). The aim was to investigate the effect of outdoor low sonic booms (62.1 dB ASEL to 69.5 dB ASEL) on participants inside the building, specifically in the living room and kitchen. These two rooms were chosen because they produced different rattle effects caused by the low sonic booms. The participants performed various tasks during the exposure to low sonic booms (tasks relating to working memory, motor skills and communication, as well as an affective cognition task) or took a break (no task but exposure to low sonic booms). Afterwards, they answered questions about the annoyance and discomfort caused by the low sonic booms and rattling (e.g., "How much did the booms/rattling disturb you during the task?", "How unpleasant did the booms/rattling sound?") and their mood (only before and after breaks). Small but significant negative effects of the low sonic booms were found on the affective cognition task as well as on the working memory and motor tasks. No startle effect was detected in the motor task. In the communication task, a trend towards deterioration due to exposure was observed, but this was not significant. These effects were found at levels between 60 dB ASEL and 70 dB ASEL, with higher levels not associated with further deterioration in performance. This could be due to the fact that the differences in sound levels decrease as soon as the low sonic booms enter the building. In addition, the low sonic booms seemed to have a greater effect on female participants than on male participants (Marmel et al. 2024). The low sonic booms were more disturbing during breaks than during the performance of tasks, and higher boom levels were more disturbing than lower boom levels (Marmel et al. 2025). Furthermore, the booms were perceived as annoying and unpleasant, especially at high boom levels and in the presence of rattle (Marmel et al. 2025).

JAXA also conducted various studies in its sonic boom simulator, including studies on the relationship between the perceived loudness of different low sonic booms and various acoustic metrics (e.g., Naka 2013). The results of one study showed that perceived loudness indoors and outdoors correlates highly with ASEL, ESEL (E-weighted SEL), PNL and various loudness metrics (Naka 2013). A cumulative evaluation of NASA and JAXA study data showed that PL, BSEL (B-weighted SEL), DSEL (D-weighted SEL) and ESEL are good predictors of annoyance caused by low sonic booms (Loubeau et al. 2015; DeGolia & Loubeau 2017). In addition, ISBAP (Indoor Sonic Boom Annoyance Predictor), which also takes heaviness (H) into account, among other factors, proved to be suitable (DeGolia & Loubeau 2017).

In addition to studies on low sonic booms, there is also increasing research on the so-called Mach cut-off flight procedure (e.g., Sparrow & Vigeant 2019). Mach cut-off can occur under certain atmospheric conditions and at a certain aircraft speed. Mach cut-off prevents sonic booms from reaching the ground, and their signature also differs from conventional N-wave sonic booms in terms of auditory experience (Sparrow & Vigeant 2019). Sparrow and colleagues investigated the effects of this Mach cut-off procedure on humans. The first step was to identify suitable descriptions of the noises. From an initial listening experiment, the terms *thunderous*, *rumbly* and *swooshing* were derived to describe the Mach cut-off noises. In addition*, annoying* was assessed as an attribute. It was found that the description thunderous in particular was associated with the annoyance rating.

4.4 Conclusion from the literature analysis

The studies described here assess the effects of noise in very different ways in some cases, and the sample sizes vary greatly. Overall, it appears that sonic booms and low sonic booms are generally perceived as more annoying inside a building. This is due, among other things, to accompanying vibrations and rattling, which can increase the perception of annoyance (e.g., Kryter 1966; Miller 2011). Some studies therefore also investigated a possible dB penalty in the presence of rattle and vibrations (e.g., Sullivan et al. 2010). The range of possible dB penalties for rattling (see also Sullivan et al. 2010) – caused in part by noises similar to sonic booms – ranges from 0 dB (Pearsons et al. 1993; Cawthorn, Dempsey & DeLoach 1978) to 20 dB: 5 dB (Fidell, Silvati & Pearsons 2002), 3 dB and 9 dB (Loubeau et al. 2013; Rathsam, Loubeau & Klos 2013), 13 dB to 20 dB (Pearsons & Kryter 1964; Schomer & Neathammer 1987; Schomer & Averbuch 1989). For vibrations, two studies yielded penalty values of 0 dB to 8 dB (Carr & Davies 2015; Rathsam, Klos & Loubeau 2015; Rathsam & Klos 2016). Earlier studies also showed that rise time was a relevant factor influencing annoyance and perceived loudness (e.g., May 1972). The consideration of rattle and vibrations therefore appears to be very relevant for the investigation and prediction of noise annoyance caused by sonic booms and low sonic booms. In the publications considered here, which compare various acoustic metrics, PL often proves to be the best predictor of noise annoyance (cf. McCurdy, Brown & Hilliard 2004; Rathsam, Loubeau & Klos 2012; Rathsam, Loubeau & Klos 2015; Carr & Davies 2015; Carr et al. 2020).

Unlike subsonic flights, where residents are mainly exposed to aircraft noise during take-off and landing, a large number of people would be exposed to low sonic booms and the associated vibrations and rattling that can occur throughout the entire flight at supersonic speeds.

5 Summary of the results of the sleep study and literature analysis, and derivation of acceptability criteria

According to Section 29b (1) of the Aviation Act, the "[...] population must be protected from hazards, severe disadvantages and severe annoyance caused by noise. Particular consideration must be given to the night-time rest of the population." Furthermore, the purpose of the Act for Protection against Aircraft Noise is to "[...] ensure structural use restrictions and structural noise protection in the vicinity of airports in order to protect the general public and the neighbourhood from hazards, severe disadvantages and severe annoyance caused by aircraft noise" (Section 1 Aircraft Noise Act, FluLärmG). In Germany, for example, the FluLärmG defines two daytime and one night-time protection zones in the vicinity of airports on the basis of noise levels. A protection zone comprises those areas in which the specified values are exceeded. For new or significantly modified civil airports, for example, the following values apply: Daytime protection zone 1 with $L_{\mathrm{Aeq,Day}} = 60$ dB(A); Day protection zone 2 with $L_{\mathrm{Aeq,Day}} = 55$ dB(A), and the night protection zone with $L_{\mathrm{Aeq,Night}} = 50$ dB(A) and $L_{\mathrm{Amax}} = 6$ times 53 dB(A) (Section 2 FluLärmG).

In its Environmental Noise Guidelines for the European Region (WHO, 2018), the WHO provides recommendations for sound levels associated with various environmental noise sources to protect the population from adverse health effects. For example, it recommends that aircraft noise should be below 45 dB L_{den} and 40 dB L_{night} at night. Therefore, to adequately protect the population from aircraft noise, clearly defined and measurable parameters are required to determine the level at which effects are acceptable and at which they are no longer acceptable. This requires, on the one hand, a definition of the effects of the noise source and, on the other hand, acoustic parameters that define when noise effects can occur.

