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Final report

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Abstract: Annoyance and sleep disturbance due to noise from air-source heat pumps and air conditioners

Air-source heat pumps (AHPs) are increasingly being installed in residential areas due to energy transition efforts, resulting in changes in noise exposure in former quiet neighbourhoods. This project aimed to investigate the noise impact of AHPs on sleep and daytime functioning and mood. Two laboratory studies were conducted, comprising a night-time sleep study and a daytime experiment, involving 40 healthy, adult subjects.

In the sleep study using polysomnography (PSG), subjects spend 3 nights exposed to 3 different noise conditions: 1) AHP noise with simulated closed or 2) tilted windows, along with a 3) quiet baseline condition. In the daytime study, subjects were exposed to AHP noise while reading texts, and their responses were compared to a quiet baseline condition. In the sleep study, small but statistically significant effects of AHP noise were observed between the two noise conditions with simulated closed and tilted windows, indicating increased noise-related arousals with tilted windows. The results of the daytime study indicated that AHP noise led to increased annoyance, difficulties in concentrating on the text, and mood disturbances. A sequence effect was noted, with more negative effects observed when the noise condition followed the quiet condition, suggesting a short-term 'change effect' in response to noise.

This research highlights the need to address the growing presence of AHPs in residential areas and their associated noise issues. Future studies should consider conducting field research to better understand the effects of AHP noise in real-life settings and develop solutions to ensure the compatibility of sustainable energy systems with healthy neighbourhood conditions.

Kurzbeschreibung: Ermittlung der Relation zwischen Belästigung und Belastung durch Lärm von Luftwärmepumpen und Klimageräten

Im Zuge der Energiewende werden zunehmend Luftwärmepumpen (LWP) in Wohngebieten installiert, was zu einer veränderten Lärmbelastung in ehemals ruhigen Wohngebieten führt. Ziel dieses Projekts war es, die Auswirkungen des Lärms von LWP auf den Schlaf, die Tagesfunktionen und die Stimmung zu untersuchen. Es wurden zwei Laborstudien durchgeführt; eine nächtliche Schlafstudie und ein Tagesexperiment mit 40 gesunden, erwachsenen Versuchspersonen.

In der Schlafstudie mit Polysomnographie (PSG) wurden die Versuchspersonen drei Nächte lang drei verschiedenen Lärmbedingungen ausgesetzt: 1) LWP-Lärm mit simulierten geschlossenen oder 2) gekippten Fenstern sowie 3) ruhige Ausgangsbedingungen. In der Tagesstudie wurden die Versuchspersonen während des Lesens von Texten LWP-Lärm ausgesetzt und ihre Reaktionen wurden mit einer ruhigen Ausgangsbedingung verglichen. In der Schlafstudie wurden geringe, aber statistisch signifikante Auswirkungen von LWP-Lärm zwischen den beiden Lärmbedingungen mit simulierten geschlossenen und gekippten Fenstern beobachtet, mit erhöhten lärmassoziierten Arousals bei gekippten Fenstern. Die Ergebnisse der Tagesstudie zeigten, dass LWP-Lärm zu erhöhter Lärmbelästigung, Schwierigkeiten bei der Konzentration auf den Text und Stimmungsstörungen führte. Es wurde ein Sequenzeffekt festgestellt, d. h. es wurden mehr negative Auswirkungen beobachtet, wenn der Lärmzustand auf den ruhigen Zustand folgte, was auf einen kurzfristigen 'Change-Effekt' bei der Reaktion auf Lärm hindeutet.

Diese Untersuchung unterstreicht die Notwendigkeit, sich mit der zunehmenden Präsenz von LWPs in Wohngebieten und den damit verbundenen Lärmproblemen zu befassen. Zukünftige Studien sollten die Durchführung von Feldforschung in Betracht ziehen, um die Auswirkungen von LWP-Lärm in realen Umgebungen besser zu verstehen und Lösungen zu entwickeln, um die Kompatibilität von nachhaltigen Energiesystemen mit gesunden Nachbarschaftsbedingungen zu gewährleisten.

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List of abbreviations

AASM	American Academy of Sleep Medicine
AHP	Air-source heat pump (Air-to-water heat pump)
ASR	Advanced Sleep Research GmbH
ASTS	Aktuelle Stimmungs-Skala (*Current Mood Scale*)
BMI	Body Mass Index
dB	Decibel
dB(A)	A-weighted decibel
ECG	Electrocardiogram
EEG	Electroencephalogram
EMG	Electromyogram
EOG	Electroocculogram
ESS	Epworth Sleepiness Scale
Hz	Hertz
ISI	Insomnia Severity Index
kHz	Kilohertz
KSS	Karolinska Sleepiness Scale
kW	Kilowatt
L_{Aeq}	A-weighted continuous sound level
L_{AF}	A-weighted sound level with fast time-weighting
L_{AFTeq}	Average sound level over L_{AFTm5}
L_{AFTm5}	Maximum level in a 5 s interval (A-weighted level with fast time-weighting)
PSG	Polysomnography
PSQI	Pittsburgh Sleep Quality Index
RIP	Respiratory inductance plethysmography
R_w	Weighted sound reduction index
REM	Rapid eye movement
SD	Standard deviation
SE	Sleep efficiency
SE	Standard error
SEL	Sound exposure level
SF-A	Schlaffragebogen A (*Sleep Questionnaire A*)
SOL	Sleep onset latency
TIB	Time in bed
TST	Total sleep time
UBA	German Environment Agency (*Umweltbundesamt*)
WHO	World Health Organization

Summary

Due to the energy and heat transition, air-source heat pumps (AHP) have recently been and will be increasingly installed and operated in the immediate residential environment. Because of technological change, these systems are no longer reserved for commercial and industrial areas (e.g., for heating and cooling office buildings, retail establishments, or production facilities) and are increasingly present in the immediate vicinity of single- and multi-family homes. Therefore, the noise exposure situation in previously quiet residential areas has already changed. Especially in formerly quieter times in the evening and at night-times, AHPs and air conditioners (AC) are now humming. Complaints and lawsuits about the noise exposure of those stationary sources have increased in recent years.

However, the binding guideline values of Technical Instructions on Noise Protection (TA Lärm) are usually not exceeded by the noise of AHPs or AC. Still, those affected are annoyed by the noise and often complain about the allegedly insufficient level of protection provided by these regulations (Eulitz et al. 2020).

This project investigated the noise impact of the noise from AHP. To examine these effects during the day and at night, two laboratory studies were conducted under controlled conditions. Sleep under different noise conditions was examined in a polysomnographic[1] study to determine the nocturnal effects; daytime effects on annoyance, concentration, and mood were studied in a psychological experiment.

The key hypotheses stated that nocturnal AHP noise has an influence on the micro- and macro-structure of sleep and that there is a temporal relationship between the occurrence of changes in the noise pattern and disturbances of the sleep structure. For the effects in the waking state, it was hypothesised that exposure to noise while reading a text would have a negative influence on mood, concentration while reading a text, and noise annoyance compared to a quiet condition. Furthermore, it was hypothesised that noise exposure would be evident in measurements of blood pressure and heart rate compared to the baseline condition.

Study design

Two studies were designed with a night-time sleep study and a daytime study investigating the effects of AHP noise on sleep and daytime concentration, mood, and annoyance.

The studies were conducted from September 2020 to November 2021 and took place in the sleep laboratory of Advanced Sleep Research GmbH (ASR) in Berlin. For the night-time sleep study, two sleeping rooms were prepared and equipped with an appropriate setup for acoustic measurement and playback. In total, 40 subjects – 21 women and 19 men - participated in both laboratory studies. For the sleep study each subject was examined in three study nights while exposed to three different sound conditions. Subjects came to the lab once a week for one night for three weeks in a row (e.g. three Mondays).

For the night-time sleep study, the three study night conditions were:

- Noise condition 1: Quiet night, Baseline
- Noise condition 2: Night with AHP noise with (simulated) window partially opened (tilt position)
- Noise condition 3: Night with AHP noise with (simulated) window closed

[1] Procedure for measuring physiological functions during sleep

The daytime examination took place once after the 3rd (last) study night and consisted of two experimental conditions, each lasting 15 minutes:

- Noise condition: AHP noise with (simulated) window partially opened (tilt position)
- Baseline condition: Quiet

Each subject participated in both experimental conditions.

During the two daytime noise conditions subjects were asked to read texts. The approach of an *imaginative everyday situation* was applied: Subjects were instructed to read the texts while imagining being at home performing the task. After each experimental condition, the subjects' physiological parameters such as pulse rate, systolic blood pressure, and diastolic blood pressure were measured. Subsequently, the subjects were asked to complete a questionnaire.

Both experimental studies were conducted as double-blind studies, i.e., the investigator as well as the subjects were not informed about the order of noise presentations or which test condition was conducted in each night or daytime test situation.

Sample and Instruments

A database of healthy individuals was used to recruit the subjects. Inclusion criteria included the age range 18-65 years, no sleep disturbances, normal functionality of hearing and eye-sight among others. In addition, exclusion criteria applied were no current participation in clinical pharmacological studies, drug or alcohol abuse, acute or chronic illnesses requiring treatment or neurologic and psychiatric diseases, and medication use that affect the sleep-wake rhythm.

Different physiological and psychological measures were applied to investigate the influence of AHP noise on sleep and waketime parameters (noise annoyance, concentration, mood). Measurement of sleep structure was performed by polysomnography (PSG) over eight hours according to the international standards of the American Academy of Sleep Medicine (AASM) (Berry et al. 2020). Polysomnographic measures included, for instance, channels of electroencephalogram (EEG), and electrocardiogram (ECG). The following parameters were determined: time in bed (TIB); total sleep time (TST); sleep efficiency (SE); sleep onset latency (SOL); the sum of the time spent in the individual sleep stages (N1, N2, N3, R) and time being awake (temporal resolution 0.5 minutes); the number of arousals and other physiological sleep and activity-related parameters. Arousals were defined as noise associated if they occurred within a time window of 90 sec after a sound event (sound resulted from different operating states, tonal components or short impulse noise of the AHP).

Self-reported sleep parameters were assessed using standardized sleep questionnaires handed in the evening before sleep and in the morning to assess sleep quality, sleepiness, and sleep disturbance linked to noise.

During the daytime study, perception of presented sounds was assessed by asking if and how subjects perceived the sound characteristics. Further, questions regarding text comprehension (reading, motivation), mood, and concentration were assessed. Conditions of subject's living situation regarding building type, window type, ventilation behaviour, sleep quality, and the influence of the Covid-19 pandemic were inquired to consider effects arising from the subject's home situation.

Acoustic set-up and stimuli

The sound emitted by an air-source heat pump (AHP) is made up of various components: While in continuous operation a broadband noise-like sound is in the foreground, tonal components or short impulse noise can also occur. The stimuli for the study were generated from measurements on various AHP in real environments. Two sound scenarios were then compiled from the audio material obtained from this system: One for the presentation during the sleep study and one for the daytime study. The noise scenario for the sleep study comprised 60 minutes, which included different operating states as well as a silence period. Noise levels were selected according to realistic operations. Different noise levels resulted from the different operating states and simulated window positions (tilted and closed). This noise cycle was presented eight times each night and formed the noise condition. For the daytime study, a shorter noise scenario of approx. 15 minutes was created.

The sound presentation in both laboratory studies was done via loudspeakers that were set up in the study rooms, which is why the noise transmission from outside to the inside had to be simulated. For this purpose, the average level (maximum average level L_{AFTeq} of the unfiltered signal) of the one-hour noise scenario (including all quiet periods) was first set to 45 dB at approx. 0.5 m from the loudspeaker, in order to represent the noise situation of a possible worst full night hour 'in front of the (simulated) window'. Subsequently, the noise was spectrally filtered to simulate the transition through the closed or tilted window.

Results

Between-group comparisons between study nights did not reveal any differences in sleep parameters for the three noise conditions ('baseline', 'window tilted', and 'window closed'). However, comparing the number of arousals during the two noise conditions ('window tilted' and 'window closed') revealed that a higher total number of arousals (sum of spontaneous, respiratory, and motoric arousals) associated with noise events occurred in the 'window tilted' condition than in the condition 'window closed'. The same was found for the number of spontaneous arousals associated with noise events. The difference of number of spontaneous arousals associated with noise between noise condition 2 and noise condition 3 was sex-specific indicating an interaction between the factors sex and noise condition: men exhibit lower mean values of spontaneous arousals associated with noise events during noise condition 3 but without significance whereas a significant change was observed among women. Noise-related spontaneous arousals were further positively correlated with sleepiness (measured with the Epworth Sleepiness Scale), meaning that more spontaneous arousals were related to greater daytime sleepiness.

The analysis of the sleep questionnaires revealed no differences in sleepiness between the three noise conditions. However, it was found that the mean difference between the evening sleepiness before PSG and the sleepiness in the morning after PSG was negative for noise condition with the simulated 'window tilted'; i.e. the average sleepiness was higher in the morning in comparison to the evening before. For the other two noise conditions the relationship was reversed.

In the psychological experiment at daytime the effect of AHP noise in comparison to a quiet baseline condition while reading a text was investigated. Most subjects noticed the AHP noise in the noise condition. Of the 33 subjects perceiving the noise, 11 subjects indicated the noise to sound like 'air conditioning' or 'ventilation systems'.

Analysis of covariance was executed to analyse potential differences in noise annoyance, difficulties in concentration on text, mood, blood pressure and heart rate between the baseline condition and the noise condition. In the analysis the effect of the covariates noise sensitivity, age, sex and order of presentation of the conditions were controlled. Main effects were found for noise annoyance due to AHP noise, difficulties in concentration on the text as well as for mood. Blood pressure and heart rate did not significantly differ between the two conditions.

An interaction effect was found for the order of the conditions in interaction with the conditions for noise annoyance and difficulties in concentration on the text. The direction of noise annoyance was equal between the conditions; in both orders, the annoyance was higher in the noise condition in comparison to the baseline. In the baseline condition subjects reported on average almost no noise annoyance regardless of the order of the conditions. However, the level of annoyance in the noise condition differed and was significantly higher in the noise condition when the noise condition follows the baseline condition. The previous condition seemed to serve as a reference condition, in this case the quiet surrounding. Similarly, effects of the order of experimental conditions can be reported for difficulties in concentration on the text. Difficulties in concentrating on the text was highest in the noise condition when this condition followed the baseline condition. Less difficulties in the concentration on the text but still higher compared to difficulties in the baseline condition was reported in the noise condition when this condition preceded the baseline scenario. However, in the order of conditions *baseline – noise* the level of difficulties with concentration was equally high in both conditions reflecting no advantage in concentration during the baseline condition. That is, both for the noise annoyance and the difficulties of concentrating on the text, the noise condition elicited stronger negative effects when it followed the baseline condition.

Discussion

In the sleep study, the subjects slept three nights in a laboratory sleeping room. In one night, they were exposed to AHP noise as heard through a (simulated) closed window; one night a tilted window was simulated for AHP noise exposure. For comparison, the third condition was 'quiet' (baseline night) without AHP noise exposure. The exposition conditions were permuted across the three nights. For the situation 'windows tilted' the average AHP $L_{\mathrm{Aeq,1h}}$ was 30.4 dB(A) with peak noise levels up to 41 dB(A) at the ear of the sleeping subject, and for the situation 'windows closed' the AHP $L_{\mathrm{Aeq,1h}}$ was 21 dB(A) with peak noise level up to 30 dB(A). In the daytime study the subjects were exposed for a duration of 15 minutes to the AHP sound levels of the 'windows tilted' scenario in comparison to 15 minutes of silence (no noise exposure).

Results from the sleep study indicate small effects of AHP noise during sleep. Only small but statistically significant effects were shown for noise-associated arousals. In the 'loudest' noise condition a higher number of arousals were found, i.e., at night with the 'windows tilted' noise scenario compared to the 'window closed' scenario. However, although the influence of the AHP noise on noise-related arousals show that the organism reacts to operation-related changes in the AHP sound during the night, this result does not necessarily imply a harmful, pathological effect of AHP sound.

The daytime study showed differences between the noise condition and the baseline condition for the main examination parameters (annoyance, difficulties in concentration on text, and mood). In the effect of AHP noise on noise annoyance and difficulties to concentrate on the text, a sequence effect was noticed. For both outcomes, annoyance and the ability to concentrate and focus on the text, more negative effects were measured when the presentation of a noise scenario took place after the quiet scenario. It seems plausible that on a short-term level this indicates the so-called change effect in responses to noise, i.e. an excess in response to noise particularly when the exposure changes to the worse (Brown & van Kamp, 2009a, b).

Further, other factors that may have an influence on sleep were excluded. As the study subjects were all categorised as sleep healthy, it is not possible to indicate whether a stronger noise effect occurs in previously ill or sleep-impaired persons. Therefore, no conclusions can be drawn about the effects of AHP noise on vulnerable groups, e.g., people with sleep disorders.

In the sleep study design study nights were conducted once a week on the same day in the subsequent three weeks. No habituation nights were realized. In sleep research, both designs are common to conduct examination nights in a weekly rhythm as well as in consecutive nights. However, study designs of previous sleep studies in the field of noise impact research using polysomnography often scheduled consecutive nights (e.g., Basner et al. 2011; Griefahn et al. 2007). Therefore, the comparability of results is slightly aggravated. The noise source types investigated in this study differ significantly from other studies in terms of frequency, duration and noise characteristics. Especially transportation noise sources show different characteristics (e.g., in tonality).

The acoustic noise scenarios selected for both studies correspond to typical sounds from AHPs installed in the field including typical states. In the generated noise scenarios, the number of changes of operation states was raised compared to a typical operation cycle. This was done to increase the chance of provoking potential effects as a normal AHP cycle only has a limited number of state changes during the night. Loudness settings were chosen to resemble a realistic situation and in accordance to TA Lärm. After all, deviating AHP scenarios exist. The focus of the study was to provoke potential effects resulting from the exposure to common AHPs by day and by night.

Both the sleep study and the daytime study give evidence for effects in a laboratory setting. Yet, the results cannot be directly transferred to a field situation for several reasons, mainly because of the lack in ecological validity. A field study would allow to map the exposure situation as well as its effects under real conditions to identify potential effects in persons living with AHP sounds for a longer period of time. Finally, the increase in AHPs in the residential environment with the resulting noise issues will have to be addressed. New solutions must be thought of for the compatibility of growth in sustainable energy systems with healthy neighbourhood conditions.

Zusammenfassung

Im Zuge der Energie- und Wärmewende wurden und werden zunehmend Luftwärmepumpen (LWP) im unmittelbaren Wohnumfeld installiert und betrieben. Aufgrund des technologischen Wandels sind diese Anlagen nicht mehr nur dem gewerblichen und industriellen Bereich (z.B. zur Beheizung und Kühlung von Bürogebäuden, Einzelhandelsbetrieben oder Produktionsstätten) vorbehalten, sondern finden sich vermehrt in der unmittelbaren Umgebung von Ein- und Mehrfamilienhäusern. Damit hat sich die Lärmbelastungssituation in ehemals ruhigen Wohngebieten bereits verändert. Vor allem in den ehemals ruhigeren Abend- und Nachtzeiten brummen nun LWP und Klimageräte. Beschwerden und Klagen über die Lärmbelastung durch diese stationären Quellen haben in den letzten Jahren zugenommen.

Die verbindlichen Richtwerte der Technischen Anleitung zum Schutz gegen Lärm (TA Lärm) werden durch die Geräusche von LWPs oder Klimaanlagen jedoch in der Regel nicht überschritten. Dennoch fühlen sich die Betroffenen durch den Lärm belästigt und beklagen sich häufig über das mutmaßlich unzureichende Schutzniveau dieser Vorschriften (Eulitz et al. 2020).

In diesem Projekt wurden die Auswirkungen des Lärms von LWP untersucht. Um diese Auswirkungen während des Tages und in der Nacht zu untersuchen, wurden zwei Laborstudien unter kontrollierten Bedingungen durchgeführt. In einer polysomnographischen Studie wurde der Schlaf unter verschiedenen Lärmbedingungen untersucht, um die nächtlichen Auswirkungen zu ermitteln; in einem psychologischen Experiment wurden die Auswirkungen am Tag auf Lärmbelästigung, Konzentration und Stimmung untersucht.

Die Kernhypothesen lauten, dass nächtlicher LWP-Lärm einen Einfluss auf die Mikro- und Makrostruktur des Schlafes hat und dass es einen zeitlichen Zusammenhang zwischen dem Auftreten von Veränderungen im Lärmmuster und Störungen der Schlafstruktur gibt. Für die Auswirkungen im Wachzustand wurde die Hypothese aufgestellt, dass die Lärmexposition während des Lesens eines Textes einen negativen Einfluss auf die Stimmung, die Konzentration beim Lesen eines Textes und die Lärmbelästigung im Vergleich zu einer ruhigen Bedingung haben. Darüber hinaus wurde angenommen, dass sich die Lärmbelastung bei der Messung des Blutdrucks und der Herzfrequenz im Vergleich zum Ausgangszustand bemerkbar macht.

Studienaufbau

Im Rahmen des Projekts wurden zwei Laborstudien konzipiert: eine nächtliche Schlafstudie und eine Tagesstudie, in der die Auswirkungen von LWP-Lärm auf den Schlaf und die Konzentration am Tag, die Stimmung und die Belästigung durch Lärm untersucht wurden.

Die Studien wurden von September 2020 bis November 2021 durchgeführt und fanden im Schlaflabor der Advanced Sleep Research GmbH (ASR) in Berlin statt. Für die nächtliche Schlafstudie wurden zwei Schlafräume vorbereitet und mit einem entsprechenden Setup für die akustische Messung und Wiedergabe ausgestattet. Insgesamt nahmen 40 Versuchspersonen - 21 Frauen und 19 Männer - an den beiden Laborstudien teil. In der Schlafstudie wurde jede Versuchsperson in drei Studiennächten untersucht, während sie drei verschiedenen Lärmbedingungen ausgesetzt war. Die Versuchspersonen kamen drei Wochen lang (z. B. drei Mal montags) einmal pro Woche für eine Nacht ins Labor.

Die nächtliche Schlafstudie hatte folgende drei Bedingungen:

- Lärmbedingung 1: Ruhenacht, Baseline

- Lärmbedingung 2: Nacht mit LWP-Lärm bei (simuliertem) teilweise geöffnetem Fenster (Kippstellung)
- Lärmbedingung 3: Nacht mit LWP-Lärm bei (simuliertem) geschlossenem Fenster

Die Untersuchung am Tag fand einmal nach der 3. (letzten) Studiennacht statt und bestand aus zwei Versuchsbedingungen, die jeweils 15 Minuten dauerten:

- Lärmbedingung: LWP-Lärm bei (simuliertem) teilweise geöffnetem Fenster (Kippstellung)
- Baselinebedingung: Stille

Jede Versuchsperson nahm an beiden Versuchsbedingungen teil.
Während der beiden Lärmbedingungen am Tag wurden die Versuchspersonen gebeten, Texte zu lesen. Dabei wurde die Methode der *imaginierten Alltagssituation* gewählt: Die Versuchspersonen wurden angewiesen, die Texte zu lesen und sich dabei vorzustellen, dass sie die Aufgabe zu Hause erledigen. Nach jeder Versuchsbedingung wurden die physiologischen Parameter der Versuchspersonen wie Pulsfrequenz, systolischer Blutdruck und diastolischer Blutdruck gemessen. Anschließend wurden die Versuchspersonen gebeten, einen Fragebogen auszufüllen.
Beide experimentellen Laborstudien wurden als Doppelblindstudien durchgeführt, d.h. sowohl die Versuchsleiter*in als auch die Versuchspersonen wurden nicht über die Reihenfolge der Geräuschdarbietungen oder darüber informiert, welche Testbedingung in der jeweiligen Nacht- oder Tagessituation durchgeführt wurde.

Stichprobe und Instrumente

Zur Rekrutierung der Versuchspersonen wurde eine Datenbank mit gesunden Personen herangezogen. Zu den Einschlusskriterien gehörten u. a. ein Alter zwischen 18 und 65 Jahren, keine Schlafstörungen und eine Hör- und Sehfähigkeit im Normbereich. Darüber hinaus galten als Ausschlusskriterien: keine aktuelle Teilnahme an klinischen pharmakologischen Studien, Drogen- oder Alkoholmissbrauch, akute oder chronische behandlungsbedürftige Krankheiten oder neurologische und psychiatrische Erkrankungen sowie die Einnahme von Medikamenten, die den Schlaf-Wach-Rhythmus beeinflussen.

Um den Einfluss von LWP-Lärm auf Schlaf- und Wachparameter (Lärmbelästigung, Konzentration, Stimmung) zu untersuchen, wurden verschiedene physiologische und psychologische Messungen durchgeführt. Die Messung der Schlafstruktur wurde mittels Polysomnographie (PSG) über acht Stunden gemäß den internationalen Standards der American Academy of Sleep Medicine (AASM) durchgeführt (Berry et al. 2020). Zu den polysomnographischen Messungen gehörten u.a. Kanäle des Elektroenzephalogramms (EEG) und des Elektrokardiogramms (EKG). Folgende Parameter wurden ermittelt: Zeit im Bett (TIB), Gesamtschlafzeit (TST), Schlafeffizienz (SE), Einschlafzeit (SOL), Summe der Zeit in den einzelnen Schlafstadien (N1, N2, N3, R) und der Wachzeit (zeitliche Auflösung 0,5 Minuten), die Anzahl der Arousals und weitere physiologische schlaf- und aktivitätsbezogene Parameter. Arousals wurden als lärmassoziiert definiert, wenn sie innerhalb eines Zeitfensters von 90 Sekunden nach einem Geräuschereignis auftraten (Geräusche resultierten aus unterschiedlichen Betriebszuständen, tonalen Komponenten oder kurzen Impulsgeräuschen der LWP).

Selbstberichtete Schlafparameter wurden mit standardisierten Schlaffragebögen erfasst, die am Abend vor dem Schlafengehen und am Morgen ausgeteilt wurden, um die Schlafqualität, die Schläfrigkeit und die lärmbedingten Schlafstörungen zu messen.

Während der Tagesstudie wurde die Wahrnehmung der dargebotenen Geräusche bewertet, indem gefragt wurde, ob und wie die Versuchspersonen die Geräuschmerkmale wahrnahmen. Außerdem wurden Fragen zum Textverständnis (Lesen, Motivation), zur Stimmung und zur Konzentration gestellt. Die Bedingungen der Wohnsituation der Versuchspersonen in Bezug auf Gebäudetyp, Fenstertyp, Lüftungsverhalten, Schlafqualität und den Einfluss der Covid-19-Pandemie wurden erfragt, um Auswirkungen zu berücksichtigen, die sich aus der Wohnsituation der Versuchspersonen ergeben.

Akustischer Aufbau und Stimuli

Der von einer Luftwärmepumpe (LWP) abgestrahlte Schall setzt sich aus verschiedenen Komponenten zusammen: Während im Dauerbetrieb ein breitbandiger geräuschvoller Schall im Vordergrund steht, können auch tonale Komponenten oder kurze Impulsgeräusche auftreten. Die Stimuli für die Studie wurden aus Messungen an verschiedenen LWP in realen Umgebungen generiert. Aus dem so gewonnenen Audiomaterial wurden zwei Geräuschszenarien zusammengestellt: Eines für die Präsentation während der Schlafstudie und eines für die Tagesstudie. Das Geräuschszenario für die Schlafstudie umfasste 60 Minuten, die sowohl verschiedene Betriebszustände als auch eine Ruhephase beinhalteten. Die Geräuschpegel wurden entsprechend dem realen Betrieb ausgewählt. Unterschiedliche Lärmpegel ergaben sich aus den verschiedenen Betriebszuständen und simulierten Fensterpositionen (gekippt und geschlossen). Dieser Geräuschzyklus wurde jede Nacht acht Mal dargeboten und bildete das Geräuschszenario. Für die Untersuchung am Tag wurde ein kürzeres Geräuschszenario von ca. 15 Minuten erstellt.

Die Geräuschdarbietung erfolgte in beiden Laborstudien über Lautsprecher, die in den Untersuchungsräumen aufgestellt waren. Daher musste die Geräuschübertragung von außen nach innen simuliert werden. Dazu wurde zunächst der Mittelungspegel (maximaler Mittelungspegel L_{AFTeq} des ungefilterten Signals) des einstündigen Geräuschszenarios (einschließlich aller Ruhephasen) in ca. 0,5 m Entfernung vom Lautsprecher auf 45 dB eingestellt, um die Geräuschsituation einer möglichen ungünstigsten vollen Nachtstunde „vor dem (simulierten) Fenster" darzustellen. Anschließend wurde der Lärm spektral gefiltert, um den Übergang durch das geschlossene oder gekippte Fenster zu simulieren.

Ergebnisse

Gruppenvergleiche zwischen den Studiennächten ergaben keine Unterschiede in den Schlafparametern für die drei Lärmbedingungen („Baseline", „Fenster gekippt" und „Fenster geschlossen"). Der Vergleich der Anzahl der Arousals während der beiden Lärmbedingungen („Fenster gekippt" und „Fenster geschlossen") ergab jedoch, dass die Gesamtzahl der Arousals (Summe der spontanen, respiratorischen und motorischen Arousals) im Zusammenhang mit den Lärmereignissen unter der Bedingung „Fenster gekippt" höher war als unter der Bedingung „Fenster geschlossen". Das Gleiche gilt für die Anzahl der spontanen Arousals in Verbindung mit Geräuschereignissen. Der Unterschied in der Anzahl der lärmassoziierten spontanen Arousals zwischen der Lärmbedingung 2 und der Lärmbedingung 3 war geschlechtsspezifisch, was auf eine Wechselwirkung zwischen den Faktoren Geschlecht und Lärmbedingung hindeutet: Männer wiesen in der Lärmbedingung 3 niedrigere Mittelwerte der lärmassoziierten spontanen Arousals auf, die jedoch nicht signifikant waren, während bei Frauen eine signifikante Veränderung beobachtet wurde. Die lärmassoziierten spontanen Arousals waren außerdem positiv mit der Schläfrigkeit (gemessen mit der Epworth Sleepiness Scale) korreliert, was bedeutet, dass mehr spontane Arousals mit einer größeren Tagesschläfrigkeit verbunden waren.

Die Auswertung der Schlaffragebögen ergab keine Unterschiede in der Schläfrigkeit zwischen den drei Lärmbedingungen. Es wurde jedoch festgestellt, dass die mittlere Differenz zwischen der abendlichen Schläfrigkeit vor der PSG und der Schläfrigkeit am Morgen nach der PSG bei der Lärmbedingung mit dem simulierten „gekippten Fenster" negativ war, d. h. die durchschnittliche Schläfrigkeit war am Morgen höher als am Abend zuvor. Bei den beiden anderen Lärmbedingungen war die Beziehung umgekehrt.

In der psychologischen Tagesstudie wurde tagsüber die Wirkung von LWP-Lärm im Vergleich zu einer ruhigen Ausgangsbedingung beim Lesen eines Textes untersucht. Die meisten Versuchspersonen nahmen das LWP-Geräusch in der Geräuschbedingung wahr. Von den 33 Versuchspersonen, die das Geräusch wahrnahmen, gaben 11 Personen an, dass das Geräusch wie eine „Klimaanlage" oder ein „Belüftungssystem" klinge.

Mit einer Kovarianzanalyse wurden mögliche Unterschiede in Bezug auf *Lärmbelästigung*, *Konzentrationsschwierigkeiten bei Text*, *Stimmung*, Blutdruck und Herzfrequenz zwischen der Ausgangsbedingung und der Lärmbedingung analysiert. In der Analyse wurden die Auswirkungen der Kovariaten *Lärmempfindlichkeit*, *Alter*, *Geschlecht* und *Reihenfolge der Präsentation der Bedingungen* kontrolliert. Haupteffekte wurden für die *Lärmbelästigung* durch LWP-Lärm, *Konzentrationsschwierigkeiten auf den Text* sowie für die *Stimmung* gefunden. Blutdruck und Herzfrequenz unterschieden sich nicht signifikant zwischen den beiden Bedingungen.

Ein Interaktionseffekt wurde für die Reihenfolge der Bedingungen in Wechselwirkung mit den Bedingungen für *Lärmbelästigung* und *Konzentrationsschwierigkeiten auf den Text* gefunden. Die Richtung der *Lärmbelästigung* war zwischen den Bedingungen gleich; in beiden Reihenfolgen war die *Lärmbelästigung* in der Lärmbedingung im Vergleich zur Ausgangsbedingung höher. In der Baselinebedingung berichteten die Versuchspersonen im Durchschnitt fast keine *Lärmbelästigung*, unabhängig von der Reihenfolge der Bedingungen. Der Grad der *Belästigung* in der Lärmbedingung unterschied sich jedoch und war in der Lärmbedingung deutlich ausgeprägter, wenn die Lärmbedingung auf die Baselinebedingung folgte. Die vorherige Bedingung schien als Referenzbedingung zu dienen, in diesem Fall die ruhige Umgebung. Weiterhin ließen sich Auswirkungen der Reihenfolge der Versuchsbedingungen auf die *Konzentrationsschwierigkeiten auf den Text* feststellen. Die Schwierigkeit, sich auf den Text zu konzentrieren, war in der Lärmbedingung am höchsten, wenn diese Bedingung auf die Baselinebedingung folgte. Geringere Schwierigkeiten bei der Konzentration auf den Text, aber immer noch höher im Vergleich zur Baselinebedingung, wurden in der Lärmbedingung berichtet, wenn diese Bedingung der Baselinebedingung vorausging. In der Reihenfolge der Bedingungen *Baseline* - *Lärm* war das Ausmaß der Konzentrationsschwierigkeiten jedoch in beiden Bedingungen gleich hoch, das heißt, die Konzentration war in der Baselinebedingung ohne Geräuschexposition nicht besser. Sowohl für die *Lärmbelästigung* als auch für die *Konzentrationsschwierigkeiten* zeigen sich in der Lärmbedingung stärkere negative Effekte, wenn diese auf die Baselinebedingung folgte.

