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LEON-T

Low particle Emissions and lOw Noise Tyres

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Revision history

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1. Introduction

Sleep is a highly complex process that is essential for physical and mental function.[1-5] Experimental investigations on sleep loss and sleep fragmentation reveal adverse physiologic changes that are precursors to disease, including neurodegeneration.[6-13] Accordingly, epidemiologic studies consistently find associations between chronic short or interrupted sleep and negative health outcomes including increased risk for obesity, diabetes, hypertension, cardiovascular disease and all-cause mortality.[14-18] Sleep of sufficient quantity and quality is therefore a key component of health, and its disruption by environmental stressors, including noise, has important public health implications.

Traffic noise is a highly prevalent environment stressor that contributes to sleep loss and fragmentation. However, reductions in total sleep time and sleep fragmentation by nocturnal traffic noise are generally less severe than in studies of experimentally-induced sleep restriction. Nevertheless, sleep disturbance by traffic noise in the long-term may lead to the development of disease, particularly cardiometabolic diseases,[19-30] and chronic exposure to nocturnal traffic noise is associated with many of the same cardiovascular diseases and metabolic disorders linked with restricted and fragmented sleep. This suggests overlapping mechanistic pathways between long-term sleep restriction and noise exposure and the genesis of disease, although evidence linking metabolic outcomes to chronic noise exposure is sparser.[31]

Within the EU-project Low particle Emissions and lOw Noise Tyres (LEON-T), we experimentally investigated the effects of tyre noise on sleep and biomarkers of cardiometabolic risk. This forms Task 4.2 of the LEON-T. This deliverable presents results of these experiments, and their implications within the context of the LEON-T project.

2. Background and aims

The experimental sleep studies have the overarching goal of deepening our understanding of sleep disruption by automotive tyre noise and changes in cardiometabolic and cognitive function. To this end, the studies addressed the following independent aims:

Aim 1: Determine the biological and neurobehavioural consequences of sleep disruption by tyre noise. We measured the sleep of healthy volunteers, and each morning we obtained blood samples for metabolomics analysis and administered a neurocognitive test battery. We compared effects on sleep, metabolomics and cognitive function between quiet nights and nights with road traffic noise.

Aim 2: Identify acoustical characteristics of tyre noise that are especially disturbing physiologically. We used different combinations of types of tyre noise in different noise exposure nights to determine differential effects on sleep and cardiovascular response.

3. Study methodology

Both studies used broadly the same experimental protocol. The two studies differed in the specific tyre noise exposures investigated, and the number of participants. These specific details are given in the relevant sections below.

3.1. Ethics

The study was approved by the local ethics committee (Swedish Ethical Review Authority, 2022-03513-01). The study protocol was registered prior to subject recruitment on ClinicalTrials.gov (NCT05611619). Study subjects provided informed consent prior to the start of the study, were financially compensated for their participation (750 SEK per night) and could discontinue at any time without explanation.

3.2. Study protocol

The study took place in the sound environment laboratory (SEL) at the University of Gothenburg Department of Occupational and Environmental Medicine. The SEL is a high-fidelity research laboratory equipped to simulate a typical apartment, including three individually light-, sound- and vibration-isolated private bedrooms. Ceiling mounted speakers in each room allowed us to create a realistic acoustic environment by transmitting sound exposures from the control room to each bedroom individually.

The study used a prospective within-subjects cross-over design. The study protocol is summarised in Figure 1. Participants spent six consecutive nights in the SEL, with a sleep opportunity between 23:00-07:00. The first night was a habituation period to the study protocol and for familiarisation with the test procedures. Study nights 2-6 were experimental nights and were randomly assigned across participants using a Latin square design to avoid first-order carryover effects. One of these nights was a quiet Control night to assess individual baseline sleep, metabolic profile, and cognitive performance. The remaining four nights involved exposure to tyre noise using a 2×2 factorial design, described in detail in section 3.4.4, with combinations of intermittent or continuous noise (Study 1) or air-filled tyres or composite tyres (Study 2), and two different sound pressure levels (35 or 40 dB L_{night} in Study 1; 28 or 35 dB L_{night} in Study 2).

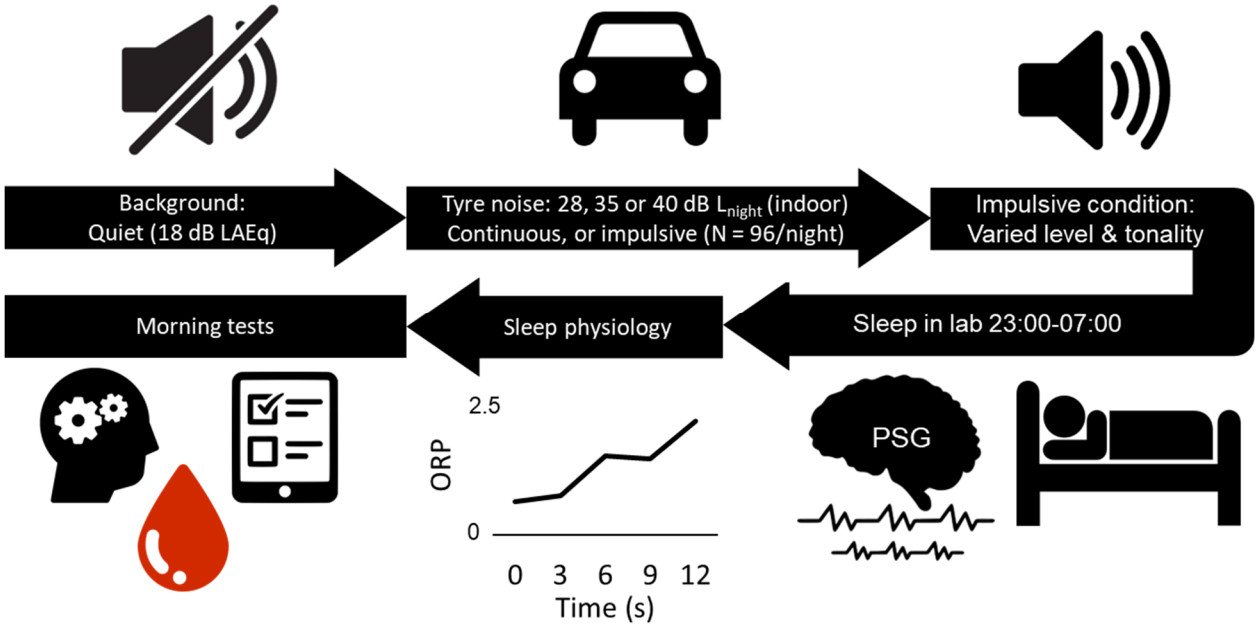

Figure 1 Overview of experimental sleep study protocol. PSG: Polysomnography. ORP: Odds Ratio Product.

Study subjects arrived at the SEL by 20:00 each evening. They then completed the *Cognition* test battery,[32,33] comprising of 10 computerised tests covering a range of cognitive domains: sensorimotor speed, spatial learning and memory, working memory, abstraction and concept formation, spatial orientation, emotion identification, abstract reasoning, complex scanning and visual tracking, risk decision making, and vigilant attention. Each night we recorded physiologic sleep with polysomnography (PSG) and cardiovascular activity with electrocardiography (ECG) and finger photoplethysmography (see 3.5.1 for further detail). Each study morning subjects completed *Cognition*, and completed a short questionnaire including different dimensions of sleep quality and disturbance in the preceding night,[34] sleepiness,[35] and sleep disturbance by noise.[36] (see section 3.6). Every morning except the first (i.e. after the habituation night), subjects also provided a 4 ml blood sample for metabolomics analysis (see section 3.5.2).

Subjects could follow their normal daytime routine, but were prohibited from alcohol, ingesting caffeine after 15:00, and napping, checked with measures of daytime activity via wrist actigraphy monitors worn continuously throughout the study. Because extreme and/or variable dietary behaviour can affect the metabolome/lipoprotein profile,[37] participants were required to eat the same evening meal on each day of the laboratory study, which was confirmed via a food diary.

3.3. Study population

Both sleep studies targeted a focused age range of 18-30 to minimise age-related differences in sleep structure.[38] Interested participants were screened for eligibility with the following exclusion criteria: 1) aged <18 or >30 years; 2) habitual sleep and wake timings more than ±1 hour different from the study sleep times (i.e. habitual sleep time should be 22:00-00:00 and habitual wake time should be 06:00-08:00, confirmed with actigraphy measured for one week before participation in the sleep study); 3) BMI>25 kg/m^2; 4) regular sleep medication use (prescribed or "over-the-counter"); 5) poor hearing acuity (measured during screening via pure tone audiometry); 6) diagnosed with sleep disorders 7) indication for high risk of sleep apnoea on the STOP-BANG questionnaire[39]; 8) shift work; 9) smoking, vaping, snus, or other nicotine use. We recorded blood oxygen saturation via pulse oximetry during the habituation night to further screen for moderate sleep apnoea, defined as more than 15 apnoea and hypopnoea events per hour of sleep. We also measured general health,[40] noise sensitivity,[41] chronotype,[42] habitual sleep quality,[43] and annoyance and sleep disturbance at home by various noise sources,[36] but these did not form part of the eligibility criteria.

3.4. Noise exposure

The set of synthesised tyre sounds were delivered as project milestone MS6. Their generation and rationale for design choices is described below.

3.4.1. Noise synthesis: Air-filled tyre

Synthesised sounds were needed so that specific acoustical characteristics of the sound could be manipulated for the sleep studies. The synthesis of the noise exposures used in the sleep studies is described in detail in two published conference papers,[44,45] and is only summarised here.

Representative tyre noise was synthesised based on analysis of measurements of N=20 different tyres under different operating conditions (50/70/90 kmph speed, engine on or engine off).[44] These measurements were performed by project partner IDIADA on an ISO 10844 test track and following UNECE Regulation R117 as part of project Task 4.1.

An impulse response is the response of a dynamic system to an external input, as a function of time. In the case of a vehicle tyre, the impulse response could be considered a description of the dynamic behaviour of the tyre when inputting an external force such as from a hammer hitting the tyre or the time-varying contact force resulting from the uneven tread pattern rolling across the uneven road surface. For synthesizing sounds for the sleep study, we created an impulse response from the recorded sound of the heavy vehicle tyre (C3) with the least prominent tonal components, that could be used for

convolving with white noise to achieve a continuous sound with similar character to the recorded sound. This was simply done by using the first part of the recording where the doppler shift would be as small as possible, and where noise from turbulent air flow around the vehicle would be minimal. A physical interpretation might be to assume that all sound radiates from the vibrating tyre that can be completely described by recording the response from an impact on the tyre trad, such as hitting it with a hammer. A tyre has a reverberation time determined by material properties, air pressure and load among other things, and can be said to be in the order of a few tenths of a second to one second or perhaps more. A value of ~0.7 s for a freely suspended tyre on a rim is given by Abd El-Salam 2017.[46] For the sound synthesis the reverberation time was set to 0.5 s as a reasonable approximation of a tyre in contact with the road and under load. The impulse response was then created by applying an exponential decay function to the beginning of the recording.

To synthesise tyre noise with tonality, tonal components were the added to the non-tonal synthesized tyre sound by using a sine wave for each tonal component identified from measurements (208 Hz, 392 Hz, 588 Hz and 802 Hz), setting the relative levels with a simple amplitude factor. Relative levels were set to 0, +1.5 and +3 dB. As the tonal character of tyres is often more of a very narrow band noise that a pure tone, frequency modulation was added to each sine wave to widen the perceived bandwidth.

Tyre noise synthesis was done in Csound (https://csound.com), a sound and music computing system developed at MIT. Built-in functions for generating white noise were used in combination with built-in convolution functionality to shape the noise to mimic tyre noise or composite wheel noise. Since individual vehicles were designed to pass at slightly different speeds to mimic a real traffic situation, the impulse response in use is continuously scaled in the time domain to simulate difference in frequency content due to variation in vehicle speed. The level is scaled accordingly by a simple gain function related to velocity. The tonal components added for the tonal tyre scenarios are created using Csound's sine wave generator with frequency modulation. Distance dampening is included as a separate gain function calculated from distance between the virtual vehicle, due to starting position and velocity, and the virtual listener's position. Finally, the built in doppler shift function in Csound is employed using relative velocity difference between virtual source and virtual receiver.

The stimuli were designed to correspond to an indoor setting, in the bedroom. It was decided within the LEON-T project that a 10 cm thick concrete wall partition with a double pane window would represent a majority of urban dwellings in Europe. A frequency response for the wall partition to be used in the sleep studies within the LEON-T project is given in Figure 2. A corresponding impulse response was created by INSA Lyon and is convolved with the synthesized tyre noise in Csound to achieve a realistic indoor noise.

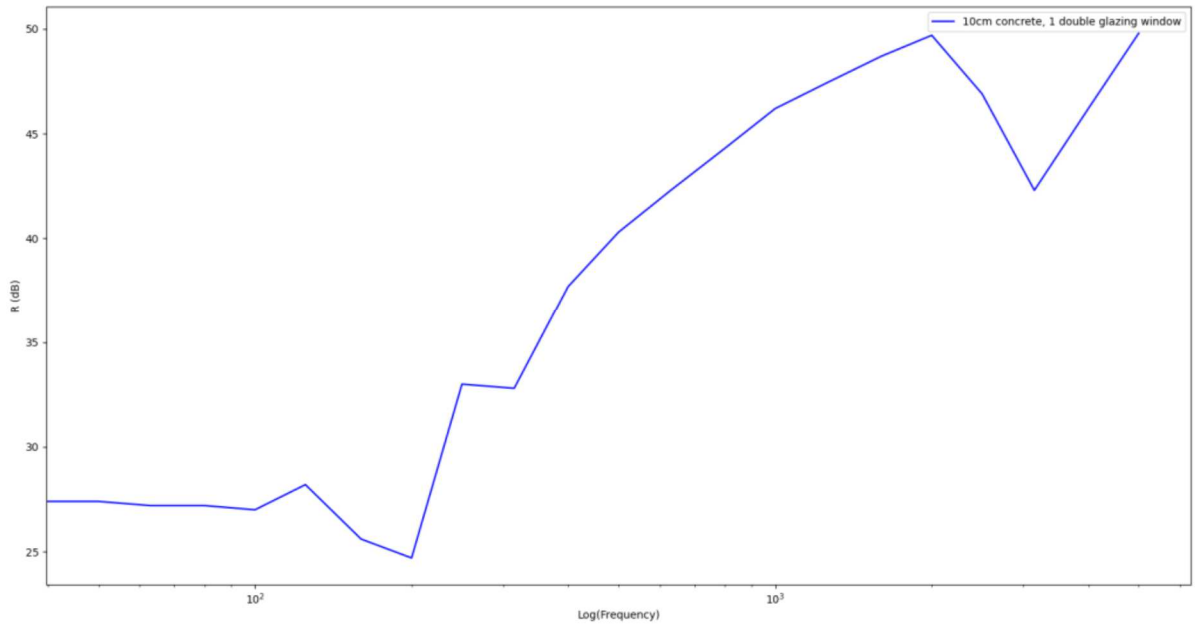

Figure 2 Sound reduction frequency response of a wall partition consisting of 10 cm concrete and a double pane window. Courtesy of INSA Lyon.

3.4.2. Comparison of air-filled and composite tyre sounds

Acoustic data for the air-filled and composite tyres are given in Figure 3. These data are based on analysis of audio recordings, at the same maximum noise level for each tyre type, made at the pillow position in the sleep lab bedrooms. These analyses therefore reflect the true noise exposure for sleep study participants, including any effects of the room. The composite tyre had lower levels in the mid- to high-frequencies (1000 – 5000 Hz), and slightly increased levels in the 315-500 Hz range.