At the European level, for example, the EU Horizon 2020 project RUMBLE (RegUlation and norM for low sonic Boom LEvels), carried out from 2017 to 2020, aimed to develop scientific principles for the regulation and standardisation of supersonic noise from new generations of supersonic aircraft. The laboratory experimental results from RUMBLE on the effects of supersonic noise (Töpken & van de Par, 2020, 2021; Marmel et al., 2024, 2025) provide important information on effects, but limits of acceptability or threshold values for supersonic noise cannot be directly derived from them. The ongoing EU Horizon2020 research project MORE&LESS (Multidisciplinary Design Optimisation and REgulations for Low boom and Environmentally Sustainable Supersonic aviation) aims to investigate the impact of future supersonic aviation on the environment on the basis of modelling and test campaigns and to support the development of global environmental standards through evidence-based recommendations. However, MORE&LESS does not address the health effects of supersonic noise.

A central element of this project is the derivation of acceptability criteria for low sonic booms and Mach cut-off flights, aimed at protecting the population. To this end, the entirety of the results from the sleep study and the literature analysis will be presented, along with the implications of these results for acceptability criteria.

In contrast to aircraft noise and conventional sonic booms, however, limited research results are available to date on the effects of low sonic booms and Mach cut-off flights. In particular, long-term effects in the field have not yet been investigated. In some cases, however, the effects of conventional sonic booms could be transferred to low sonic booms. Based on the sleep study conducted as part of the project and the literature analysis, various measurable parameters that are suitable as acceptability criteria are presented and described below.

The following parameters were assessed or taken into account in the sleep study:

- Self-reported sleep parameters based on a questionnaire:
  - Self-assessed sleep quality;
  - Self-assessed morning sleepiness;
  - Short-term annoyance;
- Physiologically measured sleep parameters:
  - Electrophysiologically measured sleep quality: a) sleep efficiency, b) time to fall asleep, c) proportion of deep sleep, d) proportion of being awake, e) number of awakenings
  - Physiologically measured awakening rate;
  - Physiologically measured arousal rate;
  - Physiologically measured rate of lightening of sleep.

The results of the sleep study can be summarised as follows:

The overall night parameters of the electrophysiological measured sleep quality in the Low-boom condition did not differ significantly from the control condition, but non-significant trends were observed: in the Low-boom condition, sleep efficiency was slightly lower and WASO, SOL, the number of awakenings and arousals were slightly higher than in the control condition. One possible explanation could be the unfamiliar laboratory environment on the first night (= control). However, the results show a significant improvement in sleep efficiency in the Mach cut-off condition compared to the Low-boom condition.

The averaged noise-induced awakening rate was 6.39% for Low-boom events and 1.67% for Mach cut-off events. A noise-induced awakening rate of 6.39% corresponds to a maximum sound pressure level $L_{\mathrm{AS,max}}$ of approximately 60 dB for conventional aircraft noise, between 55 and 60 dB for road traffic noise, and 55 dB for rail traffic noise (also in a laboratory setting). The awakening rate of 1.67% found for the Mach cut-off condition would be exceeded for conventional aircraft noise and road traffic noise at 50 dB and would be between 50 and 55 dB for rail traffic noise. The results for arousals show an averaged arousal rate of 7.8% for the Low-boom condition (compared to between 55 and 60 dB for conventional aircraft noise, 45 dB for road traffic noise and 50 dB for rail traffic noise) and 2.8% for the Mach cut-off condition (in comparison, for aircraft noise between 45 and 50 dB, for road and rail noise already exceeded at the lowest presented levels of 45 dB).

The results of the heart rate analysis indicate an orientation response to the low sonic booms: the heart rate was slower after the low-boom events than before the noise events.

The results for the self-assessed sleep parameters show that morning sleepiness was lower after the control condition than after the Low-boom condition. Sleep quality was rated as poor after the control condition and after the Low-boom condition, and both conditions were rated worse than the Mach cut-off condition. This could also be due to the unfamiliar laboratory setting on the first night (= control).

Note on the sleep study and classification of the results

With regard to the results of the sleep study, it should be noted that only the sounds of low-boom aircraft and those of low-boom aircraft applying the Mach cut-off procedure were played in the participants' bedrooms as part of this study; effects such as rattle and vibrations could not be taken into account.

The literature analysis shows that a wide variety of criteria are relevant for assessing acceptability. These can be differentiated into acoustic parameters and noise effects.

5.1.1 Acoustic parameters as acceptability criteria

Regarding low sonic booms, various metrics were used and compared in the studies. Naka (2013) found that perceived loudness (indoor and outdoor) correlates highly with ASEL, ESEL, PNL, and various loudness metrics. Joint evaluations of NASA and JAXA study data revealed that the acoustic metrics PL, BSEL, DSEL, and ESEL are effective predictors of annoyance caused by low sonic booms (Loubeau et al. 2015; DeGolia & Loubeau 2017). According to the results of the EU Horizon project RUMBLE, the ASEL metric is a good predictor of annoyance caused by low sonic booms (Töpken & van de Par 2020). When comparing several metrics, PL is often found to be the best predictor of annoyance. It should be noted that only an overview of the metrics used can be provided here; the choice of an acoustic metric as a criterion for acceptability cannot be made at this time.

When assessing the acceptability of low sonic booms, rattle and vibrations must also be taken into account, as these can occur as side effects when the sound pressure wave reaches the ground and thus also buildings and objects inside them. Studies have shown different dB penalty values for rattle (sonic booms and low sonic booms; see also Sullivan et al. 2010):

- 0 dB ASEL (Pearsons et al. 1993, Cawthorn, Dempsey & DeLoach 1978);
- 5 dB ASEL (Fidell, Silvati & Pearsons 2002);
- 3 dB and 9 dB PL (Loubeau et al. 2013; Rathsam, Loubeau & Klos 2013);
- 13 dB to 20 dB ASEL (Pearsons & Kryter 1964; Schomer & Neathammer 1987; Schomer & Averbuch 1989).

In a study, Loubeau et al. (2013) also found that the annoyance caused by rattle can vary depending on the object. For example, rattling windows and doors are perceived as more annoying than rattle from smaller objects such as glasses (Loubeau et al. 2013). With regard to vibrations caused by low sonic booms, studies show dB penalty values between 0 dB and 8 dB (Carr & Davies 2015; Rathsam, Klos & Loubeau 2015; Rathsam & Klos 2016).

Another important criterion that should be taken into account is the number of noise events: the number of low sonic booms or Mach cut-off flights (e.g., per day). Although different numbers of noise events are used in studies on sonic booms, low sonic booms and Mach cut-off flights, it is not possible to define how many noise events are still acceptable and at what number they become unacceptable. One study found that, with regard to low sonic booms, the most annoying single event of a low sonic boom is particularly well-suited as a predictor of long-term annoyance (Fidell 2013).