Diskussion

In der Schlafstudie schliefen die Versuchspersonen drei Nächte in einem Laborschlafraum. In einer Nacht wurden sie dem LWP-Lärm ausgesetzt, der durch ein (simuliertes) geschlossenes Fenster zu hören war; in einer Nacht wurde ein gekipptes Fenster für die LWP-Lärmexposition simuliert. Zum Vergleich war die dritte Bedingung „ruhig" (Basisnacht) ohne LWP-Lärmexposition. Die Expositionsbedingungen wurden in den drei Nächten permutiert. Für die Bedingung „Fenster gekippt" betrug der durchschnittliche LWP $L_{\mathrm{Aeq,1h}}$ 30,4 dB(A) mit Spitzenschallpegeln bis zu 41 dB(A) am Ohr der schlafenden Versuchsperson, und für die

Bedingung „Fenster geschlossen" betrug der LWP $L_{\text{Aeq,1h}}$ 21 dB(A) mit Spitzenschallpegeln bis zu 30 dB(A). In der Studie am Tag wurden die Versuchspersonen 15 Minuten lang den LWP-Schallpegeln der Bedingung „Fenster gekippt" ausgesetzt, im Vergleich zu 15 Minuten Stille (keine Lärmexposition).

Die Ergebnisse der Schlafstudie deuten auf geringe Auswirkungen von LWP-Lärm während des Schlafs hin. Nur geringe, aber statistisch signifikante Auswirkungen wurden für lärmassoziierte Arousals festgestellt. In der „lautesten" Lärmbedingung wurde eine höhere Anzahl an Arousals festgestellt, d. h. in der Nacht mit dem Lärmszenario „Fenster gekippt" verglichen mit dem Szenario „Fenster geschlossen". Obwohl der Einfluss des LWP-Lärms auf lärmassoziierte Arousals zeigt, dass der Organismus auf betriebsbedingte Veränderungen des LWP-Lärms während der Nacht reagiert, impliziert dieses Ergebnis nicht grundsätzlich eine schädliche, pathologische Wirkung des LWP-Lärms.

Die Tagesstudie zeigte Unterschiede zwischen der Lärmbedingung und der Baselinebedingung für die wichtigsten Untersuchungsparameter (*Belästigung*, *Konzentrationsschwierigkeiten auf den Text* und *Stimmung*). Bei der Wirkung des LWP-Lärms auf die Lärmbelästigung und die Schwierigkeiten, sich auf den Text zu konzentrieren, wurde ein Sequenzeffekt festgestellt. Für beide Ergebnisse wurden mehr negative Effekte gemessen, wenn die Präsentation eines Lärmszenarios nach dem ruhigen Szenario stattfand. Es scheint plausibel, dass dies auf einer kurzfristigen Ebene auf den so genannten „Change”-Effekt bei Reaktionen auf Lärm hinweist, d. h. auf eine übermäßige Reaktion auf Lärm, insbesondere wenn sich die Exposition zum Schlechteren verändert (Brown & van Kamp, 2009a, b).

In der Untersuchung wurde darauf geachtet, andere Faktoren, die einen Einfluss auf den Schlaf haben könnten, den Möglichkeiten entsprechend, auszuschließen. Da die Versuchspersonen alle als schlafgesund eingestuft wurden, ist es nicht möglich anzugeben, ob bei zuvor kranken oder schlafgestörten Personen eine stärkere Lärmwirkung auftritt. Daher können keine Schlussfolgerungen über die Auswirkungen von LWP-Lärm auf vulnerable Gruppen, z. B. Personen mit Schlafstörungen, gezogen werden.

Im Schlafstudiendesign wurden die Studiennächte in drei aufeinander folgenden Wochen jeweils einmal pro Woche am gleichen Tag durchgeführt. Es wurden keine Gewöhnungsnächte durchgeführt. In der Schlafforschung sind beide Designs üblich, sowohl Untersuchungsnächte in einem wöchentlichen Rhythmus als auch in aufeinanderfolgenden Nächten durchzuführen. Die Studiendesigns bisheriger Schlafstudien im Bereich der Lärmwirkungsforschung mit Polysomnographie sahen häufig konsekutive Nächte vor (z.B. Basner et al. 2011; Griefahn et al. 2007). Daher ist die Vergleichbarkeit der Ergebnisse diesbezüglich etwas erschwert. Die in dieser Studie untersuchten Lärmquellenarten unterscheiden sich in Bezug auf Häufigkeit, Dauer und Geräuschcharakteristik deutlich von anderen Studien. Insbesondere die Verkehrslärmquellen weisen unterschiedliche Eigenschaften auf (z. B. in der Tonalität).

Die für beide Studien ausgewählten akustischen Lärmszenarien entsprachen den typischen Geräuschen von im Feld installierten LWPs einschließlich typischer Betriebszustände. In den generierten Lärmszenarien wurde die Anzahl der Änderungen der Betriebszustände im Vergleich zu einem typischen Betriebszyklus erhöht. Dadurch sollte die Wahrscheinlichkeit, potenzielle Auswirkungen zu provozieren, gesteigert werden, da ein normaler LWP-Zyklus nur eine begrenzte Anzahl von Zustandsänderungen während der Nacht aufweist. Die Lautstärkeeinstellungen wurden so gewählt, dass sie einer realistischen Situation entsprechen und sich an der TA Lärm orientieren. Im Feld treten auch abweichende LWP-Szenarien auf. Der Schwerpunkt der Studie lag jedoch auf der Provokation potenzieller Effekte, die sich aus der Exposition gegenüber üblichen LWP bei Tag und bei Nacht ergeben.

Sowohl die Schlafstudie als auch die Tagesstudie liefern Hinweise auf Effekte in einer Laborumgebung. Die Ergebnisse können jedoch aus verschiedenen Gründen nicht direkt auf eine Feldsituation übertragen werden, im Wesentlichen aufgrund der fehlenden ökologischen Validität. Feldstudien würde es ermöglichen, die Expositionssituation und ihre Auswirkungen unter realen Bedingungen zu erfassen, um mögliche Auswirkungen bei Personen zu identifizieren, die über einen längeren Zeitraum mit LWP-Geräuschen leben. Schließlich wird man sich der Herausforderung stellen müssen, die Zunahme von LWP in der Wohnumgebung mit den daraus resultierenden Lärmproblemen in Einklang zu bringen und die Vereinbarkeit des Wachstums nachhaltiger Energiesysteme mit gesunden Nachbarschaftsverhältnissen sicherzustellen.

1 Introduction

As part of the energy and heat transition, the German government aims to replace conventional heating systems with energy-efficient systems. Therefore, air-source heat pumps (hereinafter referred to as AHP) in particular have recently been and will be increasingly installed and operated in the immediate residential environment.

AHPs and air conditioners (AC) are stationary systems whose operation results in noise emissions in the neighbourhood. In principle, the installation and operation of these systems are not subject to a licensing procedure. Those affected by noise are therefore not protected by official approval or monitoring and often have to take civil action against the operator for noise annoyance. In addition, the noise-relevant system components of AHPs and ACs are often installed and operated outdoors. As a result, their noise can have an unattenuated effect on the neighbourhood.

Due to technological change, these systems are no longer reserved for commercial and industrial areas (e.g. for heating and cooling office buildings, retail establishments, or production facilities). Systems with nominal heating or cooling powers up to 12 kilowatts are increasingly present in immediate vicinity of single- and multi-family homes. The distribution of AHPs is boosted by state funding and the obligation of energy saving. Protection against summer heat, large-scale glazing of buildings, climatic changes and the quality requests are causes for an increasing spread of air-conditioning units. The noise exposure situation in previously quiet residential areas has therefore already changed. Especially in formerly quiet times in the evening and at night-times, AHPs and ACs are now humming. Complaints and lawsuits about the noise of those stationary sources have increased in recent years. AHPs and ACs emit specific noise emissions, especially concerning time course and the frequency composition of the continuous noise as well as transient operating conditions (start-up, shutdown, defrosting, cleaning operation). The determination and assessment of noise from AHPs and ACs is currently carried out in Germany in accordance with *TA Lärm* (German technical regulations on protection against noise pollution, TA Lärm, 1998). However, in previously quiet residential areas, the binding guideline values of TA Lärm are usually not exceeded by the noise of AHP or ACs. Still, those affected are annoyed by the noise and often complain about the allegedly insufficient level of protection provided by these regulations (Eulitz et al. 2020).

This project investigated the relevance of the noise impact of the characteristic noise from ACs and AHPs. There are far more complaints about the noise from AHPs than from ACs. However, the characteristic sounds of both types of systems are very comparable. Therefore, in designing the studies, emphasis was placed on investigating only the effects of AHPs. To investigate the effects of LWP during the day and at night, two laboratory studies were conducted under controlled conditions. To determine the nocturnal effects, sleep under different noise conditions was examined in a polysomnographic study.

The hypotheses to be tested in the sleep study are:

1. Nocturnal AHP noise changes the macro- and microstructure of sleep.
2. There is a temporal association of the occurrence of changes in the noise pattern and disturbances of the sleep structure.

Daytime effects were studied in a psychological experiment.

In the daytime study the impact of AHP noise on daily activities such as reading a text was investigated. For this, the subjects read a Greek myth text under two 15-minutes conditions, quiet condition (baseline) and noise condition (15-minutes AHP noise scenario, 'tilted window').

It is assumed that the AHP noise as an environmental stressor (Glass & Singer 1972) has the potential to disturb daily activities, i.e. to impair the concentration on and the comprehension of the text. Further it can strain exposed people and lead to after-effects such as worsened, stressed mood and noise annoyance. This assumption led to the following hypotheses:

1. Subjects report higher difficulties concentrating on the text during the noise condition compared to the baseline condition.
2. Subjects report worse mood and more stress after having read the text under the noise condition than after having read the text under the baseline condition.
3. Subjects report to be more noise annoyed after the noise condition compared to the baseline condition.
4. Subjects have higher physiological stress after the noise condition indicated by higher blood pressure (systolic and diastolic pressure) than after the baseline condition.
5. Subjects have higher physiological stress after the noise condition indicated by a higher heart rate than after the baseline condition.

This report presents the experimental setup and procedure, reports the results of these studies and classifies them.

2 Study design

Two laboratory studies were designed with a night-time sleep study and a daytime study investigating the effects of AHP noise on sleep and daytime concentration, attention and annoyance.

2.1 Procedure

The studies were conducted from September 2020 to November 2021. The initial plan to conduct laboratory testing in spring 2020 was postponed due to the COVID-19 pandemic, as lockdown measures disrupted the research timeline. The studies took place in the sleep laboratory of Advanced Sleep Research GmbH (ASR) in Berlin. For the night-time sleep study, two sleeping rooms were prepared and equipped with an appropriate setup for acoustic measurement and playback. In total, 40 subjects were examined participating in both laboratory studies.

The sleep study took place on three nights in a weekly rhythm, i.e. one test person slept for example on three consecutive Mondays in the sleep laboratory. In each night the subject was exposed to varying sound conditions. Each visit in the sleep laboratory consisted of the following procedures:

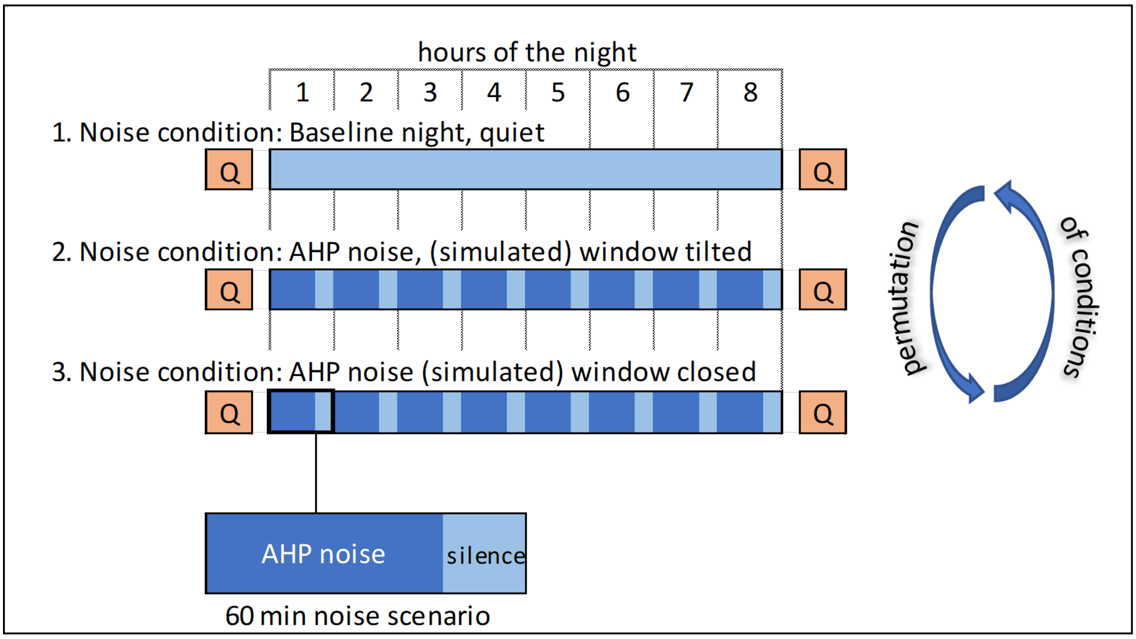
- Arriving at sleep lab ASR in the evening at appr. 19:00 hrs.
- Filling in questionnaires in the evening.
- Preparation for Sleep measures (Polysomnography, PSG).
- Conduction of PSG for 8 hours including one random noise condition.
- Filling in questionnaires in the morning.

Three noise conditions were prepared for the three study nights (see Figure 1):

- Noise condition 1: Quiet night, Baseline
- Noise condition 2: Noise night with AHP noise (simulated) window partially opened (tilt position)
- Noise condition 3: Noise night with AHP noise (simulated) window closed

The subjects were randomly assigned to an order of conditions. A noise scenario comprising 60 minutes was created that was presented eight times in the noise condition nights with exposure to AHP noise (condition 2 and 3).

Figure 1: Schematic chronological sequence of the three examination nights



Note. Q=Questionnaire. Night time ca. 22-23:00 p.m. until 06-07:00 a.m., depending on subject's bedtime.
Source: own illustration, ZEUS.

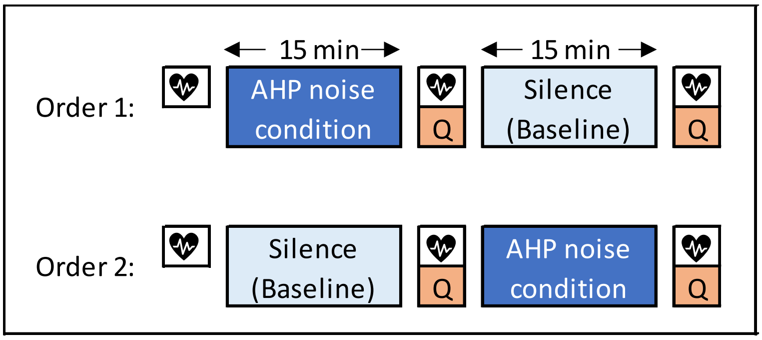
Figure 2 illustrates the design of the daytime study. Two noise conditions were performed per subject, during which they were asked to read texts. The two noise conditions were:

- Noise condition: AHP noise (simulated) window partially opened (tilt position)
- Baseline condition: Quiet

Each of the conditions lasted 15 minutes. After each experimental condition, the subject's pulse rate, systolic blood pressure, and diastolic blood pressure were measured by use of an automatic monitor with an upper arm cuff (*boso medicus uno*, BOSCH + SOHN GmbH u. Co. KG, Jungingen). Subsequently, the subject was asked to complete a questionnaire on the tablet (see Appendix A.3). After both experimental conditions, a final questionnaire was completed. Subjects were randomly assigned to the order of the conditions.

The experimental daytime study was performed in the sleep laboratory room where the subject had spent the nights in the sleep study. It was scheduled once on the day after the third study night. In exceptional cases, this could alternatively be scheduled for another date if the subject was not available directly after the third study night.

Figure 2: Design of the two experimental conditions in the daytime study



Note. Experimental conditions: Baseline condition = no sound/quiet, noise condition = AHP sounds tilted windows, ♥ = Blood pressure and heart rate measurement, Q= questionnaire.
Source: own illustration, ZEUS.

The approach of an *imaginative everyday situation* was applied. Subjects were instructed to read the texts while imagining being at home performing the task (for detailed instruction see Appendix A.8). A task with an instructed everyday situation is in line with the approach of other authors who have used instructions to try to get study subjects out of the laboratory situation (e.g. Feldmann & Carolus, 2019). In the referenced study, context effects were found in listening to AHP sounds when subjects imagined an everyday situation.

In each of the two conditions, the subject read different texts that were similar in style. Two Greek myths from the same translation volume were chosen for this purpose. The second text was changed after testing the third subject, because the reading time had turned out to be too short for one subject.

During the daytime study, the subject sat in a chair facing the speaker setup, allowing the subject to be exposed to the noise scenarios. Texts to be read were presented on a fanless tablet. The questionnaires were also to be answered on the tablet. Instructions were included to indicate when to turn to the experimenter.

Both laboratory studies were conducted as double-blind studies, i.e. the investigator as well as the subjects were not informed about the sequence of noise presentations or which test condition was conducted in each night or daytime test situation. The assignment was pseudo-randomized.

When recruiting the subjects, the real study purpose was concealed. The presentation of sounds during the study nights was not mentioned before the start of the study to avoid creating expectations that affect the responses to be measured. The study was communicated as a 'climate study' investigating the impact of indoor climate conditions on sleep. Subjects were informed about the real subject of the study after it had been conducted. Ethics proposal regarding recruiting, study procedure, measurement instruments, questionnaires, and data management was submitted to the local ethics commission of Charité-Universitätsmedizin Berlin, Campus Mitte on November 1, 2019. The approval was given on February 14, 2020 with reference EA1/020/20.

2.2 Estimation of the sample size

In laboratory and field studies investigating the effects of noise on physiologically measured sleep quality, different sample sizes between 16 and 112 persons (in the NORAH Study up to about 180 persons; Müller et al. 2015) are realized. This is evident from the presentation of the data sets compiled and re-analysed by the Virtual Institute of the Helmholtz Association VINESH ‘Transportation Noise - Effects on Sleep and Performance’ (Table 1, Griefahn et al. 2007).

Table 1: Data sets used by VINESH to investigate the effects of Transportation noise on sleep (Table 1 in VINESH final report, Griefahn et al. 2007, modified)

	N subjects	Type of traffic noise: Number of noise nights					N baseline nights	Total N nights
		Air	Road	Rail	Air + Road	Air + Road + Rail		
DLR + IfADo (Baseline nights)	24	-	-	-	-	-	312	312
DLR (Aircraft noise)	112	1008	-	-	-	-	448	1456
IfADo (Air/Road/Rail)	24	72	72	72	-	-	96	312
IfADo (Road, Rail, TF)	16	-	48	48	-	-	48	144
IfADo (Road/Rail Time)	24	-	72	72	-	-	72	216
DLR (Air/Road/Rail)	72	-	-	-	-	576	216	792
DLR (Field study Aircraft)	64			-	576	-	-	576
Σ Laboratory + Field	**336**	**1656**	**192**	**192**	**576**	**576**	**1256**	**3808**

Note. Baseline night = no noise exposure.

For the NORAH study on the effect of aircraft noise on sleep, the authors made estimates of required sample sizes based on Monte Carlo simulation. The aim was to examine the effect of aircraft noise on physiologically measured sleep quality (including sleep stage change) with sufficient statistical power and 95% confidence interval precision. These estimates were later published generalized to field studies on aircraft noise effects on sleep (Basner & Brink 2013). Basner and Brink (2013) show that the statistical power depends on the number of subjects as well as the number of noise events. They suggest a minimum sample of 40 subjects depending on the number of events. According to Basner and Brink (2013) a sample size of 30 subjects would also lead to a still acceptable statistical power. At a size of 10 or 20 subjects, the achievable statistical power is too low and no longer acceptable.

The calculation of logistic mixed models required for exposure-response functions on noise-induced awakening responses due to the measurement repetition and distribution of the target variable ‘awakening response’ is only numerical. Thus, the determination of the required sample size is only possible by means of simulations (Monte Carlo or bootstrap simulation) as done by Basner and Brink (2013). To this date, there is no polysomnographic sleep study related to AHP noise or noise from similar sources known to the authors. Therefore, the sample size in this research project was set to 40 subjects following the suggestion of Basner and Brink (2013) for a minimum sample size for aircraft noise-related sleep studies.

The sample size was accordingly also applied for the physiological effects to be investigated during the day. For the subjective data, a smaller required minimum sample size was assumed, since a more differentiated quantification (as waking reaction yes/no) can be achieved with the provided rating scales and comparative assessments. Along with this, a higher statistical power can be achieved due to the expected higher effect sizes than for physiological variables (with correlation coefficients between noise annoyance and noise levels of approx. $r > 0.30$). Both laboratory studies, i.e. the physiological and psychological effect measurements for sleep and wakefulness states, were carried out with the same subjects.

2.3 Subject recruitment

Recruitment of subjects was performed by ASR. For recruitment of subjects, a database of healthy individuals at ASR was used.

The inclusion criteria were:

- male or female
- age 18-65 years
- no sleep disturbances
- normal functionality of hearing and eye-sight
- capability to understand scope and significance of the study

Criteria for excluding persons from participation were:

- participation in clinical pharmacological trials four weeks prior to the start of the examination
- drug or alcohol abuse
- acute or chronic illness requiring treatment
- use of hypnotics or drugs affecting the sleep-wake rhythm
- neurologic or psychiatric diseases

The following instruments were used for screening the subjects (see appendix A.1):

- Epworth Sleepiness Scale (ESS; Johns, 1991), an assessment of daytime sleepiness.
- Insomnia Severity Index (ISI; Morin, Belleville, Belanger & Ivers, 2011), a brief instrument to evaluate the extent of insomnia symptoms experienced during both nighttime and daytime periods.
- Pittsburgh Sleep Quality Index (PSQI; Buysse et al., 1991), a self-report questionnaire that assesses sleep quality.
- A questionnaire evaluating hearing ability and sensitivity for environmental pollutions.
- Age, sex, and Body-Mass Index (BMI).

Table 2 illustrates the intended distribution of study sample regarding age and sex.

Table 2: Intended sample size stratified for age and sex

Age / Sex	female	male	Total
18 – 35 years	6-7	6-7	12-14
> 35 – 50 years	6-7	6-7	12-14
> 50 – 65 years	6-7	6-7	12-14
Σ	**20**	**20**	**40**

2.4 Instruments

2.4.1 Recording of sleep structure - Polysomnography

Computerized digital measurement of sleep structure was performed by polysomnography (PSG) over eight hours according to the international standards of the *American Academy of Sleep Medicine* (AASM) (Berry et al. 2020) using the *MiniScreen Pro* recording system (Löwenstein Medical, Bad Ems, Germany). All subjects underwent sleep measurements with careful placements of sensors by trained and certified staff. These included the measurement of

- six channels of electroencephalogram (EEG: F4-M1, C4-M1, O2-M1, F3-M2, C3-M2, O1-M2),
- left and right electrooculogram (EOG),
- electromyogram (EMG), chin,
- EMG, left and right leg,
- electrocardiogram (ECG),
- thoracic as well as abdominal movements recorded by respiratory inductance plethysmography (RIP),
- nasal flow recorded by nasal pressure sensor,
- arterial blood oxygen saturation assessed by pulse oximetry,
- snoring by means of laryngeal microphone,
- body position (left, right, abdomen, back, upright) by movement sensor.

Bio-calibration was performed before the light was switched-off (eye-movement, teeth grinding, breathing, snoring, leg movement).

2.4.2 Parameters of Polysomnography

Computer-assisted manual-visual determination of sleep structure, including determination of arousal, was performed by a sleep expert (somnologist) according to standard AASM guidelines (Berry et al., 2020).

The following parameters were determined:

- Time in bed (TIB): TIB is the time available for sleeping between switching off the lights in the evening and switching lights on in the morning (temporal resolution: 0.5 minutes).
- Total sleep time (TST): TST refers to the amount of time spent in any of the sleep stages N1, N2, N3, or W within TIB (temporal resolution: 0.5 minutes).
- Sleep efficiency (SE): SE is given by the formula [(TST / TIB) * 100%].
- Sleep onset latency (SOL): SOL refers to the amount of time between switching lights off and the first occurrence of any of the sleep stages N1, N2, N3, or R (temporal resolution: 0.5 minutes).
- The sum of the time spent in the individual sleep stages (N1, N2, N3, R) and awake (temporal resolution 0.5 minutes); in addition, as a percentage of the TIB
  - N1 and N2, which are Non-Rapid-Eye-Movement (Non-REM) light sleep stages.
  - N3 are non-REM deep sleep stages.
  - R are the Rapid-Eye-Movement (REM) sleep stages.
- Amount of arousal: the number of short-term EEG frequency accelerations (arousal)-induced by central nervous activation (Berry et al. 2020). Arousals were defined as noise associated if they occur within a time window of 90 sec after a noise event (sound resulted from different operating states, tonal components or short impulse noise of the AHP).
- Breathing pattern
- Heart rate
- Posture during sleep
- Snoring
- Leg movements
- Oxygen saturation state.

2.4.3 Questionnaires in sleep study

The following standardized sleep questionnaire were handed in the evening before sleep (for scales, see Appendix A.2):

- Karolinska Sleepiness Scale (KSS) (Akerstedt & Gilberg, 1990),
- Aktuelle Stimmungs-Skala (ASTS) (Dalbert, 1992)

The following standardized sleep questionnaire were handed in the morning after sleep:

- KSS (Akerstedt & Gilberg, 1990),
- ASTS (Dalbert, 1992)
- Schlaffragebogen A (SF-A) (Görtelmeyer, 1981)
- Morgenbefragung '*Klima*', page 1

2.4.4 Questionnaires Daytime study

The questionnaire implemented in the daytime study was compiled from questionnaires that the authors have already used successfully in other studies.

Perception of presented sounds was assessed using questions on if and how subjects perceive sound scenarios. The questions are adaptations of items used in studies on the effects of infrasound (Krahé et al. 2020), shooting noise (Schreckenberg & Großarth 2021), and wind turbine noise (Schmitter et al. 2022). The perception of sound characteristics in the noise condition was assessed with 23 items adapted from Feldmann and Carolus (2019).

Text comprehension, perception and motivation were assessed using questions adapted from a study on the evaluation of environmental information from a cognitive psychological perspective (Schreckenberg et al. in print). Mood was assessed using items adapted from the study of Krahé et al. (2020) on the impact of infrasound.

To consider effects arising from the subject's home situation conditions of their living situation regarding building type, window type, ventilation behaviour, sleep quality, and the influence of covid-19 pandemic were inquired.

2.5 Sample description

Date of first enrollment was September 2020 and study closing was November 2021. 42 subjects were included in the studies. After the first polysomnography (PSG) measurements two subjects discontinued their participation due to personal reasons. 40 subjects completed the two laboratory studies, i.e. participating in the daytime study and sleep study. The sample characteristics of these 40 subjects are:

- Sex: 21 female; 19 male
- Age (mean *M*, standard deviation *SD*): 37.5 ± 14.5 years
- Body Mass Index (BMI) (*M*, *SD*): 24.1 ± 3.8 kg/m^2
- ESS (*M*, *SD*): 5.4 ± 2.7
- ISI (*M*, *SD*): 3.8 ± 2.5
- PSQI (*M*, *SD*): 5.2 ± 3.9
- Noise sensitivity (*M*, *SD*): 3.2 ± 1.2
- Sensitivity to environmental pollutions (sum score; *M*, *SD*): 6.8 ± 2.7

There were no differences between males and females regarding ISI, ESS, PSQI and noise sensitivity. The values indicate general sleep quality and noise sensitivity being in a normal, non-pathologic range. Hearing was assessed in all subjects by audiometry (Appendix A.4). According to WHO criteria (WHO, 1991), all subjects were found to have normal hearing.

2.6 Acoustic stimuli

The aim of the study was to investigate the effects of noise from ACs and AHP on sleep. Both devices are often split into an indoor unit and an outdoor unit while noise conflicts are mostly referable to the outdoor units. AHP have been increasingly installed in private households in recent years, whereas AC are comparatively rare in German residential areas. Thus, the focus for the selection of acoustic stimuli for the laboratory study was placed on the sounds emitted by

AHP. The noise emitted by outdoor units of AC and AHP are rather similar because the significant noise sources are similar as well (esp. fan, compressor, condenser). So, it is to be expected that the effects measured with AHP noise will also be comparable.

The sound emitted by AHP is made up of various components: While in continuous operation a broadband noise-like sound is in the foreground, tonal components or short impulse noise can also occur, especially during load changes or when parts of the unit switch on and off. The regularity with which these additional noise components occur varies depending on the unit type, weather conditions, etc.

The stimuli for the studies were generated from measurements on various AHP in real environments. An AHP that is as representative as possible was selected from the database. Two sound scenarios were then compiled from the audio material obtained from this system: One for the presentation during the sleep study and one for the daytime study. The procedure for generating the stimuli will be explained in appendices A.5, 0, A.7 and A.8.

2.6.1 Noise scenarios

An average sleep cycle lasts about 90 to 110 minutes (Penzel 2007). Therefore, the noise scenario for the sleep study should last for a total of one hour. This promotes the occurrence of different noise states in different sleep phases in order to investigate their possible interfering effects. Noise levels were selected according to realistic operations. Different noise levels result from the different operating states and simulated window positions (tilted and closed). For the daytime study, a shorter noise scenario of approx. 15 minutes was also created.

In order to develop a noise scenario that is as close to reality as possible, the various operating states during operation were combined without using synthetic noises. At the same time, the temporal sequence of the noise scenarios should allow to determine a possible influence on sleep quality during the nights under investigation.

In addition to the noise emitted by the AHP, the noise situation in a bedroom depends to a large extent on the position of the windows: While closed windows can have a sound insulation in the range between 25 and >50 dB, the sound insulation of (partially) open windows in the tilt position is only about 15 dB. Since both variants are common in everyday life, they were both considered in the sleep study. For comparison, the third condition was ‘quiet’ (baseline night), without noise exposure from AHP. The implementation of the outside-inside transmission in the different conditions is explained in more detail in section A.8. For the daytime study the condition ‘closed window’ was omitted.

2.6.1.1 Sleep study

The noise scenario for the sleep study should include quiet periods in addition to the noise of the AHPs. The sounds of switching on/off or switching over are short-term noise events that only last a few seconds. In the time between the switching moments, the noise of continuous operation proceeds.

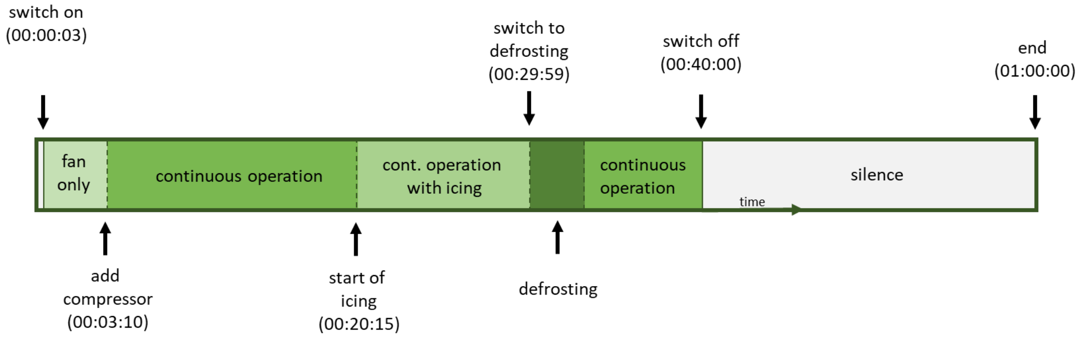
The temporal sequence of the noise scenarios should make it possible to determine a possible influence on the quality of sleep during the sleep study. Therefore, a scenario was composed of the different noise components (switching on/off, continuous operation, defrosting process, etc.). It contained the different operating states and individual events and was presented several times during one night.

For the analysis of the results, the individual events were particularly relevant, since waking reactions were to be expected especially in the case of changes in the sound situation (e.g. change from silence to noise). The length of one hour and the repetition of the scenario during the night ensured that each individual event contained in the scenario was presented to each subject several times. At the same time the number of events that can be used for the subsequent analysis was increased.

At the same time, the duration of one hour was intended to prevent synchronisation between the noise scenario and the subject's sleep cycle (duration of typical sleep cycle ~90 min). By this, it was prevented that a state of LWP was recurrently presented in the same sleep phase. This approach enabled to collect information about the impact (e.g. wake-up reactions) of each AHP state in different sleep phases.

The noise scenarios in the conditions 'window closed' and 'window tilted' showed identical time courses. In the comparative baseline night, no noise was presented. The main operating states included are switching on and off, switching to another load state and continuous operation. A defrosting process could not be recorded and was therefore simulated by spectral filtering and adjustments in the level-time curve during the previous icing of the system. As a source for the noise characteristics of AHP during the icing or defrosting process, reference was made not only to empirical values but also to a former study (Schulze et al. 2014). In the time between the switching moments, the sound of continuous operation was added. The noise ramped up to the respective operating state at different speeds. Figure 3 shows the schematic course of the noise scenario for the sleep study as a timeline for a one-hour run.

Figure 3: Schematic course of the noise scenario for the sleep study

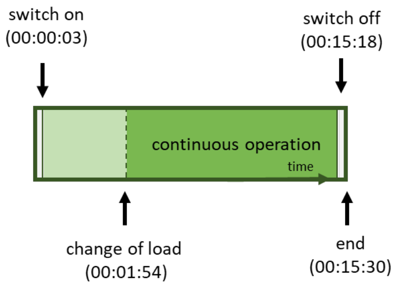


Source: own illustration, Möhler + Partner.