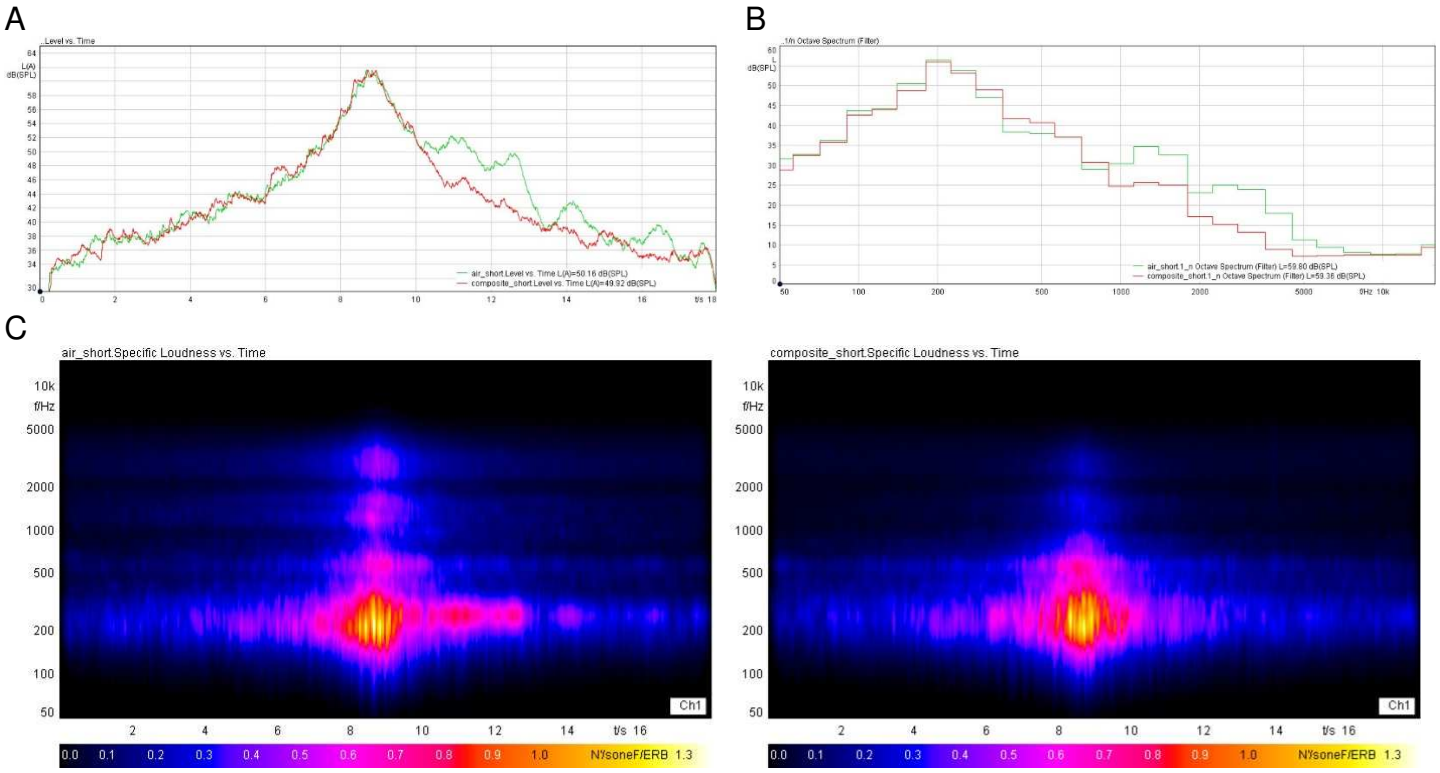

Figure 3 Comparison of air-filled (green) and composite (red) tyre noise measurements. A: Change in A-weighted sound pressure level over time. B: Third-octave frequency spectra calculated during complete vehicle passage. C: Spectrogram showing change in loudness over time (air-filled in left pane, composite tyre in right pane). Courtesy of INSA Lyon.

3.4.3. Noise synthesis: Composite tyre

The composite wheel developed within the LEON-T project was, due to natural time constraint reasons, not finished until after the sleep studies were performed. As such it was not available for noise recording as a basis for synthesis. There is a prototype composite wheel for passenger cars developed by the same inventor as is involved in the current LEON-T composite wheel design, Hans-Erik Hansson at Euroturbine AB in Sweden. Rolling noise was recorded using the Close Proximity method (CPX) for the composite wheel prototype at different speeds. Since the recording is of a passenger car wheel, and the stimuli needs to represent heavy duty vehicles, some assumptions were made. Firstly, the same approach was made for the composite wheel as for the recorded tyre, i.e. creating an impulse response from the recorded composite wheel. This is harder interpreted physically since the composite wheel lacks a resonant cavity, but the flexible spokes or the composite wheel exhibit some resonant behaviour that may behave correspondingly. Secondly, it was the assumed that the vibration wavelengths in a future heavy duty composite wheel would scale according to the difference in circumference between a passenger car wheel and a heavy-duty wheel (which is about 1.6). In practice this meant scaling the impulse response in the time domain accordingly. Finally, it was assumed that the level difference between a passenger vehicle tyre and the passenger vehicle composite wheel would be the same as the corresponding difference for heavy-

duty vehicles. While it would be possible to add tonal components to the composite wheel noise as well, it is considered likely that a wheel designed to reduce noise will have a well-designed tread pattern that minimised potentially annoying tonal components, and including tonal components would also mean a more complex and resource heavy experimental design for the sleep study.

3.4.4. Noise exposure scenarios

The noise exposure scenarios used in sleep study 1 and 2 are summarised in Table 1. These are described in more detail below.

Table 1 Acoustical and traffic flow characteristics of tyre noise exposures in sleep studies 1 and 2.

Study	Tyre noise scenario	Traffic flow	Tyre type	L_{night} (indoor)	$L_{AF,max}$ (impulsive only)	Tonality (impulsive only)
Sleep study 1	1	Impulsive	Air-filled	35 dB	53.4-62.4 dB	0, 1.5 or 3 dB
	2	Impulsive	Air-filled	40 dB	58.4-67.4 dB	0, 1.5 or 3 dB
	3	Continuous	Air-filled	35 dB	-	-
	4	Continuous	Air-filled	40 dB	-	-
Sleep study 2	1	Impulsive	Air-filled	28 dB	46.4-55.4 dB	0 dB
	2	Impulsive	Composite	35 dB	53.4-62.4 dB	0 dB
	3	Impulsive	Air-filled	28 dB	46.4-55.4 dB	0 dB
	4	Impulsive	Composite	35 dB	53.4-62.4 dB	0 dB

In Study 1, two traffic flow patterns were implemented. The first was of continuous traffic, representative of a distant highway. A reliable way of modelling semi-stochastic traffic is to use a Poisson distribution, which will spread occurrences around a given mean rate. We aimed at 1000 vehicles per hour, giving stimuli that through informal listening was decided to give a realistic impression of a high traffic flow and also representing a large number of highways around Europe. If one assumes that about 10% of the traffic flows during the night, the 1000 vehicles per hour corresponds to about 80000 vehicles per 24h which is lower than some of the more extreme situations in Europe, e.g. around Paris experiencing situations with more than 10000 vehicles per hour (Ref 1),[47] but still as high as the traffic flow that can be expected on some of the more busy highways in Sweden,[48] (Ref 2) and thus reasonably representative. The synthesized continuous traffic flow scenario was based on a mix of 80% passenger cars (EU category M1) and 20% heavy vehicles (EU category N3), in order to achieve a realistic impression of a busy highway traffic flow.

The second traffic flow condition was intermittent exposure to single noise events,[1] representing heavy vehicle (EU category N3) pass-bys on a road directly outside the bedroom window. These single events involved the 12 possible combinations of three tonalities (0 dB, 1.5 dB or 3 dB tonality) by four maximum sound pressure levels in 3-dB increments (see below for level ranges). Each of these 12 combinations occurred once per hour across the full night, for a total N=96 events (12/h) during intermittent noise nights. The interval between noise events was randomised between 3.0 to 7.0 minutes (mean interval 5.0 minutes). Noise exposures were filtered in a frequency-dependent manner to simulate the outdoor to indoor attenuation of a typical building façade. This filter resulted in a 25 dBA reduction compared to theoretical outdoor levels of 60 or 65 dB L_{night}. In the intermittent noise nights, this yielded maximum indoor sound pressure levels of 53.4-62.4 dB and 58.4-67.4 dB $L_{AF,max}$ for the two levels of L_{night} respectively. For the continuous traffic flow condition, a simplified noise prediction calculation yields that the 1000 vehicles per hour would result in outdoor L_{night} = 65 dB at a distance of a few hundred meters depending on propagation conditions, and even further for L_{night} = 60 dB.

The speed of the simulated vehicle passes was set to around 90 kph for both scenarios, with a slight random variation for each individual vehicle in the continuous traffic flow. The reason for keeping the speed constant is that the rise time for a sound event is an important factor in triggering detection and eventually awakening. Having heavy vehicles passing close to a façade in 90 kph is likely not very common. Such urban streets mostly have a speed limit of 70 kph or even 50 kph. However, due to the fact that the rise time should be kept constant and also because the individual vehicle levels was intentionally set very high for the impulsive scenario, it was decided to set the speed accordingly.

Results from Study 1 indicated that impulsive tyre noise was more disturbing than continuous tyre noise of the same level (see section 4.1). It was therefore decided to focus on impulsive noise in Study 2, to represent the more intermittent traffic flow typical of night-time and to maximise physiological and subjective response. Synthesis was implemented in the same way as described above for the impulsive scenario, except that none of the tyre sounds included tonality. Study 2 included nights with traditional air-filled tyres (as in Study 1) and also nights with composite tyres. Two different sound pressure levels were chosen: 35 and 28 dB L_{night}. The first (35 dB) was chosen because it reflects a level, albeit high, that people are actually exposure to and would facilitate comparison with Study 1. The level of 28 dB was chose to reflect the -7 dB reduction in sound pressure level targeted by implementation of composite tyres.

Noise exposure in the sleep laboratory bedrooms was introduced through 88 loudspeakers mounted within the ceiling of each room. All sound pressure levels were calibrated to 10 cm above the pillow in each bedroom prior to the study, so that levels

[1] Throughout this report, discrete noise events, i.e. single vehicle passages, are considered as “impulsive” noise events in contrast to continuous noise. Since there are relatively few of these impulsive events, they occur only intermittently throughout the night. References to “impulsive” or “intermittent” noise or traffic in this deliverable are therefore synonymous.

accurately reflect the noise exposure of the subjects during sleep. Noise playback occurred via an automated computer routine, ensuring that all tyre noise exposures were at the correct time and the correct level each study night.

3.5. Physiological measurements

3.5.1. Sleep measurement and analysis

Physiologic sleep was be measured with ambulatory PSG. This involves ten surface EEG electrodes attached to the scalp to measure electrophysiological brain activity (positions C_z, F_3, F_4, C_3, C_4, O_1, O_1, F_{pz}, A_1 and A_2, see Figure 4), two electrodes at the corner of the eyes to measure eye movements, and three electrodes under the jaw to measure muscle movement.

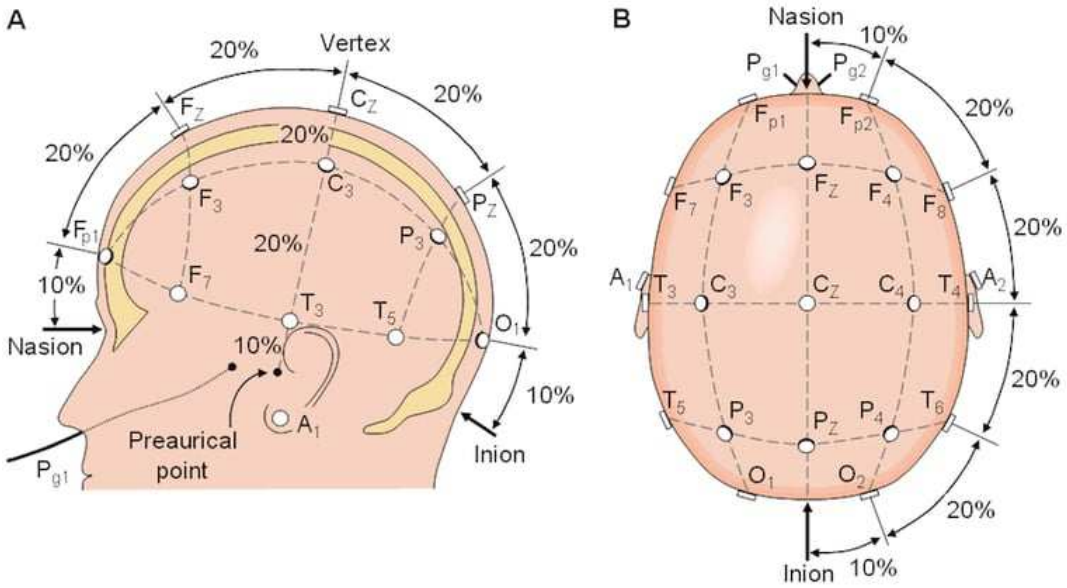

Figure 4 International 10-20 system used for EEG electrode positioning.

We analysed sleep using a novel marker of sleep depth and sleep disturbance. Specifically, the Odds Ratio Product (ORP),[49] which is a continuous measure of sleep depth and stability determined in 3-second epochs. This approach provides measures of overall sleep architecture and the dynamics of changes in sleep across the night and in response to noise. ORP can reveal short duration and/or subtle alterations in sleep activity which nevertheless may be functionally relevant. We have previously demonstrated that the ORP is more sensitive to the effects of noise on sleep than classical sleep scoring techniques.[50]

Sleep-wake activity was also measured using wrist actigraphy for one week before the laboratory study and during the laboratory study itself. These actigraphy data were to

confirm habitual sleep and rise times, and to confirm that participants did not nap during the daytime.

3.5.2. Blood biomarkers

Participants provided a 4 ml blood sample via venepuncture each study morning. This was performed by a qualified clinician, either a registered nurse or an experienced biomedical analyst. All venepuncture procedures followed established guidelines and protocols. Blood was collected in Lithium Heparin vacutainer tubes. After collection, the blood samples were immediately centrifuged, plasma was aliquoted into cryotubes, and the plasma was stored in secure -80°C freezers in the same building as the SEL.

Blood plasma samples were analysed by gas chromatography-mass spectrometry (GC-MS). All samples were destroyed immediately after analysis was completed.

No adverse events occurred after any of the blood collection procedures.

3.6. Questionnaires

Each morning subjects self-assessed different dimensions of sleep quality and disturbance in the preceding night with questionnaires, which we have previously developed and validated for studies on the effects of noise on sleep.[34] We also included validated items on sleepiness[35] and sleep disturbance by noise.[36] Since tyre noise did not continue to play after the 07:00 wakeup call, questionnaires were completed in quiet conditions, i.e. without being able to further listen to the noise exposures.

Evening questionnaires contained items on sleepiness, tiredness, tension, and happiness. Evening questionnaires also included items on daytime activities which could impact sleep, including physical activity, alcohol, caffeine, nictone, and medication. Note that several of these were prohibited by the study protocol, and these questions were therefore asked to confirm compliance.

The full questionnaires are given in section 9.2 - Appendix B: UGOT sleep study questionnaires.

Young adults are especially susceptible to impaired mood and emotion regulation following sleep restriction compared to older adults.[51] We therefore measured positive and negative affect each study morning and evening using the PANAS scale.[52]

3.7. Cognitive function measurements

Cognitive function was measured every morning and evening using the computerised *Cognition* test battery. The *Cognition* battery is fully described elsewhere by Basner et al.,[53] and is only summarised here. *Cognition* comprises a series of 10 neuropsychological tests that cover a range of cognitive domains that recruit primarily from different brain regions. The 10 tests, in order of administration, are as follows: (1) Motor Praxis (MP), assessing sensorimotor speed; (2) Visual Object Learning Test (VOLT), assessing spatial learning and memory; (3) Fractal 2-Back (F2B), assessing working memory; (4) Abstract Matching (AM), assessing abstraction and concept formation; (5) Line Orientation Test (LOT), assessing spatial orientation; (6) Emotion Recognition Task (ERT), assessing facial emotional identification; (7) Matrix Reasoning Test (MRT), assessing abstract reasoning; (8) Digit Symbol Substitution Test (DSST), assessing complex scanning, visual tracking and working memory; (9) Balloon Analog Risk Task (BART), assessing risk decision making; (10) Psychomotor Vigilance Task (PVT), assessing vigilant attention.

3.8. Statistical analysis

All statistical analyses were performed in SPSS version 29 (IBM Corp, Armonk, NY). Data were analysed in generalised linear mixed models (GLMMs) with study participants included as random effects (intercepts). This accounts for the similarity of repeated measurements made on the same individuals. Exposure condition was the main treatment variable of interest, and was included in the analysis as a 5-level categorical variable (1 control night and four noise nights). The habituation night was excluded from all analyses. All models were adjusted for sex (dichotomous variable) and day in study (continuous variable). GLMM results are presented as estimated marginal means (EMM) for categorical data and unstandardised regression coefficients for continuous data.