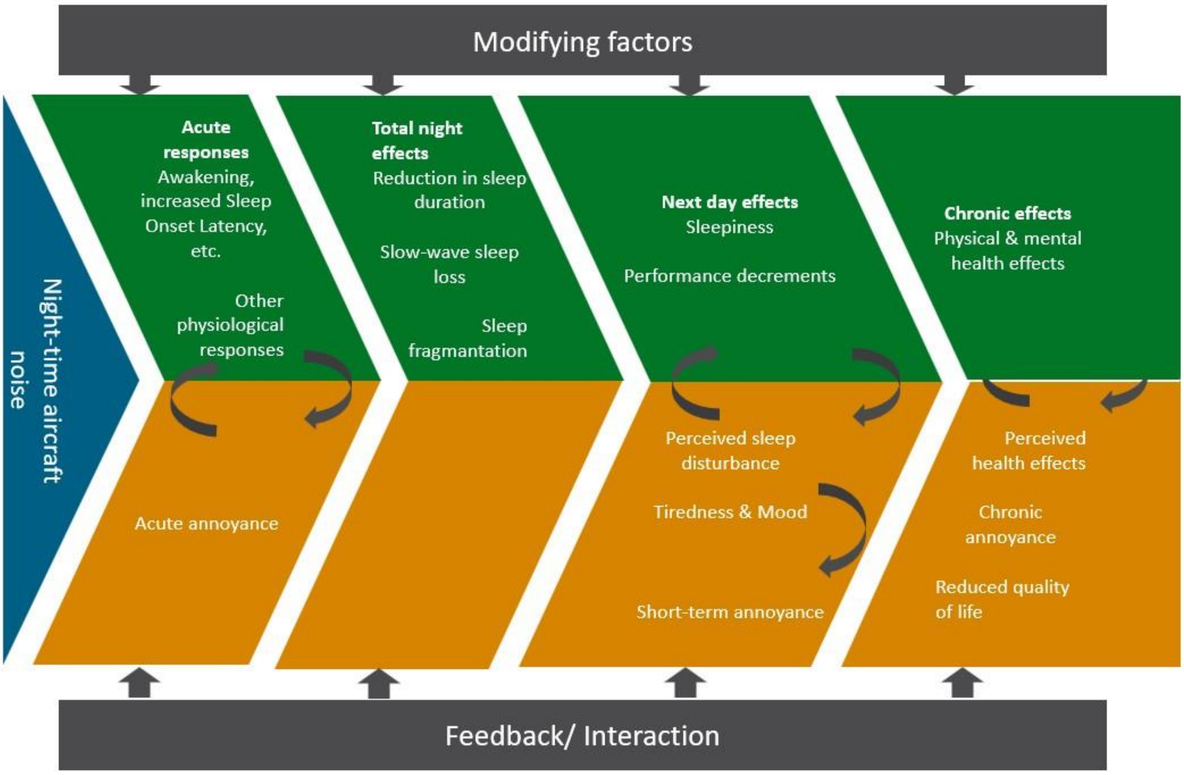
In the case of conventional sonic booms, it was also found that a shorter rise time is associated with greater annoyance or higher perceived loudness (see also Kryter, 1966; May, 1972).

5.1.2 Noise effects as acceptability criteria

Another important aspect in assessing acceptability is the effects of noise; these can be caused by both night-time and daytime exposure and also occur at both day and night. For noise effects at night (sleep disturbances), Griefahn (1990) postulates a distinction between noise effects based on their time of occurrence and their duration into primary, secondary and tertiary effects. Griefahn (1990) summarises primary effects as acute reactions to noise events, such as waking up, which can be compensated for during the same night. Secondary effects arise from the sum of the primary effects and can no longer be compensated for during the same night. These include perceived sleep quality and cognitive performance on the following day. With long-term exposure, primary and secondary effects can eventually no longer be compensated for, leading to tertiary effects.

A model developed by Porter, Kershaw and Ollerhead (2000) makes a similar but more differentiated distinction regarding the timing of various noise effects. In their model, the authors also focus on night-time aircraft noise exposure and divide the resulting noise effects into four levels of impact: acute responses, *total night effects*, *next-day effects* and chronic effects (see Figure 62). According to the authors, there are also interactions and interdependencies between the effects shown.

Figure 62: Conceptual model of the effects of night-time aircraft noise by Porter, Kershaw and Ollerhead (2000)

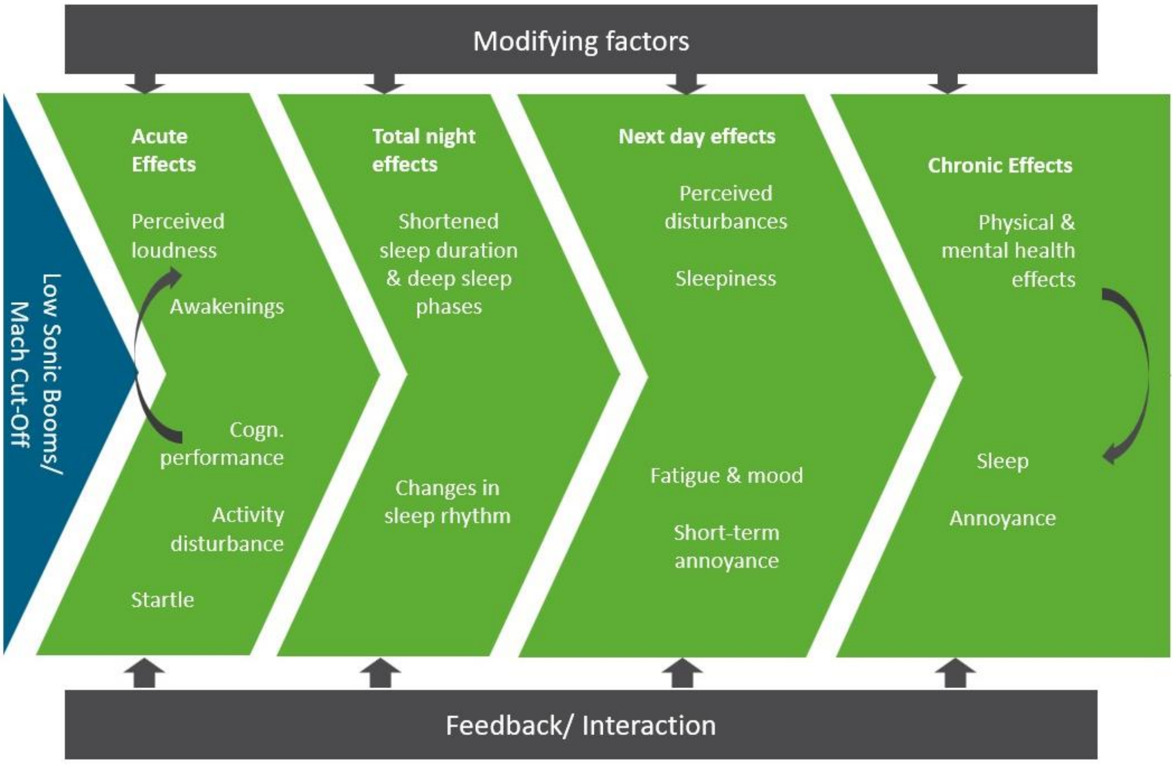


Note: Source: model by Porter, Kershaw and Ollerhead (2000).