2.6.1.2 Daytime study

For the daytime study, a short version of the noise scenario with a duration of approx. 15 min was created. It also included the essential operating states that also occur in the one-hour noise scenario for the sleep study, but the stationary continuous operation was shortened and the icing with subsequent defrosting process was omitted. Figure 4 shows the temporal course of the 15-minute stimulus schematically.

Figure 4: Schematic temporal course of the 15-minute noise stimulus in the daytime study



Source: own illustration, Möhler +Partner.

2.6.2 Selection of playback levels

The target playback level for the presentation of the stimuli was the highest noise level legally permissible in a mixed used area in Germany at night. The Technical Instructions on Noise Abatement (TA Lärm) are applicable for noise immissions from technical systems. The TA Lärm specifies binding immission values for different types of area (e.g. general residential area, mixed use area). Accordingly, the assessment during the night is based on the full night hour with the highest noise rating level to which the assessed installation contributes to a relevant extend (so-called loudest night hour). When determining the noise rating level, time corrections and possible supplements for annoyance and tone/information content shall be considered.

In mixed used and urban areas, an A-weighted noise rating level of 45 dB, including all supplements – outside, 0.5 m in front of the window - must be met during the loudest night hour according to TA Lärm. In residential areas, however, lower binding immission values apply. In this way, a worst-case situation was depicted in the presentation of the noise scenarios.

The sound presentation in both studies was done via loudspeakers that were set up in the study rooms, which is why the noise transmission from outside to the inside had to be simulated. For this purpose, the average level (maximum average level L_{AFTeq} of the unfiltered signal) of the one-hour noise scenario (including all quiet periods) was first set to 45 dB at a distance of approx. 0.5 m from the loudspeaker, in order to represent the noise situation of a possible worst full night hour 'in front of the (simulated) window'. Subsequently, the noise was spectrally filtered to simulate the transition through the closed or tilted window.

The measurement set-up and implementation, i.e. the selection of the rooms based on acoustic criteria, the noise presentation in the study rooms as well as the acoustic quality control is explained in appendix A.9. The measurement results can be found in 0. Furthermore, the setup of the examination rooms is shown in appendix A.11. The spectral characteristics of the loudspeaker covers are shown in Annex A.12.

2.7 Statistical Analysis

Descriptive statistics in terms of frequencies, means, standard deviation, and standard error were calculated for the descriptive presentation of the assessed sleep parameters and questionnaire items (questions).

Statistical analyses test for significant differences (e.g. between noise scenarios) or associations (e.g. between physiologically measured and self-reported sleep quality parameters). The *p*-value is used for test of significance. This value indicates the probability that the differences or associations tested were due to chance. The test is performed against a predetermined α-level (significance level). In the present analyses, α of 5% was used as a basis. This means that if a result has a *p*-value below $p < 0.05$, it is assumed that there is a 95% probability that the differences examined are not due to chance (Fisher, 1956). Values of $p < 0.05$ are thus considered to indicate statistical significance of differences between conditions.

Friedman test was calculated to investigate any differences in sleep parameters between experimental nights. This procedure, which does not assume any particular statistical distributions of the samples (non-parametric procedure), is used to compare more than two dependent or related samples. In the present case, this means that the subjects underwent three experimental conditions, the results of which were compared. Correlations between variables were examined using Pearson's product-moment correlation. The correlation measure r can take a value between +1 and -1. The closer the value is to the magnitude of 1, the higher is the positive (direction +1) or negative (direction -1) correlation. A positive correlation means that when the value of variable 1 increases, the value of variable 2 also increases. Conversely, a negative correlation means that as the value of variable 1 increases, the value of variable 2 decreases. No correlation is shown when the correlation value is close to 0. No causality can be derived from the correlation value. This means that a significant correlation shows an existing relationship between two variables, but it does not indicate how the two variables influence each other, i.e. about cause and consequence.

A factor analysis was conducted with the data from the daytime study to examine whether summary factors were to be formed from single items that together represent one or more latent concepts (dimensions). Only factors with eigenvalues ≥ 1 were considered (Guttman 1954; Kaiser 1960). As a result, two factors could be formed. The two factors were determined based on factor loading, commonality, and eigenvalue (see Appendix A.13). Those items were summarized to one latent concept (mean score of item ratings) that unambiguously load high on one factor (factor loadings ≥ 0.4) and low on all other factors (factor loadings < 0.4) in both experimental conditions (baseline and noise conditions). The resulting factors were 'difficulty concentrating on the text' and 'mood'.

Analyses of covariance were performed to examine whether there were differences between the two study conditions, baseline and noise scenario, in the daytime study controlling for the covariates noise sensitivity, age, sex, and order of presentation of the conditions. They were performed for possible differences in noise annoyance, difficulty with text, mood, and vital signs systolic and diastolic blood pressure and heart rate. For subjects who reported not hearing any noise in either condition, noise annoyance scores were set to 1 = not annoyed at all.

3 Results

3.1 The effect of air heat pump noise at night

3.1.1 Between-group comparisons between study nights

No influence of order of noise condition 1, noise condition 2 and noise condition 3 was observed.

The Friedman test revealed no differences between the conditions noise exposition 1, 2, and 3 for sleep variables SOL, TST, SE, REM latency, N3 latency, N1, N2, N3, REM, number of arousals, and arousal index. Table 3 shows the descriptive statistics (mean *M* ± standard deviation *SD*) for the sleep variables and the *p* values.

Table 3: Sleep variables by noise conditions and Friedman test p values

Sleep variables	Noise condition 1 (Baseline)	Noise condition 2 (Window tilted)	Noise condition 3 (Window closed)	*p* value
	M ± *SD*	*M* ± *SD*	*M* ± *SD*	
SOL (min)	18.7 ± 18.0	20.4 ± 18.6	19.2 ± 15.1	0.63
TST (min)	398.8 ± 57.8	390.9 ± 54.6	398.7 ± 50.8	0.41
SE (%)	83.1 ± 12.1	81.5 ± 11.4	83.1 ± 10.6	0.33
REM latency (min)	126.4 ± 74.3	132.2 ± 67.8	111.1 ± 65.9	0.13
N3 latency (min)	50.4 ± 46.8	46.4 ± 27.7	46.5 ± 34.2	0.94
N1 (% TST)	12.0 ± 5.6	12.1 ± 5.2	11.3 ± 5.5	0.13
N2 (% TST)	53.0 ± 8.0	53.2 ± 8.1	53.5 ± 8.3	0.97
N3 (% TST)	18.0 ± 7.7	17.9 ± 7.3	17.5 ± 7.7	0.65
REM (% TST)	17.1 ± 5.3	16.66 ± 4.9	17.6 ± 5.5	0.50
# of arousal	44.8 ± 20.8	48.3 ± 22.2	45.3 ± 21.4	0.69
Arousal index (1 / h)	6.7 ± 3.3	7.5 ± 3.6	6.8 ± 3.4	0.42

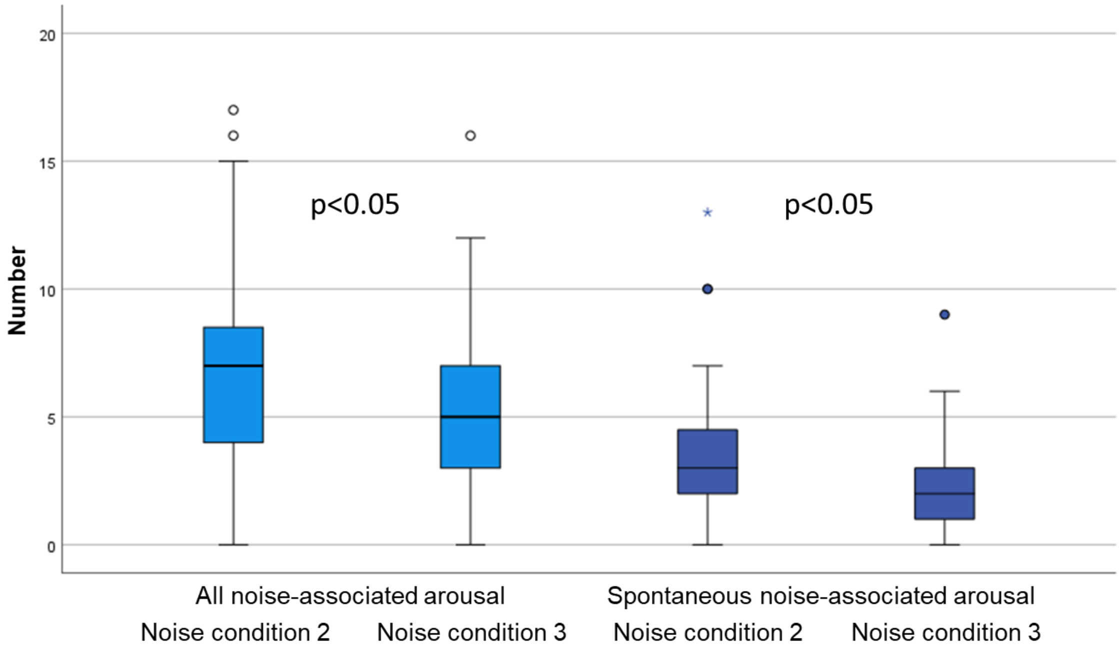
Note. *M* = mean, *SD*= standard deviation, *p* = level of significance, min= minute, TST= total sleep time, REM = Rapid eye movement.

3.1.2 Comparison of number of noise-related arousals between noise conditions

Comparing both, noise condition 2 and 3, with different noise levels during sleep it was found that with the condition 'window tilted' (noise condition 2) a higher total number of arousals (sum of spontaneous, respiratory, and motoric) associated with noise events occurred than with condition 'window closed' (noise condition 3, $p<0.05$). The same was true for the number of spontaneous arousals associated with noise events ($p<0.05$, Figure 5).

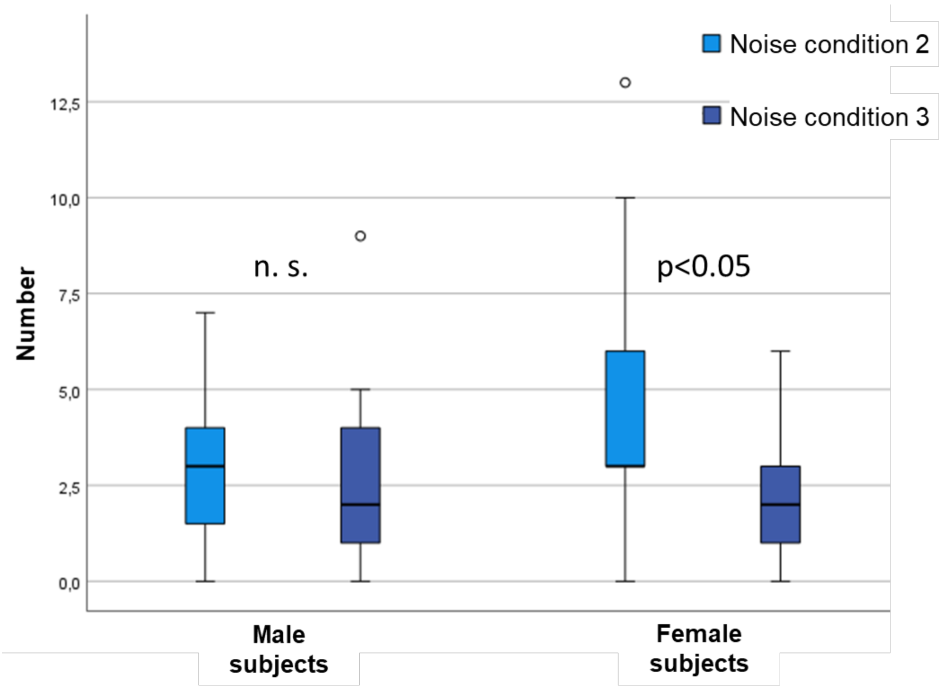
In contrast to this the number of changes from any stage of sleep to the stage wake (W) associated with noise events did not differ between noise condition 2 and noise condition 3 (3.9±2.2 and 3.7±2.5).

Figure 5: Arousals associated with noise events (noise-associated arousals) for noise condition 2 (window tilted) and condition 3 (window closed)



Note. *p* = level of significance.
Source: own illustration, ASR.

Figure 6: Spontaneous arousals associated with noise events separated for males and females for noise condition 2 (window tilted) and 3 (window closed)



Note. *p* = level of significance, n.s.= not significant.
Source: own illustration, ASR.

The difference of number of spontaneous arousals associated with noise between noise condition 2 and noise condition 3 was sex-specific indicating an interaction between the factors sex and noise condition: males exhibited lower mean values of spontaneous arousals associated with noise events during noise condition 3 but without significance whereas a significant change was observed among females ($p<0.05$, Figure 6).

Comparing the three age groups (18 – 34 years, 35 – 50 years, 51 – 65 years) there was no difference on the number of spontaneous arousals associated with noise. This finding was evident for both, noise condition 2 and noise condition 3.

Pearson's correlation of the number of spontaneous arousals associated with noise revealed:

- fewer arousals with increasing age ($r= -0.37$, $p<0.05$),
- more arousals with higher daytime sleepiness values (ESS, $r= 0.32$, $p<0.05$),
- more arousals with higher number of changes from any stage of sleep to stage wake (W, $r= 0.32$, $p<0.05$).

3.1.3 Analysis of the sleep questionnaires

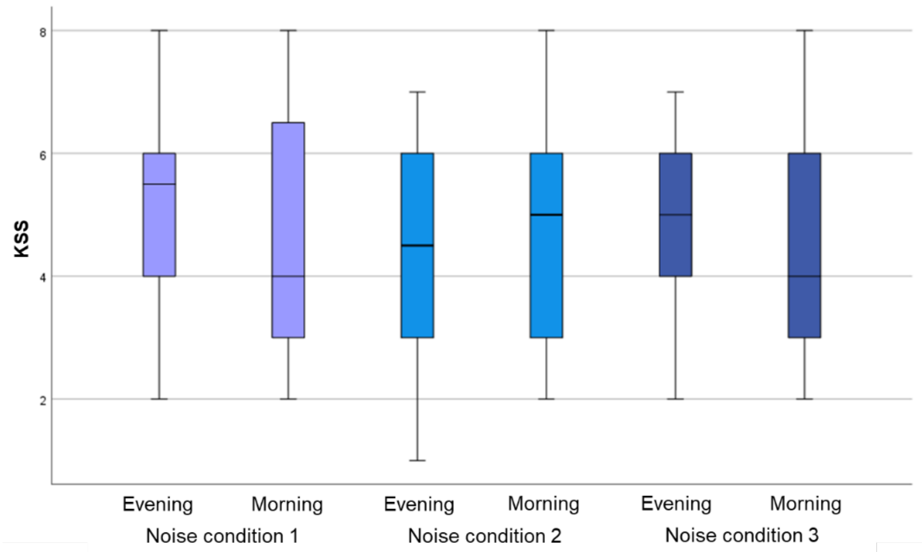
3.1.3.1 Sleepiness and Sleep quality

Comparing self-reported sleepiness in the morning after sleep between noise condition 1 (KSS: 4.6±1.9), noise condition 2 (KSS: 4.6±1.9), and noise condition 3 (KSS: 4.4±1.9) Friedman test revealed no statistical differences.

Self-reported sleepiness between morning after sleep and evening before sleep was reduced for noise condition 1 (KSS: -0.59), increased for noise condition 2 (KSS: 0.23), and reduced for noise condition 3 (KSS: 0.62) (Figure 7).

There were no differences between women and men regarding reported KSS values.

Figure 7: Karolinska Sleepiness Scale (KSS) values before sleep (Evening) and after sleep (Morning) for noise condition (baseline night) 1, noise condition 2 (window tilted), and condition 3 (window closed).



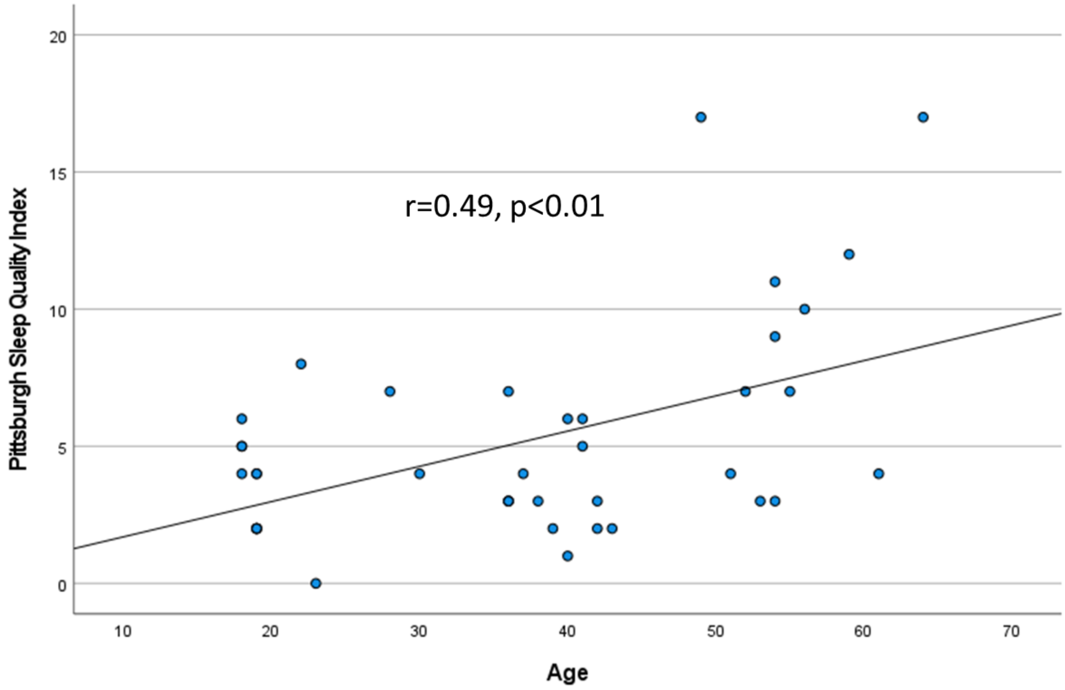
Note. KSS=Karolisnka Sleepiness Scale.
Source: own illustration, ASR.

The following associations (correlations) were significant: Decreased sleep quality (higher PSQI) was associated with older age (0.49, p<0.01, Figure 8), and

Pearson's correlation of the Pittsburgh Sleep Quality Index (PSQI) revealed:

- lower values with higher subjective sensitivity to noise (r=0.38, p<0.05),
- lower values with longer duration to reach deep sleep after 'lights out' (N3 latency, r=0.43, p<0.01).

Figure 8: Correlation of PSQI with age



Note. r = correlation coefficient, p = level of significance.
Source: own illustration, ASR.

3.1.3.2 Self-reported sleep disturbances

In the morning questionnaire subjects were asked to report sleep disturbances during the preceding night. Table 4 shows significant differences in self-reported sleep disturbances when falling asleep (Friedman Chi-square (2)= 18,3, p < 0.001, n=38), sleep during the night (Friedman Chi-square (2)= 23,8, p < 0.001, n=37) and when sleeping in (Friedman Chi-square (2)= 10,8, p < 0.01, n=38).

Table 4: Sleep disturbance variables by noise conditions and Friedman test p values

Sleep disturbance variables	Noise condition 1 (baseline)	Noise condition 2 (window tilted)	Noise condition 3 (window closed)	*p* value
	M ± SD	*M ± SD*	*M ± SD*	
Disturbance Falling asleep	1.7 ± 1.1	2.8 ± 1.2	1.7 ±0.8	< 0.001
Disturbance Sleep through	1.4 ± 0.7	2.6 ± 1.2	1.6 ±0.9	< 0.001
Disturbance Sleep in	1.4 ± 0.7	2.2 ± 1.1	1.8 ±1.1	< 0.01

Note. M = mean, SD= standard deviation, p = level of significance.

Post-hoc tests indicated significant differences in sleep disturbances related to falling asleep between the noise condition 1 (baseline night) and noise condition 2 (window tilted (z=-0.76, $p_{adjusted}$ = 0.003, Effect size according to Cohen (1988): r= 0.12). Additionally, differences are observed between condition 3 (window closed) and noise condition 2 (window tilted) (z= 0.70, $p_{adjusted}$ = 0.007, Effect size according to Cohen (1988): r= 0.11). In noise condition 2 with simulated window tilted difficulties in falling asleep were highest in comparison to the other conditions.

When it comes to night sleep, post-hoc tests revealed significantly higher sleep disturbances during the night in noise condition 2 (window tilted) as compared to the baseline night (z=-0.87, $p_{adjusted}$ = 0.001, Effect size according to Cohen (1988): r= 0.14). The same was found for noise condition 2 (window tilted) in comparison to noise condition 3 (window closed) (z=0.68, $p_{adjusted}$ = 0.011, Effect size according to Cohen (1988): r= 0.11).

Furthermore, significant differences in disturbances when sleeping in are found between the baseline condition and the noise condition 2 (windows tilted) (z=-0.59, $p_{adjusted}$ = 0.030, Effect size according to Cohen (1988): r= 0.1) showing that the average sleep disturbance when sleeping in were highest with simulated windows tilted. All effect sizes are classified as weak (Cohen, 1988, pp. 79-81).

3.2 The effect of air heat pump noise during the day

A total of 40 subjects took part in the daytime study, which was the same sample that participated in the sleep study. The allocation to the two order options of the conditions were distributed equally between two groups: 19 subjects were first in the baseline condition following the noise condition and 21 subjects with an order vice versa.

Table 5: Perception of noise in the two conditions of the daytime study

	Condition	
	Baseline	**Noise condition**
Perception with ears		
yes	6	31
no	34	9
Perception with ears, but not as sound		
yes	0	2
no	40	38
Perception with other senses		
yes	0	1
no	40	39
No perception		
yes	34	7
no	6	33
Total N	**40**	**40**

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3.2.1 Perception of noise in the two study conditions and its effects on self-reported reading performance

In the baseline condition with no presentation of noise only 6 people indicated to perceive sound during the task (Table 5). In the noise condition 33 people indicated to perceive noise, either with their ears or other senses.

Asked for the type of sound subjects heard during the condition, subjects in the baseline conditions that indicated to perceive sounds mainly described sounds occurring independently from the setting such as peep sound or sounds from the streets (Table 6). In the noise condition people mentioned mostly sounds related to air-conditioning systems or ventilation systems, rustling and buzzing/humming.

Table 6: Description of sound perceived during the two conditions

Description of sound baseline condition		Description of sound in noise condition	
non-continuous humming	1	Rustling	10
quiet beeping	1	Air conditioning	6
furniture moving, metallic noise	1	Ventilation system	5
low whirring	1	Humming	4
Street noises	1	Whirring, hissing	1
Rustling	1	Rattling	1
		Walking people	1

Subjects who indicated to hear sound while performing the reading task answered questions on how they perceived the noise while reading (Table 7), e.g. if noise disturbed them from reading. This means, in the baseline condition only those were asked to indicate disturbances that claimed to hear a sound. Coping items were higher rated in the baseline condition than in the noise condition, e.g. that subjects were better able to tune out noise or protecting themselves from the noise. In the noise condition, subjects' annoyance due to noise was rated higher and more subjects indicated noise to negatively affect reading and concentrating than in the baseline condition.

Table 7: Average perception of noise while reading and its effects on self-reported reading performance.

	Condition	
	Baseline (N=6) ***M ±SD***	**Noise condition (N= 33)** ***M ±SD***
The noise in the background disturbed me while reading.	1.5 ±0.84	2.58 ± 1.23
I could not concentrate on the text because of the noise in the background.	1.33 ± 0.82	2.18 ±1.18
The noise in the background distracted me from reading.	1.33 ± 0.5	2.21 ± 1.17
I feel at the mercy of the noise.	1 ± 0.0	1.91 ± 1.1
The noise worries me.	1 ± 0.0	1.58 ±0.83

	Condition	
The noise puts me in a bad mood.	1 ± 0.0	1.70 ±1.02
I can easily 'tune out' the noise while reading.	4.0 ±0.63	3.15 ± 1.33
The noise makes me feel uncomfortable.	1 ± 0.0	1.58 ± 0.83
The distraction of the noise upsets me.	1 ± 0.0	1.61 ± 0.9
I am good at protecting myself from the distraction of the noise.	4.17 ±0.41	3.18 ± 1.18
The distraction of the noise annoys me.	1 ± 0.0	1.7 ± 0.98
I concentrate on reading and then the noise doesn't bother me at all.	3.83 ±1.47	3.12 ± 1.43
I have come to terms with the noise.	4.17 ± 1.0	3.39 ± 1.34

Note. *M* = Mean. *SD* = Standard deviation.

3.2.2 Noise annoyance, concentration and mood during the two conditions of the daytime study

Table 8 shows average ratings of single items for noise annoyance, concentration on text and mood during two conditions in the daytime study. Noise annoyance was higher in the noise condition (*M*=2.27, *SD*=1.04) than in the baseline condition (*M*=1.5, *SD*=0.84). Further, all three items referring to difficulties to read the text were rated higher in the noise condition than in the baseline condition suggesting effects of the noise on the ability to concentrate on the text in the noise condition. The mood items showed only small differences between the conditions indicating, e.g. a more nervous (noise: *M*= 1.5, *SD*=0.72; baseline: *M*=1.3, *SD*=0.46), less relaxed (noise: *M*= 3.7, *SD*=1.07; baseline: *M*= 3.95, *SD*=0.82), and more distracted mood (noise: *M*=1.88, *SD*=0.99; baseline: *M*= 1.55, *SD*=0.81) in the noise condition.

Table 8: Average noise annoyance, concentration and mood during the two conditions of the daytime study

	Condition	
	Baseline (N=40) ***M* ±*SD***	**Noise condition (N= 40)** ***M* ±*SD***
Noise annoyance	1.5 ± 0.84	2.3 ± 1.04
Difficulties concentrating on the text		
I couldn't concentrate on the text.	2.2 ± 1.32	2.8 ± 1.5
I had to read the text several times to understand it.	2.7 ± 1.39	2.8 ± 1.33
It strained me to read the text.	2.9 ± 1.36	3.2 ± 1.28

	Condition	
Mood		
I am relaxed.	3.95 ± 0.82	3.7 ± 1.07
I am worried.	1.5 ± 1.11	1.5 ± 0.99
I am in a bad mood.	1.2 ± 0.46	1.4 ± 0.71
I am nervous.	1.3 ± 0.46	1.5 ± 0.72
I feel comfortable.	3.7 ± 0.88	3.7 ± 0.88
I feel uneasy.	1.65 ± 1.05	1.7 ± 0.99
I am alert.	3.9 ± 0.84	3.5 ± 0.96
I am distracted.	1.55 ± 0.81	1.9 ± 0.99

Note. *M* = Mean. *SD* = Standard deviation.

Factor analysis was applied to identify items to analyse main concepts of interest (Appendix A.13).

Besides noise annoyance with one item two more variables were identified to focus on in the analysis of differences between the two conditions (Table 9): *Difficulties concentrating on the text* consisting of two items. The factor *Mood* was formed from three variables on relaxation, attention and distraction.

Table 9: Result of factor analysis with three main concepts of interest

Dependent variable	Item	Item in questionnaire
Noise annoyance	All in all, I feel ... disturbed or annoyed by the noise.	Item 16
Difficulties concentrating on the text	I had to read the text several times to understand it.	Item 21
	It strained me to read the text.	Item 22
Mood	I am relaxed.	Item 23
	I am alert.	Item 29
	I am distracted.	Item 30

Results of the three main variables separated into conditions and distributed for age, sex and order are depicted in Table 10.

Table 10: Average noise annoyance, difficulties with text and mood in both conditions separated into age, sex and order of conditions

	Annoyance		Difficulties in concentrating on text		Mood	
	Baseline	**Noise condition**	**Baseline**	**Noise condition**	**Baseline**	**Noise condition**
Age	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*	*M* ± *SD*
Age 18-34	1.00 ± 0.00	1.71 ± 0.73	2.57 ± 1.44	2.64 ± 1.13	4.21 ± 0.65	3.83 ± 0.70
Age 35- 49	1.13 ± 0.52	2.67 ± 1.23	3.13 ± 1.06	3.73 ± 1.05	3.87 ± 0.75	3.29 ± 0.84
Age 50- 65	1.09 ± 0.30	1.64 ± 0.81	2.55 ± 1.31	2.36 ± 1.14	4.27 ± 0.49	4.36 ± 0.53
Total	1.08 ± 0.35	2.05 ± 1.06	2.78 ± 1.27	2.98 ± 1.23	4.10 ± 0.66	3.78 ± 0.82
Sex						
Male	1.10 ± 0.44	1.95 ± 0.97	2.79 ± 1.44	3.12 ± 1.32	4.1 ± 0.68	3.71 ± 0.73
Female	1.05 ± 0.23	2.16 ± 1.17	2.76 ± 1.1	2.82 ± 1.15	4.11 ± 0.67	3.84 ± 0.93
Total	1.08 ± 0.35	2.05 ± 1.06	2.78 ± 1.27	2.98 ± 1.23	4.1 ± 0.66	3.78 ± 0.82
Order of conditions						
Order 1	1.11 ± 0.46	2.58 ± 1.22	3.47 ± 1.01	3.37 ± 1.14	3.91 ± 0.69	3.49 ± 0.97
Order 2	1.05 ± 0.22	1.57 ± 0.60	2.14 ± 1.16	2.62 ± 1.23	4.27 ± 0.60	4.03 ± 0.58
Total	1.08 ± 0.35	2.05 ± 1.06	2.78 ± 1.27	2.98 ± 1.23	4.10 ± 0.66	3.78 ± 0.82

Note. *M*= Mean, *SD*= Standard deviation, Order 1= 1. Condition baseline, 2. Noise condition. Order 2= 1. Noise condition, 2. Baseline condition.

3.2.3 Comparison of baseline and noise condition for annoyance, difficulties in text, mood and blood pressure with analysis of covariance

3.2.3.1 Results of analysis of covariance for noise annoyance, difficulties with text and mood

Analysis of covariance was executed to analyse potential differences in noise annoyance, difficulties in concentration on text, mood, blood pressure and heart rate between the baseline condition and the noise condition. In the analysis the effect of the covariates noise sensitivity, age, sex and order of presentation of the conditions were controlled. Table 11 shows results for noise annoyance, difficulties in text and mood.

Table 11: Analysis of covariance for noise annoyance, difficulties with text and mood

Factor	Noise annoyance	Difficulties text	Mood
Main effects			
Condition	F(1, 25)=9.81, *p* = 0.004	F(1,25)=7.89, *p* = 0.009	F(1,25)=4.40, *p* = 0.046
Noise sensitivity	F(1,25)=0.09, *p* = 0.764	F(1,25)=4.36, *p* = 0.047	F(1,25)=1.68, *p* = 0.207
Sex	F(1,25)=0.12, *p* = 0.733	F(1,25)=2.58, *p* = 0.121	F(1,25)=0.66, *p* = 0.424
Age	F(2,25)=2.89, *p* = 0.074	F(2,25)=3.04, *p* = 0.066	F(2,25)=5.09, *p* = 0.014
Order	F(1,25)=7.71, *p* = 0.010	F(1,25)=7.80, *p* = 0.010	F(1,25)=10.95, *p* = 0.003
Sex*Age	F(2,25)=0.57, *p* = 0.571	F(2,25)=1.50, *p* = 0.243	F(2,25)=3.93, *p* = 0.033
Sex*Order	F(1,25)=0.00, *p* = 0.998	F(1,25)=2.88, *p* = 0.102	F(1,25)=1.76, *p* = 0.197
Age*Order	F(2,25)=0.56, *p* = 0.579	F(2,25)=1.56, *p* = 0.230	F(2,25)=1.78, *p* = 0.190
Age*Sex*Order	F(1,25)=1.89, *p* = 0.181	F(1,25)=0.41, *p* = 0.526	F(1,25)=4.82, *p* = 0.038
Interaction Condition ...			
*Noise sensitivity	F(1,25)=0.11, *p* = 0.744	F(1,25)=5.03, *p* = 0.034	F(1,25)=1.65, *p* = 0.211
*Sex	F(1,25)=0.24, *p* = 0.627	F(1,25)=3.25, *p* = 0.084	F(1,25)=0.01, *p* = 0.927
*Age	F(2,25)=4.18, *p* = 0.027	F(2,25)=4.15, *p* = 0.028	F(2,25)=3.30, *p* = 0.053
*Order	F(1,25)=16.37, *p* ≤ .001	F(1,25)=4.82, *p* = 0.038	F(1,25)=0.84, *p* = 0.369
*Sex*Age	F(2,25)=3.59, = 0.043	F(2,25)=0.13, *p* = 0.882	F(2,25)=0.70, *p* = 0.505
*Sex*Order	F(1,25)=1.38, *p* = 0.251	F(1,25)=1.81, *p* = 0.191	F(1,25)=1.49, *p* = 0.233
*Age*Order	F(2.19)=0.24, *p* = 0.790	F(2,25)=0.10, *p* = 0.905	F(2,25)=1.04, *p* = 0.369
*Age*Sex*Order	F(1,25)=2.45, *p* = 0.130	F(1,25)=2.98, *p* = 0.097	F(1,25)=0.01, *p* = 0.926

Note. *p*= significance level.

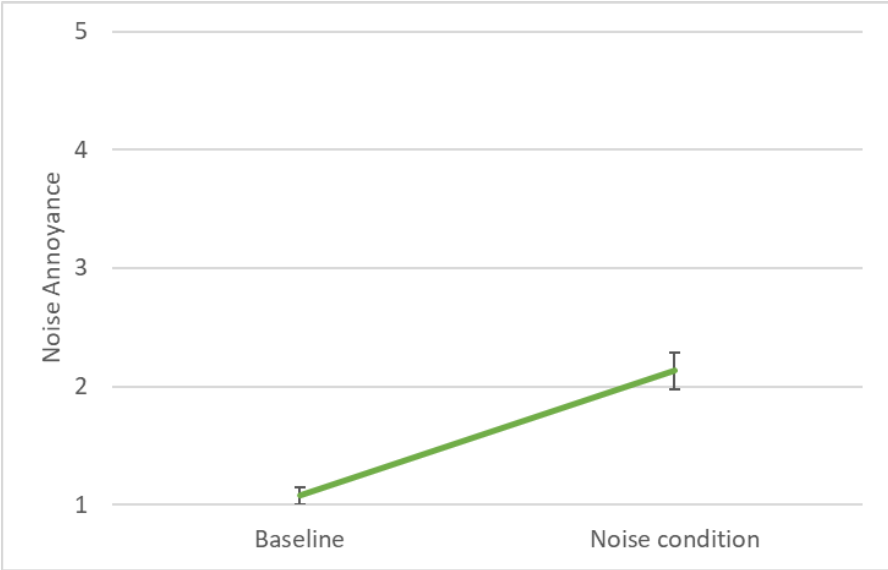
3.2.3.2 Noise annoyance

A main effect of condition was found for annoyance, which is illustrated in Figure 9. Noise annoyance was significantly higher in the noise condition in comparison to the baseline ($F(1,25)=9.81$, $p < 0.01$).