To account for multiple hypothesis testing, we used the Benjamini-Hochberg method to control for a false discovery rate (FDR) of $q^* = \alpha = 0.05$.[54] Where Type III effects were significant after FDR adjustment, post-hoc tests were performed with sequential Bonferroni adjustments to account for multiple hypothesis testing.

3.8.1. Event-related analysis

We analysed two a priori selected measures of event-related change in ORP as dependent variables. The first event-related outcome was the maximum change in ORP relative to the average ORP in the 30s pre-noise baseline. The time window to calculated ΔOP_{ER} was equal to the duration of each noise event (45 seconds).

The second event- related outcome was the area under the ORP curve from the point of noise onset. Area under the curve (AUC) for event-related ORP change was calculated using the trapezoid rule in 3s intervals corresponding to the 3s width of ORP epochs. The average 3s AUC during the 30s pre-noise interval was subtracted from the AUC of each 3s segment after noise onset, so that AUC data are individually normalised to pre-noise levels. Event-related AUC was calculated both 60s and 90s from noise onset, to test for effects of persistent elevations in ORP after noise cessation.

In both event-related analyses we implemented an adjusted GLMM that in addition to the variables included in models of between-night effects (i.e. noise condition, sex, and day in study), further included level of the noise event, sleep depth at noise onset (mean ORP in 30s pre-noise period), ORP at noise onset, and time of night as covariates.

3.8.2. Cognition analysis

For each of the 10 *Cognition* tests, one key indicator of accuracy and one key indicator of speed were chosen as the main outcome variables of interest (see Smith et al.[55] for full details). *Cognition* outcome data were corrected for practice and stimulus set difficulty effects prior to statistical analysis for a ≤5-day administration interval.[56] To facilitate comparisons between tests and the generation of summary scores, accuracy, and speed outcomes of each test were z-transformed using the average and standard deviation of test performance prior to the start of the isolation period (excluding the first test bout, which was used for familiarizing subjects with the *Cognition* battery). Speed scores were inverted during transformation so that higher z-scores always reflect better (i.e. faster, more accurate) performance. Summary accuracy and speed scores were calculated by averaging across cognitive domains. Risk taking on the BART was considered a separate category and not included in the accuracy summary score.

4. Results

This section presents results of the sleep studies. Results are presented separately for Study 1 and Study 2. The overall implications of the results from both studies are given in the discussion (section 5).

4.1. Study 1

4.1.1. Participants

Fifteen healthy participants (see Table 2) were recruited via public advertisement around the University of Gothenburg campus and online. They were habitually good sleepers

with a habitual mean bedtime closely aligning with the experimental sleep opportunity times. They did not suffer from any sleep disorder, use any sleep medications or medications with potential side effects impacting sleep. All participants had normal hearing, which was assessed via pure tone audiometry to 20 dB HL.

Table 2 Study subjects in Sleep Study 1

Variable	Level / Metric	Value
Sex (n)	Male	7
	Female	8
Age	Mean ± SD	22.4 ± 3.0 years
	Range	18-30 years
Habitual sleep quality (PSQI) [43]	Mean ± SD	2.7 ± 1.1
	Range	1-5
Weinstein noise sensitivity score [41]	Mean ± SD	67.2 ± 15.2
	Range	37-93
Annoyance at home by road noise (0-10 ICBEN-scale) [36]	Mean ± SD	1.5 ± 2.1
Annoyance at home by rail noise (0-10 ICBEN-scale) [36]	Mean ± SD	0 ± 0
Annoyance at home by air noise (0-10 ICBEN-scale) [36]	Mean ± SD	0.5 ± 1.0
Sleep disturbance at home by road noise (0-10 ICBEN-like scale)	Mean ± SD	0.4 ± 0.7
Sleep disturbance at home by rail noise (0-10 ICBEN-like scale)	Mean ± SD	0.1 ± 0.5
Sleep disturbance at home by air noise (0-10 ICBEN-like scale)	Mean ± SD	0.1 ± 0.5
Road noise exposure at home [a]	Mean ± SD	54.6 ± 6.9 dB $L_{AEq,24h}$
	Range	47.5-67.5 dB $L_{AEq,24h}$
Chronotype (n) [b]	Definite morning type	2
	Somewhat morning type	3
	Intermediate type	4
	Somewhat evening type	4
	Definite evening type	2

[a] Extracted from publicly available modelled noise maps based on 2018 traffic flow data (https://karta.miljoforvaltningen.goteborg.se/). Data available for N=12 subjects only, the remaining three lived outside the mapped area.
[b] Based on single-item question

To check subject compliance to the self-regulated lights out time (23:00), we manually scored actigraphy data during the in-lab study period. Across all subjects and study nights, the mean ± SD lights out time was 22:58 ± 00:10. This indicates good adherence to the protocol. The actigraphy records indicated that one subject was non-compliant with the no-napping protocol and had daytime naps on two study days (~2.5 h sleep on each occasion). There were no indications that these naps were followed by delayed sleep timing the subsequent nights, therefore data from these two occasions were retained in the analysis.

4.1.2. Data completeness

One subject dropped out after completing 4 of the 6 study nights. As a result, there are no data for the quiet Control or 35 dB impulsive exposure nights for this subject. Data completeness for all outcomes is summarized in Table 3. Almost all missing data were due to the subject dropout. Insufficient blood volume could be collected on one study morning. No other data were missing.

Table 3 Study 1 data completeness for all outcomes across all 15 subjects and all 6 study nights

Measure	Total expected data (n)	Data obtained (n)	Data completeness compared to expected
Blood	75	72	96.0%
PSG	90	88	97.8%
Questionnaires - morning	90	88	97.8%
Questionnaires - evening	90	88	97.8%
Cognition - morning	90	88	97.8%
Cognition - evening	90	88	97.8%
Food diary	75	73	97.3%
Actigraphy (in-lab period)	105	103	98.1%

4.1.3. Questionnaires

Results of the morning and evening questionnaires are given in Table 4. After correction for multiple testing, there were significant effects of noise exposure on sleeping worse than usual and sleep disturbance by noise. All subjects reported increased sleep disturbance by noise in the nights with tyre noise compared to the quiet Control night. They also reporting sleeping worse than usual in both 40 dB L_{night} nights and in the 35 dB L_{night} night compared to Control.

No statistically significant effects were found for any of the evening questionnaire items.

*Table 4 Study 1 daily questionnaire results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects. Significant p-values after correction for multiple testing (FDR) are indicated with * (adjusted p<.05). Pairs with significant post-hoc pairwise comparisons (p<.05 after sequential Bonferroni correction) are denoted with superscript characters.*

Questionnaire item	Estimated means					P-value
	Control	35 dB Continuous	40 dB Continuous	35 dB Impulsive	40 dB Impulsive	
Morning questions						
Sleep quality (0-10)	7.2 (6.1; 8.3)	4.9 (3.8; 5.9)	5.6 (4.6; 6.7)	6.4 (5.3; 7.5)	5.9 (4.9; 7.0)	.022
Sleep quality (5-pt verbal)	4.1 (3.7; 4.5)	3.5 (3.1; 3.9)	3.5 (3.1; 3.9)	3.6 (3.2; 4.1)	3.7 (3.3; 4.1)	.214
Sleepiness (KSS, 0-8)	3.8 (3.0; 4.7)	5.0 (4.2; 5.8)	4.8 (4.0; 5.6)	4.5 (3.7; 5.3)	5.0 (4.2; 5.8)	.036
Tired (0) – Rested (10)	6.6 (5.6; 7.6)	5.1 (4.1; 6.1)	5.0 (4.0; 5.9)	5.7 (4.7; 6.7)	4.8 (3.9; 5.8)	.022
Tense (0) – Relaxed (10)	6.8 (5.8; 7.7)	6.1 (5.2; 7.0)	6.3 (5.4; 7.2)	6.0 (5.0; 6.9)	5.9 (4.9; 6.8)	.530
Irritated (0) – Happy (10)	7.1 (6.2; 8.1)	6.1 (5.2; 7.0)	6.8 (5.9; 7.7)	6.7 (5.8; 7.6)	6.8 (5.8; 7.7)	.530
Sleep onset (minutes)	16.0 (8.1; 24.0)	25.1 (17.3; 32.9)	23.6 (15.8; 31.4)	24.4 (16.4; 32.3)	25.7 (17.9; 33.5)	.100
Recalled awakenings (n)	1.5 (0.4; 2.6)	2.3 (1.2; 3.3)	2.5 (1.5; 3.5)	2.4 (1.3; 3.4)	2.4 (1.4; 3.4)	.526
Easy (0) – Difficult (10) to sleep	2.5 (1.1; 3.9)	5.5 (4.1; 6.8)	4.7 (3.3; 6.1)	4.8 (3.5; 6.2)	5.1 (3.7; 6.4)	.021
Slept better (0) – worse (10) than usual	4.4 (3.4; 5.4) [abc]	6.7 (5.7; 7.6) [a]	6.5 (5.5; 7.4) [b]	5.6 (4.6; 6.6)	6.3 (5.3; 7.2) [c]	**.005 ***
Deep sleep (0) – Light sleep (10)	2.9 (1.7; 4.1)	4.7 (3.5; 5.8)	4.6 (3.4; 5.7)	4.8 (3.6; 6.0)	4.9 (3.8; 6.1)	.085
Never woke (0) – Woke often (10)	2.8 (1.4; 4.3)	4.0 (2.6; 5.5)	4.7 (3.2; 6.1)	4.3 (2.8; 5.8)	4.3 (2.9; 5.8)	.281
Sleep disturbance by noise (0-10)	0.7 (0.0; 2.2) [abcd]	3.5 (2.0; 5.0) [a]	4.0 (2.5; 5.5) [b]	3.7 (2.2; 5.3) [c]	4.1 (2.6; 5.6) [d]	**.004 ***
Noise caused poor sleep (5-pt verbal)	1.3 (0.7; 1.9)	2.1 (1.5; 2.7)	2.3 (1.7; 2.9)	2.2 (1.6; 2.8)	2.2 (1.7; 2.8)	.051
Noise caused awakenings (5-pt verbal)	1.4 (0.8; 2.0)	1.9 (1.2; 2.5)	2.3 (1.7; 3.0)	2.3 (1.7; 3.0)	2.5 (1.9; 3.1)	.053
Noise caused difficulty sleeping (5-pt verbal)	1.4 (0.8; 2.0)	2.1 (1.5; 2.7)	2.1 (1.5; 2.6)	2.0 (1.4; 2.6)	2.3 (1.7; 2.9)	.189
Noise caused tiredness in morning (5-pt verbal)	1.4 (0.7; 2.0)	2.3 (1.6; 2.9)	2.5 (1.8; 3.1)	2.4 (1.7; 3.1)	2.3 (1.7; 2.9)	.062
Positive affect	22.6 (18.1; 27.2)	20.8 (16.3; 25.3)	22.0 (17.4; 26.6)	21.9 (17.3; 26.4)	22.7 (18.2; 27.2)	.654
Negative affect	11.6 (10.6; 12.7)	12.2 (11.2; 13.2)	11.8 (10.8; 12.9)	11.7 (10.7; 12.7)	11.4 (10.4; 12.4)	.705
Evening questions						
Sleepiness (KSS, 0-8)	6.1 (5.2; 7.1)	6.7 (5.6; 7.7)	6.1 (5.2; 7.1)	6.2 (5.2; 7.1)	6.6 (5.6; 7.6)	.787
Tired (0) – Rested (10)	3.9 (3.0; 4.9)	3.8 (2.8; 4.8)	4.0 (3.1; 4.9)	4.1 (3.2; 5.1)	3.6 (2.7; 4.5)	.919
Tense (0) – Relaxed (10)	6.3 (5.5; 7.2)	6.6 (5.7; 7.6)	7.1 (6.3; 8.0)	6.8 (5.9; 7.7)	6.6 (5.7; 7.4)	.447
Irritated (0) – Happy (10)	7.1 (6.1; 8.1)	6.7 (5.6; 7.8)	7.0 (6.0; 8.0)	7.0 (6.0; 8.0)	7.2 (6.2; 8.2)	.969
Positive affect	20.1 (16.3; 24)	20 (15.9; 24.2)	19.1 (15.2; 23)	21.2 (17.3; 25.1)	18.8 (14.9; 22.6)	.811
Negative affect	12.4 (10.9; 13.8)	12.4 (10.8; 14.0)	12 (10.5; 13.5)	11.6 (10.1; 13.1)	12.1 (10.6; 13.5)	.907

4.1.4. Acute sleep fragmentation

Event-related change in ORP under different exposure conditions are given in Figure 5. In both impulsive noise nights, which involve discrete noise events, there is an increase in ORP following noise onset at time 0s. This reflects upward shifts towards wakefulness and less deep, more unstable sleep. ORP peaks occurred around 30-45s after noise onset, before gradually returning towards pre-noise baseline ORP levels. This corresponds to the noise peak of the vehicle passage. In the continuous noise conditions, which are instead characterised by a constant, more distant noise source, there are expectedly no event-related increases in ORP (since there are no discrete events).

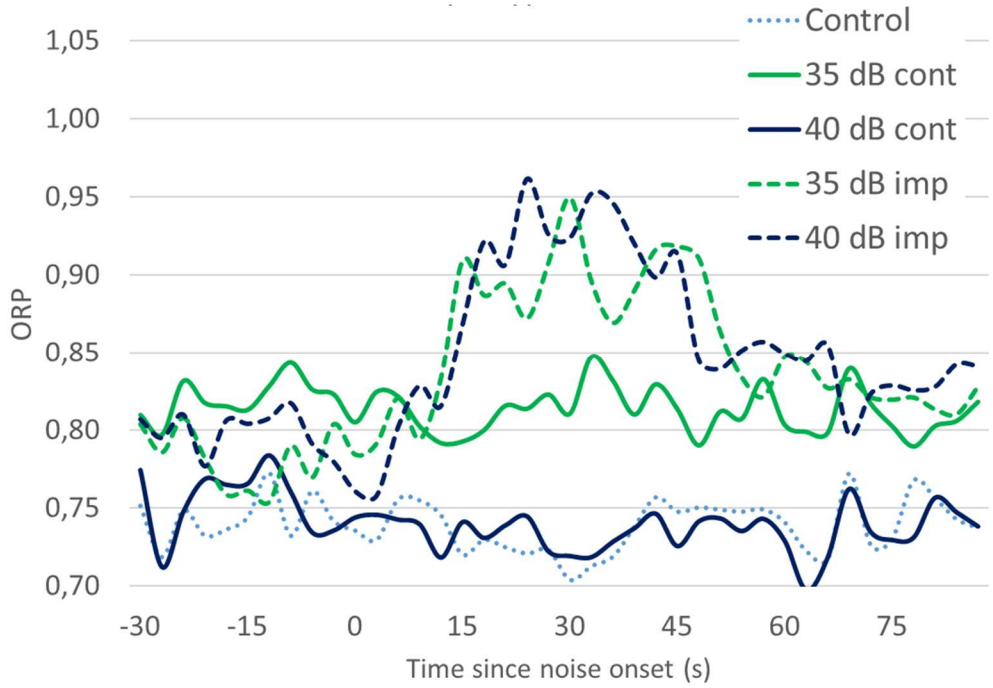

Figure 5 Event-related change in Odds Ratio Product (ORP) in all study conditions. Data are arithmetic means across all subjects and noise events. Data from the Control and Continuous conditions are derived from data in those nights at clock times corresponding to the timing of events in the Impulsive noise nights.

Event-related changes in ORP were analysed statistically as described in section 3.8.1. Results from the models are given in Figure 6. In all three models, there were significant effects of noise exposure condition ($p<.001$). Post-hoc testing indicates that the two impulsive nights induced stronger event-related responses than the Control condition of the two continuous noise conditions (adjusted $p<.05$), while not differing significantly from one another.