Porter, Kershaw and Ollerhead (2000) define acute responses of night-time aircraft noise as direct or immediate physiological and psychological effects. Physiological effects include, for example, sleep disturbances characterised by waking up, difficulty falling asleep or changes in sleep depth. Other physiological effects of night-time aircraft noise can include a short-term increase in heart rate and blood pressure. One acute psychological effect is acute annoyance. The so-called *"total night effects"* include effects that accumulate throughout the night as a result of the acute responses. These include, for example, a reduction in overall sleep duration, a reduction in the duration of deep sleep and a general change in the normal sleep rhythm. The third level of effects includes effects that are noticeable the next day and are caused by the first two levels of effects (*"next-day effects*"). These *next-day effects* include sleepiness, reduced cognitive performance, noise annoyance, self-reported sleep disturbance during the previous night and mood swings. The fourth and final level of effects comprises long-term, chronic effects that can occur as a result of the first three levels of effects. Chronic effects include cardiovascular disease, high blood pressure, mental illness, noise annoyance and reduced quality of life. The effects included and described in the model are interdependent and can influence each other. Furthermore, the authors emphasise that there are numerous factors that exert an influence in addition to the acoustical characteristics of aircraft noise. These include, for example, attitudes, trust in those responsible, and individual noise sensitivity (Porter, Kershaw & Ollerhead 2000).

The noise effects utilised in the sleep study and those identified in the literature analysis, which could potentially serve as acceptability criteria, overlap in part with the noise effects cited by Porter, Kershaw, and Ollerhead (2000) and can be assigned to the various effect levels in an adapted model. In contrast to the model by Porter, Kershaw and Ollerhead (2000), which focuses on night-time exposure to aircraft noise, the adapted model takes into account both night-time and daytime exposure. Based on the model by Porter, Kershaw and Ollerhead (2000), the effects of low sonic booms and Mach cut-off flights identified as relevant were categorised into the four effect levels. Figure 63 shows an overview of this categorisation, and the individual effects are described in more detail below.

Figure 63: Adapted model (based on Porter, Kershaw & Ollerhead 2000) with relevant noise effects for acceptability criteria



Source: own visualisation, ZEUS, adapted model according to Porter, Kershaw and Ollerhead (2000).

Ac*ute* effects of low sonic booms include perceived loudness, awakenings, cognitive performance, activity disturbances, and the startle response. The startle response has been extensively studied in relation to conventional sonic booms. In the St. Louis study, for example, 90% of participants felt most disturbed by building vibrations and startle responses caused by sonic booms (Nixon & Hubbard 1965; Nixon & Borsky 1966). In a study, Fidell (2013) found that the number of startle reactions in a day and the highest level of annoyance caused by rattles were significant predictors of long-term annoyance.

Perceived loudness may also be relevant: Töpken and van de Par (2020) found a positive correlation between volume (dB) and perceived loudness. An increase of 6 dB was associated with a higher perceived loudness of 2 to 3 points on the respective scale (Töpken & van de Par

2020). Low sonic booms can also impair cognitive performance. Marmel et al. (2024) investigated this relationship and found small but significant negative effects on affective cognition tasks and tasks involving working memory and motor skills.

Total night effects include reduced sleep duration, fewer or shorter deep sleep phases, and a change in sleep rhythm caused by the disturbances. After a night disturbed by noise (*next-day effects*), sleepiness and mood swings, as well as annoyance (short-term annoyance), may occur. For example, 42% of participants in the St. Louis study reported sleep disturbances (Nixon & Hubbard 1965), and night-time supersonic flights were less acceptable than supersonic flights during the day (Nixon & Borsky 1966). Results from the sleep study conducted in this project showed that participants rated their morning sleepiness higher after the low sonic boom condition than after the control condition. For short-term annoyance caused by low sonic booms, Töpken and van de Par (2020) showed that an increase of 6 dB is associated with an increase of 2 to 3 points on the respective scale (Töpken & van de Par 2020).

Long-term effects of aircraft noise include chronic sleep disturbances, long-term annoyance and increased risks of physical and mental disorders. Based on current research, these effects cannot be ruled out for low sonic booms and Mach cut-off flights, even though no research results are yet available on the long-term effects of these types of noise. Results from the WSPR study show that the perception of annoyance is primarily related to the disturbances caused by low sonic booms (Page et al. 2014). In the QSF18 study, 1% of participants were highly annoyed by low sonic booms (1%HA). There was a positive association between level and %HA for the single event assessment. However, there was no significant correlation between the annoyance rating for low sonic booms at the end of each day and the sound levels; this could, however, be due to the relatively low %HA (Page et al. 2020; Lee, Rathsam & Wilson 2020).

Not necessarily as a criterion of acceptability itself, but as a side note, studies of conventional sonic booms from the 1960s found that military supersonic flights are more acceptable than commercial supersonic flights (Nixon & Hubbard 1965; Nixon & Borsky 1966). The same could also be true for newer supersonic aircraft.

5.1.3 Recommendations for deriving acceptability criteria

One of the aims of this research project was to develop acceptability criteria for assessing low sonic booms and Mach cut-off flights. The project does not include the specification of concrete values for these acceptability criteria.

Similar to what has already been done for other noise sources (see WHO 2018), it is also appropriate for the assessment of low sonic booms and Mach cut-off flights to rank the various effects, for example – based on the work of the WHO – to rank them as critical, important and unimportant effects. For medium to long-term noise effects, so-called DALYs (*disability adjusted life years)* are calculated for other environmental noise sources. This allows the quantification of different noise effects, including their severity, and could also be useful in the future for the effects of low sonic booms and Mach cut-off flights.

Based on the current state of research, it is not yet possible to make any concrete proposals for a ranking of acceptability criteria or for possible limit values for the acceptability criteria. The sleep study conducted here is an important first step in investigating the noise impact of low sonic booms and Mach cut-off flights. As the first field study on low sonic booms, *NASA's X59*

Quesst Community Survey Campaign[2], currently planned for 2026 to 2028, will also provide important insights into the impact of low sonic booms.