The interaction between condition and age has a significant effect on noise annoyance (F(2, 25)=4,176, $p < 0.05$). In the age group 35-49 years subjects were significantly more annoyed by the AHP noise in the noise condition than subjects in the younger and older age groups (Figure 10).

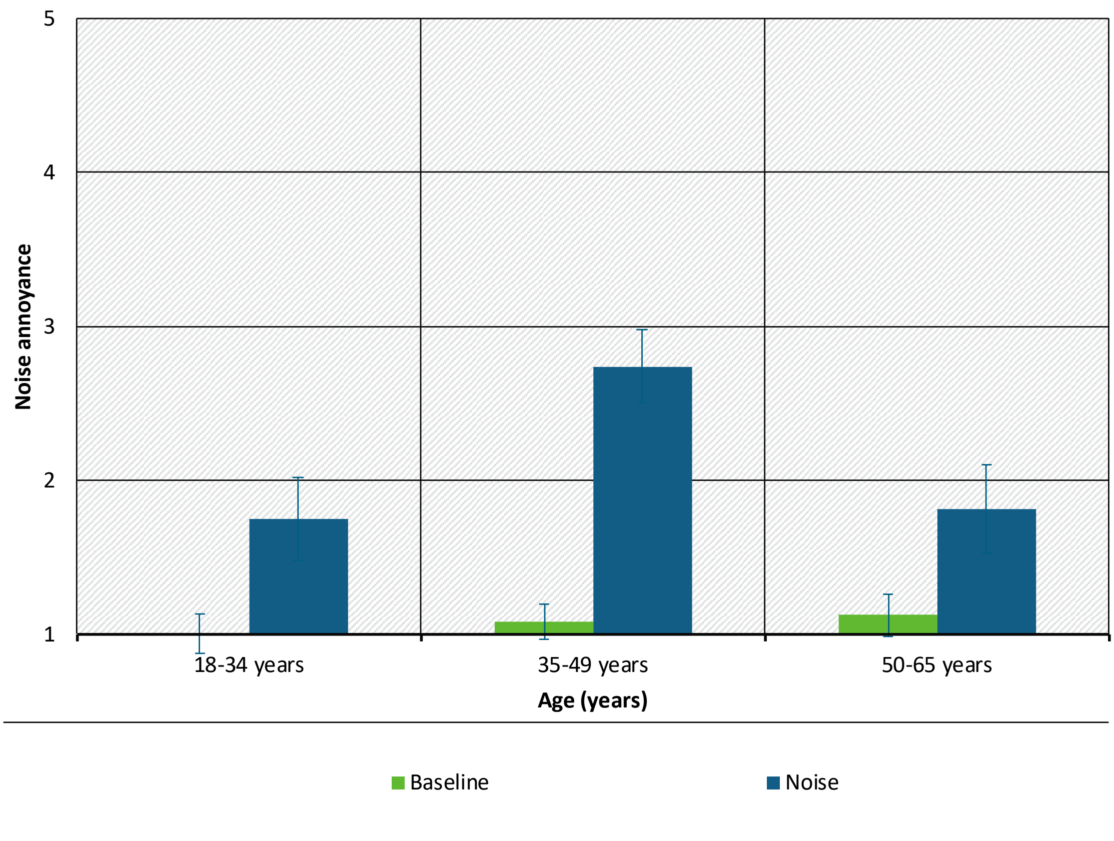
An interaction effect was found for condition*sex*age showing that in the noise condition women older than 34 years were more annoyed by AHP noise than younger women (Figure 11). The male subjects in the middle age group 35-49 years were more annoyed than younger and older men ($F(2, 25)=3.59$, $p < 0.05$).

Figure 9: Main effect of condition for noise annoyance



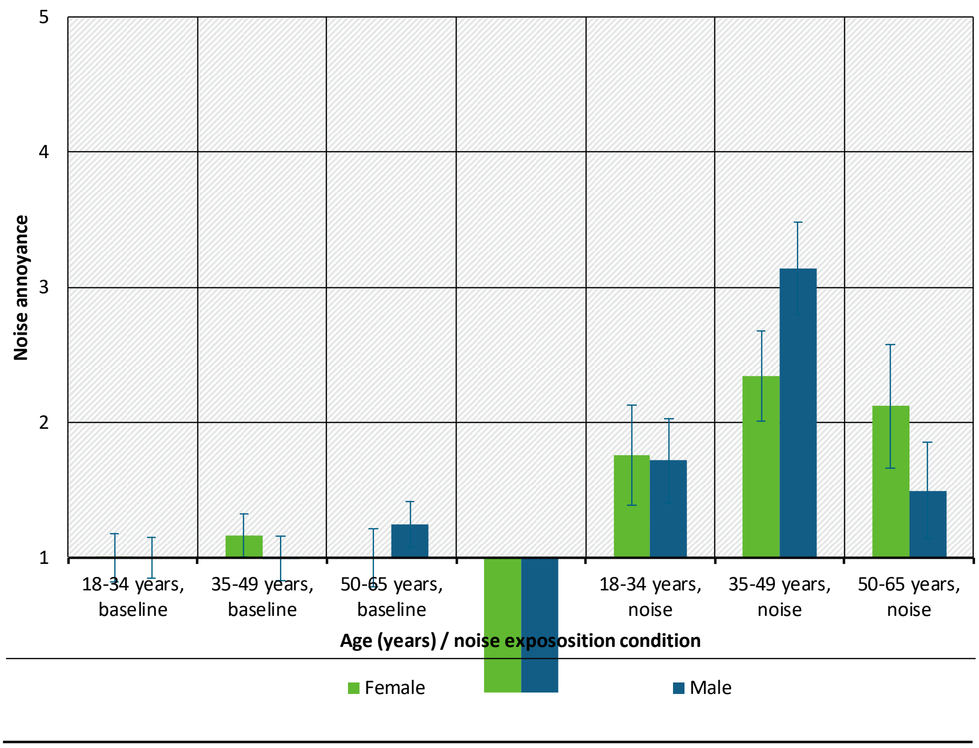
Note. Scale from 1= not at all to 5= extremely.
Source: own illustration, ZEUS.

Figure 10: Interaction effect of age and condition on noise annoyance



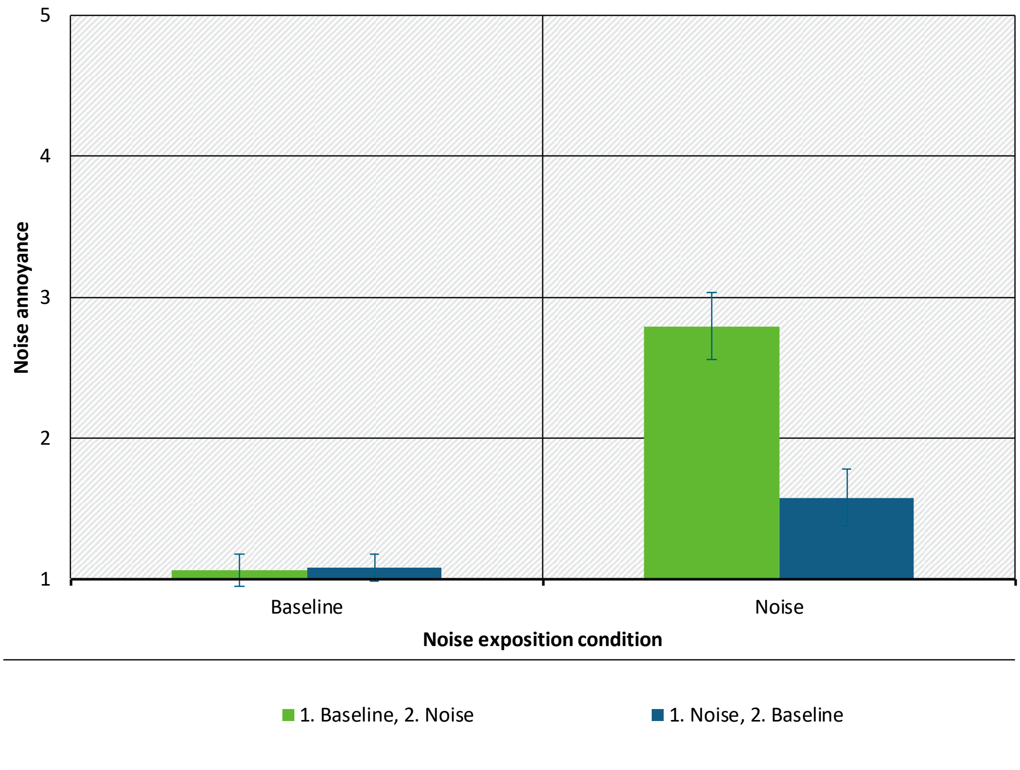
Note. Noise annoyance scale from 1= not at all to 5= extremely.
Source: own illustration, ZEUS.

Figure 11: Interaction effect of age, sex and condition on noise annoyance



Note. Noise annoyance scale from 1= not at all to 5= extremely.
Source: own illustration, ZEUS.

Figure 12: Noise annoyance depending on the order of presentation of the conditions



Note. Noise annoyance scale from 1= not at all to 5= extremely.
Source: own illustration, ZEUS.

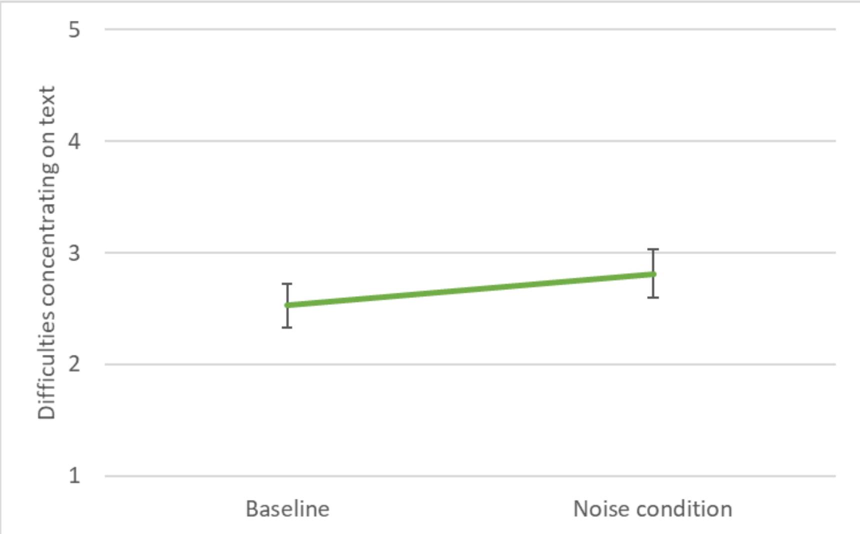
Besides, the order of conditions in interaction with the conditions influenced the degree of annoyance ($F(1, 25)=16.37$, $p < 0.001$). The direction of noise annoyance was equal between the conditions, in both orders the annoyance was higher in the noise condition in comparison to the baseline (Figure 12). However, the intensity, i.e. the level of annoyance differed and was significantly higher in the noise condition when the noise condition followed the baseline condition. The previous condition served as a reference condition, in this case the quiet surrounding.

3.2.3.3 Difficulties in concentration on the text

In the noise condition self-reported difficulties in concentration on the text was significantly higher than in the baseline condition ($F(1,25) = 7.89$, $p < 0.01$; Figure 13).

Also, the individual disposition of noise sensitivity affected the difficulties in concentrating on the text ($F(1,25)=4.36$, $p < 0.05$), indicating higher noise sensitive subjects having more difficulties in concentrating on the text. This was particularly true for difficulties in concentration in the baseline condition ($F(1,25) = 5.03$, $p < 0.05$). A correlation analysis showed that the self-reported noise sensitivity correlated with the score on difficulties in concentration in the quiet baseline condition ($r = .372$, $p < 0.05$), but not in the noise condition ($r = .138$, $p = 0.417$).

Figure 13: Main effect of condition on difficulties in concentrating on text

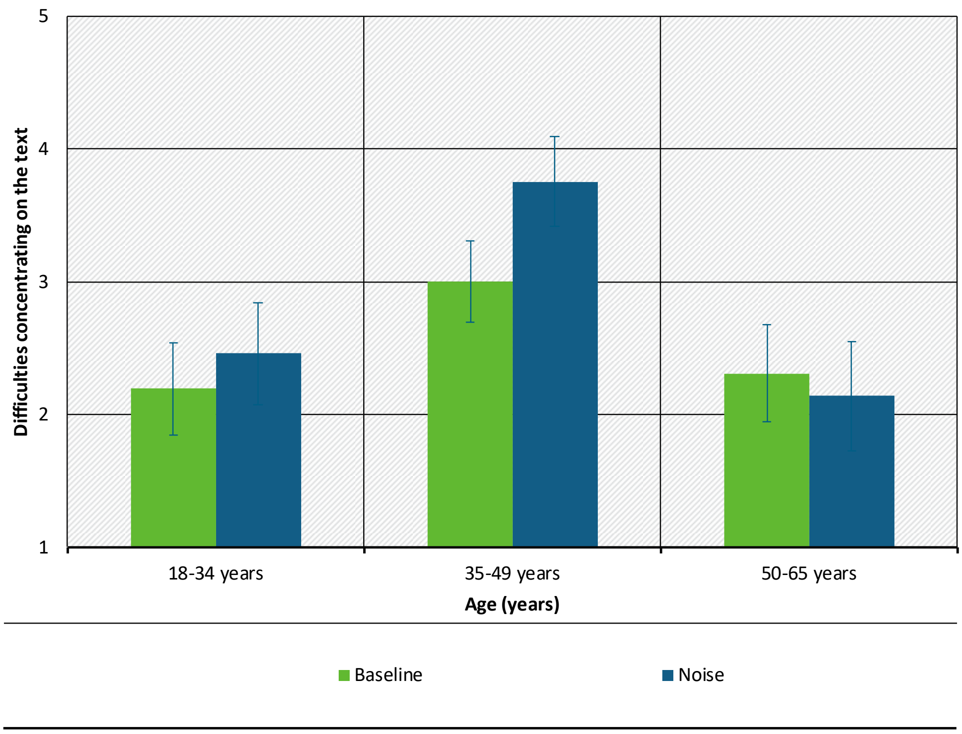


Note. Scale from 1= not to 5= very true with higher values indicating higher concentration difficulties.
Source: own illustration, ZEUS.

Figure 14 shows the interaction effect of condition and age on difficulties in concentrating on text. It illustrates that the age group 35-49 years seemed to have the biggest difficulties to focus and concentrate on the text, in particular in the noise condition.

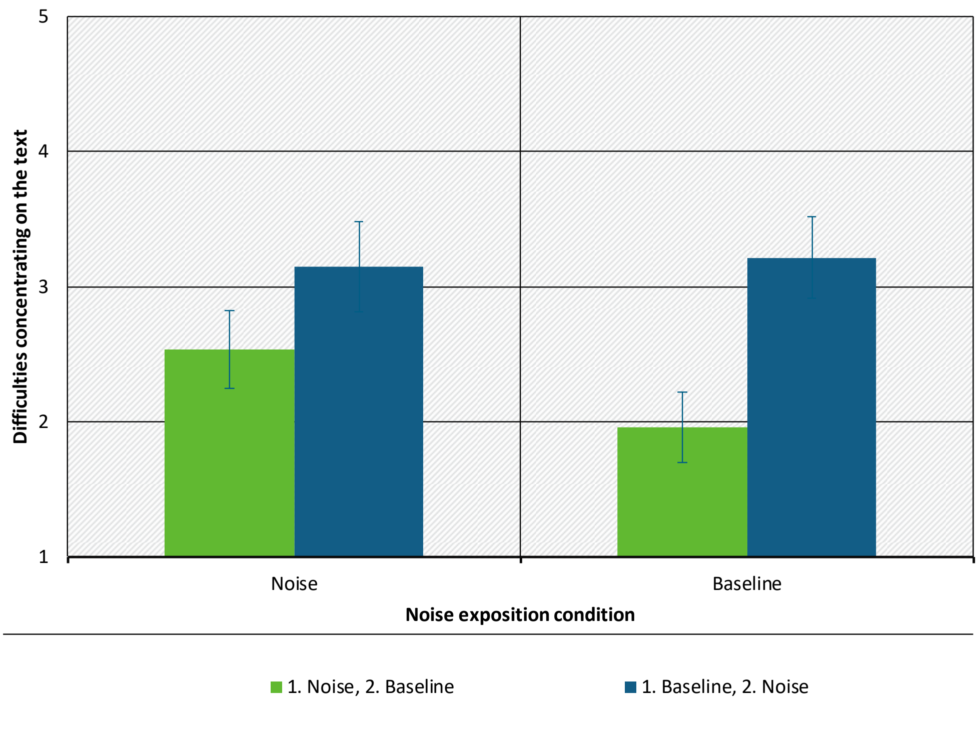
The order of the conditions was significantly influencing the difficulties in concentration on the text in the two noise conditions ($F(1,25)=4.82$, $p < 0.05$). Figure 15 illustrates that in the group with the order of baseline condition followed by the noise condition no difference in the concentration on the text occurred in the baseline and noise condition. That means, difficulties in concentrating on the text during the baseline condition were similarly high as in the following noise condition. In contrast, in the group with the *noise – baseline* order subjects reported less difficulties in concentrating on the text in the baseline condition compared to the (preceding) noise condition.

Figure 14: Interaction effect of condition and age on difficulties in concentrating on text



Note. Scale from 1= not to 5= very true with higher values indicating higher concentration difficulties.
Source: own illustration, ZEUS.

Figure 15: Interaction effect of condition and order of conditions on difficulties in concentrating on text



Note. Scale from 1= not to 5= very true with higher values indicating higher concentration difficulties.
Source: own illustration, ZEUS.

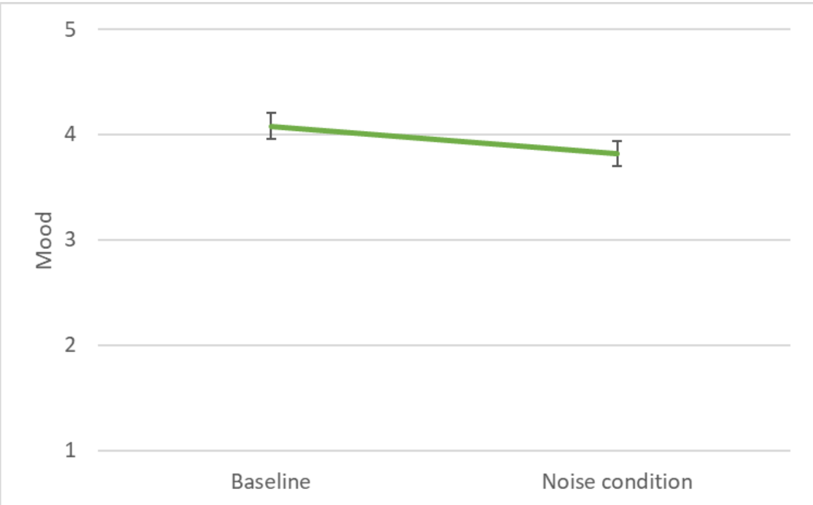
3.2.3.4 Mood

For mood only a main effect for the two conditions was found (F(1,25)=4.40, $p < 0.05$). In the noise condition subjects were significantly less relaxed and alert than in the baseline condition (Figure 16).

Mood differed significantly with age with the middle aged group 35-49 years (F(2,25=5.09, $p <$ 0.05) being in less relaxed and alert and more distracted mood (M = 3.5, SE = 0.15) than the younger (M = 4.2, SE = 0.17) and the older group (M = 4.2, SE = 0.18). The age effect on mood interacted with sex (F2,25)=3.9, $p < 0.05$) indicating that the oldest male group (50-65 years) reported the most positive (relaxed, not distracted) mood (M = 4.4, SE = 0.23) compared to all other male groups (18-34 years: M = 4.0, SE = 0.20; 35-49 years: M = 3.5, SE = 0.22). In contrast, the youngest female group (18-34 years) reported the highest positive mood (relaxed, alert, not districted) than the other female age groups (35-49 years: M = 3.6, SE = 0.21; 50-65 years: M = 4.04, SE = 0.29).

Regarding the main effect of the order of conditions (F(1,25)=10.95, $p < 0.01$) overall, subjects were in a better mood when the quiet baseline condition followed the noise condition (M = 4.2, SE = 0.13) than vice versa (M = 3.6, SE = 0.15). When the first text was read in the quiet baseline condition and then in second order in the noise condition, this had a negative effect on mood, especially for middle-aged men, compared to the mood and conditions in the other groups (F(1,25)=4.82, $p < 0.05$). Further interactions regarding mood were not observed.

Figure 16: Main effect of condition for mood



Note. Scale from 1= not to 5= very true, with higher values indicating higher relaxation and alertness.
Source: own illustration, ZEUS.

3.2.3.5 Blood pressure and heart rate

Vital functions were measured three times during the daytime study: At the beginning of the study (start, T0) and after each study condition (T1 and T2) blood pressure and heart rate was measured. Analysis of covariance was performed separately for systolic value of blood pressure and diastolic value of blood pressure as well as heart rate. Covariates were included to control for potential confounding effects: noise sensitivity, sex, age, and order of conditions.

Table 12 shows the results of the three analyses of covariance. The time of measurement (T0, T2, T2) had no main effect on blood pressure and heart rate. The main effect of sex on systolic blood pressure indicated a higher systolic blood pressure for male (M = 123.4, SE = 2.53) than female (M = 111.9, SE = 2.77).

Table 12: Analysis of covariance for blood pressure and heart rate: Main effects and interactions with time of measurement

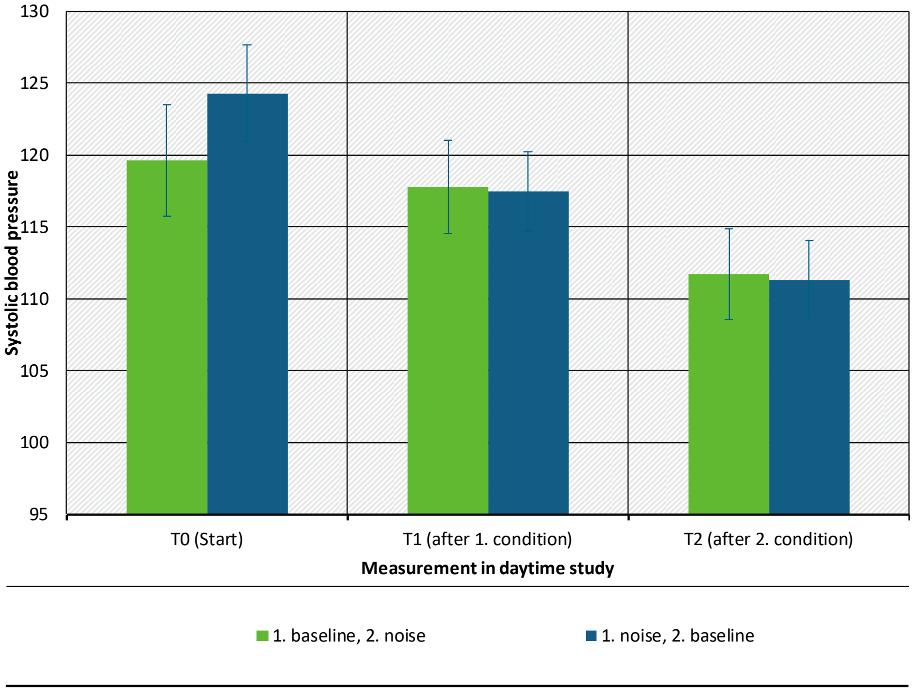
Factor	Blood pressure: systolic value	Blood pressure: diastolic value	Heart rate
Main effects			
Time of measurement	F(2,50)=2.99, *p*= 0.059	F(2,50)=1.16, *p*= 0.322	F(2,50)=0.06, *p*= 0.939
Noise sensitivity	F(1,25)=0.02, *p*= 0.880	F(1,25)=0.63, *p* = 0.435	F(1,25)=0.03, *p* = 0.866
Sex	F(1,25)=7.93, *p*= 0.009	F(1,25)=2.91, *p* = 0.100	F(1,25)=0.90, *p* = 0.351
Age	F(2,25)=0.39, *p*= 0.681	F(2,25)=0.29, *p* = 0.755	F(2,25)=1.15, *p* = 0.334
Order of conditions	F(1,25)=0.13, *p*= 0.718	F(1,25)=0.00, *p* = 0.999	F(1,25)=0.13, *p* = 0.718
Sex*Age	F(2,25)=2.71, *p* = 0.086	F(2,25)=0.66, *p* = 0.528	F(2,25)=3.49, *p* = 0.046
Sex*Order	F(1,25)=0.88, *p* = 0.356	F(1,25)=0.65, *p* = 0.430	F(1,25)=0.16, *p* = 0.696
Age*Order	F(2,25)=1.266, *p* = 0.302	F(2,25)=0.43, *p* = 0.654	F(2,25)=0.63, *p* = 0.542
Age*Sex*Order	F(1,25)=2.69, *p* = 0.113	F(1,25)=1.27, *p* = 0.271	F(1,25)=0.90, *p* = 0.352
Interaction: Time of measurement …			
*Noise sensitivity	F(2,50)=1.12, *p* = 0.336	F(2,50)=0.88, *p* = 0.421	F(2,50)=0.39, *p* = 0.679
*Sex	F(2,50)=0.00, *p* = 0.999	F(2,50)=2.14, *p* = 0.128	F(2,50)=1.57, *p* = 0.219
*Age	F(4,50)=1.28, *p* = 0.291	F(4,50)=2.60, *p* = 0.047	F(4,50)=4.32, *p* = 0.004
*Order	F(2,50)=5.60, *p* = 0.006	F(2,50)=6.64, *p* = 0.003	F(2,50)=5.41, *p* = 0.007
*Sex*Age	F(4,50)=0.56, *p* = 0.694	F(4,50)=3.02, *p* = 0.026	F(4,50)=1.78, *p* = 0.148
*Sex*conditions	F(2,50)=0.86, *p* = 0.429	F(2,50)=1.68, *p* = 0.196	F(2,50)=2.15, *p* = 0.127
*Age*Order	F(4,50)=1.44, *p* = 0.236	F(4,50)=1.97, *p* = 0.113	F(4,50)=2.40, *p* = 0.062
*Age*Sex*Order	F(2,50)=1.79, *p* = 0.177	F(2,50)=0.88, *p* = 0.421	F(2,50)=0.58, *p* = 0.564

Note. *p*= significance level.

Effects of conditions (baseline and noise condition) can be seen from the interaction between time of measurement, in particular the measurements at T1 and T2, and the order of conditions. This interaction was statistically significant for all three measures (Table 12). Note, that the subjects were allocated to the order of conditions by random.

Figure 17 illustrates the interaction effect of time of measurement and order of baseline/noise conditions on the systolic blood pressure (F(2,50) = 5.60, $p < 0.01$). All in all, Figure 17 shows a decreasing systolic blood pressure over time from T0 to T3. Further, it reveals similar blood pressures at measurement T2 and T3, respectively, regardless of the conditions (baseline and noise). The difference turned out to be at the start, that is before exposed to one of the conditions baseline or noise, the blood pressure of the group with noise as the first condition was already higher at the beginning of the experiment. This result does not support an effect of the exposition condition itself.

Figure 17: Interaction between time of measurement (T0, T1, T2) and order of the conditions (baseline and noise) on systolic blood pressure



Source: own illustration, ZEUS.

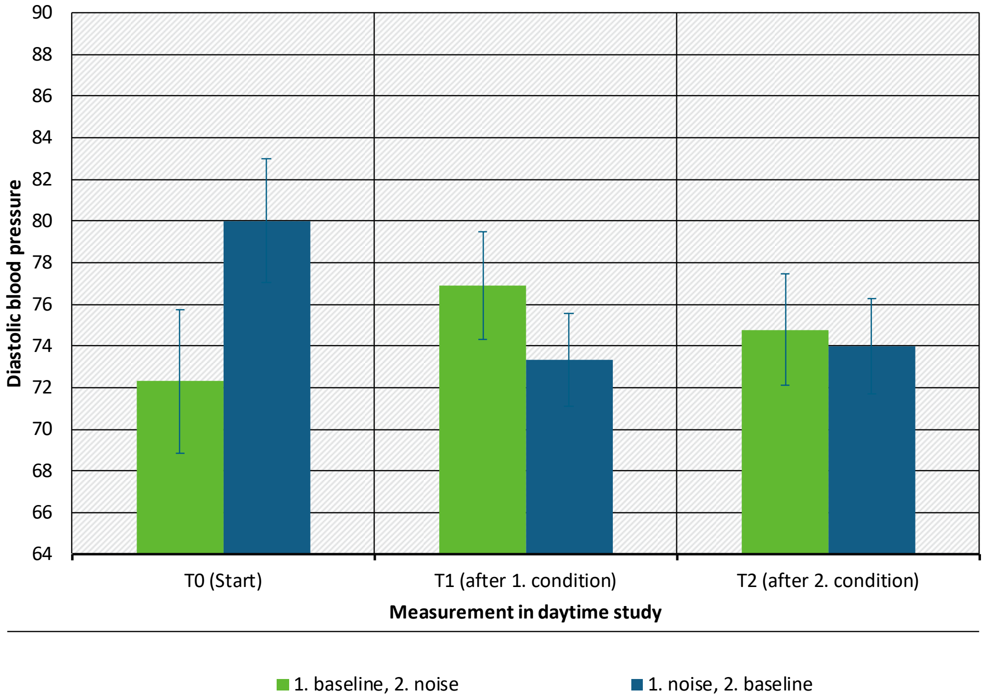
A similar picture of results was obtained for the diastolic blood pressure. The main difference in blood pressure were shown at the beginning of the experiment, whereas in this study the different conditions (baseline and noise) seemed not to have an impact on the blood pressure (Figure 18).

Regarding the diastolic blood pressure, age interacted with the time of measurement ($F(4,50) = 2.60$, $p < 0.05$), see Figure 19. For all age groups up to 49 years, the diastolic blood pressure values were lower at the second (T1) and third (T2) measurement compared to the first one (T0) at the beginning of the experiment. In contrast to this, the diastolic pressure of the 50-65 years old group increased from T0 to T1 and decreased again from T1 to T2 to a lower level than at the beginning of the daytime study.

However, when sex was considered additionally, the group of 50-65 years male subjects showed the highest diastolic blood pressure at the beginning (T0) (highest compared to all other male groups). The female subjects in this age group had the highest diastolic blood pressure after the first condition (T1) ($F(4,50) = 3.02$, $p < 0.05$), see Figure 20. Also, at almost all times of measurement male subjects had higher diastolic blood pressure than female subjects. The difference was higher in the youngest group (18-34 years) and the older group (50-65 years) compared to the middle-aged subjects.

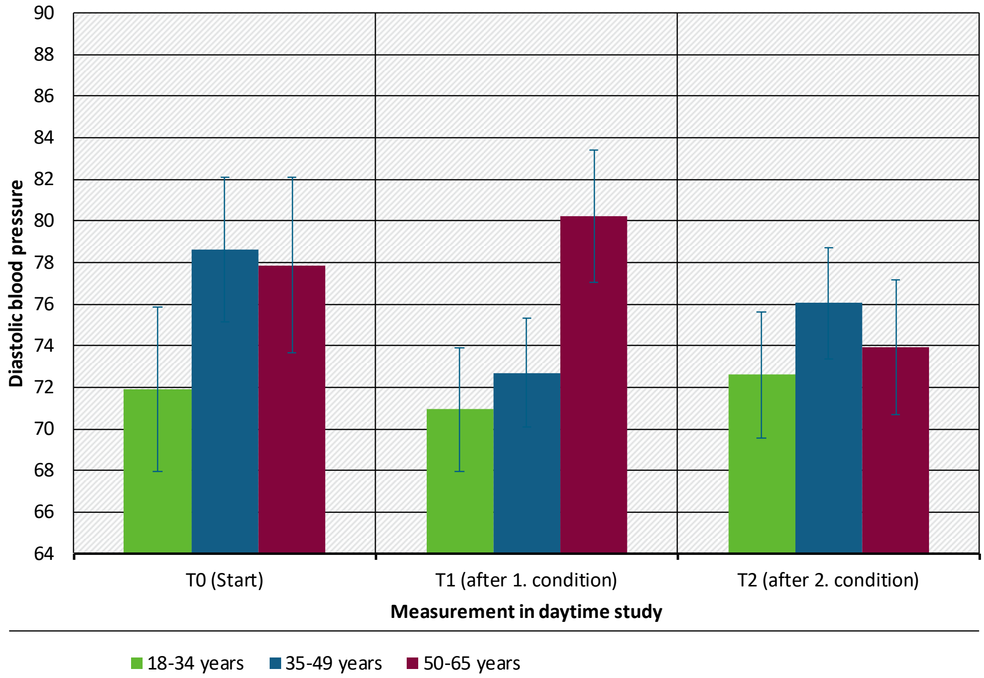
Figure 21 shows the results of the interaction between the condition and the order of the condition for heart rate ($F(2,50) = 5.41$, $p < 0.01$)). In the group of subjects first reading the text in the noise condition (T1) and then in the baseline condition (T2) the heart rate decreased from T0 to T2. Assuming that the decrease in heart rate indicates relaxation from physiological stress, the results show that in the baseline condition in the second part of the experiment (T2) subjects were able to relax. However, the group of subjects receiving first the baseline condition (T1) and then the noise condition, could not calm down in the (quiet) baseline condition.