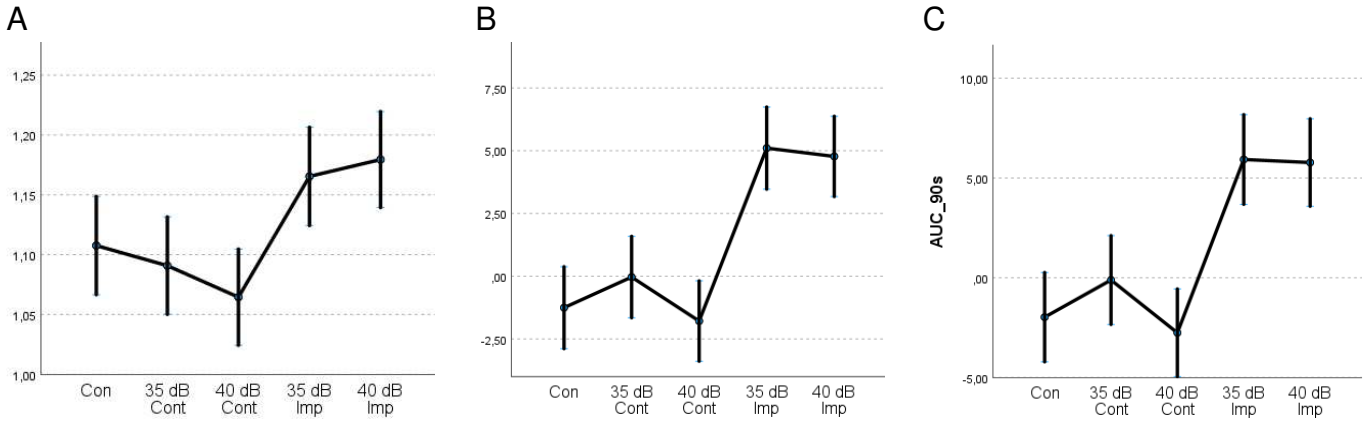

Figure 6 Estimated means for maximum change in ORP during noise pass-by (panel A), event-related area under the curve, derived with a 60s window (panel B) and 90s window (panel C). Data adjusted for day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3,94; Event start time=03:07:12; ORP 30s baseline =0.78; ORP at noise onset=0.77. Error bars indicate 95% confidence intervals.

In the impulsive noise nights, we further examined associations between exposure to discrete noise events and acute changes in sleep depth and stability occurring during the noise period, stratified by the acoustical character of the tyre noise (Figure 7). There was substantial overlap in the event-related change in ORP.

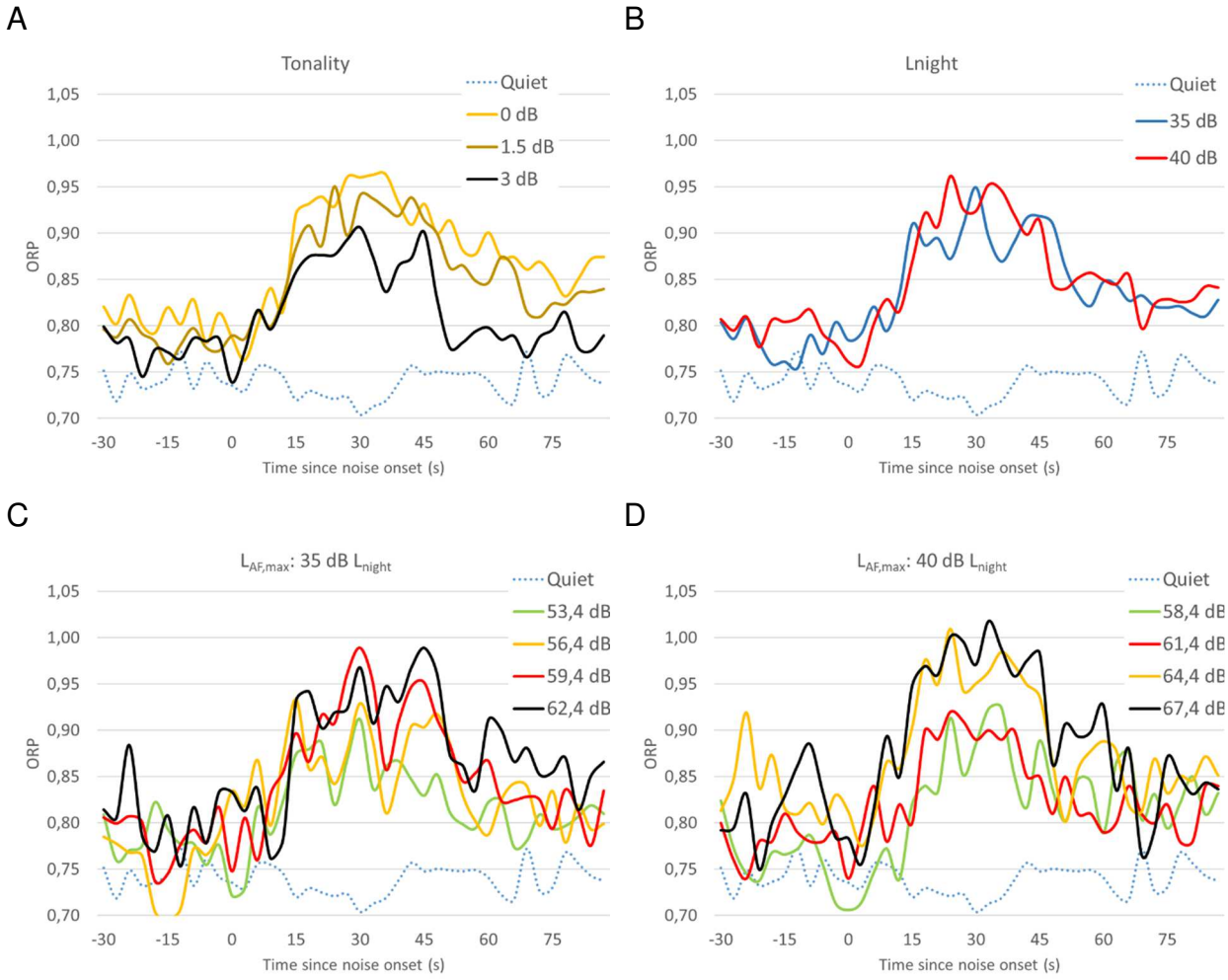

Figure 7 Event-related change in Odds Ratio Product (ORP). Data are arithmetic means across all subjects and noise events, stratified by tonality (panel A), L_{night} (panel B), and $L_{AF,max}$ (panels C and D). Data for the Quiet condition are derived from data in the Control night at clock times corresponding to the timing of events in the noise nights.

These acute responses were analysed in statistical models, restricted to the two impulsive noise conditions. There were no significant effects of tonality, maximum level or L_{night} on event-related maximum change in ORP (Figure 8) or AUC in the 60s following noise onset (Figure 9). With a 90s analysis window, there was a significant effect of tonality, but not maximum level or L_{night}, on increased AUC (Figure 10). Post-hoc tests indicate that the AUC was significantly lower for 3dB tonality tyres than 0 dB tonality tyres (adjusted p = .045). Taken together with the absence of significant effects with the 60s analysis window, this indicates that the elevated ORP recovers towards pre-noise baseline levels more quickly for the 3dB tonality tyres. This can be seen in Figure 7A, particularly after 45s from noise onset.

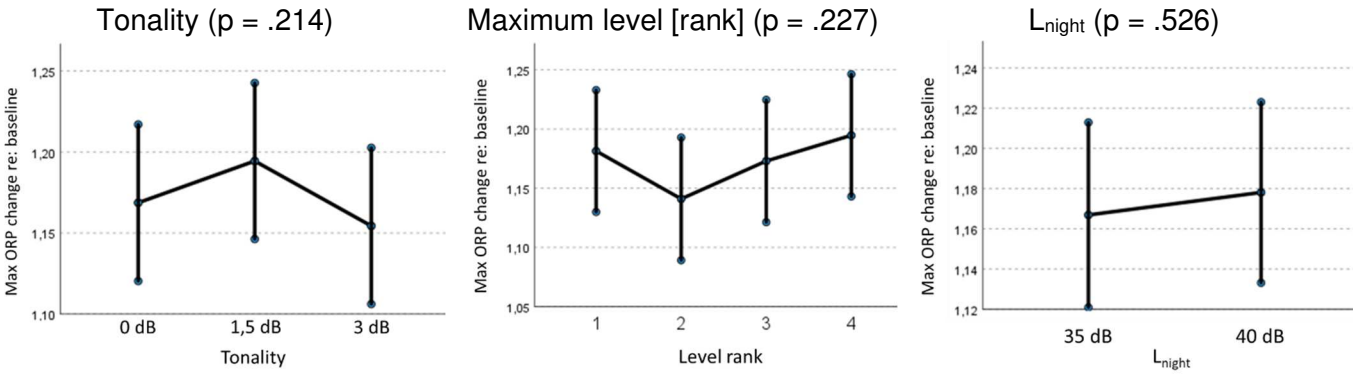

Figure 8 Estimated means for effect of tonality (left panel), maximum sound pressure level (centre panel) and L_{night} (right panel) on maximum change in ORP during noise pass-by. Data adjusted for day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3.96; Event start time=03:07:12; ORP 30s baseline =0.79; ORP at noise onset=0.79. Error bars indicate 95% confidence intervals.

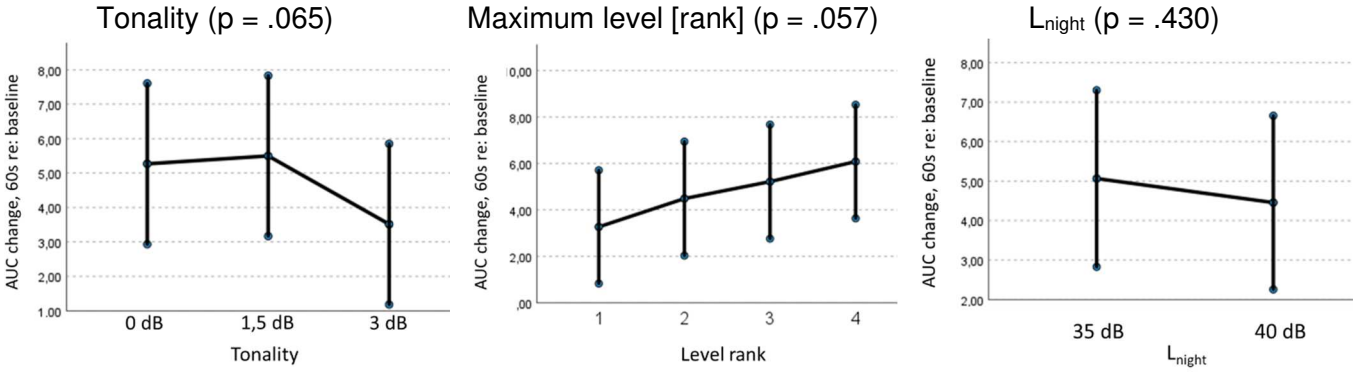

Figure 9 Estimated means for effect of tonality (left panel), maximum sound pressure level (centre panel) and L_{night} (right panel) on event-related area under the curve, derived with a 60s window. Data adjusted for day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3.95; Event start time=03:07:12; ORP 30s baseline =0.79; ORP at noise onset=0.79. Error bars indicate 95% confidence intervals.

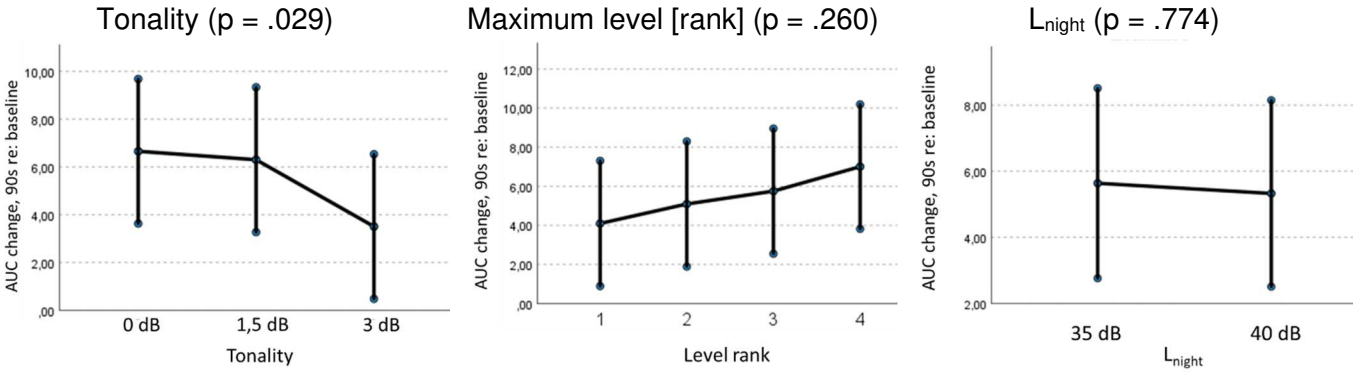

Figure 10 Estimated means for effect of tonality (left panel), maximum sound pressure level (centre panel) and L_{night} (right panel) on event-related area under the curve, derived with a 90s window. Data adjusted for day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3.95; Event start time=03:07:12; ORP 30s baseline =0.79; ORP at noise onset=0.79. Error bars indicate 95% confidence intervals.

4.1.5. Overall sleep structure

Whole-night PSG sleep macrostructure data are given in Table 5. ORP during NREM sleep was higher in the 40 dB Impulsive night than the Control, indicating decreased sleep depth. This decreased sleep depth was driven mainly by a non-significant (after FDR correction) increase in ORP during intermediate N2 sleep, a non-significant reduction in the total amount of deep N3 sleep. There was an approximately 25 minute reduction in the total amount of REM sleep in the 35 dB Continuous night than in the Control and both 40 dB nights.

The number of ORP elevations over 1.75 was greater in the 40 dB Impulsive night than the Control condition, on both brain hemispheres. This indicates multiple intrusions of aroused brain activity into sleep, and can be considered a marker of fragmented sleep. Further, on the right brain hemisphere, there were more ORP elevations over 1.75 that in the 40 dB Continuous night. This suggests that impulsive traffic flow conditions are more physiologically fragmenting for sleep than continuous noise of the same overall average level. Additionally, it is noteworthy that there were no significant effects on traditional EEG measures of sleep fragmentation, i.e., EEG arousals, awakenings, or arousal index. This indicates that the novel ORP metric is a more sensitive measure of noise-induced sleep fragmentation than classical sleep scoring methods, especially for event-related disturbances.

There were no significant effects of noise exposure on any other sleep macrostructure parameters.