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[2] https://ntrs.nasa.gov/api/citations/20230015240/downloads/Rathsam%20et%20al%20Technical%20Seminar%20at%20IDA%20v4.pdf

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A Literature analysis

A.1 Studies identified in the literature search

Table 20: Overview of relevant studies identified in the literature search according to PEOS

Authors, year	Population	Exposure	Outcomes	Study design	Results
Anton-Guirgis, Culver, Wang, Taylor 1986 (USA, Nevada)	Residents of Nevada	Real sonic booms	Mortality, morbidity	Epidemiological study	No evidence for or against a relationship between exposure to sonic booms and negative health effects
Borsky 1965 (USA, Oklahoma)	2852	1253 real sonic booms, during the day, 8 per day (M = 128.64 dB, 11 weeks; 129.38 dB, 8 weeks; 131.66 dB, 7 weeks); distance	Disturbances, startle response, annoyance, anxiety, complaint behaviour, attitudes, acceptance	Field, 6 months, 3 measurement points (t1, t2, t3)	Almost all participants reported disturbances caused by sonic boom-induced rattling and vibrations; 40% of participants living within a radius of up to 12.9 km reported startle responses and anxiety, as did 30% of participants living further away; 10–15% of the first group and 5% of the second group reported sleep, rest and conversation disturbances due to sonic booms; 11 weeks after the start (M = 128.64 dB SPL), 37% were seriously annoyed; then 44% at M= 129.38 dB SPL and 56% at 131.66 dB SPL → unclear whether the increase in annoyance is caused by the higher levels or the prolonged exposure time; desire to complain: t1 = 16%, t2 = 23%, t3 = 22%; 5% complained→ low percentage of complaints could also be due to ignorance of where to complain or the perceived point of complaining: overall, there are only few complaints in Oklahoma; at t3, 27% stated that they could not accept sonic booms for an indefinite period of time; attitudes had an effect on acceptance
Broadbent & Robinson 1964 (Great Britain)	79	Jet aircraft (98.7 dB SPL, 111.7 dB PNL), piston-engine aircraft (96.9 dB SPL, 102.5 dB PNL), sonic booms indoors (114 dB SPL)	Annoyance (0-100; reference 10 = jet aircraft)	Experiment	Annoyance and loudness show similar correlations with SPL; the increase is steeper for sonic booms; upper acceptance limit for sonic booms indoors at 133.15 dB SPL (possibly +/- 6 dB)
Carr & Davies 2015 (USA)	30 (NASA test) & 35 (Purdue test)	Simulated and recorded low sonic booms; door slams, explosions, gunfire;	Annoyance (5-point scale; NASA: slider could be moved to any	Experiment	Both indoor and outdoor acoustic metrics are suitable for annoyance models. Models with multiple metrics and high variance explanation included PL, duration, H, loudness; loudness and annoyance capture different concepts; the role of low-frequency

Authors, year	Population	Exposure	Outcomes	Study design	Results
		PL, PNL, A, B, C, E SEL, long-term and short-term loudness, Zwicker loudness, duration, H (CSEL-ASEL); NASA with simulator and Purdue with headphones	position; Purdue according to Fields et al. 2001)		components differs between loudness and annoyance; the best single-metric models include maximum Zwicker loudness and PL
Carr, Davies, Loubeau, Rathsam & Klos 2020 (USA)	30 (NASA test) & 35 (Purdue test)	Simulated and recorded low sonic booms; door slams, explosions, gunfire; PL, PNL, A, B, C, E SEL, long-term and short-term loudness, Zwicker loudness, duration, H (CSEL-ASEL); NASA with simulator and Purdue with headphones	Annoyance (5-point scale; NASA: slider could be moved to any position; Purdue according to Fields et al. 2001)	Experiment	Loud sonic booms are the most annoying, mostly synthetic and not 50 Hz high-pass filtered; less annoyance with noises with lower frequencies; the Purdue group's annoyance rating is higher for annoyance values below 5, and the NASA group's average annoyance indicates a saturation effect; higher amplitude is associated with higher annoyance; low frequencies between 25-50 Hz could lead to higher annoyance if sufficiently present; results from Purdue and NASA correlate highly with each other when vibrations are absent or low; no difference in annoyance below 25 Hz, but differences in annoyance below 50 Hz
Chiles & West 1972 (USA)	24	8 simulated sonic booms per hour per night (6th–17th test night) with 127.85 dB SPL outdoors	Performance tasks (monitoring, mental arithmetic, pattern recognition)	Experiment	No effects of night-time sonic booms on performance tasks
Clark 1967 (USA, Edwards)	approx. 300	Real sonic booms, 3-8 per day, 4 years	Acceptance	Experiment	Sonic booms heard outdoors are less acceptable than those heard indoors; the perceived annoyance of sonic booms increased faster than the intensity or loudness of the sonic booms; 27% of Edwards residents and 40% of residents in other municipalities consider sonic booms at 132.14 dB SPL to be almost intolerable; Participants reacted more sensitively to sonic booms than to conventional aircraft noise; differences of 1 dB in sonic booms could be perceived and distinguished by participants; 71% stated that sonic booms are the most unacceptable noise they have ever heard

Authors, year	Population	Exposure	Outcomes	Study design	Results
Collins & Iampietro 1972 (USA)	24	Simulated sonic booms, hourly, 6th-17th night, 127.58 dB SPL outdoors	Awakenings, sleep rhythm (BSR[3] , EEG, ECG[4] , EMG[5] , EOG[6])	Experiment, 21 consecutive days	None of the measurements showed a significant effect of sonic booms on sleep rhythm; in all participants, individual sonic booms led to changes in ECG, EMG and BSR; within one minute of a sonic boom, the heart rate increased; EMG reactions occurred in 40-45% of sonic booms and BSR changes occurred in 19% of sonic booms; these reactions occurred more frequently with increasing age; measured reactions were roughly comparable to reactions to a passing truck at 40-45 dB(A)
Fidell, Silvati & Pearsons 2002 (USA)	29	Simulated sonic booms indoors and recorded regular aircraft; 97 pairs: B-727 take-off (ASEL); short and long sonic booms with and without rattle (CSEL); 63 Hz and 1 kHz octave bands	Annoyance (pair comparisons)	Experiment	Noises with a low-frequency octave band were just as annoying as sonic booms, and both were rated 10 dB lower than noises with more high-frequency components; no difference between the different durations of the sonic booms; rattle had a significant effect: 73 dB without rattle and 78 dB with rattle; annoyance was positively correlated with sonic boom levels; the increase in annoyance caused by sonic booms without rattle was 2:1 compared to regular aircraft noise and more high-frequency noise (CSEL); at the same level of annoyance, the average dB values of non-impulsive variables were 5 dB higher for sonic booms with rattle compared to sonic booms without rattle
Galloway, Johnson, Kryter, Schomer & Westervelt 1981 (USA)			Annoyance	Reanalysis	Annoyance increases more rapidly with higher levels for high-energy impulsive noises than for conventional noises (see also Kryter 1968 and Borsky 1965).
Griefahn & Jansen 1975 (Germany)	2	2 - 16 sonic booms on exposure nights (127.6 - 137.2 dB SPL (80 – 89 dB(A); M = 83.5 dB(A)), typical N-wave, duration of 300 ms	Sleep (finger pulse amplitude, EEG)	Experiment, 57 nights	Sleep disturbances were observed across all noise scenarios; no habituation effect; a tendency to compensate was observed on nights with 4 sonic booms; sonic booms significantly shortened the deep sleep phase
Griefahn 1975a (Germany)	4 (2 per experiment)	2–16 sonic booms on exposure nights (127.6–137.2 dB SPL (80–89	Sleep (finger pulse amplitude, EEG)	Experiment	Significant decrease in finger pulse amplitude, 3 seconds after exposure, followed by increase to previous value; no correlation between sonic boom volume and finger pulse amplitude