Figure 18: Interaction between time of measurement (T0, T1, T2) and order of the conditions (baseline and noise) on diastolic blood pressure



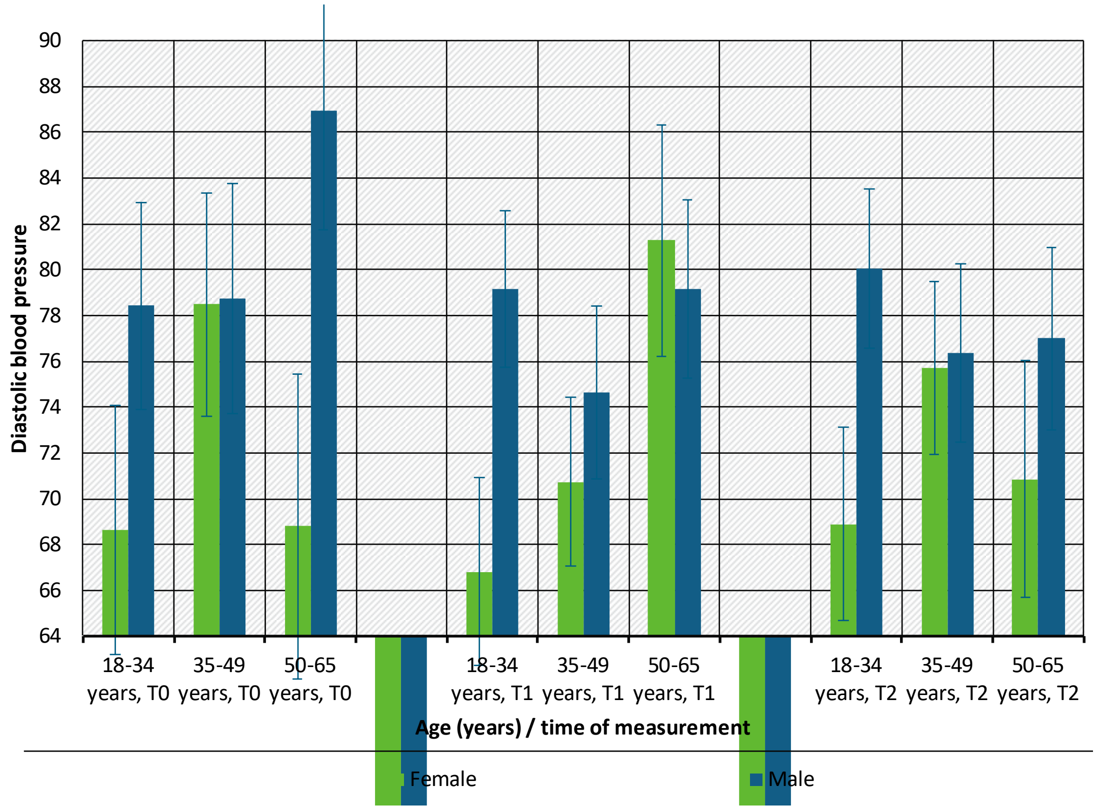
Source: own illustration, ZEUS.

Figure 19: Interaction between time of measurement (T0, T1, T2) and age on diastolic blood pressure



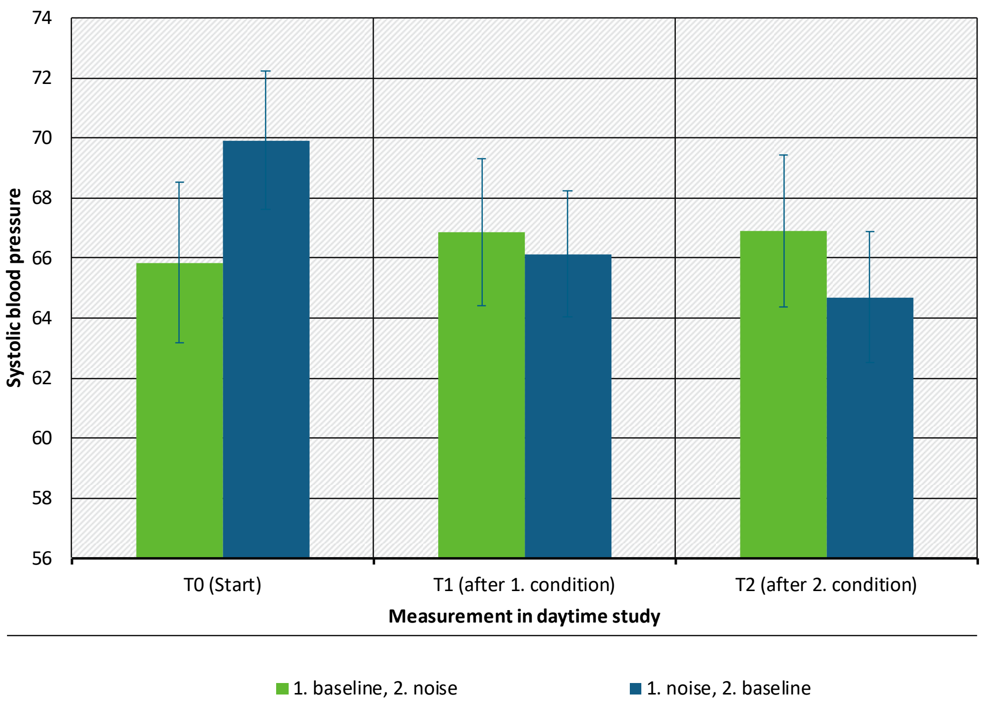
Source: own illustration, ZEUS.

Figure 20: Interaction between time of measurement (T0, T1, T2), sex and age on diastolic blood pressure



Source: own illustration, ZEUS.

Figure 21: Interaction between time of measurement (T0, T1, T2) and order of the conditions (baseline and noise) on heart rate

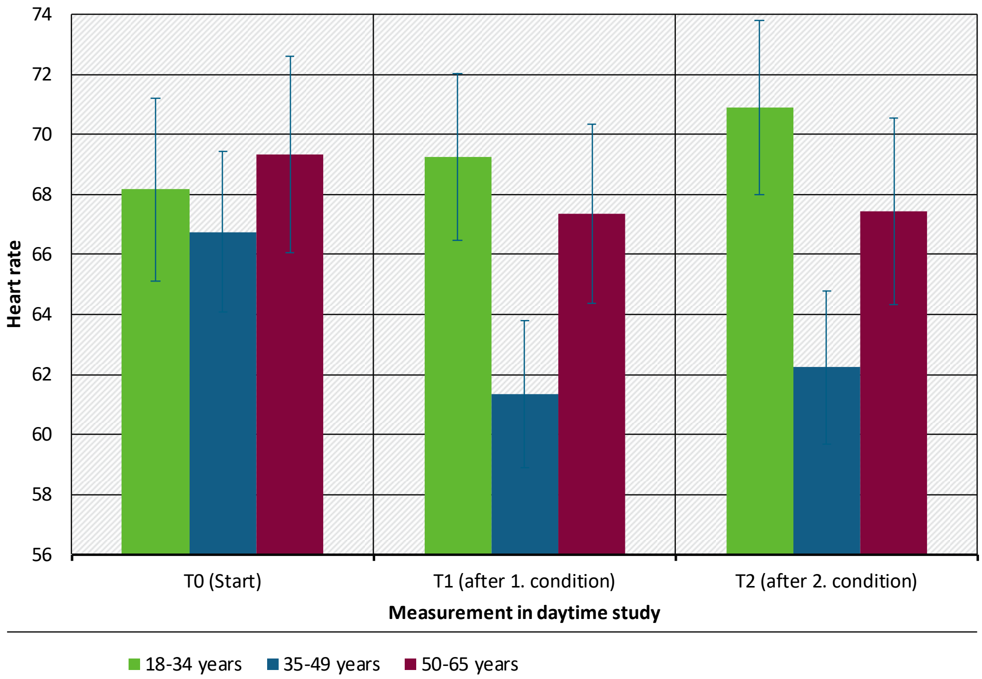


Source: own illustration, ZEUS.

The heart rate differed with regard to sex and age ($F(2,25) = 3.49$, $p < 0.05$), see Figure 22. Female subjects in older age groups had lower heart rates than younger ones (18-34 years: *M* = 71.61, *SE* = 3.82; 35-49 years: *M* = 68.61, *SE* = 3.42; 50-65 years: *M* = 63.9, *SE* = 4.67). Male subjects' relation between heart rate and age was non-linear: The middle-aged men (35-49 years) had the lowest average heart rate in the experiment (*M* = 58.3, *SE* = 3.52), followed by the youngest (18-34 years) (*M* = 65.1, *SE* = 3.16) and the oldest group (50-65 years) (*M* = 72.1, *SE* = 3.62).

There was also an interaction effect of age and time of measurement on the heart rate ($F(4,50)=4.320$ $p < .01$). In the age group 18-34 years, the heart rate was increasing from T0 to T2. In contrary, in the middle-aged group (35-49 years) the heart rate was lower at T2 and T3 compared to T0 with lowest value at T2. The oldest group (50-65 years) had the highest average heart rate at the beginning (T0). In this age group the average heart rate at T2 and T3 was lower with minor difference between T2 and T3.

Figure 22: Interaction between age and time of measurement (T0, T1, T2) on heart rate



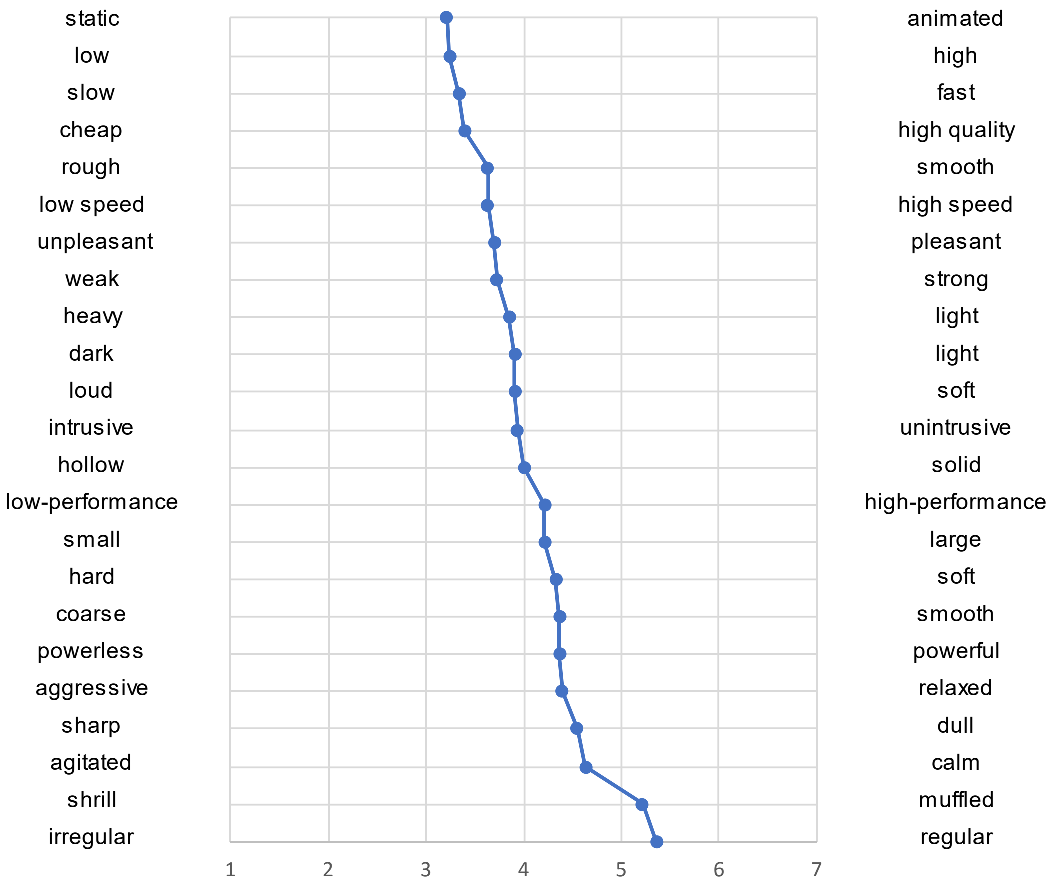
Source: own illustration, ZEUS.

3.2.4 Perception of sound characteristics of heat pump sounds

Sound characteristics of the AHP noise condition was rated on two scales. First, perception of noise was assessed using a semantic differential scale with 23 pairs of opposite sound descriptions (Figure 23). On average, the subjects judged the AHP noise in particular as muffled, cheap, slow, static, and regular.

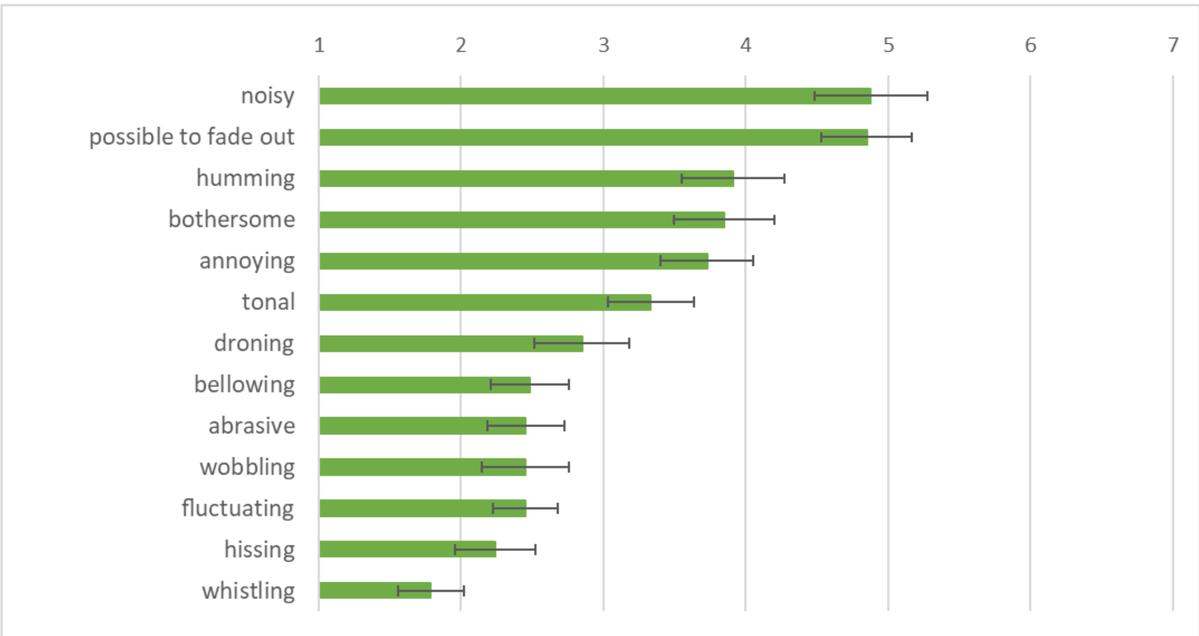
Further 14 sound characteristics were evaluated to be answered on a 7pt-scale from 1= *not at all* to 7= *completely* (Figure 24). According to the evaluation the noise condition could be described as more hideable, humming and noisy, rather annoying and disturbing but less whistling and hissing.

Figure 23: Perceived characteristics of the heat pump sound



Source: own illustration, ZEUS.

Figure 24: AHP noise scenario evaluated along 13 sound characteristics

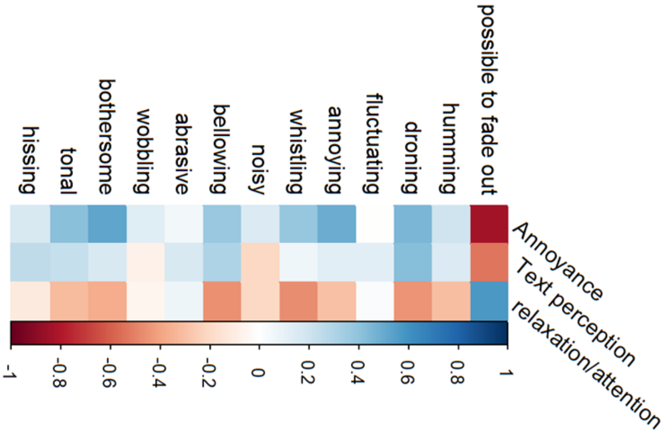


Note. Scale from 1= not at all to 7= completely.
Source: own illustration, ZEUS.

3.2.5 Relationship between sound characteristics and dependant variables noise annoyance, difficulties with concentration on text, mood

Correlations between sound characteristics and the three main dependent variables noise annoyance, difficulties with text and mood are illustrated in Figure 25. The stronger the correlation between two variables, the more intense is the colour. Blue represents a positive correlation, red represents a negative correlation between the variables.

Figure 25: Correlations between sound characteristics and three main variables noise annoyance, difficulties text and mood



Source: own illustration, ZEUS.

Table 13: Correlations between sound characteristics and three main variables noise annoyance, difficulties with concentration on text and mood

Characteristics	DV1 Noise annoyance	DV2 Difficulties with concentration on text	DV3 Mood
possible to fade out	-0.836***	-0.538**	0.575***
humming	0.201	0.157	-0.302
droning	0.459**	0.423*	-0.444*
fluctuating	-0.002	0.120	0.028
annoying	0.493**	0.121	-0.298
whistling	0.386*	0.061	-0.463**
noisy	0.159	-0.202	-0.2
bellowing	0.373*	0.306	-0.458**
abrasive	0.056	0.165	0.071
wobbling	0.136	-0.071	-0.057
bothersome	0.523**	0.168	-0.364*
tonal	0.414*	0.234	-0.313
hissing	0.164	0.256	-0.116

Note. DV= dependant variable, Scale from 1= not at all to 7= completely. *** *p* < 0.001, ** *p* < 0.01, * *p* 0.05.

Table 13 shows the coefficients of the correlation between these variables. When sound was perceived as not possible to fade out, annoyance, difficulties to concentrate on text were higher and subjects less relaxed and alert. Similar effects were shown for the sound characteristic *droning*: if sound was perceived as droning it was rated as more annoying and difficult to focus on a text while the mood was worse. Annoyance also correlated with the sound characteristics whistling, bellowing and tonal sound. Mood was e.g. negatively impacted by whistling and bellowing sound.

3.2.6 Final evaluation of texts

At the end of the daytime study, ten statements regarding the texts in general were assessed to be answered on a 5-pt scale from 1= not to 5= very (see Appendix A.8). Results are illustrated in Table 14. On average people indicated to be slightly used to read such texts (*M*=2.05, *SD*=1.1) and some words were unfamiliar for the average sample (*M*=3.05, *SD*= 1.2). Yet, texts were evaluated on average as moderately exciting (*M*=2.73, *SD*=1.3) and interesting (*M*=2.83, *SD*=1.5).

Table 14: Final evaluation of Greek myths read during the daytime study

Characteristics	*M*	*SD*	Min	Max
The texts were easy to understand.	2.65	1.1	1	5
Some words in the texts were unfamiliar to me.	3.05	1.2	1	5
I had problems following the texts.	2.65	1.3	1	5
I can give the message of the texts in a few sentences.	2.78	1.2	1	5
I am used to reading such texts.	2.15	1.1	1	5
I enjoyed reading the texts.	2.33	1.2	1	5
The content of the texts interested me.	2.83	1.5	1	5
Reading texts that are similar in difficulty to the texts I have read is part of my everyday life.	2.40	1.3	1	5
It was fun to read the texts.	2.65	1.4	1	5
The texts were exciting.	2.73	1.3	1	5

Note. Scale from 1= not to 5 = very, *M*= mean, *SD* = standard deviation.

4 Discussion and conclusions

In this research project, the effects of AHP noise on sleep, daytime functioning and mood were investigated in the laboratory. The key hypotheses were that nocturnal AHP noise has an influence on the micro- and macro-structure of sleep and that there is a temporal relationship between the occurrence of changes in the noise pattern and disturbances of the sleep structure. For the effects in the waking state, it was hypothesised that exposure to noise while reading a text would have a negative influence on mood, concentration while reading a text, and annoyance by noise compared to a quiet condition. Furthermore, it was hypothesised that noise exposure would be evident in measurements of blood pressure and heart rate compared to the baseline condition.

In the sleep study, the subjects slept three nights in a laboratory sleeping room. In one night, they were exposed to AHP noise as heard through a (simulated) closed window, one night a tilted window was simulated for noise exposure. For comparison, the third condition was 'quiet' (baseline night), without noise exposure. The exposure conditions were permuted across the three nights. For the condition 'windows tilted' the average $L_{\mathrm{Aeq,1h}}$ was 30.4 dB(A) with peak noise levels up to 41 dB(A) at the ear of the sleeping person, and for the condition 'windows closed' the $L_{\mathrm{Aeq,1h}}$ was 21 dB(A) with peak noise level up to 30 dB(A). In the daytime study the subjects were exposed for a duration of 15 minutes to the AHP sound levels of the 'windows tilted' scenario in comparison to 15 minutes of silence (no noise exposure).

4.1 Effects of air-source heat pump noise while awake and asleep

In the 40 subjects who participated in two laboratory studies, effects of exposure to AHP noise on sleep, impairment in daytime activities and noise annoyance were detected in both the sleep study and the daytime study.

Results from the sleep study indicate small effects of AHP noise during sleep. Regarding sleep parameters only small but statistically significant effects were shown for noise-associated arousals. In the 'loudest' noise condition a higher number of arousals were found, i.e. at night with the 'windows tilted' noise scenario compared to the 'window closed' scenario. However, although the influence of the AHP noise on noise-related arousals shows that the organism reacts to operation-related changes in the AHP sound during the night, this result does not imply a harmful, pathological effect of AHP sound.

Studies on the impact of transportation noise on sleep reveal that physiological responses to noise events ('awakenings') start at sound exposure level *SEL* of approx. 33 dB(A) (Basner & McGuire 2018). The peak levels L_{Amax} in this study were higher, but presumably too short in duration for awakening responses beyond arousals. Regarding the sleep parameters referring to the sleep of the whole night, it could be shown in previous noise-related sleep studies that noise-related changes of the sleep structure could at least partly be compensated across the night (Basner et al. 2011).

The daytime study showed differences between the noise condition and the baseline condition for the main examination parameters (annoyance, difficulties in concentration on text and mood). For the effect on noise annoyance and difficulties to concentrate on the text, a sequence effect was noticed. For both outcomes, annoyance and the ability to concentrate and focus on the texts, more negative effects were measured when the presentation of a noise scenario took place after the quiet scenario. One interpretation is that the first condition presented hereby serves as a reference, thus noise following quiet is perceived more intensely. It seems plausible that on a short-term level this indicates the so-called change effect in responses to noise. The change effect means that when facing a change in noise-exposure people respond with an excess in the responses in the direction of the change in exposure. The change-effect is more pronounced in noise situations getting worse (increase in noise exposure) (Brown & van Kamp 2009, a, b; Schreckenberg et al. 2019). Transferred to the real situation in residential areas, this could explain the increasing number of complaints about newly installed AHPs, especially in rural areas. It gives further evidence for the argument, that perceived contrast between two conditions is highly important for noise perception.

4.2 Methodological considerations and limitations of the study

All subjects in the laboratory study were screened for sleep disorders and categorised as sleep healthy. Factors that may have an influence on sleep were excluded where possible. Therefore, it is not possible to indicate whether a stronger noise effect occurs in previously ill or sleep-impaired persons. Hence, no conclusions can be drawn about the effects of AHP noise on other vulnerable groups, e.g. people with sleep disorders. It is advisable to carry out further studies, in particular in the field, i.e. in residential areas where AHPs are in use.

The COVID-19 pandemic affected recruitment and implementation of the study and continued to cause delays in completion. For example, in the phase of early 2021 older subjects were difficult to reach or motivate to participate because people in this age group were more concerned about potential COVID-19 infections. Nevertheless, the study could be successfully completed in 2021. In the study design study nights were conducted in a weekly rhythm on the same day of the week. No habituation nights were realized. In sleep research, both designs are common to conduct examination nights in a weekly rhythm as well as in consecutive nights.

In the present study, two designs were discussed:

- To conduct four consecutive nights with N= 30 subjects, of which one night serves as a habituation night, or
- To conduct three nights at weekly intervals with N= 40 subjects without a habituation night.

Previously conducted noise-related sleep studies that can be found in the literature were measured on consecutive nights (e.g. Basner, Müller & Elmenhorst 2011; Müller et al. 2015). To follow this approach would have had the advantage of comparability. A habituation night is well established in sleep research, as studies suggest that the first night may differ significantly from subsequent nights (Agnew et al. 1966). However, the dermatological burden on subjects by the application of the electrodes, particularly to the head, is substantial for four consecutive nights. In addition, only a sample size of 30 subjects would have been feasible for four nights. On consecutive nights, a transfer of the stress from previous nights is also possible (Carry over effect). Therefore, a washout period between study nights is required to avoid this effect and then a statistical test of the recorded data must be performed to demonstrate efficacy of setup (Wellek & Blettner, 2010). Although this effect would have been the same for all subjects, it would have occurred at different conditions due to the permutation of the conditions in the three test nights. Furthermore, the influences of the individual chronobiology as well as the personal weekly routines of the individual on measurement results have been disregarded in the past.

Option 2 with three nights in a weekly interval without habituation night and 40 subjects was chosen, allowing more subjects to be included. Furthermore, a longer period between the nights allows the skin to regenerate, especially on the head. A transfer of the stress from the preceding nights to the following nights can also be excluded. A habituation night is thereby not necessary, since the so-called 'First Night Effect' (Agnew et al. 1966) has the same effect again in all nights. Therefore, a potentially higher drop-out risk was accepted. The comparability with other noise-related sleep studies is reduced, because measurements have been performed in consecutive nights so far in previous noise-related sleep studies using polysomnographic measurements (e.g. Basner et al. 2011; Griefahn et al. 2007). However, the noise source types investigated in this study differ significantly from other studies in terms of frequency, duration and noise characteristics. Especially transportation noise sources show different characteristics (e.g. in tonality).

It can be argued that the imaginary everyday situation chosen for the daytime study is unable to create measurable performance effects. Moreover, possible effects of the noise condition on concentration and attention are self-reported. Two options were initially considered: the use of standardized cognitive performance tests or an imaginary everyday situation (Feldmann & Carolus 2019).

For the annoyance assessment two factors have to be considered:

- The annoyance situation should reflect an everyday life situation and it should be possible to produce a possible disturbance by noise exposure. If subjects are simply asked to judge their annoyance based on their auditory experience, the annoyance judgement is very close to the loudness judgment (correlates very strongly). A more realistic scenario is the creation of an everyday situation in which an activity can be disturbed.
- The artificiality of the laboratory situation should be counteracted by creating an *imagined* everyday situation. When using standardized cognitive performance tests, effects of the noise situation on cognitive performance would be investigable. At the same time the subjects would have a task that in principle can be disturbed by noise. Nevertheless, the performance of tests is not very close to everyday life and the subject remains completely in the artificial laboratory situation.

Since the survey of annoyance caused by the noise scenarios was the main focus in the daytime study and this study part was to be designed close to everyday life, the approach of the imagined everyday situation was chosen. The consideration of systematically varying the instruction for the daytime study and thus conducting two different instructions was discarded in order to avoid further subdivision of the sample, since combining night time and daytime studies could lead to an increase in measurement error.

Referring to the choice of reading material during the daytime study it can be argued that the Greek myths as a particular text type might be demanding for the common reader. The analysis of the potential difficulties concentrating on the text showed, that engaging with the Greek myths seems generally more difficult at first. However, in the *noise – baseline* order the engagement with the texts seems to improve for the second condition. For the group with the order *baseline – noise* the sounds from AHPs might be preventing proper engagement with the texts even in the second condition. Therefore, it could be considered to adjust the choice of reading material in future studies to a simpler alternative.

Specific sound characteristics of the AHP sounds were identified to be associated with higher annoyance. The results might be used for optimising the psychoacoustic features of AHPs. The acoustic noise scenarios selected for both studies correspond to typical sounds from AHPs installed in the field including typical states. In the generated noise scenarios, the number of changes of operation states was raised compared to a typical operation cycle. This was done in order to increase the chance of provoking potential effects as a normal AHP cycle only has a limited number of changes in state during the night. Loudness settings were chosen to resemble a realistic situation. The selection of sound level was based on the highest noise level legally permissible in a mixed used area according to TA Lärm. Louder AHPs in the field may exist, but due to ethical reasons it was opted against focusing on systems with improper sound emission. However, no assumptions can be made about the effect of the exposure to higher sound levels or effects of being exposed to the sounds of several AHPs. Effects of the exposure to several AHPs might be linked to coinciding noise states.

4.3 Open research questions and outlook

Both the sleep study and the daytime study give evidence for effects in a laboratory setting. A laboratory study is conducted to determine whether effects are present under controlled conditions. Yet, the results cannot be directly transferred to a field situation for several reasons, mainly because of the lack in ecological validity. The laboratory setting is an artificial setting beneficial to control for potential confounders. AHPs in residential areas still are a relatively new form of energy use but the number is continuously increasing. By gradually replacing conventional heating systems, they contribute in meeting the societal climate change-related goals of efficient and sustainable energy consumption. However, yet, the subjects may not had much experience with AHP noise in their everyday life. Hence, other influencing factors in people experiencing exposure to AHP sounds in their neighbourhood are not taken into account.

Effects are found in this laboratory study, which provides indications of the need for a field study. A field study would allow to map the exposure situation as well as its effects under real conditions to confirm potential effects in persons living with AHP sounds for a longer time (more than three nights over a period of three weeks). Field studies could also give a lead to new limit values for AHP noise emission. The Environmental noise guidelines for the European Region (World Health Organization, WHO, 2018) already recommend maximum level values for different environmental noise sources like wind turbines or aircrafts. With sufficient data comparable values could be derived for AHPs.

The number of people working from home is increasing. Even after the measures due to the COVID-19 pandemic were lifted there seems to be a shift in the work environment with people not returning to the office but establish a work culture including working remotely. As a result, more people desire their home to be compatible for remote work. New solutions have to be thought of for the compatibility of growth in sustainable energy systems and noise reduction in neighbourhoods. Need for regulation should be reviewed (e.g. position and direction of systems) in order to be able to meet the needs of those complaining about the noise. Moreover, new technical solutions for improvement should be checked and developed.

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A Appendix

A.1 Screening questionnaire

- ESS: Epworth Sleepiness Scale (Johns, 1991)

- ISI: Insomnia Severity Index (Morin, Belleville, Belanger & Ivers, 2011)

- PSQI: Pittsburgh Sleep Quality Index (Buysse et al., 1991)

► Hearing, and sensitivity to environmental pollutions:

Fragen zum Screening

Hörfähigkeit

Hörfähigkeit	
Haben Sie ein Hörgerät?	☐ ja ☐ nein
Können Sie **hören bzw. verstehen**, was in einem **Gespräch** gesagt wird, wenn mehrere Personen gleichzeitig sprechen, gegebenenfalls mit Hörgerät?	☐ Ja, ohne Schwierigkeiten ☐ Ja, mit leichten Schwierigkeiten ☐ Ja, mit großen Schwierigkeiten

Empfindlichkeit gegenüber Umweltbelastungen

Als nächstes geht es um die **Empfindlichkeit gegenüber den Belastungen aus der Umwelt**. Für wie empfindlich halten Sie sich gegenüber...

		nicht	wenig	mittel-mäßig	ziemlich	sehr
1.	...Gerüchen?	☐	☐	☐	☐	☐
2.	... Stress allgemein?	☐	☐	☐	☐	☐
3.	... Wetter?	☐	☐	☐	☐	☐
4.	... Lärm?	☐	☐	☐	☐	☐

A.2 Questionnaires used in the sleep study

German version of Karolinska Sleepiness Scale (KSS) (Akerstedt & Gilberg, 1990)

Die Karolinska Schläfrigkeits-Skala
KSS

Name: ...

Datum: ... Uhrzeit: ...

Wählen Sie bitte diejenige Aussage, die am besten den Grad ihrer Schläfrigkeit (bzw. Wachheit) beschreibt. Zutreffendes bitte ankreuzen. Bitte nur ein Kästchen ankreuzen!

1. Extrem wach ... ☐
2. Sehr wach ... ☐
3. Wach ... ☐
4. Ziemlich wach ... ☐
5. Weder wach noch schläfrig ... ☐
6. Einige Anzeichen von Schläfrigkeit ... ☐
7. Schläfrig, aber kann noch ohne Mühe wach bleiben ... ☐
8. Schläfrig, habe Mühe wach zu bleiben ... ☐
9. Sehr schläfrig, kann nur mit großer Mühe wach bleiben; kämpfe gegen den Schlaf ... ☐

1

Sleep Questionnaire A (SF-A) (Görtelmeyer, 1981):

CIPS Collegium Internationale Psychiatriae Scalarum	______ ______ ______	**SF-A** Schlaffragebogen A

Anleitung:
Die folgenden Fragen beziehen sich darauf, wie Sie in der **letzten Nacht** geschlafen haben. Kreuzen Sie bitte die Antworten an, die für Sie am **ehesten** zutreffen! Gehen Sie bei der Beantwortung der Fragen **zügig voran und lassen Sie keine Frage aus! Bitte sofort nach dem Aufstehen morgens ausfüllen!**

1. Wann haben Sie sich gestern abend schlafen gelegt (Licht gelöscht)?	Beispiel: 22 : 15 (Std. Min.) ___ : ___ (Std. Min.)	
2. Wie lange hat es gestern abend nach dem Lichtlöschen gedauert, bis Sie eingeschlafen waren?	weniger als 1 Minute	1
	1 bis 5 Minuten	2
	6 bis 15 Minuten	3
	16 bis 30 Minuten	4
	mehr als 30 Minuten	5
3. Woran hat es Ihrer Meinung nach gelegen, wenn Sie nicht gleich einschlafen konnten? (Mehrfachnennungen möglich)	persönliche/berufliche Probleme	1
	Geräusche im Zimmer oder von draußen	2
	Beschäftigung mit Tagesereignissen	3
	ich mußte zur Toilette	4
	Gedanken drehten sich ständig um ein Thema	5
	ich war angespannt	6
	ungewohnte Umgebung	7
	sonstige: ______	8
4. In der Einschlafphase hat man hin und wieder plötzlich deutliche Bildeindrücke. War dies gestern abend bei Ihnen so?	nein	1
	bin nicht sicher	2
	ja, sehr deutlich	3
5. Hatten Sie in der Einschlafphase Muskelzuckungen in den Armen oder Beinen?	nein	1
	leicht	2
	stark	3
6. Hatten Sie gestern nacht ein Stechen in der Herzgegend oder ein Ziehen im linken Arm verspürt?	nein	1
	leicht	2
	stark	3
7. Sind Sie gestern nach dem Einschlafen nachts wieder aufgewacht?	nein	1
	ja, einmal	2
	ja, zweimal	3
	ja, dreimal	4
	ja, mehr als dreimal	5
		8

Bitte prüfen Sie ob Sie alle Fragen zutreffend beantwortet haben! Bitte umblättern!