*Table 5 Study 1 sleep macrostructure. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects. Significant p-values after correction for multiple testing (FDR) are indicated with * (adjusted p<.05). Pairs with significant post-hoc pairwise comparisons (p<.05 after sequential Bonferroni correction) are denoted with superscript characters.*

Outcome	Estimated means					P-value
	Control	35 dB Continuous	40 dB Continuous	35 dB Impulsive	40 dB Impulsive	
Mean ORP Wake	2.05 (1.97; 2.12)	2.08 (2.01; 2.16)	2.06 (1.99; 2.14)	2.10 (2.03; 2.18)	2.05 (1.98; 2.13)	.631
Mean ORP NREM	0.59 (0.52; 0.66) [a]	0.62 (0.56; 0.69)	0.62 (0.55; 0.69)	0.64 (0.58; 0.71)	0.66 (0.60; 0.73) [a]	**.005 ***
Mean ORP N1	1.04 (0.96; 1.12)	1.03 (0.95; 1.11)	1.07 (0.99; 1.15)	1.06 (0.98; 1.14)	1.08 (1.00; 1.16)	.351
Mean ORP N2	0.61 (0.55; 0.68)	0.64 (0.58; 0.71)	0.64 (0.58; 0.70)	0.66 (0.6; 0.73)	0.67 (0.61; 0.74)	.023
Mean ORP N3	0.31 (0.26; 0.37)	0.34 (0.29; 0.39)	0.35 (0.30; 0.40)	0.34 (0.28; 0.39)	0.35 (0.30; 0.41)	.648
Mean ORP REM	0.96 (0.82; 1.10)	0.98 (0.84; 1.12)	0.96 (0.82; 1.10)	1.02 (0.88; 1.16)	1.00 (0.86; 1.14)	.045
Mean ORP whole night	0.77 (0.69; 0.85)	0.83 (0.75; 0.91)	0.79 (0.71; 0.87)	0.84 (0.76; 0.92)	0.84 (0.76; 0.92)	.082
Mean ORP Last 2h	0.83 (0.65; 1.00)	0.91 (0.73; 1.08)	0.87 (0.70; 1.04)	0.94 (0.77; 1.12)	0.82 (0.65; 1.00)	.661
Mean ORP NREM, first half	0.18 (0.14; 0.23)	0.21 (0.16; 0.25)	0.22 (0.18; 0.27)	0.21 (0.16; 0.25)	0.22 (0.17; 0.26)	.166
Wake (minutes)	36.7 (25.3; 48.0)	51.6 (40.6; 62.6)	35.6 (24.7; 46.6)	43.4 (32.1; 54.7)	37.5 (26.6; 48.5)	.142
N1 (minutes)	35.9 (28.9; 42.9)	45.7 (38.9; 52.5)	37.6 (30.8; 44.4)	40.9 (33.9; 47.9)	43.2 (36.5; 50)	.131
N2 (minutes)	232.9 (213.7; 252.1)	241.5 (222.6; 260.4)	241.3 (222.3; 260.2)	239.6 (220.4; 258.8)	236.4 (217.5; 255.3)	.775
N3 (minutes)	76.2 (60.1; 92.3)	77.8 (61.8; 93.7)	78.3 (62.3; 94.2)	70.3 (54.2; 86.3)	66.2 (50.2; 82.1)	.059
REM (minutes)	91.9 (78.0; 105.9) [a]	64.6 (51.0; 78.1) [abc]	87.3 (73.8; 100.9) [b]	84.0 (70.0; 97.9)	92.6 (79.0; 106.1) [c]	**.006 ***
TST (minutes)	437.4 (422.4; 452.3)	429.5 (414.9; 444.0)	444.4 (429.9; 459.0)	435.3 (420.3; 450.2)	438.4 (423.8; 452.9)	.508
% Awake	7.6 (5.3; 9.9)	10.7 (8.4; 12.9)	7.4 (5.2; 9.7)	9.0 (6.7; 11.3)	7.9 (5.6; 10.2)	.144
Awakenings (n)	21.7 (17.0; 26.5)	23.1 (18.5; 27.8)	21.6 (16.9; 26.3)	20.8 (16.0; 25.5)	24.5 (19.8; 29.1)	.537
Arousals (n)	121.6 (103.2; 140.1)	116.7 (98.5; 135.0)	119.9 (101.7; 138.2)	129.2 (110.7; 147.6)	135.5 (117.3; 153.8)	.062
Awakening-arousal index (n/h)	16.6 (14.1; 19.2)	16.3 (13.8; 18.8)	16.2 (13.6; 18.7)	17.9 (15.3; 20.4)	18.7 (16.2; 21.2)	.076
ORP > 1.75 / hr left hemisphere	114 (87.6; 140.4) [a]	117 (90.8; 143.3)	116.7 (90.4; 142.9)	130.6 (104.3; 156.9)	132.8 (106.6; 158.9) [a]	**.004 ***
ORP > 2.0 / hr left hemisphere	85.4 (66.2; 104.5)	86.1 (67.1; 105.1)	86.0 (66.9; 105)	96.8 (77.8; 115.8)	97.8 (78.9; 116.8)	.016
ORP > 1.75 / hr right hemisphere	112.7 (86.2; 139.2) [a]	124.5 (98.1; 151)	120.8 (94.4; 147.1) [b]	125.8 (99.5; 152.2)	140.1 (113.9; 166.2) [ab]	**.003 ***
ORP > 2.0 / hr right hemisphere	85.5 (66.2; 104.8)	91.2 (71.9; 110.5)	88.6 (69.5; 107.8)	94.6 (75.4; 113.7)	103.5 (84.5; 122.5)	.013

4.1.6. Cognitive function

Results of cognitive tests are given for the morning test administrations in Table 6 and for the evening test administrations in Table 7. There were no statistically significant associations between noise exposure and cognitive performance the following morning. In the evening tests results, the association between exposure condition and MP accuracy did not survive correction for multiple testing. Although point estimates are suggestive of a small (z-score difference = -0.2) effect of reduced morning cognitive accuracy after nights of 40 dB impulsive noise relative to Control (see Figure 11), and reduced evening accuracy after all noise conditions (see Figure 12), this cannot be confirmed statistically. This is potentially due to insufficient statistical power to detect effects of such size but may alternatively simply reflect natural variance in the data.

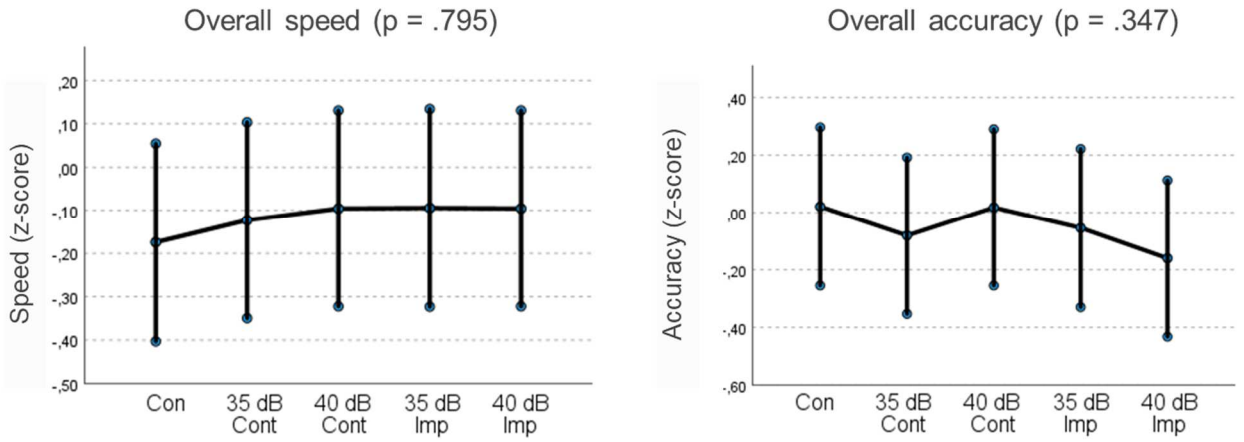

Figure 11 Overall cognitive speed (left pane) and accuracy (right pane) in the morning, averaged over all cognitive domains included in the test battery. P-values indicate main Type III effects. Error bars indicate 95% confidence intervals.

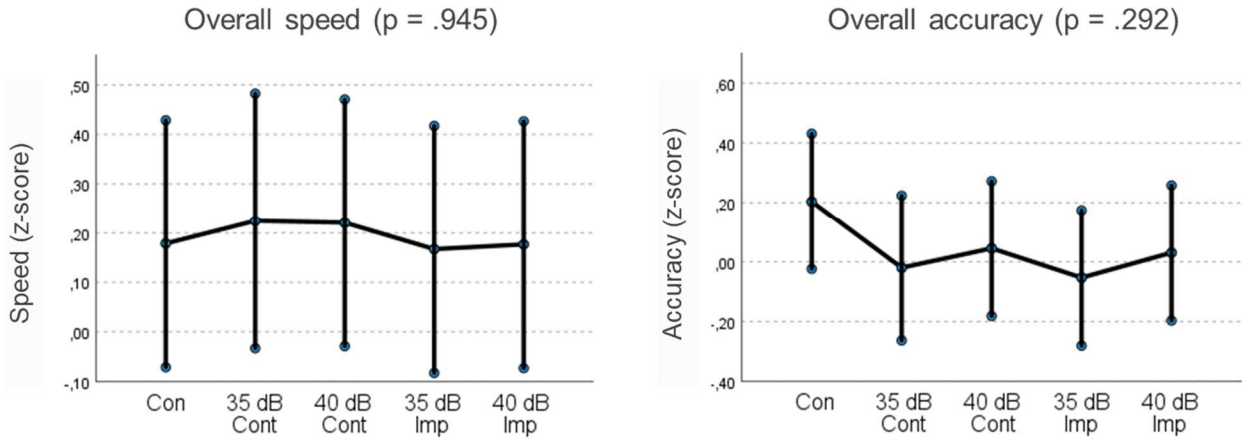

Figure 12 Overall cognitive speed (left pane) and accuracy (right pane) in the evening, averaged over all cognitive domains included in the test battery. P-values indicate main Type III effects. Error bars indicate 95% confidence intervals.

Table 6 Study 1 morning Cognition results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects.

Outcome	Estimated means					P-value
	Control	35 dB Continuous	40 dB Continuous	35 dB Impulsive	40 dB Impulsive	
MP speed	-0.05 (-0.62; 0.52)	-0.12 (-0.67; 0.44)	-0.29 (-0.85; 0.27)	-0.17 (-0.74; 0.40)	-0.21 (-0.76; 0.35)	.927
MP accuracy	-0.02 (-0.58; 0.53)	-0.23 (-0.77; 0.31)	-0.23 (-0.76; 0.31)	-0.15 (-0.70; 0.41)	-0.74 (-1.28; -0.21)	.219
VOLT speed	-0.39 (-0.91; 0.13)	0.09 (-0.42; 0.60)	0.17 (-0.34; 0.69)	-0.15 (-0.68; 0.37)	0.10 (-0.41; 0.61)	.133
VOLT accuracy	0.03 (-0.52; 0.59)	-0.18 (-0.72; 0.37)	-0.02 (-0.57; 0.53)	-0.04 (-0.60; 0.51)	0.01 (-0.53; 0.56)	.878
NBCK speed	-0.39 (-0.93; 0.15)	0.04 (-0.49; 0.57)	-0.14 (-0.66; 0.39)	-0.21 (-0.75; 0.33)	-0.03 (-0.56; 0.49)	.612
NBCK accuracy	-0.16 (-0.76; 0.43)	-0.42 (-1.00; 0.17)	-0.12 (-0.70; 0.46)	-0.12 (-0.72; 0.47)	-0.06 (-0.65; 0.52)	.814
AM speed	-0.03 (-0.58; 0.53)	-0.05 (-0.60; 0.51)	-0.17 (-0.72; 0.39)	-0.03 (-0.59; 0.53)	-0.33 (-0.88; 0.23)	.439
AM accuracy	0.09 (-0.42; 0.60)	-0.03 (-0.53; 0.47)	0.34 (-0.16; 0.84)	0.08 (-0.43; 0.59)	0.14 (-0.36; 0.63)	.639
LOT speed	-0.03 (-0.63; 0.57)	-0.15 (-0.75; 0.44)	-0.22 (-0.81; 0.37)	-0.08 (-0.68; 0.51)	-0.03 (-0.62; 0.56)	.804
LOT accuracy	0.14 (-0.44; 0.72)	0.16 (-0.40; 0.72)	-0.21 (-0.77; 0.35)	-0.10 (-0.68; 0.48)	0.03 (-0.53; 0.59)	.840
ERT speed	-0.11 (-0.60; 0.37)	-0.11 (-0.58; 0.37)	-0.10 (-0.57; 0.38)	0.02 (-0.46; 0.51)	0.09 (-0.39; 0.57)	.802
ERT accuracy	0.12 (-0.35; 0.59)	0.19 (-0.27; 0.65)	-0.08 (-0.54; 0.39)	0.09 (-0.38; 0.57)	-0.41 (-0.87; 0.05)	.122
MRT speed	-0.32 (-0.79; 0.16)	-0.07 (-0.54; 0.39)	0.13 (-0.33; 0.60)	-0.13 (-0.61; 0.34)	0.18 (-0.28; 0.64)	.198
MRT accuracy	0.05 (-0.47; 0.57)	0.05 (-0.46; 0.56)	0.23 (-0.29; 0.74)	-0.13 (-0.65; 0.39)	-0.27 (-0.78; 0.24)	.288
DSST speed	-0.04 (-0.59; 0.51)	-0.32 (-0.86; 0.22)	-0.16 (-0.70; 0.38)	-0.08 (-0.63; 0.47)	-0.22 (-0.76; 0.32)	.586
DSST accuracy	0.18 (-0.33; 0.68)	0.04 (-0.45; 0.53)	0.22 (-0.27; 0.71)	-0.01 (-0.51; 0.49)	0.03 (-0.47; 0.52)	.877
BART speed	-0.26 (-0.77; 0.25)	-0.23 (-0.74; 0.27)	-0.07 (-0.58; 0.43)	0.05 (-0.46; 0.56)	0.0 (-0.50; 0.50)	.490
BART risk	-0.06 (-0.52; 0.41)	-0.16 (-0.61; 0.29)	0.09 (-0.36; 0.54)	0.03 (-0.43; 0.50)	0.08 (-0.37; 0.54)	.849
PVT speed	-0.16 (-0.71; 0.40)	-0.31 (-0.86; 0.24)	-0.12 (-0.67; 0.43)	-0.19 (-0.74; 0.37)	-0.51 (-1.06; 0.04)	.345
PVT accuracy	-0.20 (-0.84; 0.44)	-0.32 (-0.95; 0.31)	0.02 (-0.61; 0.65)	-0.08 (-0.72; 0.56)	-0.16 (-0.79; 0.47)	.640
Overall speed	-0.17 (-0.40; 0.05)	-0.12 (-0.35; 0.10)	-0.10 (-0.32; 0.13)	-0.09 (-0.32; 0.13)	-0.10 (-0.32; 0.13)	.795
Overall accuracy	0.02 (-0.26; 0.30)	-0.08 (-0.35; 0.19)	0.02 (-0.26; 0.29)	-0.05 (-0.33; 0.22)	-0.16 (-0.43; 0.11)	.347

Table 7 Study 1 evening Cognition results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects.

Outcome	Estimated means					P-value
	Control	35 dB Continuous	40 dB Continuous	35 dB Impulsive	40 dB Impulsive	
MP speed	0.07 (-0.42; 0.57)	0.19 (-0.32; 0.71)	0.33 (-0.16; 0.82)	0.13 (-0.36; 0.62)	-0.04 (-0.53; 0.45)	.559
MP accuracy	-0.22 (-0.75; 0.31)	0.13 (-0.45; 0.71)	0.86 (0.33; 1.40)	0.03 (-0.50; 0.57)	0.50 (-0.04; 1.03)	.024
VOLT speed	0.35 (-0.07; 0.77)	0.17 (-0.28; 0.62)	0.24 (-0.18; 0.66)	0.14 (-0.28; 0.56)	0.52 (0.10; 0.95)	.362
VOLT accuracy	0.02 (-0.51; 0.56)	-0.62 (-1.21; -0.04)	-0.05 (-0.58; 0.49)	0.11 (-0.43; 0.64)	-0.06 (-0.60; 0.48)	.301
NBCK speed	0.48 (0.0; 0.96)	0.31 (-0.20; 0.82)	0.35 (-0.13; 0.82)	0.09 (-0.39; 0.57)	0.41 (-0.06; 0.89)	.503
NBCK accuracy	0.22 (-0.29; 0.72)	0.18 (-0.36; 0.72)	0.21 (-0.29; 0.72)	-0.10 (-0.61; 0.41)	0.41 (-0.10; 0.91)	.469
AM speed	0.11 (-0.43; 0.64)	0.16 (-0.39; 0.71)	0.14 (-0.40; 0.67)	0.15 (-0.39; 0.68)	0.18 (-0.36; 0.71)	.995
AM accuracy	0.21 (-0.38; 0.80)	-0.23 (-0.86; 0.39)	-0.26 (-0.84; 0.33)	-0.25 (-0.84; 0.34)	-0.13 (-0.71; 0.46)	.510
LOT speed	0.16 (-0.24; 0.56)	0.28 (-0.13; 0.68)	0.13 (-0.26; 0.53)	0.27 (-0.13; 0.67)	0.19 (-0.21; 0.58)	.662
LOT accuracy	0.39 (-0.17; 0.95)	0.05 (-0.56; 0.65)	-0.18 (-0.73; 0.38)	-0.25 (-0.81; 0.31)	0.22 (-0.34; 0.78)	.252
ERT speed	-0.03 (-0.64; 0.58)	0.30 (-0.34; 0.94)	0.0 (-0.61; 0.61)	0.08 (-0.53; 0.69)	-0.12 (-0.73; 0.50)	.664
ERT accuracy	0.37 (-0.28; 1.02)	0.01 (-0.69; 0.71)	-0.12 (-0.77; 0.54)	0.02 (-0.64; 0.67)	-0.51 (-1.16; 0.15)	.224
MRT speed	-0.06 (-0.62; 0.51)	0.18 (-0.42; 0.78)	0.03 (-0.54; 0.60)	0.03 (-0.54; 0.60)	0.14 (-0.43; 0.71)	.901
MRT accuracy	0.25 (-0.27; 0.78)	-0.08 (-0.65; 0.50)	0.01 (-0.51; 0.54)	0.09 (-0.44; 0.62)	-0.25 (-0.78; 0.28)	.665
DSST speed	0.23 (-0.29; 0.76)	0.22 (-0.33; 0.77)	0.24 (-0.29; 0.76)	0.29 (-0.24; 0.81)	0.38 (-0.15; 0.90)	.956
DSST accuracy	0.34 (-0.31; 0.99)	0.01 (-0.70; 0.73)	-0.30 (-0.95; 0.35)	-0.14 (-0.79; 0.51)	-0.19 (-0.84; 0.46)	.609
BART speed	-0.01 (-0.64; 0.62)	0.08 (-0.58; 0.74)	0.26 (-0.37; 0.89)	0.16 (-0.47; 0.79)	-0.20 (-0.83; 0.43)	.425
BART risk	0.08 (-0.41; 0.56)	0.23 (-0.30; 0.76)	0.21 (-0.27; 0.69)	0.01 (-0.47; 0.50)	0.05 (-0.43; 0.54)	.944
PVT speed	0.48 (-0.02; 0.98)	0.31 (-0.22; 0.84)	0.48 (-0.02; 0.98)	0.31 (-0.19; 0.82)	0.30 (-0.20; 0.80)	.855
PVT accuracy	0.27 (-0.09; 0.63)	0.25 (-0.14; 0.63)	0.26 (-0.10; 0.62)	0.03 (-0.33; 0.39)	0.28 (-0.08; 0.64)	.632
Overall speed	0.18 (-0.07; 0.43)	0.22 (-0.03; 0.48)	0.22 (-0.03; 0.47)	0.17 (-0.08; 0.42)	0.18 (-0.07; 0.43)	.945
Overall accuracy	0.20 (-0.02; 0.43)	-0.02 (-0.26; 0.22)	0.04 (-0.18; 0.27)	-0.05 (-0.28; 0.17)	0.03 (-0.20; 0.26)	.292

4.1.7. Blood biomarkers

Different metabolites have widely different ranges of concentrations. Therefore concentrations were standardised (z-transformed) to allow comparison of the effect of noise exposure between different metabolites. Results are given in Figure 13. Generally, there was a trend for an increase in metabolite concentrations after nights with higher noise level, and with impulsive traffic flow. However, none of the effects were statistically significant, even at the borderline level ($p<.01$).