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[3] BSR = Basal Skin Resistance

[4] ECG = Electrocardiogram

[5] EMG = Electromyogram

[6] EOG = Electrooculogram

Authors, year	Population	Exposure	Outcomes	Study design	Results
		dB(A); M = 83.5 dB(A)), typical N-wave, duration of 300 ms			
Griefahn 1975b (Germany)	4 (2 per experiment)	2–16 sonic booms on exposure nights (127.6–137.2 dB SPL (80–89 dB(A); M = 83.5 dB(A)), typical N- wave, duration of 300 ms	Sleep (finger pulse amplitude, EEG)	Experimen t	Significant decrease in finger pulse amplitude, 3 seconds after exposure, followed by increase to previous value; no correlation between sonic boom volume and finger pulse amplitude
Higgins & Sanlorenzo 1975 (USA)	42	15 simulated sonic booms, 83-107 dB PL, 80-100 ms	Annoyance, acceptance	Experimen t	At the same level dB PL, sonic booms heard indoors are significantly less acceptable than if they were heard outdoors; if a sonic boom of 90 dB PL is heard indoors and measured outdoors, 98% find it acceptable; if the sonic boom is both perceived and measured indoors, this results in an equivalent of 98% acceptance at 69 dB PL; 80% acceptance results at 90 dB PL when the sonic boom is heard and measured outdoors.
Kryter, Johnson & Young 1967 (USA, Edwards)	Approx. 300	Real sonic booms, aircraft (measured indoors)	Acceptance (13-point scale: very acceptable to unacceptable)	Experimen t	Participants who had been exposed to sonic booms for several years showed higher acceptance compared to participants with no previous exposure experience; Participants with previous exposure rated a sonic boom of 132.19 dB SPL as less acceptable than conventional aircraft noise of 109 dB PNL; frequencies between 20 and 500 Hz seem to be the main cause of reactions to sonic booms
Kryter, Johnson & Young 1968 (USA, Edwards)	Approx. 300	Real sonic booms, aircraft (measured indoors)	Acceptability (13-point scale: very acceptable to unacceptable)	Experimen t	Participants who had been exposed to sonic booms for several years showed higher acceptance compared to participants with no previous exposure experience; Participants with previous exposure rated a sonic boom of 132.19 dB SPL as less acceptable than conventional aircraft noise of 109 dB PNL; frequencies between 20 and 500 Hz seem to be the main cause of reactions to sonic booms
Leatherwood & Sullivan 1992 (USA)	40	Simulated asymmetric and symmetric N-wave; sonic boom signatures with varied rise times and overpressure levels, duration of 300 ms; ASEL, PL; 225 test stimuli	Loudness	Experimen t	At the same PL, asymmetric signatures were less loud than symmetric signatures; depending on the direction of asymmetry, loudness decreased to varying degrees with higher sonic boom asymmetry.

Authors, year	Population	Exposure	Outcomes	Study design	Results
Leatherwood & Sullivan 1993 (USA)	72	Simulated outdoor and indoor sonic booms; two conditions: open and closed windows; 135 simulated N-wave and FSM (front shock minimised) signatures	Loudness, annoyance	Experiment	Loudness and annoyance are equally suitable as measurement criteria for outdoor sonic booms, but not for indoor sonic booms; indoor annoyance was significantly higher than indoor loudness; PL suitable for predicting noise effects of sonic booms
Leatherwood & Sullivan 1994 (USA)	96 (32/experiment)	Simulated sonic booms (symmetrical N-wave with 1 ms and 3 ms rise time; recorded regular aircraft noise (indoors); PL, PNL, CSEL, ASEL	Annoyance: Experiments 1 and 3: 11-point scale; Experiment 2: Pair comparisons	Experiment	Almost all sonic boom levels were higher than regular overflight noise at the same annoyance level, with the exception of ASEL
Lee, Rathsam & Wilson 2020 (USA, Galveston)	371	52 quiet sonic booms; 56-90 dB PL	Annoyance (sonic boom heard; 5-point scale)	Field	1% HA; comparison of multilevel logistic and ordinal regression models: exposure-response curves are very similar, but differ when exposure is calculated for a specific % HA (difference of 2.5 dB is within the CI); comparison with WSPR: similar annoyance values, although WSPR participants had previously been exposed to sonic booms
Ludlow & Morgan 1972 (United Kingdom)	16	Simulated sonic booms: 71.2, 74.2 and 77.6 dB(A) in the first experiment and 69, 79 and 84.5 dB(A) in the second experiment	Waking up by pressing a button, Subjective Stress Scale, Subjective Fatigue Scale, Clyde Mood Scale, personality test, sleep questionnaire	Experiment	First experiment: no influence on the frequency of awakening (pressing the button); exposure to sonic booms had a significant influence on the values of the Subjective Fatigue Scale 2nd experiment: significantly more frequent awakenings during nights of exposure, and the louder the sonic booms, the more frequently participants woke up; all sleep-related tests showed significantly worse values the louder the sonic booms were
Lukas & Dobbs 1972 (USA)	8	Simulated jet flyovers (101, 113, 119 dB PNL), sonic booms (124.1, 135.54, 141.56 dB SPL), measured outdoors	Awakenings (EEG)	Experiment, 14 consecutive days	42% of jet flyover noises and 15% of sonic booms led to awakenings; compared to men (data from another study), women woke up more often due to jet flyovers and less often due to sonic booms
Lukas & Kryter 1968 (USA)	8	Simulated sonic booms (outdoors), jet overflights; 127.58 dB SPL outdoors;	Startle (EMG), awakenings (EEG, REM[7]	Experiment	In stage 2 sleep, sonic booms at 127.58 dB SPL and 133.6 dB SPL outdoors led to significantly more awakenings than quieter sonic booms (n=2); Adaptation to lower

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[7] REM = Rapid Eye Movement sleep