CIPS **Collegium Internationale Psychiatriae Scalarum**	__________ __________ __________	**SF-A** **Schlaffragebogen A**

8. Woran hat es Ihrer Meinung nach gelegen, wenn Sie nachts wach wurden?	persönliche/berufliche Probleme	1
	Geräusche im Zimmer oder von draußen	2
	ich mußte zur Toilette	3
	ich hatte geträumt	4
	ich hatte noch keinen richtigen Schlaf gefunden	5
	sonstige: __________	6
9. Falls Sie in der Nacht aufgewacht sind, wie lange waren Sie insgesamt wach?	weniger als 1 Minute	1
	1 bis 5 Minuten	2
	6 bis 15 Minuten	3
	16 bis 30 Minuten	4
	mehr als 30 Minuten	5
10. Können Sie sich erinnern, ob Sie heute nacht geträumt haben?	nein, ich kann mich nicht erinnern geträumt zu haben	1
	ja, ich habe geträumt, kann mich aber nicht an den Trauminhalt erinnern	2
	ja, ich habe geträumt und kann mich an den Trauminhalt erinnern	3
11. Falls Sie sich an Ihre Träume erinnern können: welche Gefühle hatten Sie während des Träumens?	angenehme Gefühle	1
	neutrale Gefühle	2
	unangenehme Gefühle	3
12. Haben Sie in der letzten Zeit nachts geschwitzt?	nein	1
	leicht	2
	stark	3
13. Wann sind Sie heute morgen aufgewacht?	Beispiel: 06 : 30 (Std. Min.) __ : __ (Std. Min.)	
14. Sind Sie heute morgen geweckt worden (Radio-Wecker, Radio, Personen etc.) oder wurden Sie von allein wach?	ich wurde von allein wach	1
	ich wurde aus dem Halbschlaf geweckt	2
	ich wurde aus dem Tiefschlaf geweckt	3
15. Sind Sie heute morgen **zu früh** wach geworden und konnten dann nicht mehr einschlafen?	ja	1
	nein	2
16. Haben Sie heute morgen Kopfschmerzen?	nein	1
	leicht	2
	stark	3
17. Haben Sie gestern abend nach dem Abendessen Alkohol (Bier, Wein, Schnaps) getrunken?	nein	1
	ja, über den Abend verteilt	2
	ja, unmittelbar vor dem Schlafengehen	3
18. Haben Sie gestern abend ein Schlafmittel benutzt?	nein	1
	ja	2
19. Falls ja, welches Präparat/welche Präparate:	__________ __________	
20. War der gestrige Tag für Sie sehr anstrengend?	nein	1
	ein wenig	2
	sehr	3

Bitte prüfen Sie ob Sie alle Fragen zutreffend beantwortet haben! Bitte umblättern!

CIPS **Collegium Internationale Psychiatriae Scalarum**	__________ __________ __________	**SF-A** **Schlaffragebogen A**

Anleitung:
Auf dieser Seite finden Sie einige Wörter, mit denen Sie beschreiben können, wie Sie sich gestern abend, vor dem Schlafengehen, fühlten, wie Sie heute nacht geschlafen haben und wie sie sich heute morgen fühlen. Kreuzen Sie hinter **jedem** Wort an, in welchem Ausmaß es für Sie zutrifft! Bitte antworten Sie zügig und **lassen Sie keine Zeile aus!**

		nicht	wenig	mittel	ziemlich	sehr
21. Wie haben Sie in der vergangenen Nacht geschlafen?	gleichmäßig	1	2	3	4	5
	tief	1	2	3	4	5
	unruhig	1	2	3	4	5
	entspannt	1	2	3	4	5
	ungestört	1	2	3	4	5
	gut	1	2	3	4	5
	ausgiebig	1	2	3	4	5
22. Wie fühlten Sie sich gestern vor dem Schlafengehen?	sorglos	1	2	3	4	5
	erschöpft	1	2	3	4	5
	schlafbedürftig	1	2	3	4	5
	überfordert	1	2	3	4	5
	ausgeglichen	1	2	3	4	5
	ruhig	1	2	3	4	5
	müde	1	2	3	4	5
	entspannt	1	2	3	4	5
23. Wie fühlen Sie sich heute morgen?	ausgeglichen	1	2	3	4	5
	dösig	1	2	3	4	5
	tatkräftig	1	2	3	4	5
	munter	1	2	3	4	5
	frisch	1	2	3	4	5
	ausgeschlafen	1	2	3	4	5
	entspannt	1	2	3	4	5
	Bitte prüfen Sie, ob Sie kein Wort ausgelassen haben!					

Bemerkungen/Fragen:

Current Mood Scale (Aktuelle Stimmungsskala, ASTS), Dalbert, 1992:

sade

MOMENTANES BEFINDEN

Nachfolgend finden Sie eine Liste mit Wörtern, die verschiedene Gefühle und Gefühlszustände beschreiben. Bitte lesen Sie sorgfältig jedes einzelne Wort und kreuzen Sie dann die Zahl an, die am besten Ihren Gefühlszustand **im Moment** beschreibt. Bitte machen Sie bei jeder Aussage ein Kreuz.

		sehr stark	stark	ziemlich	etwas	schwach	sehr schwach	überhaupt nicht
1	zornig	7	6	5	4	3	2	1
2	abgeschlafft	7	6	5	4	3	2	1
3	unglücklich	7	6	5	4	3	2	1
4	traurig	7	6	5	4	3	2	1
5	angenehm	7	6	5	4	3	2	1
6	betrübt	7	6	5	4	3	2	1
7	freudig	7	6	5	4	3	2	1
8	hoffnungslos	7	6	5	4	3	2	1
9	müde	7	6	5	4	3	2	1
10	verärgert	7	6	5	4	3	2	1
11	frohgemut	7	6	5	4	3	2	1
12	entmutigt	7	6	5	4	3	2	1
13	fröhlich	7	6	5	4	3	2	1
14	erschöpft	7	6	5	4	3	2	1
15	heiter	7	6	5	4	3	2	1
16	verzweifelt	7	6	5	4	3	2	1
17	wütend	7	6	5	4	3	2	1
18	entkräftet	7	6	5	4	3	2	1
19	lustig	7	6	5	4	3	2	1

Bitte überprüfen Sie nochmals, ob Sie kein Wort ausgelassen haben.

Morning survey 'climate' (Morgenbefragung Klima)

Morgenbefragung „Klima" Seite 1

Bitte beziehen Sie sich bei Ihren Antworten auf die letzte Nacht im Schlaflabor

Raumklima im Laborschlafzimmer	
Beim Aufstehen empfinde ich die **Raumtemperatur** im Laborschlafzimmer als…	☐ viel zu warm ☐ zu warm ☐ gerade angenehm ☐ zu kalt ☐ viel zu kalt ☐ weiß nicht/keine Angabe
Beim Aufstehen empfinde ich die **Luftfeuchtigkeit** im Laborschlafzimmer als…	☐ viel zu trocken ☐ zu trocken ☐ gerade richtig ☐ zu feucht ☐ viel zu feucht ☐ weiß nicht/keine Angabe
Beim Aufstehen empfinde ich die **Luftqualität** im Laborschlafzimmer als…	☐ sehr abgestanden ☐ abgestanden ☐ neutral ☐ frisch ☐ sehr frisch ☐ weiß nicht/keine Angabe
Insgesamt empfinde ich beim Aufstehen das Raumklima im Laborschlafzimmer als… angenehm.	☐ nicht ☐ wenig ☐ mittelmäßig ☐ ziemlich ☐ sehr …angenehm.

Lichtverhältnisse im Laborschlafzimmer	
Die **Lichtverhältnisse** im Laborschlafzimmer empfinde ich als … für meine Schlafqualität.	☐ sehr angenehm ☐ angenehm ☐ neutral ☐ unangenehm ☐ sehr unangenehm ☐ weiß nicht/keine Angabe
Beim Aufstehen empfinde ich die **Luftfeuchtigkeit** im Laborschlafzimmer als…	☐ viel zu trocken ☐ zu trocken ☐ gerade richtig ☐ zu feucht ☐ viel zu feucht ☐ weiß nicht/keine Angabe

Umgebungsqualität im Laborschlafzimmer	
Alles in allem bin ich mit der Umgebungsqualität im Laborschlafzimmer … zufrieden.	☐ sehr zufrieden ☐ zufrieden ☐ neutral ☐ unzufrieden ☐ sehr unzufrieden ☐ weiß nicht/keine Angabe

Morgenbefragung „Klima" Seite 2

Bitte beziehen Sie sich bei Ihren Antworten auf die letzte Nacht im Schlaflabor

Geräusche im Laborschlafzimmer

		überhaupt nicht	etwas	mittel-mäßig	stark	äußerst
	Wie stark wurden Sie durch Geräusche in den folgenden Situationen insgesamt gestört?					
1.	... beim Einschlafen?	☐	☐	☐	☐	☐
2.	... beim Nachtschlaf?	☐	☐	☐	☐	☐
3.	... beim Ausschlafen am Ende der Schlafzeit?	☐	☐	☐	☐	☐
4.	*Falls etwas – äußerst:* Welche(s) Geräusch(e) haben Sie gestört?	______ (Freitext)				
		überhaupt nicht	etwas	mittel-mäßig	stark	äußerst
5.	Wenn Sie einmal an die vergangene Nacht im Laborschlafzimmer denken, wie stark haben Sie sich durch Geräusche gestört oder belästigt gefühlt?	☐	☐	☐	☐	☐
6.	*Falls etwas – äußerst:* Welche(s) Geräusch(e) haben Sie gestört?	______ (Freitext)				

Gerüche im Laborschlafzimmer

		überhaupt nicht	etwas	mittel-mäßig	stark	äußerst
1.	Wenn Sie einmal an die vergangene Nacht im Laborschlafzimmer denken, wie stark haben Sie sich durch Gerüche gestört oder belästigt gefühlt?	☐	☐	☐	☐	☐
2.	*Falls etwas – äußerst:* Welcher Geruch/welche Gerüche haben Sie gestört?	______ (Freitext)				

A.3 Questionnaire used in the daytime study

a) **Imaginierte Wohnzimmersituation:** Stellen Sie sich vor, Sie sitzen mittags in einem/ihrem(?) Wohnzimmer und lesen. Bitte lesen Sie diesen Text. Zwischendurch werden wir Sie bitten, ein paar allgemeine Fragen zu beantworten. Am Ende der Untersuchung werden wir Ihnen dann Fragen zum Text stellen.

b) **Instruktion Lesen:** Bitte lesen Sie diesen Text. Zwischendurch werden wir Sie bitten, ein paar allgemeine Fragen zu beantworten. Am Ende der Untersuchung werden wir Ihnen dann Fragen zum Text stellen.

Bitte füllen Sie die folgenden Fragen aus. Sind Sie sich bei einer Frage nicht sicher, so wählen Sie die Antwortmöglichkeit aus, die am ehesten zutrifft.

1. Nehmen Sie gerade in diesem Raum ein dauerhaftes Geräusch im Hintergrund mit Ihren Sinnen wahr? (Mehrfachnennungen möglich)

❒1 ja, ich kann es mit meinen Ohren hören.
❒2 ja, ich kann es mit meinen Ohren wahrnehmen, aber nicht als Geräusch.
❒3 ja, ich nehme es über einen anderen Sinn wahr, nämlich ______________.
❒4 nein, ich nehme nichts wahr.

Wenn Sie mit „nein, ich nehme nichts wahr“ geantwortet haben, machen Sie direkt bei Frage 21 weiter.

2. *Wenn 1= ja:*
Worum handelt es sich bei diesem Geräusch im Hintergrund?
Was ist das für eine Art Geräusch im Hintergrund?

____

____(Freitext)

3. Das Geräusch im Hintergrund hat mich beim Lesen gestört.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❒1	❒2	❒3	❒4	❒5

4. Ich konnte mich wegen des Geräusches im Hintergrund nicht auf den Text konzentrieren.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❒1	❒2	❒3	❒4	❒5

5. Das Geräusch im Hintergrund hat mich vom Lesen abgelenkt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❒1	❒2	❒3	❒4	❒5

6. Ich musste den Text mehrmals lesen, um ihn zu verstehen.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❒1	❒2	❒3	❒4	❒5

7. Es hat mich angestrengt, den Text zu lesen.

Stimmt …

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

8. Alles in allem fühle ich mich durch das Geräusch … gestört oder belästigt.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

9. Das Geräusch beunruhigt mich.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

10. Das Geräusch bereitet mir schlechte Laune.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

11. Die Störung durch das Geräusch ärgert mich.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

12. Das Geräusch bereitet mir Unbehagen.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

13. Die Ablenkung durch das Geräusch regt mich auf.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

14. Ich kann mich vor der Ablenkung durch das Geräusch gut schützen.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

15. Ich kann das Geräusch beim Lesen gut „ausblenden".

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

16. Ich konzentriere mich auf das Lesen und das Geräusch stört mich dann gar nicht mehr.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

17. Ich fühle mich dem Geräusch ausgeliefert.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

18. Ich habe mich mit dem Geräusch abgefunden.

überhaupt nicht	etwas	mittelmäßig	stark	äußerst
❐1	❐2	❐3	❐4	❐5

19. *Wenn Frage 1=ja:*
Bitte geben Sie auf der Skala für folgende Wortpaare an, wie Sie das Geräusch empfinden.
Bitte machen Sie in jeder Zeile nur 1 Kreuz.

a.	aggressiv	❒1	❒2	❒3	❒4	❒5	❒6	❒7	entspannt
b.	aufdringlich	❒1	❒2	❒3	❒4	❒5	❒6	❒7	unaufdringlich
c.	billig	❒1	❒2	❒3	❒4	❒5	❒6	❒7	hochwertig
d.	schrill	❒1	❒2	❒3	❒4	❒5	❒6	❒7	dumpf
e.	dunkel	❒1	❒2	❒3	❒4	❒5	❒6	❒7	hell
f.	grob	❒1	❒2	❒3	❒4	❒5	❒6	❒7	sanft
g.	hart	❒1	❒2	❒3	❒4	❒5	❒6	❒7	weich
h.	hohl	❒1	❒2	❒3	❒4	❒5	❒6	❒7	massiv
i.	klein	❒1	❒2	❒3	❒4	❒5	❒6	❒7	groß
j.	schwach	❒1	❒2	❒3	❒4	❒5	❒6	❒7	stark
k.	langsam	❒1	❒2	❒3	❒4	❒5	❒6	❒7	schnell
l.	laut	❒1	❒2	❒3	❒4	❒5	❒6	❒7	leise
m.	leistungsschwach	❒1	❒2	❒3	❒4	❒5	❒6	❒7	leistungsstark
n.	niedertourig	❒1	❒2	❒3	❒4	❒5	❒6	❒7	hochtourig
o.	rau	❒1	❒2	❒3	❒4	❒5	❒6	❒7	glatt
p.	kraftlos	❒1	❒2	❒3	❒4	❒5	❒6	❒7	kräftig
q.	schwer	❒1	❒2	❒3	❒4	❒5	❒6	❒7	leicht
r.	statisch	❒1	❒2	❒3	❒4	❒5	❒6	❒7	bewegt
s.	scharf	❒1	❒2	❒3	❒4	❒5	❒6	❒7	stumpf
t.	tief	❒1	❒2	❒3	❒4	❒5	❒6	❒7	hoch
u.	unangenehm	❒1	❒2	❒3	❒4	❒5	❒6	❒7	angenehm
v.	ungleichmäßig	❒1	❒2	❒3	❒4	❒5	❒6	❒7	gleichmäßig
w.	unruhig	❒1	❒2	❒3	❒4	❒5	❒6	❒7	ruhig

20. *Wenn Frage 1=ja:*

Bitte geben Sie für folgende Beschreibungen an, wie sehr sie auf das Geräusch zutreffen, von (1) *völlig* bis (7) *überhaupt nicht*.

		völlig			überhaupt nicht			
a.	ausblendbar	❒1	❒2	❒3	❒4	❒5	❒6	❒7
b.	brummend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
c.	dröhnend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
d.	fluktuierend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
e.	lästig	❒1	❒2	❒3	❒4	❒5	❒6	❒7
f.	pfeifend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
g.	rauschhaft	❒1	❒2	❒3	❒4	❒5	❒6	❒7
h.	röhrend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
i.	schleifend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
j.	schwankend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
k.	störend	❒1	❒2	❒3	❒4	❒5	❒6	❒7
l.	tonhaltig	❒1	❒2	❒3	❒4	❒5	❒6	❒7
m.	zischend	❒1	❒2	❒3	❒4	❒5	❒6	❒7

21. *Wenn Frage 1 = nein: Bitte beantworten Sie Frage 21 – 31.*

Ich konnte mich nicht auf den Text konzentrieren.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

22. Ich musste den Text mehrmals lesen, um ihn zu verstehen.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

23. Es hat mich angestrengt, den Text zu lesen.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

24. Ich bin entspannt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

25. Ich bin beunruhigt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

26. Ich bin schlecht gelaunt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

27. Ich bin nervös.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

28. Ich fühle mich wohl.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

29. Ich fühle mich unbehaglich.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

30. Ich bin aufmerksam.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

31. Ich bin abgelenkt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

Wenn Sie mit der Beantwortung der Fragen fertig sind, wenden Sie sich bitte an die Versuchsleitung.

Abschlussfragen zum Text

Nun haben wir noch Fragen, die sich auf den gesamten Versuchsablauf beziehen.

31. Die Texte waren einfach zu verstehen.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

32. Einige Wörter in den Texten waren mir unbekannt.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

33. Ich hatte Probleme den Texten zu folgen.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

34. Die Botschaft der Texte kann ich in wenigen Sätzen wiedergeben.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

35. Ich bin geübt im Lesen solcher Texte.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

36. Das Lesen der Texte hat mir Freude bereitet.

Stimmt ...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

37. Der Inhalt der Texte hat mich interessiert.

Stimmt...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

38. Das Lesen von Texten, die eine ähnliche Schwierigkeit wie die gelesenen Texte aufweisen, ist Alltag für mich.

Stimmt...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

39. Es hat Spaß gemacht die Texte zu lesen.

Stimmt...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

40. Die Texte waren spannend.

Stimmt...

nicht	wenig	mittelmäßig	ziemlich	sehr
❐1	❐2	❐3	❐4	❐5

Abschlussfragen

Ihr Schlafverhalten in dieser Studie und die Angaben, die Sie in der heutigen Tagesuntersuchung gemacht haben können von Ihren Vorerfahrungen zuhause abhängen. Diese wiederum können verbunden sein mit den Wohnbedingungen und den Gebäudemerkmalen in Ihrem Zuhause.

Daher haben wir zum Abschluss die folgenden Fragen zu Ihren Wohnbedingungen:

Wohnbedingungen

Gebäudetyp der Wohnung/des Hauses der Untersuchungsperson

In welcher Art von Gebäude wohnen Sie?

- ☐ freistehenden Einfamilienhaus
- ☐ Reihenendhaus
- ☐ Reihenmittelhaus
- ☐ Doppelhaushälfte
- ☐ Wohnung in einem mehrstöckigen Mehrfamilienhaus

Fensterart in der Wohnung der Untersuchungsperson

Fensterart, Lüftungsgewohnheiten			
Welche Verglasung haben die Fenster im Wohnraum Ihrer Wohnung bzw. Ihres Hauses (Hauptwohnraum)?	☐ einfache Fensterscheiben ☐ Doppelverglasung oder Doppelfenster (Isolierglas, Kastenfenster) ☐ Schallschutzfenster, Dreifachverglasung oder Fenster mit dicken Scheiben ☐ Schallschutzfenster in Verbindung mit Lüftern ☐ Weiß nicht/keine Angabe		
Welche Verglasung haben die Fenster in Ihrem Schlafzimmer?	☐ einfache Fensterscheiben ☐ Doppelverglasung oder Doppelfenster (Isolierglas, Kastenfenster) ☐ Schallschutzfenster, Dreifachverglasung oder Fenster mit dicken Scheiben ☐ Schallschutzfenster in Verbindung mit Lüftern ☐ Weiß nicht/keine Angabe		
Wie ist das bei Ihnen üblicherweise in den warmen Jahreszeiten?			
	geschlossen	gekippt	geöffnet
Haben Sie nachts die Fenster in Ihrem Schlafzimmer überwiegend geschlossen, gekippt oder geöffnet?	☐	☐	☐
Wie haben Sie nachts die Fenster in Ihren Wohnräumen überwiegend?	☐	☐	☐
Haben Sie bei sich zuhause im Schlafzimmer eine Klimaanlage, eine Lüftungsvorrichtung oder ähnliches?	☐ nein ☐ ja, eine Klimaanlage ☐ ja, eine Lüftungsvorrichtung ☐ Ja, sonstiges und zwar: _________		

Sichtverbindung in der Wohnung zur Strasse

Ausrichtung des Wohn- und Schlafzimmers	
Wie ist/war die Ausrichtung Ihres Wohnraum (Hauptwohnraum) zur Straße mit dem meisten Verkehr in Ihrem Wohngebiet?	☐ von der Straße abgewandt ☐ seitlich zur Straße ausgerichtet ☐ der Straße zugewandt

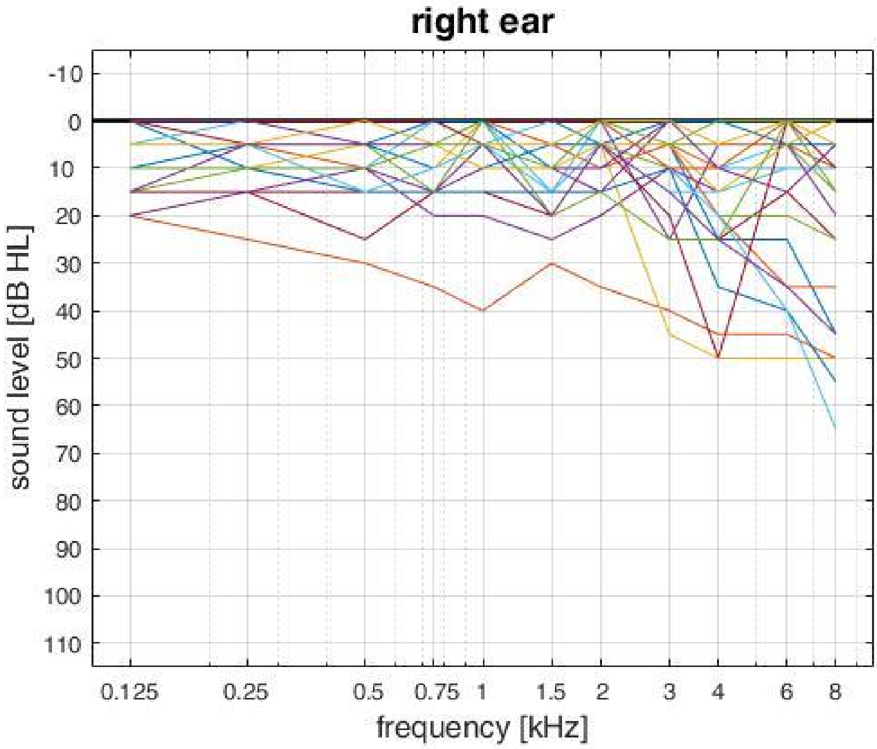
Hinweis: Bei Kreuzung gleich stark befahrener Straßen bezieht sich die Frage auf die Ausrichtung zur Straßenkreuzungsmitte.	
Wie ist/war die Ausrichtung Ihres Schlafzimmers zur Straße mit dem meisten Verkehr in Ihrem Wohngebiet? Hinweis: Bei Kreuzung gleich stark befahrener Straßen bezieht sich die Frage auf die Ausrichtung zur Straßenkreuzungsmitte.	☐ von der Straße abgewandt ☐ seitlich zur Straße ausgerichtet ☐ der Straße zugewandt

Corona-Fragen

Corona-Fragen	
Hat sich mit den Einschränkungen der Corona-Pandemie Ihre Schlafqualität verändert?	☐ ja ☐ nein
Wenn ja, wie?	______________________________
Hat sich mit den Einschränkungen der Corona-Pandemie Ihre Schlafdauer verändert?	☐ ja ☐ nein
Wenn ja, wie?	______________________________
Haben Sie mit den Einschränkungen aufgrund der Corona-Pandemie sonstige Veränderungen bezüglich Ihres Schlafs bemerkt?	☐ ja ☐ nein
Wenn ja, wie?	______________________________

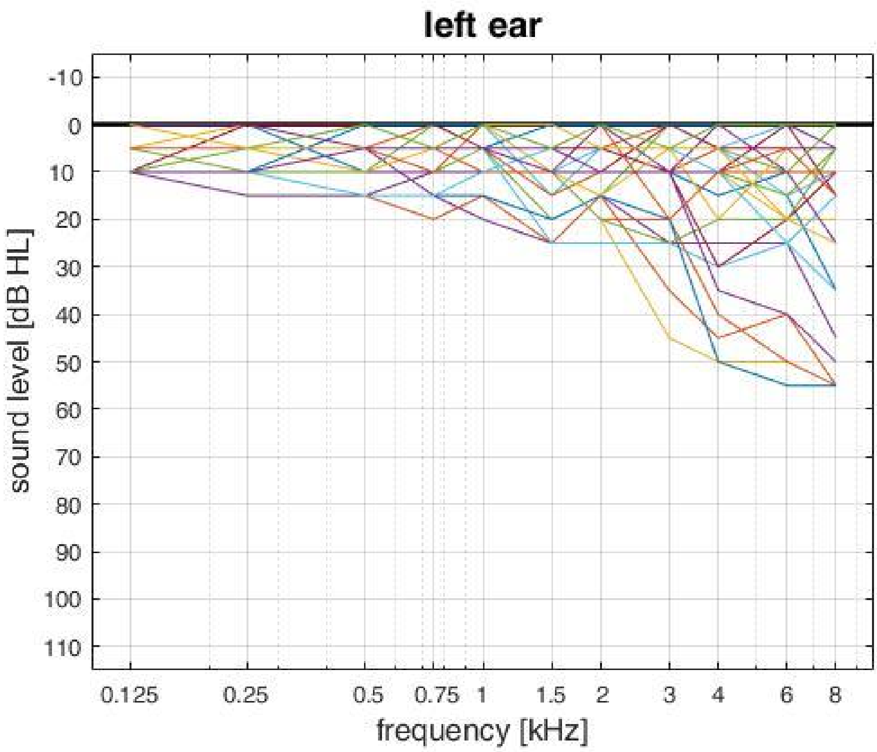
A.4 Audiometry

Figure A 1: Results of audiometry measurement, right ear



Source: own illustration, Möhler + Partner.

Figure A 2: Results of audiometry measurement, left ear



Source: own illustration, Möhler + Partner.

A.5 Recording of the sound material

The outdoor units of various AHP types and manufacturers were recorded under real operating conditions (Table A 1). Prior research revealed that there are similarities in the noises due to similar technologies of AHP. For example, the fan and the compressor often lead to tonal low-frequency noise components in a frequency range from 50 Hz to 200 Hz (Schulze et al., 2014). On the other hand, there are differences due to the manufacturer/design/age or other factors (switching noises, tonal components, frequency position, etc.). Finally, three characteristic AHPs from different manufacturers and at different locations were used for the measurement series (Figure A 3).

Figure A 3: Air-source heat pumps during recording

AHP1	AHP2	AHP3

Source: own illustration, Möhler + Partner.

Table A 1: Technical data of the measured AHP

Device	AHP 1	AHP 2	AHP 3
Designation	Vaillant VWL 11/4 SA	2Daikin ERLQ011CAW1	Rotex RRLQ008CAV3
Type	Space heating/ Hot Water	Space heating/ Hot Water	Space heating/ Hot Water
Indoor/Outdoor Compact/Split	Outdoor unit of a split device -AHP	Outdoor unit of a split device AHP	Outdoor unit of a split device AHP
Nominal heating power	11.5 kW	11.2 kW	8 kW
Sound power level	LWA 56 dB(A)	LWA 64 dB(A)	LWA 62 dB(A)
Installation location	detached	on wall	detached

The measurements took place in February 2020. In total, more than five hours of audio material were collected during the series of measurements. This includes switch-on and switch-off processes as well as load changes and stationary continuous operation. Due to the weather conditions, no icing of the evaporator was detected, so that the emitted noises during the de-icing process could not be recorded. They had to be simulated by spectral filtering and adjustments in the level-time curve during the previous icing of the system.

The emitted noises were recorded at least two different measuring points. Due to the free-standing position of AHP1 (cf. photo documentation), five measuring points were selected. For level control, the sound pressure level (L_{Aeq}, L_{AF}, L_{AFTm5}) was also recorded during all measurements. The following measurement equipment was used:

Recording

- 2 pc ½''-measuring microphone MTG MK 221 (Microtech Gefell)
- 2 pc preamp MTG MV 225.1 (Microtech Gefell)
- RME Fireface UFX II
- 2 pc pop shield MTG W2
- Magix Samplitude 11

Monitoring

- Sound level meter 'Tango Plus' (SINUS Messtechnik)
- calibrator Larson Davis CAL200
- 1 pc pop shield

During continuous state, the measured sound pressure levels ranged between L_{Aeq} = 56 dB and L_{Aeq} = 62 dB, at a distance of approx. 0.5 m. During the recordings, isolated disturbing noises occurred such as birdsong, cars passing by, wind and communication noises. These were recorded and discarded for further processing.

The results of the measurements are recorded in Appendix 0 in form of the average FAST-weighted third-octave and narrow-band spectra (1.56 Hz bandwidth) during continuous operation, each normalised to an average level of L_{Aeq} = 60 dB. In addition, load changes and switch-on processes of the individual units are shown as examples in the form of level-time curves and frequency spectra during the individual operating states. A photo documentation also can be found in Appendix 0.

A.6 Photographic documentation of audio recording

Figure A 4: Photographic documentation of AHP 1

Outdoor Unit

Indoor Unit

Measurement setup

Source: own illustration, Möhler + Partner.

Figure A 5: Photographic documentation of AHP 2

Outdoor Unit

Technical data

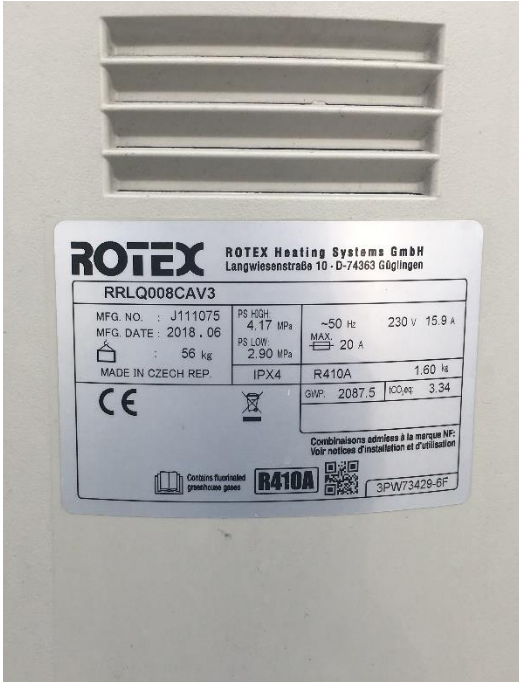
Measurement setup

Source: own illustration, Möhler + Partner.

Figure A 6: Photographic documentation of AHP 3

Outdoor Unit

Technical data



Measurement setup

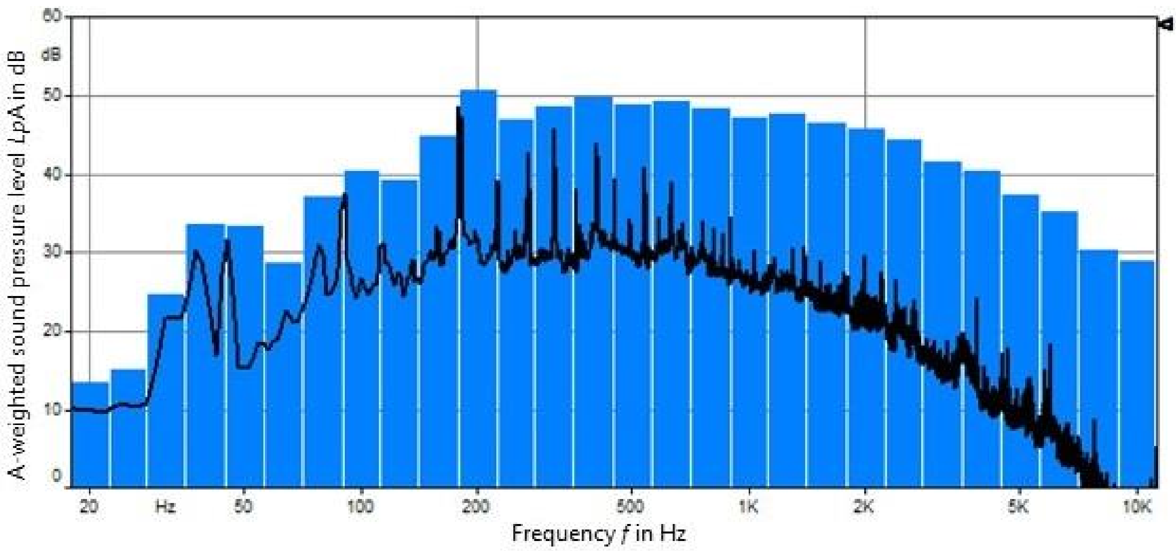
Source: own illustration, Möhler + Partner.