Metabolite	Exposure condition				
	Control	35 dB Cont.	40 dB Cont.	35 dB Imp.	40 dB Imp.
L-α-aminoadipic acid	-.25	-.30	-.04	.41	.20
L-α-amino-n-butyric acid	-.25	-.08	-.07	.12	.30
L-Alanine	-.09	-.34	.18	.13	.13
L-Arginine	-.08	-.18	.12	.07	.07
L-asparagine	-.20	-.23	.08	.20	.16
L-aspartic acid	-.04	-.23	.03	.14	.11
D,L-β-aminoisobutyric acid	-.23	-.02	.15	-.08	.17
L-Citrulline	-.15	-.22	.10	.12	.17
L-glutamine	-.19	-.19	.16	.06	.16
L-glutamic acid	-.20	-.32	.14	.31	.09
Glycine	-.32	-.11	.29	.15	-.03
Hydroxy-L-proline	-.16	-.23	.26	.17	-.03
Isoleucine	-.23	-.27	-.05	.28	.29
Leucine	-.18	-.23	-.08	.24	.28
Methionine	-.59	.16	-.07	.23	.24
Ornithine	.06	-.32	.22	.10	-.05
O-phosphoethanolamine	-.04	-.17	.13	.00	.08
Phenylalanine	-.18	-.32	.04	.25	.24
Proline	-.08	-.28	.06	.16	.15
Serine	-.27	-.15	.17	.24	.01
Taurine	-.03	-.18	.30	-.10	.00
Threonine	-.19	-.09	.00	.21	.07
Tryptophan	-.20	-.27	.13	.18	.18
Tyrosine	-.12	-.30	.08	.25	.10
Valine	-.27	-.22	.01	.22	.28

Scale (z-score) -.60 0 +.60

Figure 13 Heatmap of metabolite concentrations (z-scored) in Study A.

4.1.8. Study 1 discussion

Overall, results show that discrete tyre noise events induce acute physiologic disturbance of sleep. When occurring at a higher level (i.e. 40 dB L_{night}), there is subsequently an increase in the overall number if ORP elevations above 1.75 and a decrease in the depth of non-REM sleep across the night. Tyre noise was associated with subjective reports of higher levels of sleep disturbance and sleeping worse than usual, but this was largely independent of noise level or traffic flow condition. There were no effects of night-time

tyre noise on cognitive performance in either the morning or the following evening. There were no statistically significant effects of noise exposure on blood biomarkers of cardiometabolic function.

The point estimates of several outcomes suggest worse sleep in the impulsive noise conditions. These data are not always statistically significant, however. This is likely due to limited statistical power as a result of a sample size of N=15. Nevertheless, the indications across the overall body of evidence in multiple domains (sleep macrostructure, questionnaires, blood biomarkers) are at least suggestive of an effect. Individual car passages, i.e. the impulsive condition, are also more representative of night-time traffic flows than continuous traffic flow. It was therefore decided that the noise exposures in Study 2 should consist of individual vehicle passages. In this way the noise exposure is more realistic, while also increasing the likelihood of eliciting, and thus detecting, noise-induced sleep disturbance with a limited sample size.

A surprising finding was that following acute disturbance, sleep depth more quickly recovered after exposure to tyres with a high amount of tonality (3 dB) compared to tyres with no tonal components. We had hypothesised, following the psychoacoustical listening tests results (deliverables D4.1 and D4.2), that if any differences existed in the physiological response, we would expect a stronger response from the tyres with greater tonality.

4.2. Study 2

4.2.1. Participants

Thirty healthy participants (see Table 8) were recruited via public advertisement around the University of Gothenburg campus and online. They had a habitual mean bedtime closely aligning with the experimental sleep opportunity times. They did not suffer from any sleep disorder, use any sleep medications or medications with potential side effects impacting sleep. All participants had normal hearing, which was assessed via pure tone audiometry to 20 dB HL.

Table 8 Study subjects in Sleep Study 2

Variable	Level / Metric	Value
Sex (n)	Male	12
	Female	18
Age	Mean ± SD	23.4 ± 2.8 years
	Range	19-29 years
Habitual sleep quality (PSQI) [43]	Mean ± SD	4.1 ± 1.9
	Range	1-8
Weinstein noise sensitivity score [41]	Mean ± SD	67.5 ± 15.6
	Range	44-109
Annoyance at home by road noise (0-10 ICBEN-scale) [36]	Mean ± SD	1.3 ± .18
Annoyance at home by rail noise (0-10 ICBEN-scale) [36]	Mean ± SD	0.2 ± 0.8
Annoyance at home by air noise (0-10 ICBEN-scale) [36]	Mean ± SD	0.3 ± 0.9
Sleep disturbance at home by road noise (0-10 ICBEN-like scale)	Mean ± SD	0.7 ± 1.7
Sleep disturbance at home by rail noise (0-10 ICBEN-like scale)	Mean ± SD	0.0 ± 0.0
Sleep disturbance at home by air noise (0-10 ICBEN-like scale)	Mean ± SD	0.1 ± 0.4
Road noise exposure at home [a]	Mean ± SD	54.5 ± 8.3 dB $L_{AEq,24h}$
	Range	42.5-72.5 dB $L_{AEq,24h}$
Chronotype (n) [b]	Definite morning type	4
	Somewhat morning type	7
	Intermediate type	6
	Somewhat evening type	10
	Definite evening type	3

[a] Extracted from publicly available modelled noise maps based on 2018 traffic flow data at most exposed façade (https://karta.miljoforvaltningen.goteborg.se/). Data available for N=28 subjects only, the remaining two lived outside the mapped area.
[a] Based on single-item question

To check subject compliance to the self-regulated lights out time (23:00), we manually scored actigraphy data during the in-lab study period. Across all subjects and study

nights, the mean ± SD lights out time was 22:56 ± 00:12. This indicates good adherence to the protocol. One subject was non-compliant with the scheduled lights outs time on two occasions, with actigraphy records indicating the start of the rest period at 21:41 and 21:45. PSG data show that this subject fell asleep shortly after this time on each occasion. This indicates actual non-compliance, i.e. we did not incorrectly score quiescent wakefulness prior to bedtime as sleep in the actigraphy data.

The actigraphy records did not indicated that any subjects were non-compliant with the no-napping protocol.

Two subjects dropped out of the study for personal reasons. Neither subject withdrew their consent. One male dropped out after completing 4 nights (habituation, control, 28 dB composite tyre noise and 35 dB air-filled tyre noise), and one female dropped out after completing 2 nights (habituation and the 28 dB air-filled tyre noise). Available data from completed nights are included in analyses where possible.

4.2.2. Data completeness

Data completeness for all outcomes is summarized in Table 9. Most missing data were due to the dropout of the two subjects after 2 and 4 nights respectively. A further two nights of PSG data were lost due to bad EEG signals (1× habituation night, 1× 35 dB Air tyre noise night). Insufficient blood volume could be collected on one study morning. Three subjects did not fully complete the food diary with dinner information. One subject wore the Actigraph during the week prior to entering the lab but did not wear it during the experimental study week.

Table 9 Study 2 data completeness for all outcomes across all 30 subjects and all 6 study nights

Measure	Total expected data (n)	Data obtained (n)	Data completeness compared to expected
Blood	150	143	95.3%
PSG	180	172	95.6%
Questionnaires - morning	180	174	96.7%
Questionnaires - evening	180	174	96.7%
Cognition - morning	180	174	96.7%
Cognition - evening	180	174	96.7%
Food diary	150	128	85.3%
Actigraphy (in-lab period)	210	197	93.8%

Good quality EEG data were available for event-related analysis during N=12,199 (89.6%) noise events and Control night sham events (i.e. the 96 time periods during the quiet night corresponding to when noise events occurred during the tyre noise nights). Missing data were due to poor quality data, e.g. movement artefact, high electrode

impedance, that precluded accurate ORP scoring during the pre-noise baseline, during the noise pass-by, or both.

4.2.3. Questionnaires

Results of the morning and evening questionnaires are given in Table 10. After correction for multiple testing, there were significant effects of noise exposure on numerical and verbal sleep quality, morning happiness, difficulty sleeping, sleeping worse than usual, sleep disturbance by noise, and noise causing poor sleep. For each of these except happiness, sleep was worse in the 35 dB composite tyre noise night than in the Control night. Sleep in the 35 dB composite tyre noise night was generally worse than in one or both of the 28 dB nights. Conversely, sleep in the 35 dB air-filled tyre noise night was generally not worse than in other nights, with the exception of greater difficulty sleeping and higher sleep disturbance than in the quiet control night.

These results suggest a dose-response relationship, whereby nights with 35 dB L_{night} noise are for multiple outcomes more subjectively disturbing for nights without noise or with 28 dB L_{night} noise. Composite tyres appear to be more disturbing than traditional air-filled tyres of the same level.

No statistically significant effects were found for any of the evening questionnaire items.

*Table 10 Study 2 daily questionnaire results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects. Significant p-values after correction for multiple testing (FDR) are indicated with * (adjusted p<.05) and *** (adjusted p<.001). Pairs with significant post-hoc pairwise comparisons (p<.05 after sequential Bonferroni correction) are denoted with superscript characters.*

Questionnaire item	Estimated means					P-value
	Control	28 dB air-filled	28 dB composite	35 dB air-filled	35 dB composite	
Morning questions						
Sleep quality (0-10)	6.2 (5.5; 7.0) [a]	5.9 (5.2; 6.7)	6.4 (5.7; 7.2) [b]	6.0 (5.2; 6.7)	4.9 (4.1; 5.6) [ab]	**.017 ***
Sleep quality (5-pt verbal)	2.8 (2.4; 3.1) [a]	2.8 (2.5; 3.1) [b]	2.8 (2.4; 3.1) [c]	2.7 (2.4; 3.1)	2.1 (1.8; 2.5) [abc]	**.013 ***
Alertness (KSS, 0-8)	4.2 (3.6; 4.8)	4.1 (3.5; 4.8)	4.1 (3.4; 4.7)	4.2 (3.6; 4.9)	3.8 (3.2; 4.5)	.823
Tired (0) – Rested (10)	5.9 (5.2; 6.6)	5.5 (4.8; 6.3)	5.7 (5.0; 6.4)	5.2 (4.4; 5.9)	4.8 (4.0; 5.5)	.084
Tense (0) – Relaxed (10)	6.3 (5.6; 7.1)	6.2 (5.5; 7.0)	6.3 (5.5; 7.0)	6.3 (5.5; 7)	5.6 (4.8; 6.3)	.324
Irritated (0) – Happy (10)	6.1 (5.4; 6.9)	6.4 (5.7; 7.2) [a]	6.3 (5.6; 7.1)	6.5 (5.7; 7.3) [b]	5.2 (4.5; 6.0) [ab]	**.018 ***
Sleep onset (minutes)	26.2 (19.2; 33.3)	24.8 (17.6; 32.0)	27.4 (20.3; 34.5)	28.4 (21.2; 35.5)	35.2 (28.0; 42.5)	.081
Recalled awakenings (n)	2.3 (1.6; 3.0)	2.6 (1.9; 3.4)	2.3 (1.6; 3.1)	2.8 (2.0; 3.5)	2.6 (1.8; 3.3)	.791
Easy (0) – Difficult (10) to sleep	4.4 (3.5; 5.2) [a]	4.0 (3.2; 4.9) [b]	4.3 (3.5; 5.2) [c]	4.4 (3.5; 5.3) [d]	6.0 (5.1; 6.9) [abcd]	**.008 ***
Slept better (0) – worse (10) than usual	4.7 (4; 5.4) [ab]	5.7 (5.0; 6.4)	5.5 (4.8; 6.1)	5.7 (5.0; 6.4) [a]	6.9 (6.2; 7.6) [b]	**<.001 *****
Deep sleep (0) – Light sleep (10)	4.2 (3.5; 4.9)	4.6 (3.8; 5.3)	4.4 (3.7; 5.2)	4.6 (3.9; 5.3)	5.2 (4.5; 5.9)	.311
Never woke (0) – Woke often (10)	4.8 (4; 5.7)	5.2 (4.3; 6.1)	4.7 (3.8; 5.5)	5.3 (4.5; 6.2)	5.2 (4.3; 6.1)	.751
Sleep disturbance by noise (0-10)	2.0 (1.1; 2.9) [ab]	3.5 (2.5; 4.4)	3.4 (2.5; 4.4)	4.0 (3.0; 4.9) [a]	4.7 (3.8; 5.7) [b]	**<.001 *****
Noise caused poor sleep (5-pt verbal)	0.6 (0.3; 0.9) [a]	1.0 (0.7; 1.4)	0.9 (0.5; 1.2)	1.1 (0.8; 1.5)	1.4 (1.1; 1.8) [a]	**.003 ***
Noise caused awakenings (5-pt verbal)	0.7 (0.3; 1.0)	1.1 (0.7; 1.5)	1.1 (0.7; 1.5)	1.2 (0.9; 1.6)	1.4 (1.0; 1.8)	.033
Noise caused difficulty sleeping (5-pt verbal)	0.7 (0.3; 1.0)	0.7 (0.3; 1.1)	0.8 (0.4; 1.1)	0.8 (0.5; 1.2)	1.1 (0.7; 1.4)	.482
Noise caused tiredness in morning (5-pt verbal)	0.8 (0.4; 1.1)	0.9 (0.5; 1.3)	1.0 (0.7; 1.4)	1.1 (0.7; 1.5)	1.3 (1.0; 1.7)	.124
Positive affect	20.3 (17.9; 22.7)	20.2 (17.8; 22.6)	21.8 (19.4; 24.2)	20.6 (18.2; 23.1)	18.4 (16; 20.8)	.040
Negative affect	13.0 (11.9; 14.1)	12.1 (11.0; 13.3)	12.2 (11.1; 13.3)	12.5 (11.3; 13.6)	13.2 (12.1; 14.3)	.235
Evening questions						
Alertness (KSS, 0-8)	2.6 (2.0; 3.2)	3.2 (2.6; 3.8)	3.5 (2.9; 4.1)	3.3 (2.7; 3.9)	2.9 (2.3; 3.5)	.150
Tired (0) – Rested (10)	3.9 (3.2; 4.6)	4.3 (3.6; 5.0)	4.7 (4.0; 5.4)	4.4 (3.7; 5.1)	3.7 (3.0; 4.3)	.157
Tense (0) – Relaxed (10)	5.6 (4.7; 6.5)	6.5 (5.7; 7.4)	6.1 (5.3; 6.9)	6.2 (5.4; 7.0)	5.9 (5.1; 6.8)	.383
Irritated (0) – Happy (10)	6.1 (5.2; 7.0)	6.8 (5.9; 7.7)	6.5 (5.6; 7.4)	6.7 (5.8; 7.6)	5.9 (5.0; 6.8)	.385
Positive affect	19.1 (16.6; 21.7)	20.0 (17.5; 22.5)	20.3 (17.8; 22.8)	19.1 (16.6; 21.6)	18.3 (15.8; 20.8)	.333
Negative affect	11.9 (11.0; 12.8)	12.0 (11.1; 12.9)	12.8 (11.9; 13.7)	12.7 (11.8; 13.6)	12.7 (11.8; 13.6)	.122

4.2.4. Acute sleep fragmentation

Event-related change in ORP under different exposure conditions are given in Figure 14. The temporal pattern of ORP change is expectedly the same as in the impulsive noise conditions in Study 1. Following noise onset at time 0s, there is an increase in ORP, reflecting upward shifts towards wakefulness and less deep, more unstable sleep. ORP peaks occurred around 30-45s after noise onset, before gradually returning towards pre-noise baseline ORP levels.