Authors, year	Population	Exposure	Outcomes	Study design	Results
		duration 100 ms; 10 ms rise time	using electrodes); motor performance task		levels; startle responses occur; in motor performance tasks, sonic booms led to slower speeds among participants, but had no effect on accuracy
Mabry & Oncley 1973 (USA)	12 families	Simulated sonic booms, daytime (3 levels and 2 frequency distributions)	Acceptance, disturbance, annoyance	Field (in-home community noise simulation system)	A level of 87 dB (Stevens' Mark VI) is proposed as the sonic boom design/certification threshold for the acceptance of sonic booms in relation to indoor living with no more than 15 sonic booms per day and no night-time exposure to sonic booms.
Mabry & Parry 1973 (USA)	50	Simulated sonic booms between 127-136.68 dB SPL and rise times of 7 ms and 15 ms	Sleep, rest, dozing, disturbances	Experiment	No difference in EEG measurements; the majority of participants (92%) did not feel disturbed by sonic booms, but sonic booms with shorter rise times are more disturbing; 94% were not disturbed by sonic booms at 100 dB PNL; to achieve approximately 100% acceptance among the population, sonic booms should probably not be louder than 90 dB PNL
May 1972 (Germany)	39	Overflights generated 53 sonic booms (only sonic booms audible outdoors were taken into account→ N-Wave); 131 dB SPL; 2 ms - 39 ms rise time	Startle (reference: door slamming), location	Field, 10 consecutive days	Shorter rise times are associated with higher startle values at the same dB level
McCurdy, Brown & Hilliard 2004 (USA)	33	4-63 simulated sonic booms per day; 56 days; conventional N-waves indoors and outdoors and shaped N-waves outdoors; 66, 70, 74 dB ASEL; 4, 10, 13, 25, 33, 44, 63 times within a 14-hour test period SEL, ASEL, CSEL), Zwicker loudness, PNL, PL	annoyance (11-point scale), activities, location, startle (yes/no)	Field (in-home noise generation)	Annoyance increases with higher number of sonic booms; PL was significantly better at predicting annoyance than other metrics; no significant difference between waveforms; higher annoyance when person also shows startle response; higher annoyance equivalent to 1.5 dB per hour sleeping, napping & resting; lower annoyance (0.75 dB) per hour of communication and watching television/listening to the radio or similar (0.5 dB); higher annoyance, equivalent to an increase of 0.25 dB per year of age
Niedzwiecki & Ribner 1979 (Canada)	25	Simulated sonic booms, N-wave, rise time 1 ms and duration 150 ms;	Loudness, annoyance (pair comparisons)	Experiment	Lower frequencies resulted in slightly less loudness and slightly more annoyance

Authors, year	Population	Exposure	Outcomes	Study design	Results
		frequencies below 25 Hz and 50 Hz were cut off			
Nixon & Borsky 1966 (USA, St. Louis)	1043	66 supersonic flights; overpressure measurement of sonic booms	Complaint behaviour	Field (before/after survey)	Inside a building, sonic booms were less acceptable than outside, possibly due to their longer duration, the rattling or shaking of objects and vibrations; no overpressure limit below which no reactions to sonic booms occur or all sonic booms are acceptable; Reactions to sonic booms were highly variable and complex; although almost all residents reported disturbances caused by sonic booms, the annoyance was relatively low; The total number of complaints was related to the number of overflights. Military-induced sonic booms are more acceptable than sonic booms from commercial air traffic. Commercial supersonic air traffic was considered important by only a few participants. Acceptance was lower at night than during the day. A single overpressure value as a predictor of acceptance seems to make little sense.
Nixon & Hubbard 1965 (USA, St. Louis)	1043	66 supersonic flights; overpressure measurement of sonic booms	Disturbances, annoyance, complaints	Field (before/after survey)	Building vibrations and startle reactions were cited as the most common disturbances; 90% reported a few disturbances, 35% were annoyed, less than 10% wanted to complain and less than 1% did complain; within 3 months of the main study being completed (66 overflights), 74 further flights took place, leading to a significant increase in complaints
Nixon et al. 1968 (USA)	Staff & residents	4 real sonic booms per day, generated by F-4C, 165-170 dB SPL under flight path & 161-169 dB SPL at various distances	Observation of effects on personnel, interruptions to tasks, startle; reported physiological symptoms from residents	Field	Even very loud sonic booms do not cause direct injury to humans; residents reported no physiological symptoms; personnel: task performance was not interrupted, startle response was observed, as was ducking or flinching
n.a.* 1970 (USA)	6	Simulated sonic booms, jet flyovers	Sleep (EEG, push button)	Experiment	Age group difference (old, middle-aged, young): 67% of the time, the older group woke up due to sonic booms and jet noise, the middle-aged group 5% of the time and the children 2%; older group shows some adaptation in the second sleep phase
Rathsam, Klos & Loubeau 2015 (USA)	30	Simulated and recorded low sonic booms, vibration (insulated and non-insulated chair), gunshots, car doors slamming, explosions (47-87 dB PL)	Annoyance (5-point scale)	Experiment	Average annoyance depends on previous annoyance assessment (previously insulated or non-insulated chair)→ Reanalysis with only one insulation group (n=15) shows a small effect of vibration on annoyance

Authors, year	Population	Exposure	Outcomes	Study design	Results
Rathsam, Loubeau & Klos 2015 (USA)	33	Simulated low sonic booms and recorded rattle; 124 signals: combination of sonic booms (65, 73, 81 dB PL) with and without rattle and with different amplitudes; PL CSEL, ASEL	Annoyance (cursor on continuous scale translated into value between 0 (not at all) and 4 (extreme)	Experiment	Indoor PL is well suited for predicting indoor annoyance from low sonic booms with and without rattle; fictitious annoyance models that include indoor rattle are useful, although psychological factors are not taken into account; annoyance models with rattle effects can be expressed in terms of outdoor noise
Rylander & Dancer 1978 (France)	39	Simulated sonic booms (133.97, 137.5, 140 dB SPL), rise times of 1 ms, 5 ms, 8 ms; duration 300 ms; with and without traffic noise (group 1: 60 dB(A); group 2: 75 dB(A))	Startle (via hand stability measurement)	Experiment	Startle responses decreased for low and medium sonic boom levels; at high levels, startle responses decreased more slowly and did not reach a plateau; habituation effect was evident, number of participants showing a startle response remained the same; greater startle response with shorter rise times of sonic booms
Rylander, Sörensen & Berglund 1972 (Sweden)	189 soldiers for sleep study (179 also took part in survey), 212 civilians (survey)	7 real sonic booms with 109.5-130.1 dB SPL (always at 04:25)	Sleep (press button & bed motion sensor under bed; control nights without booms); annoyance, frequency of awakenings, evaluation and comparison of sonic booms with traffic noise, gunfire noise, conventional aircraft noise and thunderstorms; personality test; questionnaire: number of booms perceived, difficulty falling asleep after waking	Field	Reactions were related to the outdoor overpressure of the sonic booms; at 129.5 dB SPL, soldiers showed a 10% increase in the probability of waking up; no correlation between rise time, overpressure and bed movements or pressing the button; Soldiers who woke up due to sonic booms had higher neurotic scores; 2% reported difficulty falling back asleep, 21% found the sonic booms annoying and 3% found them very annoying; no effects were found at 109.5 dB SPL; 56% of civilians reported difficulty falling back asleep at 129.5 dB SPL; regardless of the number of sonic booms actually heard, most civilians rated the sonic booms as annoying; 50% of those who had heard 3 or more sonic booms were severely annoyed; more sleep disturbances are reported with increasing age
Rylander, Sörensen, Berglund &	33 women (testing, survey), 165	42 real sonic booms; up to 142.2 dB SPL	Visual performance task, tracking task, annoyance, activities	Experiment, field	Sonic booms led to fewer correct answers in the visual performance task, and in the tracking task, accuracy decreased significantly at both lower and higher sonic boom levels.→ Sonic boom level has no influence, but exposure itself does; a survey showed