A.7 Selection of a heat pump for the noise conditions

Since no reliable information on current sales figures and market shares of various AHP models could be obtained, the AHP was selected on the basis of the noise characteristics of the collected audio material and the unit performance.

The nominal heating power of the recorded AHPs ranged from 8 kW (AHP3) to 11.5 kW (AHP1). The output of AHP2 is 11.2 kW and thus best represents the average. Based on the collected measurement data, AHP2 was therefore selected as the representative device for generating the stimuli. Figure A 7 shows the continuous A-weighted third-octave level spectrum (blue bars) and a narrowband spectrum (bandwidth 1.56 Hz, black line) of the selected AHP2 in continuous operation, each normalised to an average level of L_{Aeq} = 60 dB. It shows clearly that the spectrum shows the typical curve for air-to-water AHPs: In the low-frequency range there are noticeable tonal components, while the noise level decreases towards higher frequencies.

Figure A 7: A-weighted third-octave level spectrum and narrowband spectrum of AHP2 during continuous state, normalized to 60 dB(A)



Note. Blue bars = 3rd octave SPL, black line = narrowband spectrum.
Source: own illustration, Möhler + Partner.

A.8 Simulation of the outside-inside transmission

The previously described noise scenario was filtered with a 1/3-octave band filter bank, each for the sound insulation of a tilted window and a closed window. The different operating conditions and simulated window positions result in different noise levels during the nights under investigation.

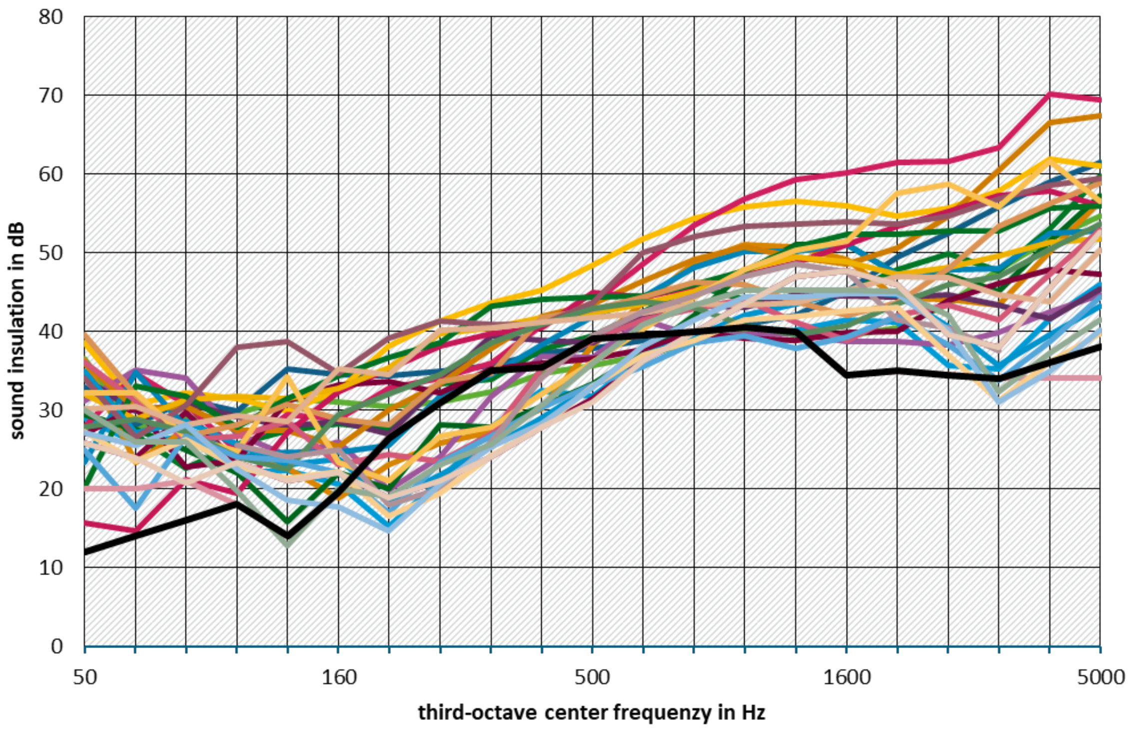
A.8.1 Noise condition 'window closed'

For the condition 'noise exposition window closed', a standard insulating glass window with double glazing of sound insulation class 2 (i.e. a sound insulation value of approximately R_w = 32 dB, without special sound insulation) was selected. The reason for this selection is the assumption that in areas where there are complaints about AHP noise, the selection of windows is mainly based on thermal insulation, but not on sound insulation. That is because comparatively low noise pollution (e.g. from transportation noise) can be expected there.

In order to find a representative curve for the frequency-dependent sound reduction index R_w, the first step was to research different versions of this window type. In this way, information was obtained about an approximate range of sound insulation of different windows. Subsequently, a specific frequency-dependent curve was selected for the stimuli.

The frequency-dependent sound insulation used for the closed window was taken from a former investigation (Liepert & Möhler 2007). Figure A 8 shows the curve used in the study (bold, black) in comparison to the results of the literature research (coloured).

Figure A 8: Frequency-dependent sound insulation of different types of (closed) windows



Note. Coloured: frequency-dependent sound insulation of 'real' windows; black: Liepert & Möhler 2007)

Source: own illustration, taken from Liepert & Möhler (2007)

Averaging over different transmission curves is not appropriate in this application, as the characteristic course of these curves (e.g. due to reflections between the panes there are peaks in the curve) should not be smoothed unrealistically. It should remain as close to a real window as possible.

It turns out that the curve from the 2007 study is similar to the sound insulation of commercially available windows in the medium frequency range. In the range of distinctly high and low frequencies, however, the curve shows a (significantly) lower sound insulation than the windows shown for comparison. However, the curve was linearly extrapolated in the frequency range < 100 Hz and > 3.15 kHz, which explains the different curve in the border areas. The deviations in the marginal ranges < 100 Hz and > 3.15 kHz are to be minimised in the following by changing the extrapolation.

The curve used in Liepert and Möhler (2007) is well suited for the intended purpose (with the exception of the boundary areas), as it does not have a high sound attenuation. Noise conflicts caused by AHPs in the neighbourhood are to be expected especially in quiet residential areas. Due to the prevailing quiet ambient noise conditions there, windows with comparatively low sound insulation are to be assumed accordingly while sound-insulating windows are hardly to be expected in quiet residential areas. On the other hand, although the curve shows a typical frequency response, it does not exhibit any specific characteristics that would occur when using the curve of a real window. The later investigation results can thus be transferred to different window types. At the same time, the use of low sound insulation again creates a 'worst case situation'.

A.8.2 Noise exposition 'window tilted'

The sound insulation of the tilted window is determined by the gap opening and is accordingly almost frequency independent. The used filter function of a window in tilt position (with 80 mm maximum gap width) is taken from a publication by Kötz (2004). In relation to the window measurements (glass area and gap area) the weighted sound reduction index is R_w = 11 dB.

Figure A 9 shows the curve according to Kötz (2004) in comparison with two measured insulation spectra (Ahlefeldt et al. 2006). It can be seen that the curve according to Kötz clearly deviates from the measurements of Ahlenfeldt et al. (2006) in the distinct low-frequency range. In the frequency range > 200 Hz, however, the curves show a similar course and lie in a comparable level range. The deviations in the low-frequency range are to be reacted to in the following by changing the extrapolation method.

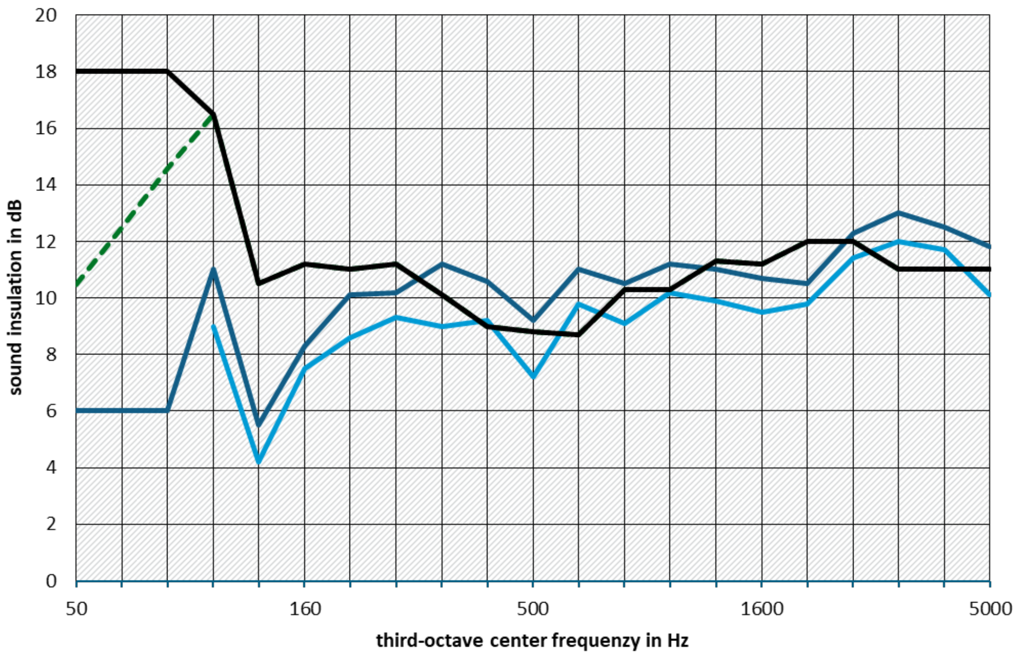
A.8.3 Extrapolation of missing values

The filter functions for the adaptation of the noise scenarios must include the entire hearing range between 20 Hz and 20 kHz instead of the usual representations between 100 Hz and 3.15 kHz in building acoustics measurements. For the extrapolation of the missing values in the high-frequency range, an increase in sound attenuation of 6 dB per octave was calculated on the basis of Berger's law of mass (Fasold & Veres, 1998). For the low-frequency range < 100 Hz, the prediction formula of Mühlbacher et al. (2016) was used:

$$dL_{Terz} = [\ 20 * \log(f_{Terz}) + R'(100Hz) - 40]\ dB$$

This means that in the range < 100 Hz and > 3.15 kHz, the filter functions used for stimuli generation deviated from the functions shown in the literature. In this way, there is better approximation with the insulation spectra of commercially available windows collected during the literature research. Figure A 10 shows the filter functions combined from the above-mentioned sources, which were used for the two window conditions.

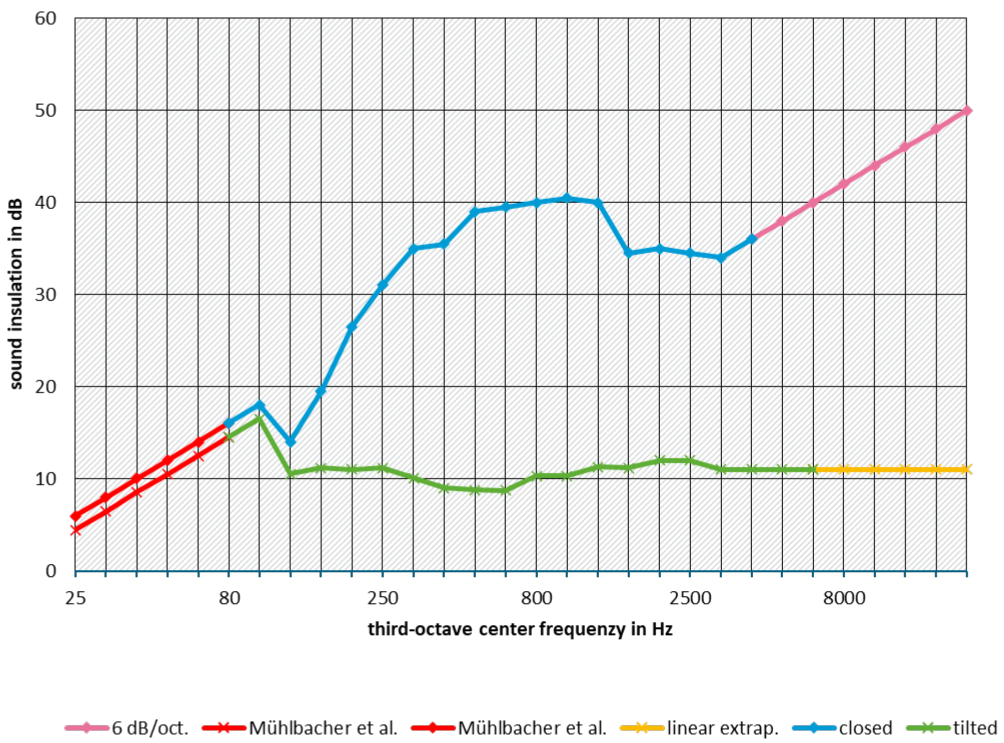
Figure A 9: Frequency-dependent sound insulation of different tilted windows



Note. Coloured: curves taken from Ahlenfeldt et. al. (2006), black: curve taken from Kötz (2004)

Source: own illustration, Möhler + Partner.

Figure A 10: Frequency-dependent filter functions of the conditions 'window partially open' and 'window closed'



Source: own illustration, Möhler + Partner.

A.9 Acoustic measurement setup

A.9.1 Selection of the premises

In the ASR premises in Berlin, there are potentially several sleeping rooms available for the study nights. In order to select a suitable sleeping room for the study nights, room acoustic measurements were carried out. Based on the measurement results, two rooms were selected in which the sleep study and the daytime study were conducted.

Preparatory measurements

Within the scope of the room acoustic measurements, the quiescent sound levels and the reverberation times of the rooms available for selection were determined in order to find out which rooms are best suited for conducting the study.

In order to minimise the duration of the study, an identical measurement set-up should be installed in two bedrooms to be able to invite several subjects for the same night. In order to ensure the comparability of the individual measurements in this case, it was important that the rooms do not show any significant differences in room acoustics parameters that could influence the measurement result.

For the selection of the rooms, the ambient noise and the reverberation times in the different bedrooms were measured during the night of 27 to 28 June 2019. Two of the investigated rooms are located on the street side, one room faces the inner courtyard, and one room is located completely inside the building, i.e. has no windows. The size of the rooms is between 8 and 13 m^2; all rooms have a ceiling height of 2.65 m. Appendix A.11 shows a photographic documentation of the bedrooms and the used measurement setups.

Measured quiescent levels

In the first half of the night, the continuous measurement showed quiet sound levels between 18 and 22 dB(A) in all rooms. In the room with windows facing the street, as well as in the room without windows, the ambient noise remained at a similarly low level throughout the entire measurement period. In the room with a window facing the courtyard, however, the indoor noise level rose to up to 30 dB(A) in the second half of the measurement period. This level increase is due to a ventilation system located in the immediate vicinity of the window on the building façade.

After consultation with the operators, the operation of this ventilation system cannot be avoided for the entire duration of the study. For this reason, the room with a window overlooking the courtyard is unsuitable for the study, as such noise could influence the measurement results.

The room without a window has the lowest quiescent sound level, as no street traffic noise enters the room. Although a low quiescent sound level is desirable in principle for the purpose of the study, the question arises to what extent a windowless bedroom makes it possible to simulate a realistic sound situation for the subject, since the sound presentation is supposed to represent the sound coming in 'through a closed or tilted window'.

Regarding the goal of creating an environment that is as close to everyday life as possible during the studies, the rooms with windows facing the street proved to be the most suitable. Although noise influences, e.g. from road traffic noise, cannot be completely excluded in these rooms, the measured indoor levels are in such a low-level range that a sufficient level difference between the stimuli played (AHP noise) and the prevailing quiet level can be maintained. Furthermore, the analysis of the measured frequency-spectra does not reveal any clear level peaks, so that no interference from individual sounds (e.g. from technical equipment) is to be expected.

Measured reverberation time

Reverberation time measurements were carried out in the above-mentioned rooms. The measurements show reverberation times of 0.28 to 0.42 s. The measured reverberation times are in a range that is comparable to the acoustic conditions of typical bedrooms in a residential environment. Thus, no measures are necessary to create room acoustics close to everyday life during the noise exposition. Due to the relatively low reverberation times, the examined rooms are also well suited for reproducing the sound recordings.

Reverberation radius

The reverberation radius is the distance at which the direct sound level of a source is equal to the diffuse sound level in an enclosed space. The subject's ear should be outside of this reverberation radius to largely eliminate influences from the directivity of the loudspeakers and to ensure that the sounds are perceived naturally as simulated external noise. The reverberation radius for all examined rooms is in the range between 0.4 and 0.6 m. By positioning the sound source near the window and aligning the beds with the foot end facing the window, it was possible to ensure that the subject's ears were outside the reverberation radius.

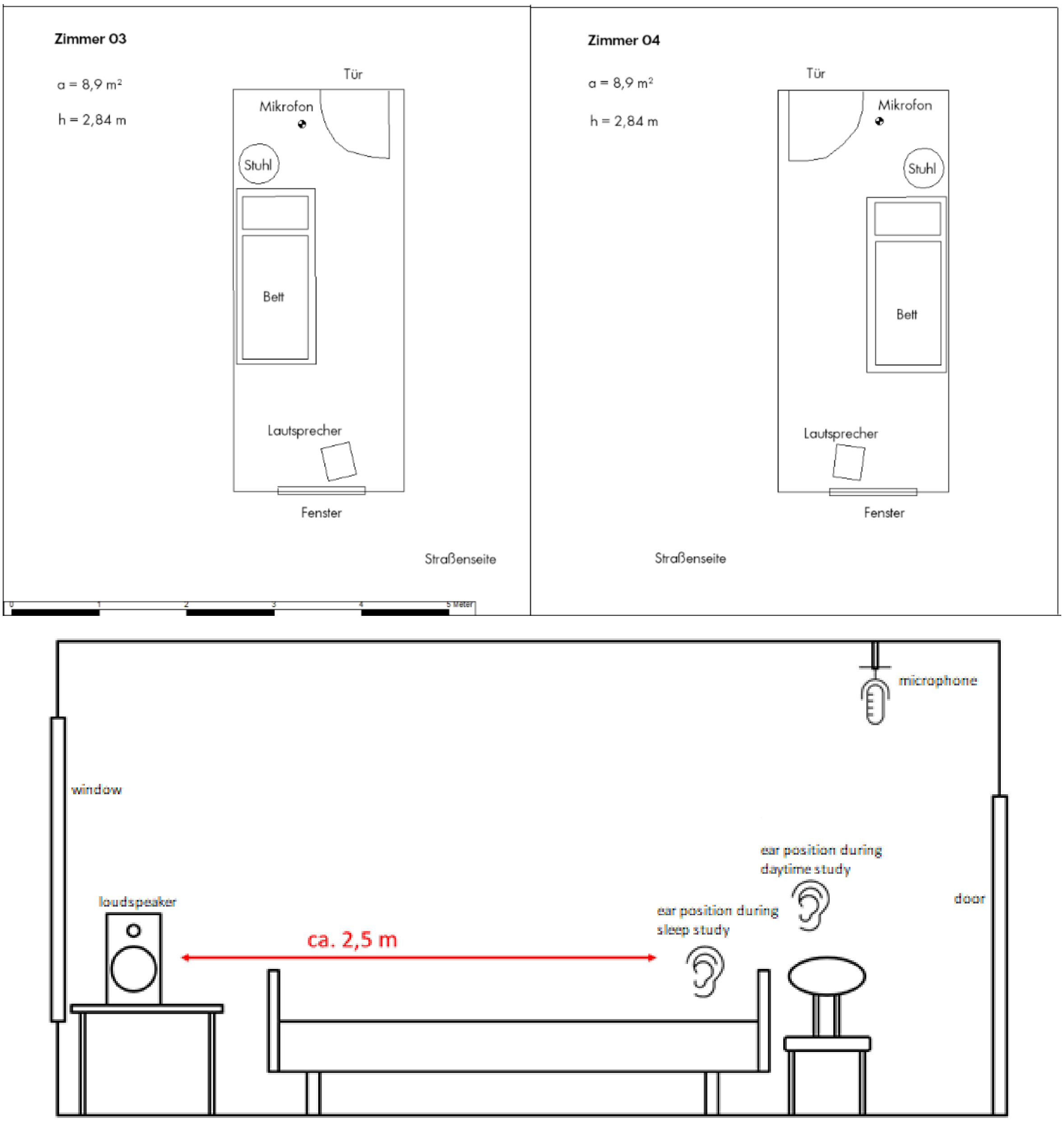
A.9.2 Sound reproduction

Measurement setup

The acoustic stimuli were played into the sleeping room via a loudspeaker near the window in order to simulate the effect of sound coming through the window. The distance between the loudspeaker and the head of the bed was about 2.50 m in both rooms. Thus, the ears were in the diffuse field of the loudspeaker (not in the near field). At the same time, the sound system had to be placed as inconspicuously as possible in order to avoid influencing the subjects. For example by drawing their attention to the study content through conspicuous loudspeaker arrays. The quiet sleeping environment should have as natural an effect as possible on the subjects. For the daytime study, the subjects sat on a chair at the head of the bed, so the position relative to the loudspeaker only differs in this case.

The loudspeakers were covered with acoustically transparent fabric. That way, the subjects were not immediately made aware that they would be exposed to sound during the study. Its acoustic effects on the frequency spectrum were compensated for by spectral adjustment of the audio files (Appendix A.12). The loudspeakers were placed on a table directly in front of the window. The orientation was towards the head end of the bed. Under the ceiling, placed near the entrance door, there was a measurement microphone, for level control of the sound presentation (so-called reference measuring point) (cf. Figure A 11).

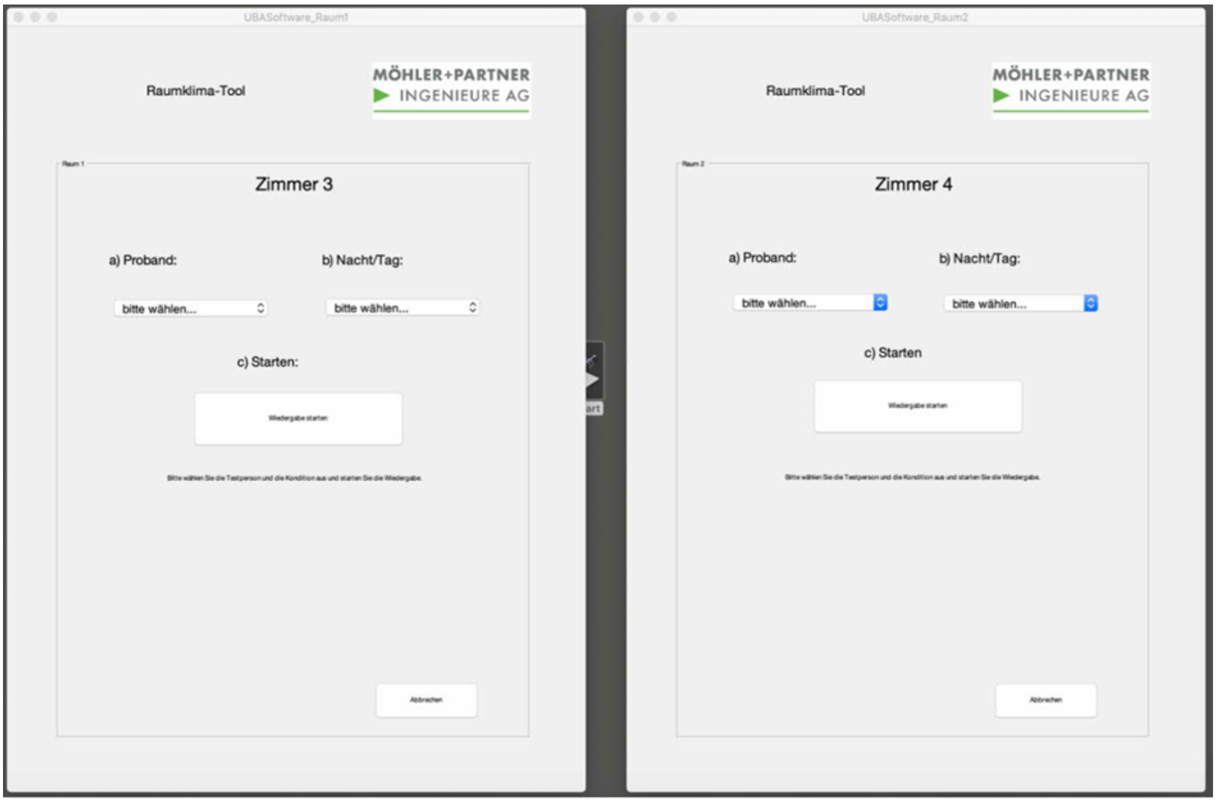
Figure A 11: Setup of acoustic equipment in study bedrooms



Source: own illustration, Möhler + Partner.

Speakers and microphones were connected to a computer with an audio interface, which was placed in the control room of the sleep laboratory. The software used was a proprietary application programmed in MATLAB, which ensured the playback of the stimuli on the one hand and the level control via the microphones on the other. The user interface of the software did not allow any conclusion about the presented sound scenarios. The operator only had to enter the subject number and the respective number of the measurement condition (1st to 3rd examination night respectively 1st to 2nd day study condition, see Figure A 12). The appropriate sound scenario (closed window/tilted window/baseline night) was then automatically selected and played.

Figure A 12: Graphical user interface of the MATLAB sound presentation software



Source: own illustration, Möhler + Partner.

In addition, electric trigger signals were sent to the polysomnography device for certain sound events. That allows to assign any awakening reactions and arousals that may have occurred due to the sound events.

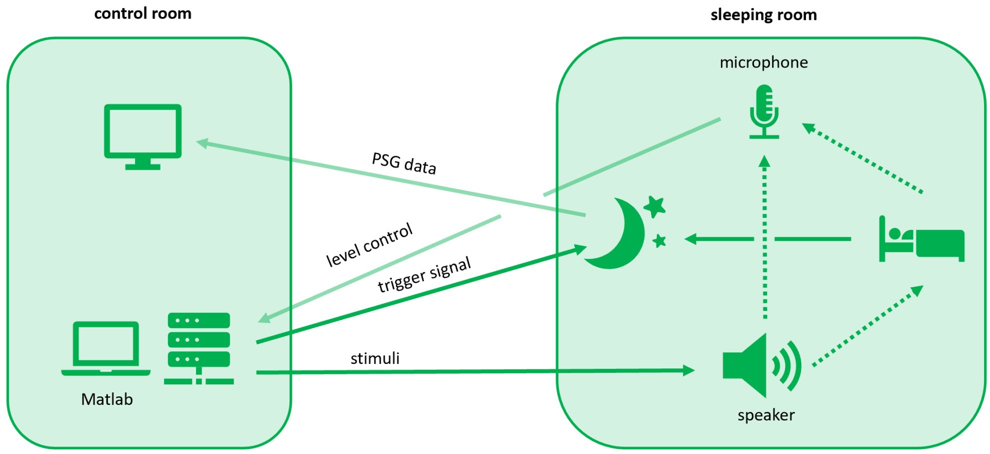
Figure A 13 shows the experimental set-up in the dormitories schematically. Details can be seen on the photos in Appendix A.11.

The following equipment was used:

- Macbook Pro 16“, 2019
- RME Fireface UFX II
- 2pc Yamaha HS 8i speakers
- 2 pc ½’’-measuring microphone MTG MK 221 (Microtech Gefell)
- 2 pc preamp MTG MV 225.1 (Microtech Gefell)
- acoustically transparent fabric[2] for speaker covers

[2] The effects of the acoustic fabric on the frequency spectrum of the stimuli reproduction were compensated by spectral filtering. For frequency adjustment see (‘Acoustic fabric 1-fold’) Mauelshagen (n.d).

Figure A 13: Scheme of the experimental setup in the sleep-laboratory



Source: own illustration, Möhler + Partner.

Noise scenarios

The sound pressure level during the sleep study was chosen in such a way that a target rating level of 45 dB(A) outside the window was simulated. For the noise condition 'tilted window' during the stationary continuous operation of the AHP, an average sound level of L_{Aeq} = 30 dB prevails at the ear of the subject. This value results from the difference between the target rating level of 45 dB(A) outside the window and the average sound insulation of a tilted window of approx. 12-15 dB in combination with the resulting sound field in the room. The head of the bed (about 2.5 m away from the loudspeaker and about 30 cm above the upper edge of the mattress) was chosen as the measuring point.

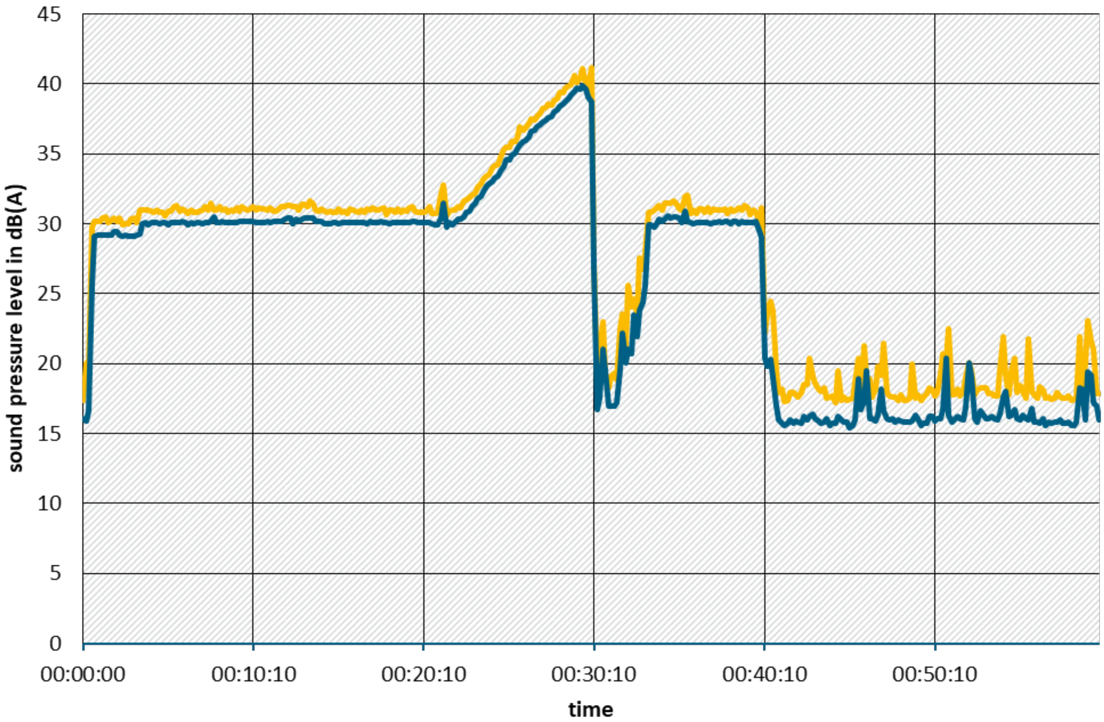
During the one-hour noise scenario (see Figure A 14), the different operating states of the simulated sound source result in peak levels of up to 41 dB(A) (at the end of the icing process). The peak level criterion of the TA Lärm for short-term noise peaks ($L_{\text{AFmax}} \leq 45 + 20$ dB(A) at night), which is used as an aid for orientation, is thus implemented. Within the quiet states of the noise scenario average levels between 15 and 20 dB(A) were measured. This results in an average level of $L_{\text{Aeq,1h}}$ = 30.4 dB(A) over the entire period of one hour.

The sound pressure levels were correspondingly lower in the condition 'closed window'. The difference between the sound pressure levels of the two scenarios 'tilted' and 'closed' window result from the differences in the frequency-dependent sound insulation and the used filter functions.

An average level of approximately L_{Aeq} = 21 dB(A) was measured in this way in the 'closed window' scenario both during stationary continuous operation and when averaged over the entire duration of one hour (Figure A 15). The benchmarks of the TA Lärm were used again for orientation.

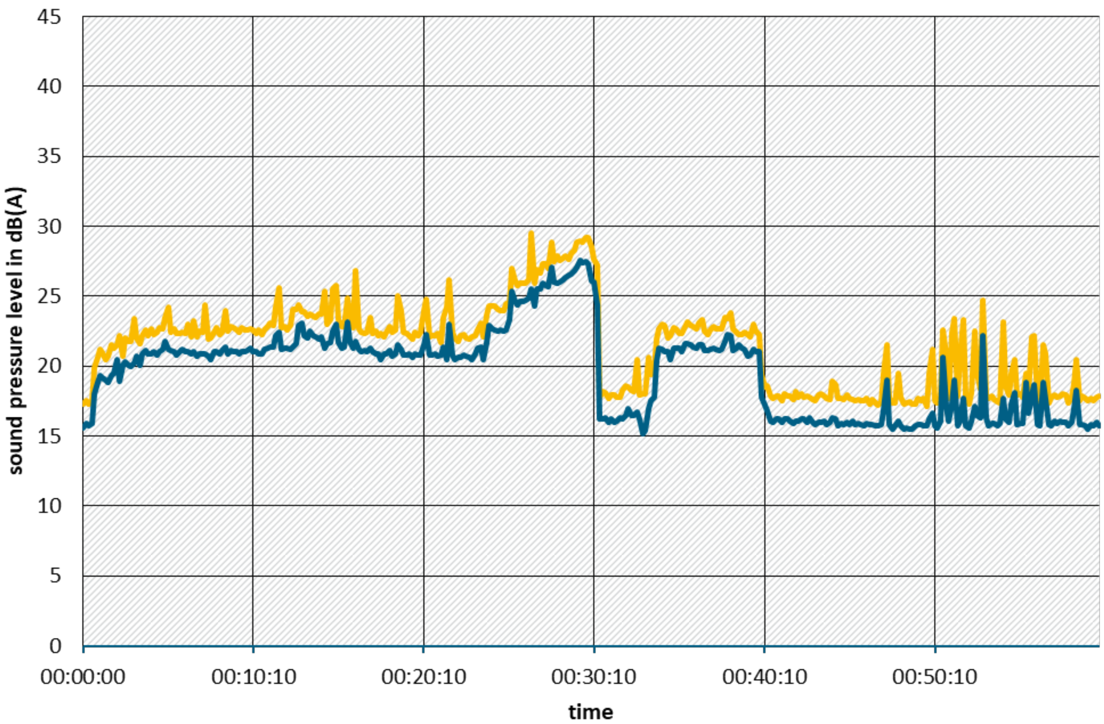
For noise transmissions within buildings or for structure-borne noise transmissions, inside buildings indoor noise levels of 25 dB(A) must be observed, regardless of their location. Short-time noise peaks must not exceed this value by more than 10 dB. At the peak, sound pressure levels of up to 30 dB(A) are measured at the subject's sleeping position. Similar indoor levels result from the permissible noise level outside the window and the usual sound insulation of a window when it is closed. Both established criteria based on the protection mechanism of the TA Lärm are fulfilled. Thus, the noise situations 'at the ear of the sleeping person' through the stimuli presentation were plausible in both measurement conditions ('tilted' and 'closed' window).