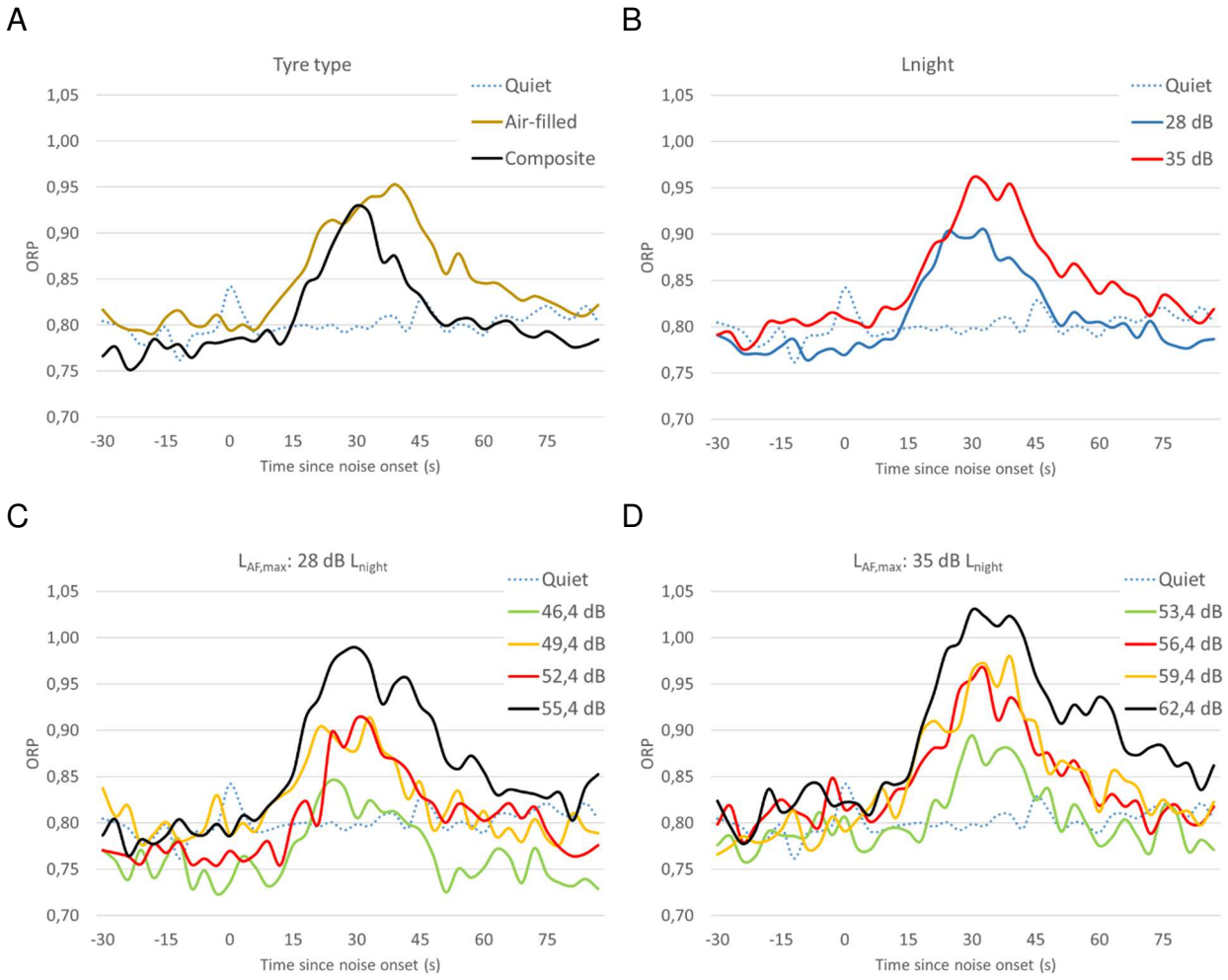

*Figure 14 Event-related change in Odds Ratio Product (ORP). Data are arithmetic means across all subjects and noise events, stratified by type of tyre (panel **A**), L_{night} (panel **B**), and $L_{AF,max}$ (panels **C** and **D**). Data for the Quiet condition are derived from data in the Control night at clock times corresponding to the timing of events in the noise nights.*

The maximum ORP change related to pre-noise baseline was used as one measure of noise-induced sleep fragmentation (see section 3.8.1). There was a statistically significant main effect of exposure condition (p<.0001, Figure 15). There was higher noise-induced fragmentation in all four noise nights compared to the Control (all adjusted post-hoc comparisons p<.0001). None of the four noise nights were significantly different from each other (adjusted p >.05). There was a significant within-night exposure-response effect for the fragmenting effects of noise, with greater disturbance at higher maximum noise levels (p<.0001, Figure 16). Adjusted post-hoc tests indicate that Level rank 3 was significantly higher than Rank 1 (p<.001), and Level rank 4 was significantly higher than Ranks 1, 2 and 3 (all p<.05).

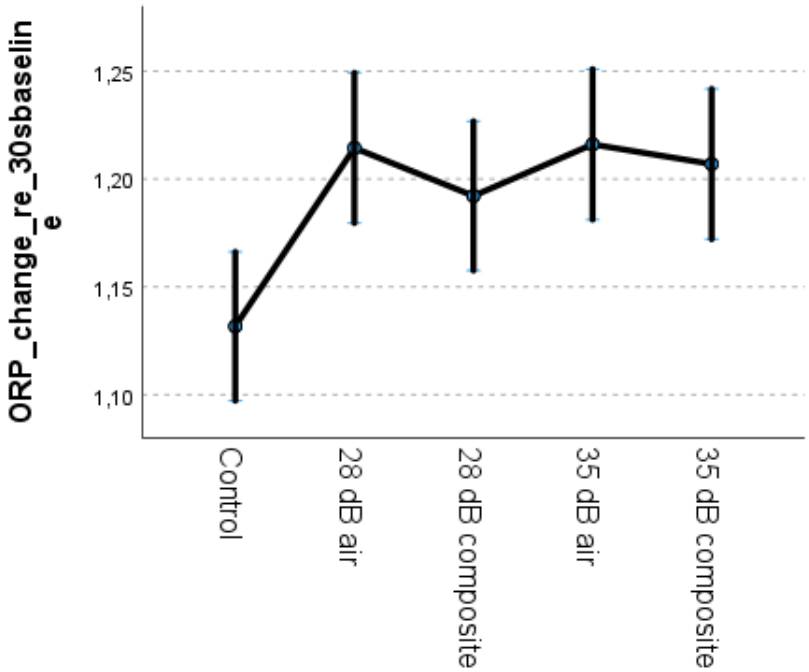

Figure 15 Estimated means for maximum change in ORP during noise pass-by. Data adjusted for $L_{AF,max}$ (rank order 1-4), day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3,98; Event start time=03:00:14; ORP 30s baseline =0.79; ORP at noise onset=0.80. Error bars indicate 95% confidence intervals.

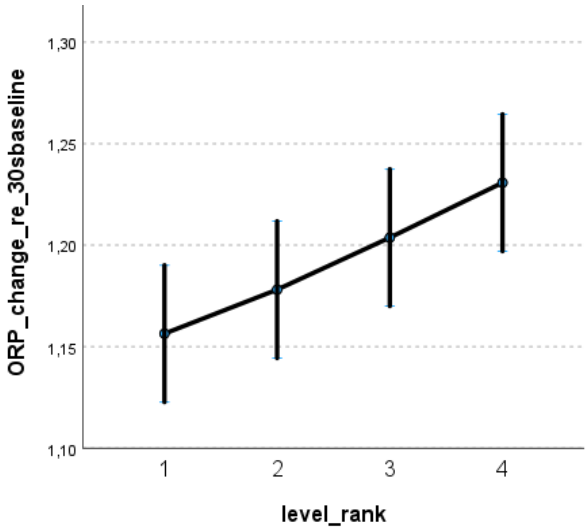

Figure 16 Estimated means for maximum change in ORP during noise pass-by as a function of maximum noise level (rank order). Corresponding maximum levels in the 28 dB L_{night} conditions are 46.4 dB, 49.4 dB, 52.4 dB and 55.4 dB $L_{AF,max}$. Corresponding maximum levels in the 35 dB L_{night} conditions are 53.4 dB, 56.4 dB, 59.4 dB and 62.4 dB $L_{AF,max}$. Data adjusted for noise condition (C/28A/28C/35A/35C), day in study, event start time, ORP baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3,98; Event start time=03:00:14; ORP 30s baseline =0.79; ORP at noise onset=0.80. Error bars indicate 95% confidence intervals.

We further examined the area under the curve, results given in Figure 17. With the 60s AUC window, there was a significant effects of exposure condition. Post-hoc tests indicate that all noise nights had a higher AUC than the Control condition (adjusted p<0.0001 for all comparisons). Furthermore, the AUC was higher during 35dB air-filled noise events than 28 dB composite noise events (adjusted p=.0005). With the 90s AUC window, the same pairwise comparisons are significant as in the 60s window.

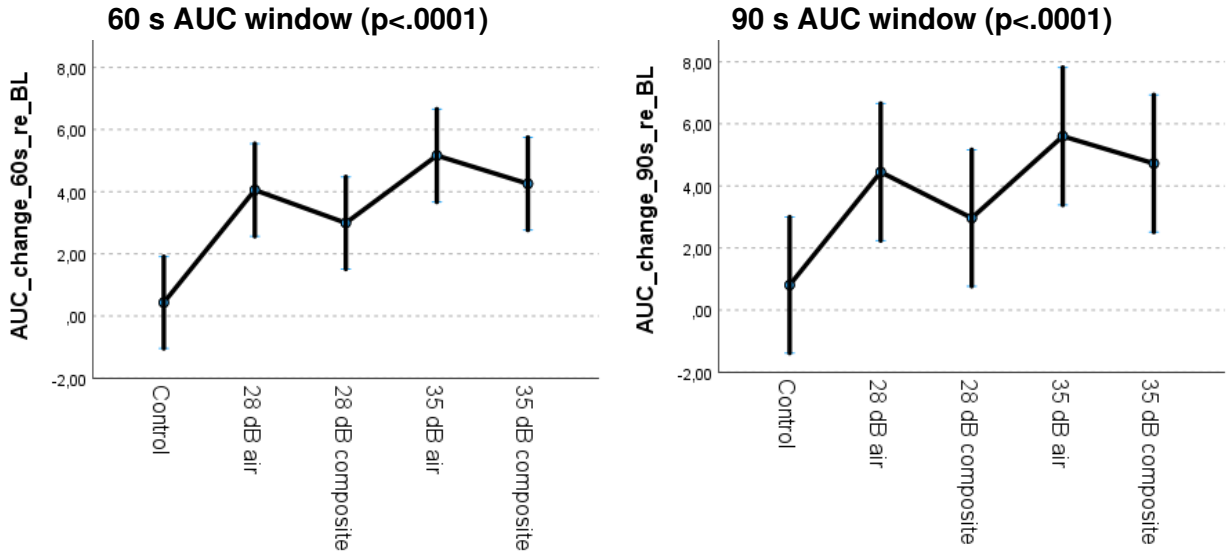

Figure 17 Estimated means for event-related area under the curve, derived with a 60s window (left pane) and 90s window (right pane). Data adjusted for $L_{AF,max}$ (rank order 1-4), day in study, event start time, AUC 30s baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3,98; Event start time=03:00:14; AUC 30s baseline = 2.32. Error bars indicate 95% confidence intervals.

As with maximum change in ORP, there is an evident dose-response relationship between the noise level of an event and the overall increase in AUC (Figure 18). With both 60s and 90s AUC windows, all level ranks are significantly different from all other ranks (all adjusted p<.05).

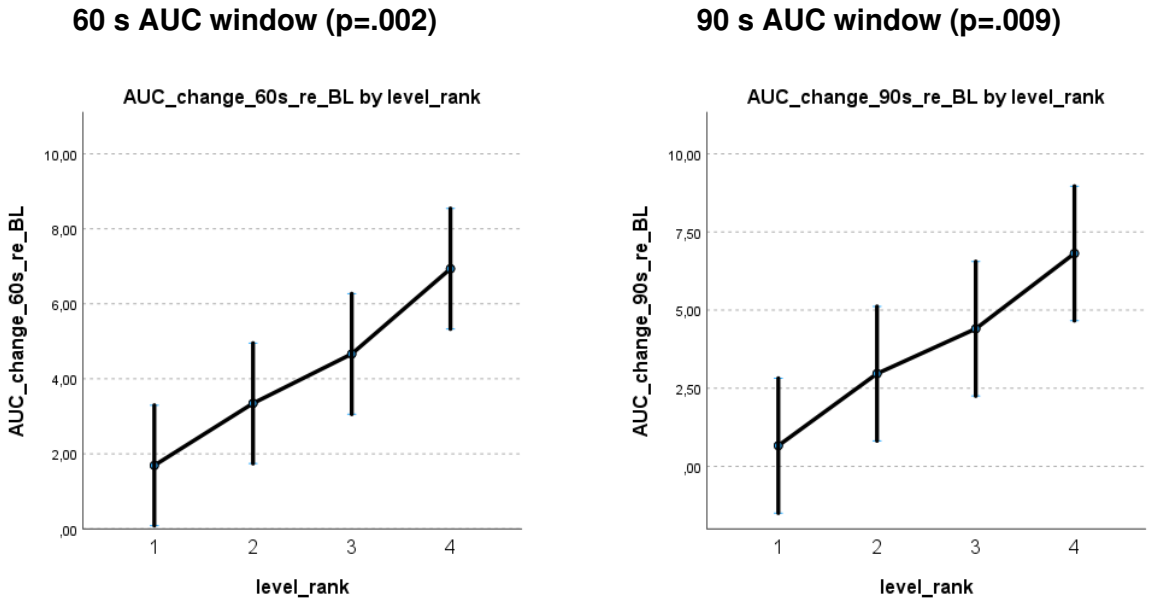

Figure 18 Estimated means for event-related area under the curve, derived with a 60s window (left pane) and 90s window (right pane). Corresponding maximum levels in the 28 dB L_{night} conditions are 46.4 dB, 49.4 dB, 52.4 dB and 55.4 dB $L_{AF,max}$. Corresponding maximum levels in the 35 dB L_{night} conditions are 53.4 dB, 56.4 dB, 59.4 dB and 62.4 dB $L_{AF,max}$. Data adjusted for noise condition (28A/28C/35A/35C), day in study, event start time, ORP AUC 30s baseline, and sex. Continuous predictors are fixed at the following values: Day in study=3,98; Event start time=03:00:14; AUC 30s baseline = 2.32. Error bars indicate 95% confidence intervals.

4.2.5. Overall sleep structure

Whole-night PSG sleep macrostructure data are given in Table 11. After FDR correction for multiple testing, there were no statistically significant associations between noise exposure and sleep macrostructure.