Authors, year	Population	Exposure	Outcomes	Study design	Results
Brodin 1972 (Sweden)	soldiers (survey)				that the proportion of soldiers who felt annoyed increased significantly with increasing sonic boom levels up to 133.9 dB SPL; with increasing sonic boom levels, %HA increases linearly; at 133 dB SPL, 50% said they felt annoyed and at 132 dB SPL, 8% felt very annoyed; More soldiers than test participants reported being annoyed: Participants had a more positive attitude towards sonic booms, and sonic booms sound rounder inside a building than outside.
Schomer 1978 (USA)			Disturbance	Reanalysis	Growth function as result: a 10 dB increase is accompanied by a doubling of annoyance
Schomer, Sias & Maglieri 1997 (USA)	232	20 real sonic booms (120–135 dB), 30 explosions (125–130 dB); comparison with white noise; ASEL, CSEL; tests in heavy brick house, timber-framed building, mobile office trailer; one 2.5-hour test per day in each case	Annoyance (pair comparisons)	Experiment	At the same CSEL, the annoyance caused by sonic booms is higher than that caused by explosions (5 dB difference); in addition, outdoor CSEL correlates better with the annoyance recorded indoors than indoor CSEL.
Shepherd & Sutherland 1967 (USA)	20-40	Simulated sonic booms; varying rise times and durations; 0.5 N-wave (standard and N-sawtooth)	Annoyance, loudness	Experiment	Longer rise times are associated with lower annoyance and loudness; duration has no effect; the spike-bow modification resulted in higher loudness
Smith & Hutto 1972 (USA)	24	Simulated sonic booms; hourly exposure on nights 6–17; outdoors: 127.58 dB SPL; measured in bedrooms: 107.58 dB SPL	Mood changes (Composite Mood Adjective Checklist)	Experiment, 21 consecutive nights	Sonic booms had no effect on mood (as a proxy for sleep); according to the authors, sonic booms at such low levels are unlikely to have a negative effect on mood
Sullivan & Leatherwood 1993a (USA, White Sands)	48	Simulated and recorded sonic booms (optimised N-wave, optimised booms with medium shocks); the recorded sonic booms included the following	Loudness	Experiment	In terms of PL, there are no differences in loudness assessment between the different shape categories→ PL is responsible for waveform differences; optimised sonic booms with intermediate shocks were assessed as quieter than recorded sonic booms (2.7 dB PL less loud)

Authors, year	Population	Exposure	Outcomes	Study design	Results
		shape categories: N-wave, pointed, rounded, U-shaped; PL, Zwicker loudness level			
Sullivan & Leatherwood subjective 1993b (USA)	48	Sonic booms from N-Wave and minimised signatures with front shock times of 3, 6 and 9 ms and a duration of 300 ms; reflected sonic booms with a delay of 0–12 ms	Loudness	Experiment	Reflected sonic booms with delay (≠ 0 ms) were perceived as less loud than sonic booms without reflection delay (0 ms); in particular, when the delay and front shock rise time were the same, the loudness was lowest and was sometimes accompanied by a reduction of up to 6 - 7 dB; PL is well suited for measuring loudness
Thackray, Rylander & Touchstone 1973 (Sweden)	60	Real supersonic and subsonic flights (129.5–146.44 dB SPL); testing of habituation effect; starting pistol as reference (107 dB)	Startle (hand stability, video recorded)	Experiment (6 days)	Average reaction amplitude differed significantly between low and high exposure; older participants showed fewer startle reactions; no habituation effect; 10% of participants showed a startle reaction at outdoor levels of 130.8–135.5 dB SPL and 75% at 143.5 dB SPL; at outdoor levels of 137.5–139 dB SPL, there was an abrupt increase in startle responses; it is questionable whether the entire population would ever show an habituation effect; the threshold for startle responses is probably 127.95 dB SPL or less
Thackray, Touchstone & Bailey 1973 (USA)	20	Simulated sonic booms (outdoor SPL 127.95–137.5 dB); rise time of 5.5 ms; indoor measurements (dB and dB(A)); comparison with pistol shot	Arm-hand startle, skin conductance, heart rate, blink reflex	Experiment	Significant difference in startle frequency between lower and higher sonic boom levels; no difference between lower and higher levels in terms of degree of startle response; a small percentage showed a slight startle response (arm/hand) at 127.95 dB SPL; lower levels appear to lead more to orientation responses and higher levels to startle responses; no difference between exposure groups to the pistol shot
Thackray, Touchstone & Jones 1971 (USA)	40	4 simulated sonic booms outdoors over a 30-minute period; 127.58 dB SPL, 133.6 dB SPL, 139.6 dB SPL; 295 ms	Tracking task, skin conductance, heart rate	Experiment	No effect on performance was found for any of the overpressure levels; after a sonic boom, performance improved significantly and skin conductance and heart rate also increased→ this may be more of an alarm or orientation response than a startle response; however, rise times should be taken into account
Töpken & van de Par 2020 (Germany)	16	24 simulated and recorded sonic booms (low sonic booms, conventional N-wave outdoor); different	Loudness (11-point scale 0 = not loud at all, 10 = extremely loud), short-term annoyance (11-	Experiment	Higher ASEL is associated with higher annoyance and loudness values; annoyance and loudness increase by 2–3 scale points for every 6 dB increase (for all signatures)

Authors, year	Population	Exposure	Outcomes	Study design	Results
		signature shapes; maximum pressure of 55.5 - 69.8 dB(A); peak overpressures of 106.5 dB SPL - 123.1 dB SPL	point scale 0 = not annoying at all, 10 = extremely annoying); noise sensitivity, attitudes towards traffic and traffic noise; residential satisfaction		
Töpken & van de Par 2021 (Germany)	16	24 simulated and recorded sonic booms (low sonic booms, conventional N-wave outdoor); different signature shapes; maximum pressure of 55.5 - 69.8 dB(A); peak overpressures from 106.5 dB SPL to 123.1 dB SPL	Loudness (11-point scale 0 = not loud at all, 10 = extremely loud), short-term annoyance (11-point scale 0 = not annoying at all, 10 = extremely annoying); noise sensitivity, attitudes towards traffic and traffic noise; residential satisfaction	Experiment	Higher ASEL is associated with higher annoyance; medium and high frequencies (> 1 kHz) play a greater role in annoyance and loudness ratings than frequencies below 1 kHz; providing information about the study has no effect; loudness and annoyance ratings are related; gender effect
Tracor, Inc. 1972 (USA)			Annoyance, disturbances	Reanalysis	Merging and reanalysis of two data sets from NASA projects to identify any effect of the participants' environment on the impact of sonic booms: for example, participants who were already exposed to conventional aircraft noise showed stronger reactions to aircraft noise than to sonic booms, and participants who had not previously experienced regular exposure to aircraft noise showed stronger reactions to sonic booms; attitudes towards the source are related to the living environment

Note: *n.a. = no author