Figure A 14: Sound levels at the sleeping person's ear in noise condition 'windows tilted'



Source: own illustration, Möhler + Partner.

Figure A 15: Sound levels at the sleeping person's ear in noise condition 'windows closed



Source: own illustration, Möhler + Partner.

A.9.3 Acoustical monitoring/quality check

During the experiment, the playback level in the bedrooms was monitored continuously via the microphones attached to the ceiling. The audio was recorded simultaneously via the duplex-capable audio interface. The level difference between the ear position of the sleeping person and the measurement microphones on the ceiling was determined separately in advance. This was carried out in both rooms with a calibrated multi-channel system in relation to the noise presentations. So, the microphone recordings at the reference measurement points can be transferred to the respective playback level at the ear of the sleeping person.

The sound pressure levels were checked continuously by the ceiling microphones. For this purpose, the average level (L_{Aeq} in dB(A)) in the stationary part of the stimulus (continuous operation of the AHP) is determined over a period of 5 minutes for a randomly selected night hour. The level difference to the desired target value is then formed. Based on the recorded level-time curve, a section with the least possible influence of background noise (e.g. caused by the subject) is selected. For the various measurement conditions, the target value (L_{target}) during stationary continuous operation of the AHP is L_{Aeq} = 21 dB(A) for the 'closed window' condition or L_{Aeq} = 30 dB(A) for the 'tilted window'.

In addition, the sound pressure level is determined at the loudest point of the stimulus (end of the icing process, just before switching off). The target value for the peak level is L_{Amax} = 41 dB(A) for the 'tilted window' or L_{Amax} = 30 dB(A) for the 'closed window'.

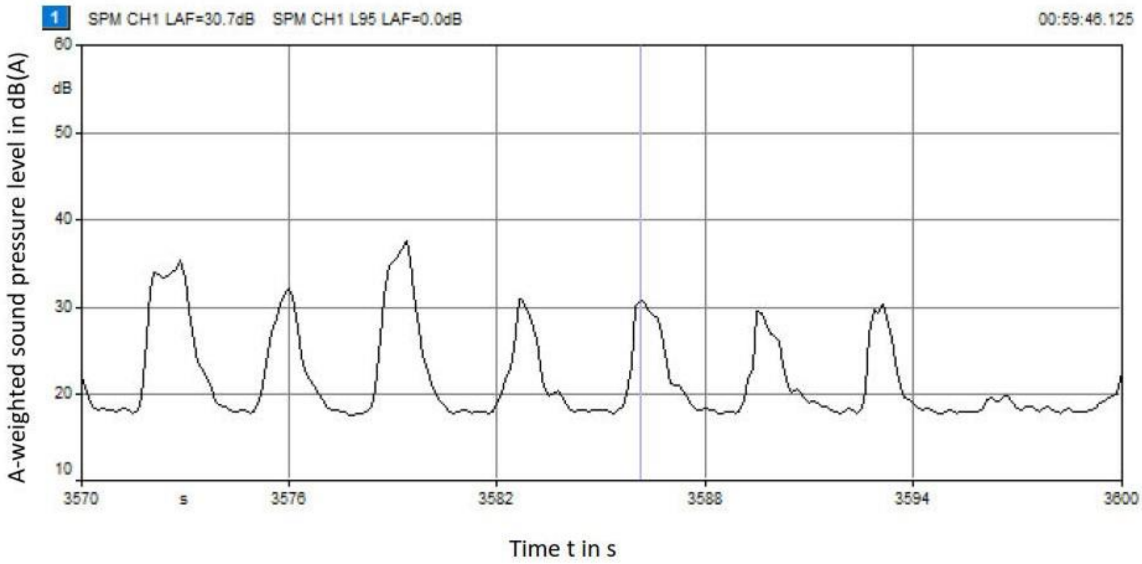
The deviation of the measured sound pressure level from the respective target value was constantly checked by evaluating the level-time curves. The controls showed no irregularities. The noise presentation was therefore correct.

Background noise

In addition to individual short-term interfering noises (e.g. closing doors, sirens), deviations in the recorded levels were determined which were caused by the subjects themselves, in particular by snoring, see Figure A 16.

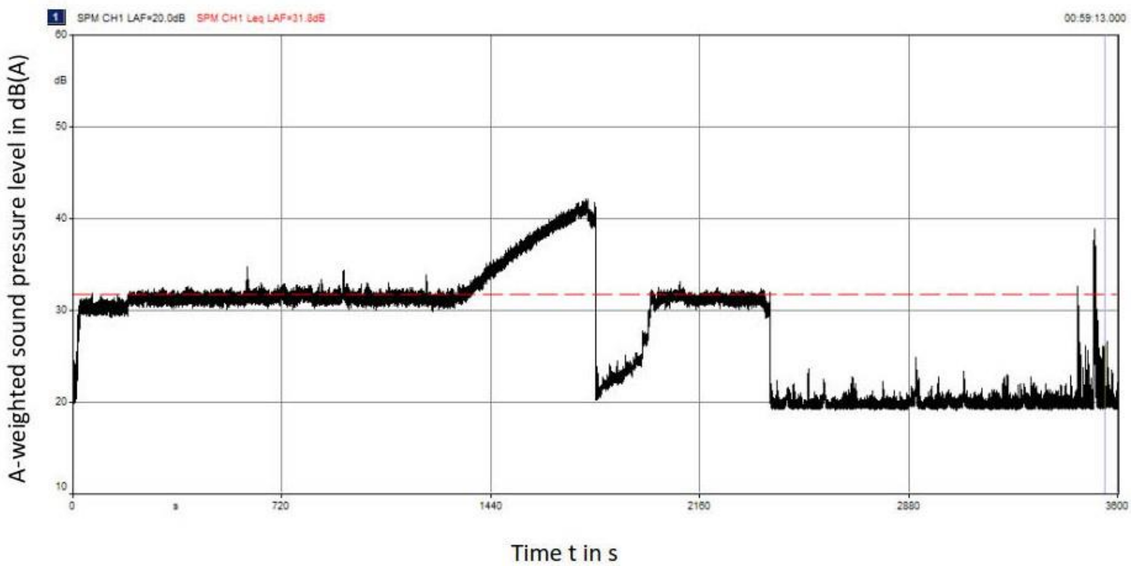
Over the entire course of a one-hour control recording, these breath sounds develop into a relatively constant noise source that interferes with the presented stimuli (compare Figure A 17, Figure A 18, Figure A 19). The measured resting noise level between the noise presentations is therefore strongly dependent on the sleep noises of the subject (snoring, movements, etc.). However, regular control measurements without people in the room ensured that the level deviations measured were due to the background noise. On the other hand, the playback levels of the recorded stimuli were not subject to any critical deviations.

Figure A 16: Level-time curve (excerpt) of snoring without any noise stimulus



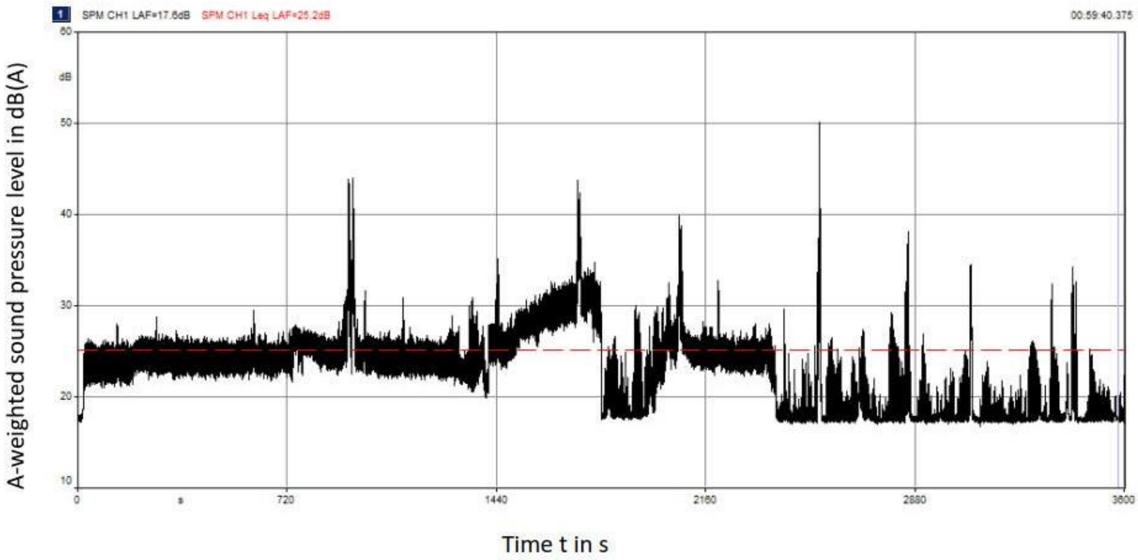
Source: own illustration, Möhler + Partner.

Figure A 17: Level-time curve (one hour) during a night with 'tilted window' noise and low background noise



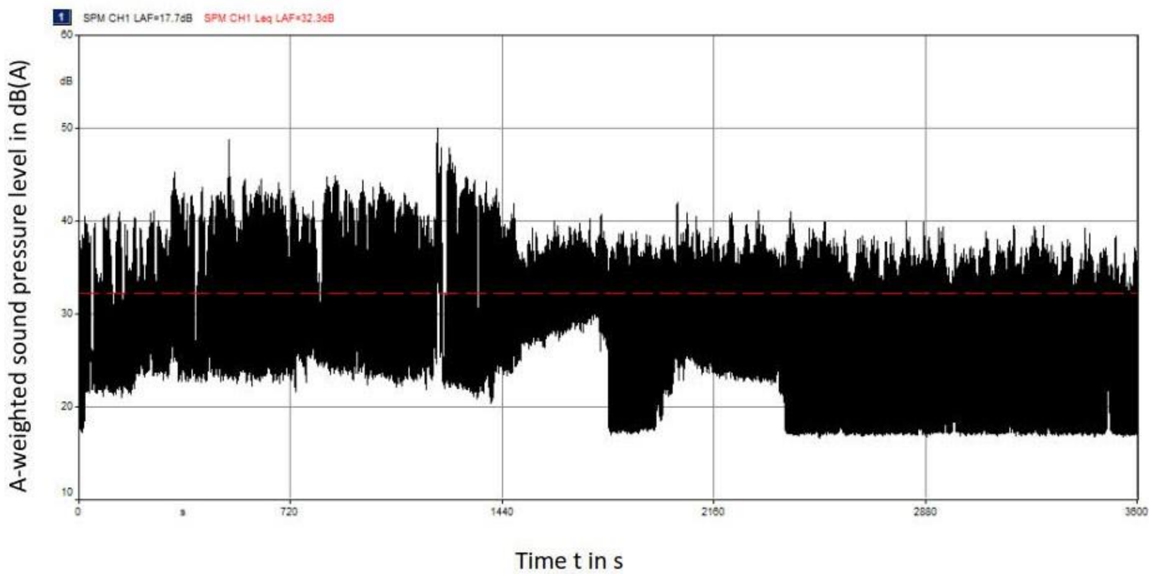
Source: own illustration, Möhler + Partner.

Figure A 18: Level-time curve (one hour) during a night with 'closed window' noise and moderate background noise-



Source: own illustration, Möhler + Partner.

Figure A 19: Level-time curve (one hour) during a night with 'closed window' and severe background noise

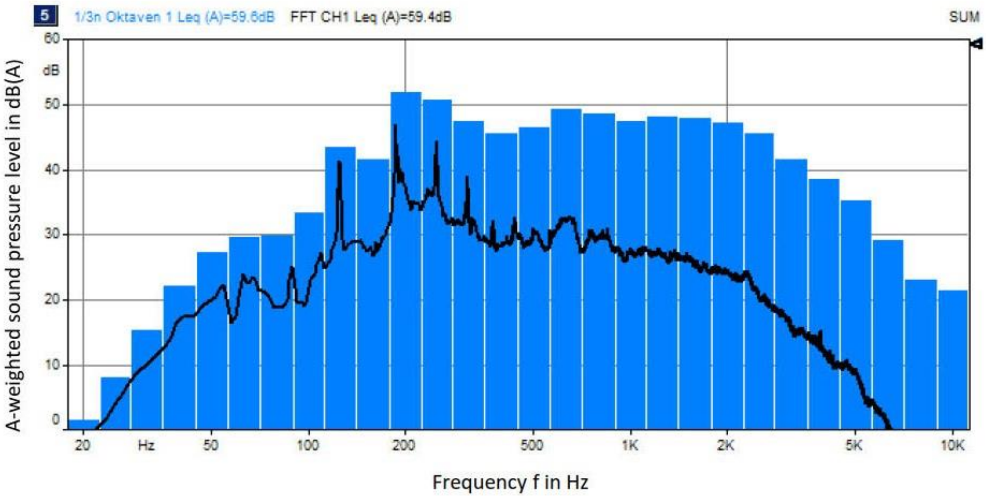


Source: own illustration, Möhler + Partner.

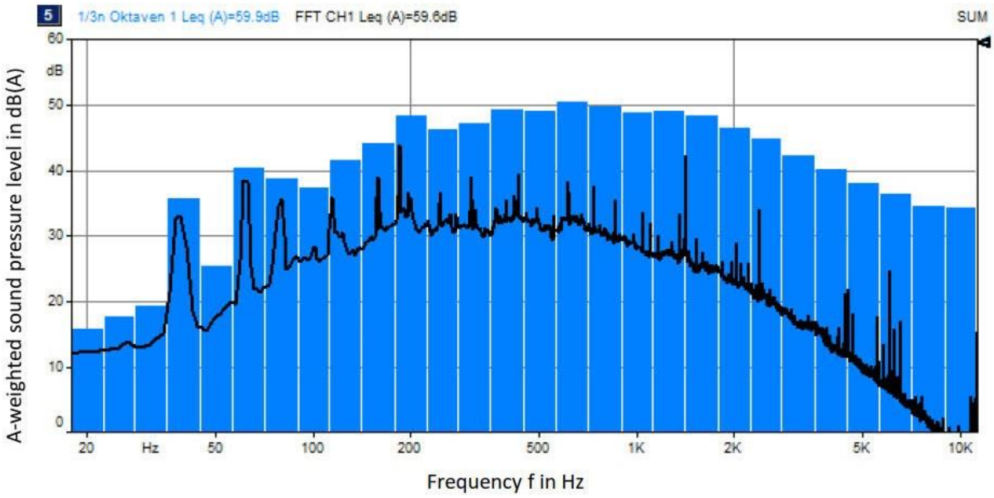
A.10 Measurement results

Figure A 20: Third octave (blue) and narrowband (black) spectra during continuous operation

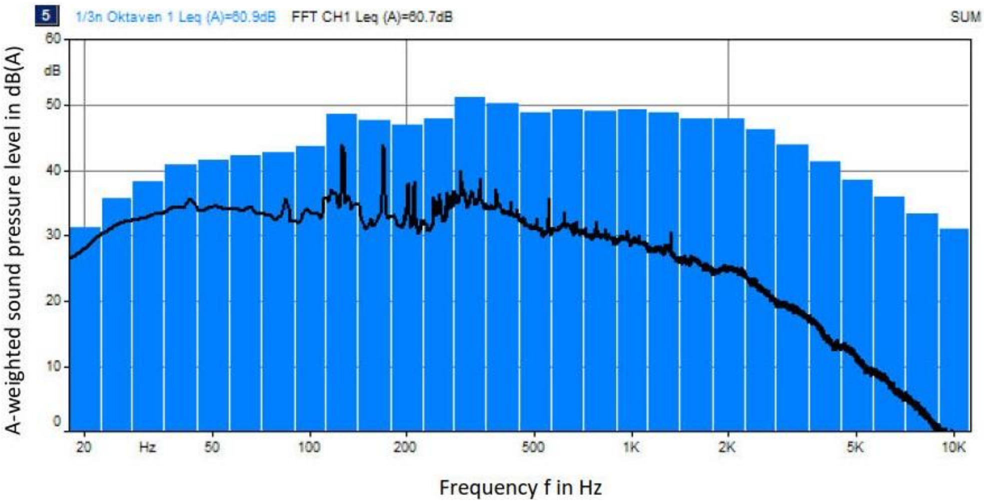
AHP 1



AHP 2



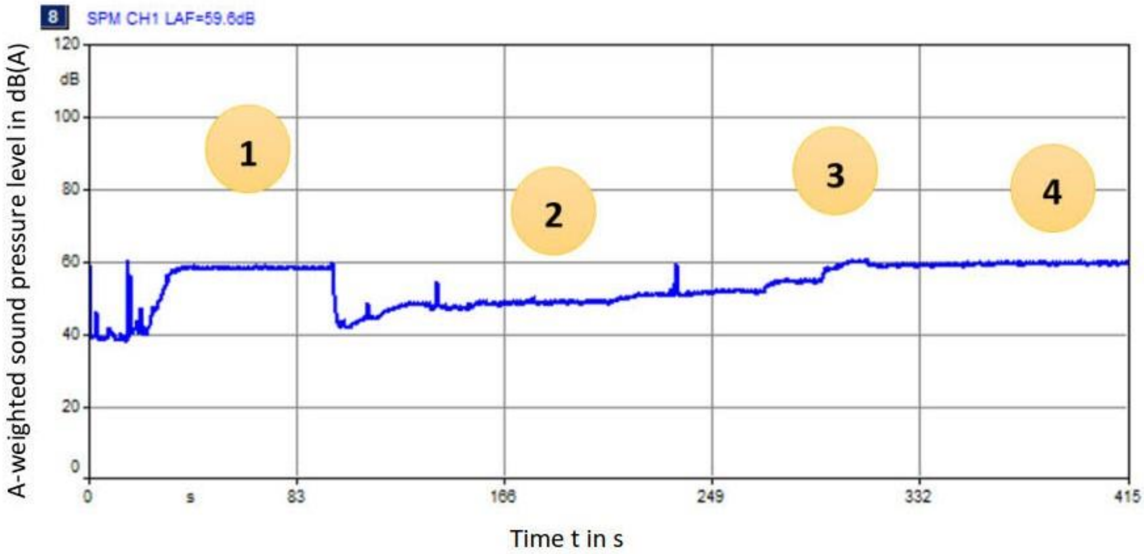
AHP 3



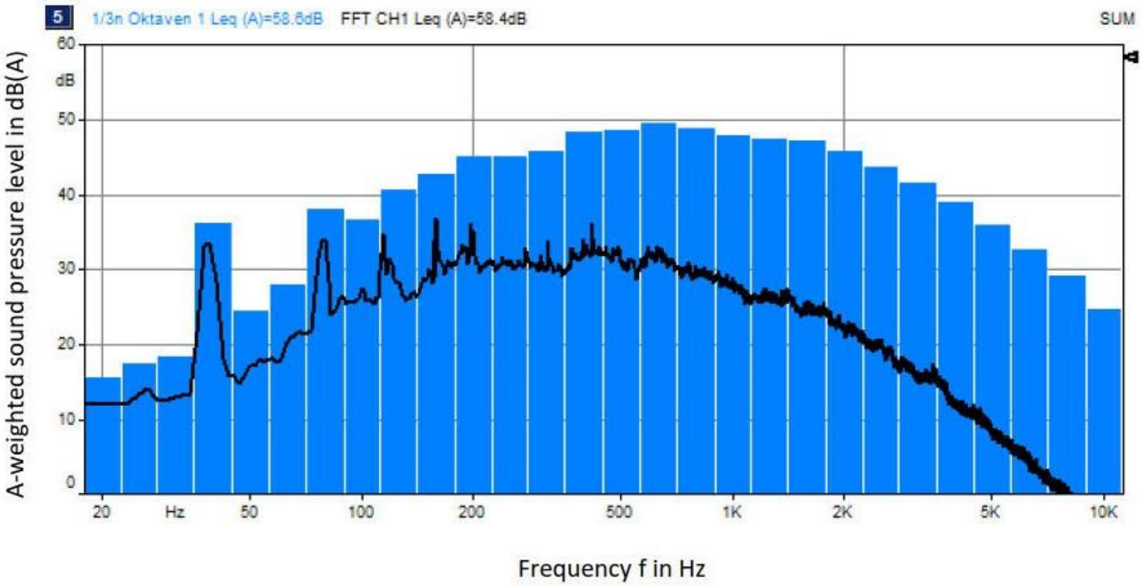
Source: own illustration, Möhler + Partner.

Figure A 21: Different operating states of AHP2

Sound pressure level plotted over time and markers for various operating states

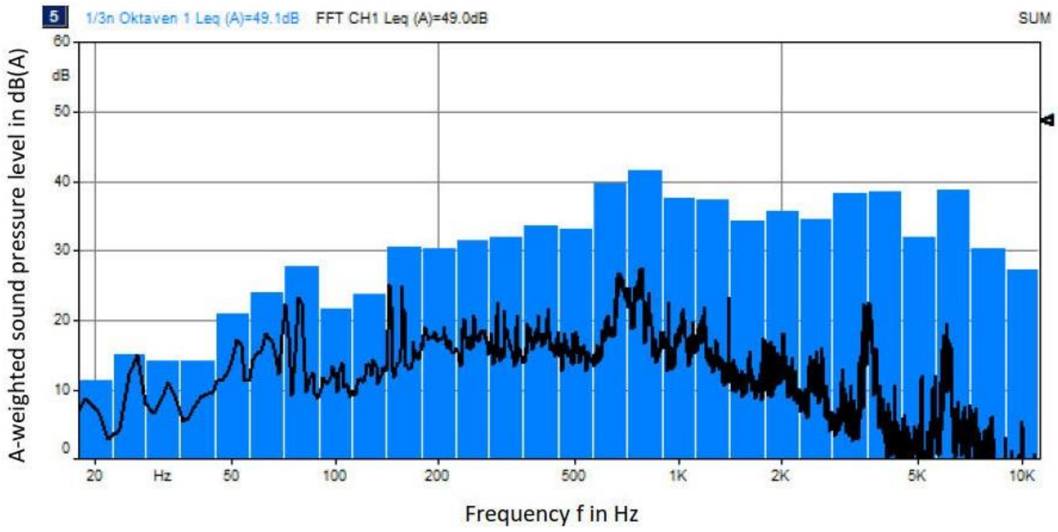


Frequency spectra in point 1

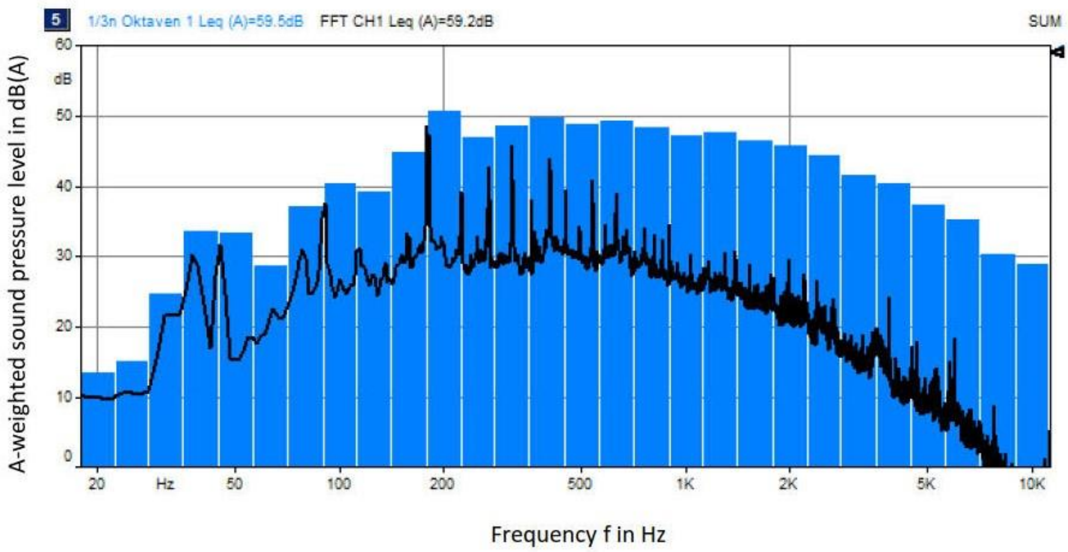


Source: own illustration, Möhler + Partner.

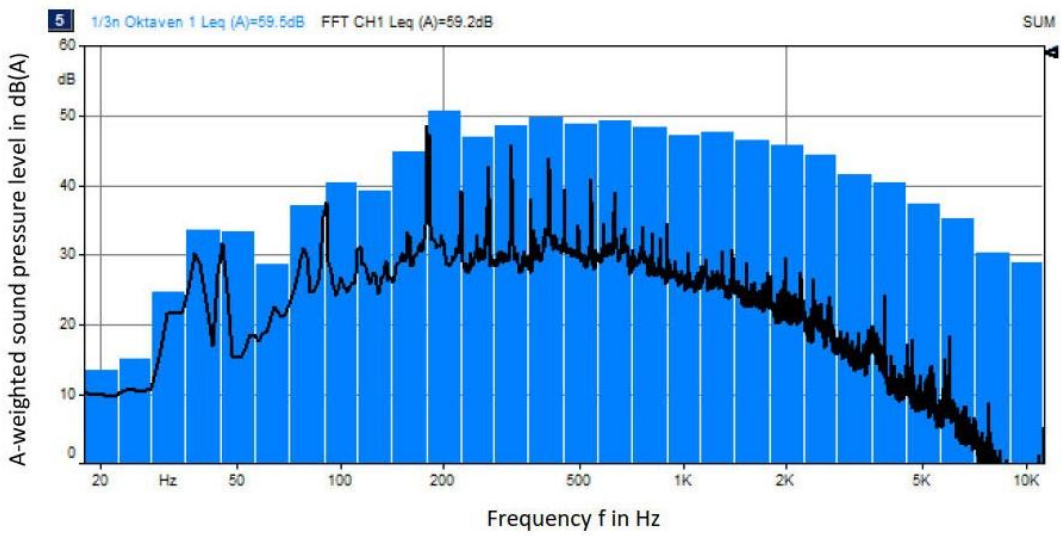
Frequency spectra in point 2



Frequency spectra in point 3



Frequency spectra in point 4

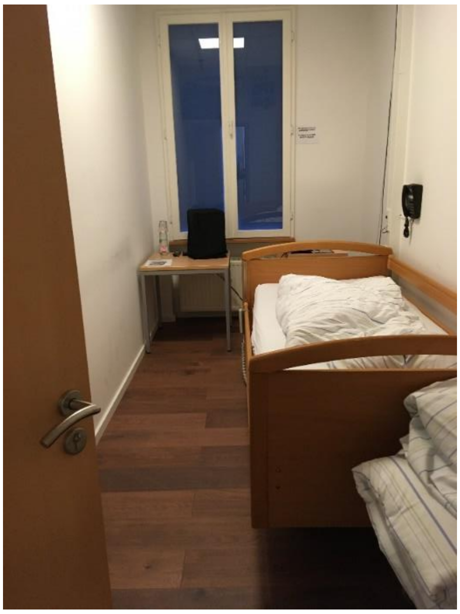


Source: own illustration, Möhler + Partner.

A.11 Setup of study bedrooms

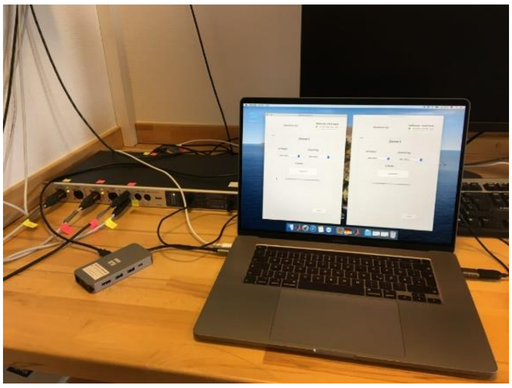
Speaker with fabric cover (room 3)

Study room (room 4)



Microphone suspension for level control (room3)

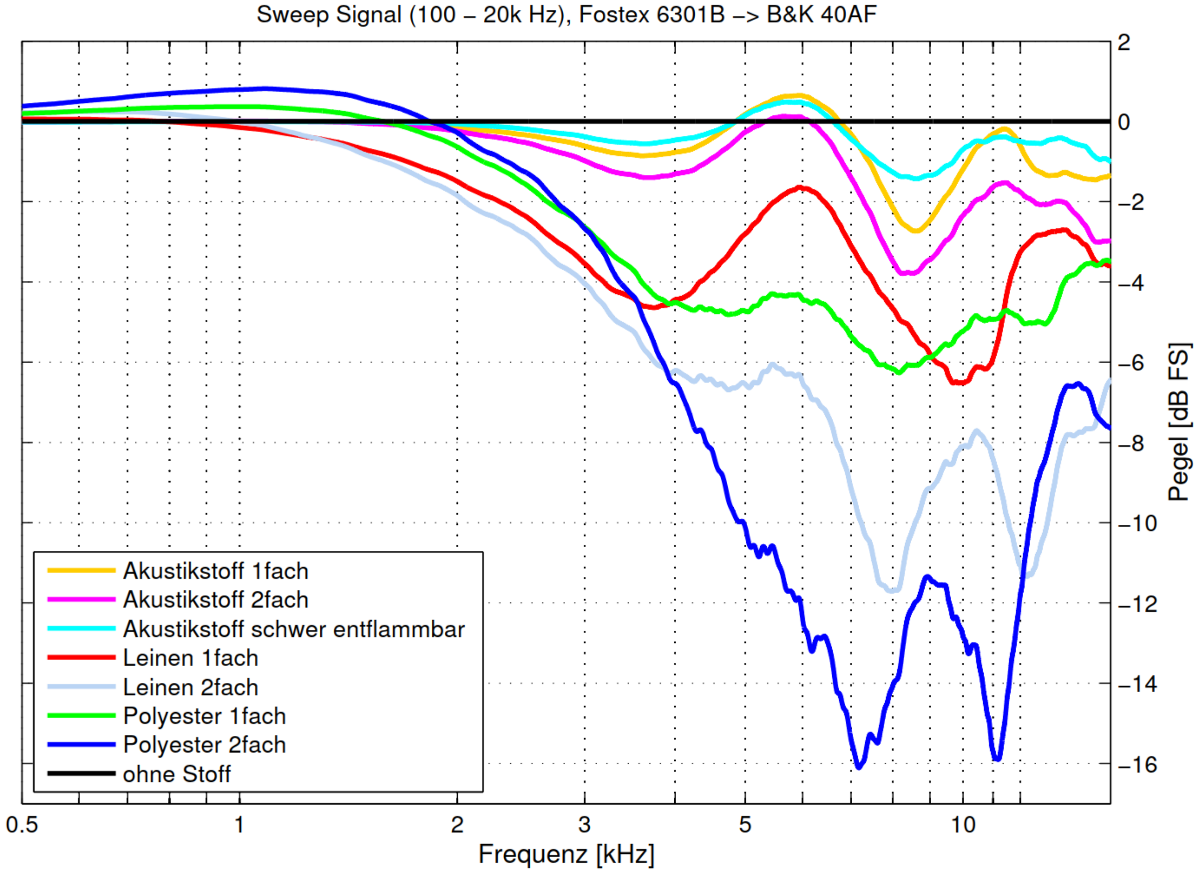
control room setup (MacBook + interface)



Source: own illustration, Möhler + Partner.

A.12 Spectral properties of the fabric used for speaker covers

Used fabric = yellow curve



Source: https://www.akustikstoff.com/

A.13 Factor analyses on items in the daytime questionnaire

A.13.1 Mood

	Mood in baseline condition			**Mood in noise condition**	
Explained variance	46.30%			52.50%	
	Factor			Factor	
Items	1	2	3	1	2
I am alert	**0.942**			**0.785**	
I am relaxed	**0.614**			**0.554**	
I am distracted	**0.585**			**0.754**	
I am in a bad mood	0.403			0.494	-0.401
I feel uneasy		0.586		-0.501	
I feel comfortable	0.427	-0.484		0.832	
I am worried			0.608		0.862
I am nervous			0.590		0.512

Note. Factor loadings < 0.40 not shown. Factor analysis: Principal Axes Factor Analysis (PFA) with Promax rotation

A.13.2 Difficulties concentrating on the text

Items	**Baseline condition**	**Noise condition**
Explained variance	52.70%	62.20%
	Factor	Factor
Items	1	1
It strained me to read the text.	**0.969**	**0.821**
I had to read the text several times to understand it.	**0.739**	**0.965**
I couldn't concentrate on the text.	0.313	0.510

Note. Factor loadings < 0.40 not shown. Factor analysis: Principal Axes Factor Analysis (PFA) with Promax rotation