Table 11 Study 2 sleep macrostructure. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects. There were no significant p-values after correction for multiple testing (FDR).

Outcome	Estimated means					P-value
	Control	28 dB Air-filled	28 dB Composite	35 dB Air-filled	35 dB Composite	
Mean ORP Wake	2.02 (1.97; 2.07)	2.00 (1.95; 2.04)	2.00 (1.95; 2.04)	2.00 (1.95; 2.04)	2.01 (1.96; 2.06)	.829
Mean ORP NREM	0.63 (0.58; 0.69)	0.66 (0.60; 0.72)	0.64 (0.58; 0.70)	0.66 (0.60; 0.72)	0.64 (0.58; 0.70)	.540
Mean ORP N1	1.02 (0.96; 1.08)	1.02 (0.96; 1.08)	1.01 (0.94; 1.07)	1.02 (0.96; 1.08)	1.02 (0.95; 1.08)	.916
Mean ORP N2	0.65 (0.58; 0.71)	0.67 (0.61; 0.73)	0.65 (0.59; 0.72)	0.67 (0.61; 0.73)	0.65 (0.59; 0.71)	.533
Mean ORP N3	0.37 (0.33; 0.42)	0.37 (0.32; 0.42)	0.35 (0.30; 0.40)	0.37 (0.32; 0.42)	0.37 (0.32; 0.42)	.841
Mean ORP REM	0.91 (0.82; 1.00)	0.89 (0.80; 0.98)	0.88 (0.79; 0.97)	0.89 (0.80; 0.98)	0.91 (0.82; 1.00)	.239
Mean ORP whole night	0.83 (0.75; 0.90)	0.83 (0.75; 0.90)	0.81 (0.74; 0.89)	0.83 (0.75; 0.90)	0.84 (0.76; 0.91)	.839
Mean ORP Last 2h	0.88 (0.75; 1.00)	0.81 (0.68; 0.93)	0.83 (0.71; 0.95)	0.81 (0.68; 0.93)	0.90 (0.78; 1.03)	.231
Mean ORP NREM, first half	0.23 (0.19; 0.27)	0.22 (0.18; 0.26)	0.22 (0.18; 0.26)	0.22 (0.18; 0.26)	0.23 (0.19; 0.27)	.644
Wake (minutes)	52.8 (41.1; 64.5)	47.1 (35.3; 58.9)	49.5 (37.8; 61.2)	47.1 (35.3; 58.9)	55.6 (43.8; 67.4)	.529
N1 (minutes)	45.5 (37.8; 53.2)	49.2 (41.4; 57.0)	50.8 (43.1; 58.5)	49.2 (41.4; 57.0)	47.6 (39.8; 55.3)	.518
N2 (minutes)	226.3 (215.5; 237.1)	230.8 (219.8; 241.7)	230.8 (220; 241.7)	230.8 (219.8; 241.7)	232.5 (221.6; 243.5)	.554
N3 (minutes)	80.5 (68.8; 92.1)	70.3 (58.6; 82.0)	74.9 (63.3; 86.6)	70.3 (58.6; 82.0)	70.2 (58.5; 81.9)	.029
REM (minutes)	76.6 (64.4; 88.9)	82.7 (70.4; 95.1)	80.8 (68.6; 93.0)	82.7 (70.4; 95.1)	79.4 (67; 91.8)	.791
TST (minutes)	429.0 (417.4; 440.5)	433.1 (421.4; 444.8)	437.4 (425.9; 449)	433.1 (421.4; 444.8)	429.8 (418.1; 441.5)	.597
% Awake	10.9 (8.5; 13.2)	9.8 (7.4; 12.1)	10.1 (7.7; 12.5)	9.8 (7.4; 12.1)	11.4 (9.0; 13.8)	.569
Awakenings (n)	23.8 (19.7; 27.9)	25.5 (21.4; 29.6)	25.1 (21; 29.1)	25.5 (21.4; 29.6)	26.8 (22.8; 30.9)	.478
Arousals (n)	123.1 (109.7; 136.6)	138.6 (125.1; 152.1)	133.8 (120.4; 147.3)	138.6 (125.1; 152.1)	137.3 (123.8; 150.8)	.012
Awakening-arousal index (n/h)	17.3 (15.4; 19.3)	19.4 (17.4; 21.3)	18.4 (16.5; 20.4)	19.4 (17.4; 21.3)	19.3 (17.4; 21.3)	.030
ORP > 1.75 / hr left hemisphere	117.7 (99.4; 135.9)	126.1 (107.8; 144.4)	115.2 (96.9; 133.5)	126.1 (107.8; 144.4)	122.5 (104.2; 140.8)	.198
ORP > 2.0 / hr left hemisphere	87.0 (73.4; 100.6)	92.5 (78.8; 106.1)	84.7 (71.1; 98.4)	92.5 (78.8; 106.1)	90.8 (77.2; 104.5)	.090
ORP > 1.75 / hr right hemisphere	111.1 (91.4; 130.9)	121.6 (101.9; 141.4)	116.2 (96.5; 135.9)	121.6 (101.9; 141.4)	119.1 (99.2; 139.0)	.112
ORP > 2.0 / hr right hemisphere	83.4 (68.3; 98.4)	88.9 (73.9; 104.0)	87.0 (72.0; 102.0)	88.9 (73.9; 104.0)	88.2 (73.0; 103.3)	.240

4.2.6. Cardiovascular arousal

We looked at the number of cardiac arousals. There was a significant main effect (p = .048) for an association between noise exposure condition and the total number of arousals (see Figure 19). Post-hoc testing indicated that the number of cardiac arousals was elevated in the 35 dB air-filled tyre night relative to the quiet Control night (adjusted p = .045).

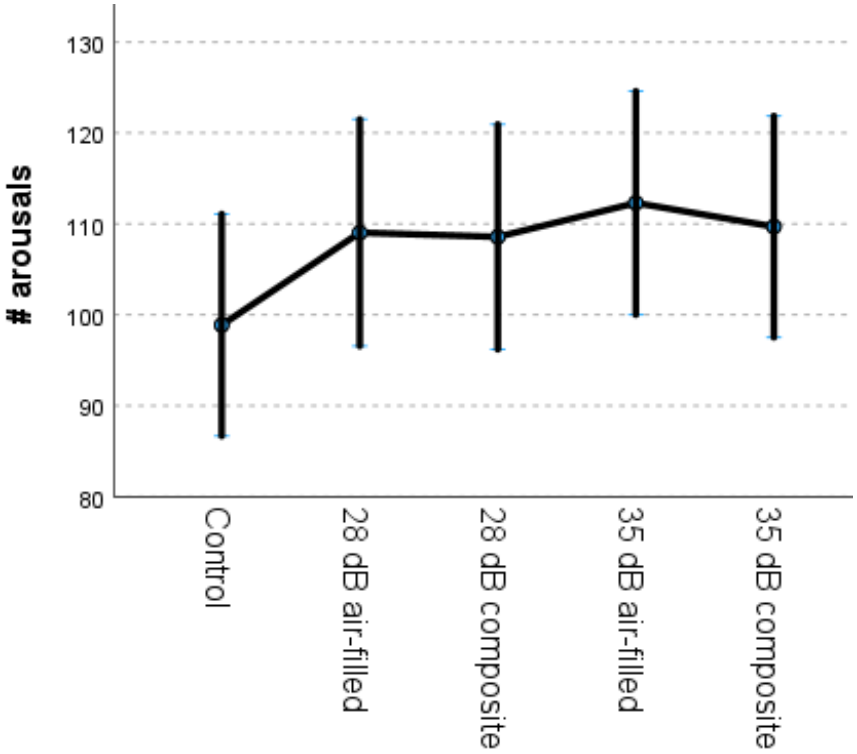

Figure 19 Cardiac arousals in Study 2. Error bars indicate 95% confidence intervals.

4.2.7. Cognitive function

Results of cognitive tests are given for the morning test administrations in Table 12 and for the evening test administrations in Table 13. In the morning tests results, the association between exposure condition and VOLT speed did not survive correction for multiple testing. There were no statistically significant effects for associations between noise exposure during the prior night and accuracy or speed in any of the cognitive domains assessed, either in the morning or in the following evening.

Table 12 Study 2 morning Cognition results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects.

Variable	Estimated means (z-score)					
	Control	28 dB Air-filled	28 dB Composite	35 dB Air-filled	35 dB Composite	P-value
MP speed	-0.14 (-0.51; 0.23)	-0.14 (-0.52; 0.24)	0.07 (-0.31; 0.44)	-0.09 (-0.46; 0.29)	-0.26 (-0.64; 0.12)	.231
MP accuracy	-0.16 (-0.52; 0.20)	-0.15 (-0.53; 0.22)	0.0 (-0.37; 0.37)	-0.30 (-0.66; 0.07)	-0.02 (-0.39; 0.35)	.723
VOLT speed	-0.37 (-0.74; 0.0)	-0.06 (-0.44; 0.32)	-0.05 (-0.42; 0.33)	0.04 (-0.34; 0.41)	0.19 (-0.19; 0.57)	.020
VOLT accuracy	0.03 (-0.34; 0.41)	-0.09 (-0.47; 0.29)	0.06 (-0.32; 0.43)	0.14 (-0.24; 0.51)	0.10 (-0.27; 0.48)	.678
NBCK speed	-0.35 (-0.69; -0.01)	-0.14 (-0.49; 0.21)	0.0 (-0.34; 0.35)	-0.09 (-0.43; 0.26)	-0.06 (-0.41; 0.29)	.229
NBCK accuracy	-0.08 (-0.45; 0.28)	0.03 (-0.34; 0.40)	0.09 (-0.28; 0.46)	0.01 (-0.36; 0.38)	0.17 (-0.21; 0.54)	.679
AM speed	0.01 (-0.37; 0.39)	-0.21 (-0.59; 0.18)	-0.06 (-0.44; 0.32)	0.0 (-0.38; 0.38)	-0.28 (-0.67; 0.10)	.304
AM accuracy	-0.01 (-0.38; 0.37)	0.04 (-0.34; 0.42)	0.11 (-0.26; 0.49)	0.05 (-0.33; 0.42)	-0.02 (-0.40; 0.36)	.945
LOT speed	-0.16 (-0.53; 0.21)	-0.05 (-0.43; 0.32)	-0.04 (-0.41; 0.34)	-0.02 (-0.39; 0.35)	0.0 (-0.37; 0.38)	.909
LOT accuracy	-0.05 (-0.40; 0.31)	0.07 (-0.30; 0.44)	0.04 (-0.32; 0.40)	0.03 (-0.33; 0.39)	0.12 (-0.25; 0.49)	.969
ERT speed	-0.21 (-0.57; 0.15)	-0.18 (-0.55; 0.19)	-0.17 (-0.54; 0.19)	-0.11 (-0.48; 0.25)	-0.12 (-0.49; 0.25)	.967
ERT accuracy	0.11 (-0.26; 0.47)	0.17 (-0.20; 0.55)	0.22 (-0.15; 0.59)	-0.09 (-0.46; 0.28)	0.25 (-0.13; 0.62)	.621
MRT speed	-0.28 (-0.62; 0.06)	-0.09 (-0.43; 0.26)	-0.04 (-0.38; 0.30)	0.09 (-0.26; 0.43)	0.10 (-0.24; 0.45)	.064
MRT accuracy	0.23 (-0.13; 0.58)	0.16 (-0.21; 0.52)	0.13 (-0.23; 0.49)	-0.03 (-0.39; 0.33)	-0.18 (-0.55; 0.18)	.332
DSST speed	-0.17 (-0.53; 0.19)	-0.09 (-0.45; 0.28)	0.08 (-0.29; 0.44)	-0.22 (-0.58; 0.15)	-0.02 (-0.39; 0.34)	.137
DSST accuracy	-0.10 (-0.46; 0.26)	-0.13 (-0.50; 0.24)	0.05 (-0.32; 0.41)	-0.11 (-0.48; 0.25)	-0.01 (-0.38; 0.36)	.884
BART speed	-0.04 (-0.40; 0.32)	-0.10 (-0.47; 0.26)	-0.02 (-0.38; 0.34)	0.06 (-0.30; 0.43)	0.0 (-0.36; 0.37)	.881
BART risk score	0.04 (-0.31; 0.39)	0.22 (-0.14; 0.58)	0.06 (-0.30; 0.41)	-0.18 (-0.53; 0.18)	-0.37 (-0.73; -0.01)	.064
PVT speed	-0.11 (-0.43; 0.21)	0.01 (-0.32; 0.33)	-0.27 (-0.60; 0.05)	-0.18 (-0.50; 0.14)	-0.20 (-0.53; 0.12)	.267
PVT accuracy	-0.07 (-0.39; 0.24)	0.09 (-0.23; 0.42)	-0.17 (-0.49; 0.15)	-0.11 (-0.43; 0.21)	-0.08 (-0.40; 0.25)	.509
Overall speed	-0.18 (-0.37; 0.01)	-0.10 (-0.30; 0.09)	-0.05 (-0.24; 0.15)	-0.05 (-0.24; 0.14)	-0.06 (-0.26; 0.13)	.171
Overall accuracy	-0.01 (-0.18; 0.16)	0.02 (-0.16; 0.19)	0.06 (-0.12; 0.23)	-0.05 (-0.22; 0.13)	0.03 (-0.14; 0.21)	.689

Table 13 Study 2 evening Cognition results. Data shown are Estimated Means (95% CI) from GLMMs, adjusted for sex and day in study. P-values are Type III main effects.

Variable	Estimated means (z-score)					P-value
	Control (95% CI)	28 dB Air-filled	28 dB Composite	35 dB Air-filled	35 dB Composite	
MP speed	0.01 (-0.39; 0.41)	0.05 (-0.35; 0.44)	0.17 (-0.23; 0.56)	0.38 (-0.02; 0.77)	0.19 (-0.20; 0.59)	.430
MP accuracy	0.20 (-0.21; 0.61)	0.30 (-0.11; 0.70)	-0.05 (-0.45; 0.35)	0.17 (-0.23; 0.57)	0.26 (-0.14; 0.67)	.685
VOLT speed	0.29 (-0.04; 0.62)	0.17 (-0.16; 0.50)	0.15 (-0.18; 0.48)	0.33 (0.0; 0.66)	0.16 (-0.17; 0.48)	.520
VOLT accuracy	-0.01 (-0.40; 0.39)	0.07 (-0.32; 0.46)	0.19 (-0.20; 0.58)	0.27 (-0.12; 0.66)	-0.06 (-0.46; 0.33)	.562
NBCK speed	0.20 (-0.19; 0.58)	0.22 (-0.16; 0.60)	0.3 (-0.09; 0.68)	0.32 (-0.06; 0.70)	0.35 (-0.03; 0.74)	.885
NBCK accuracy	-0.01 (-0.38; 0.36)	0.06 (-0.31; 0.42)	0.19 (-0.17; 0.56)	0.31 (-0.05; 0.68)	0.15 (-0.21; 0.52)	.501
AM speed	0.09 (-0.26; 0.44)	0.03 (-0.32; 0.38)	0.16 (-0.18; 0.51)	0.17 (-0.18; 0.51)	0.15 (-0.19; 0.50)	.815
AM accuracy	0.12 (-0.26; 0.51)	-0.10 (-0.48; 0.28)	0.11 (-0.27; 0.49)	0.04 (-0.34; 0.41)	-0.16 (-0.54; 0.22)	.447
LOT speed	0.25 (-0.08; 0.58)	0.47 (0.15; 0.80)	0.21 (-0.12; 0.54)	0.20 (-0.13; 0.52)	0.42 (0.09; 0.75)	.256
LOT accuracy	-0.08 (-0.50; 0.35)	0.05 (-0.36; 0.46)	0.11 (-0.30; 0.52)	0.10 (-0.31; 0.51)	-0.11 (-0.53; 0.30)	.891
ERT speed	-0.04 (-0.42; 0.34)	0.0 (-0.38; 0.38)	0.05 (-0.33; 0.42)	0.15 (-0.23; 0.52)	0.20 (-0.18; 0.57)	.504
ERT accuracy	-0.17 (-0.60; 0.25)	0.06 (-0.35; 0.48)	-0.05 (-0.46; 0.37)	-0.21 (-0.62; 0.21)	-0.26 (-0.68; 0.15)	.720
MRT speed	-0.07 (-0.48; 0.34)	0.15 (-0.25; 0.56)	-0.19 (-0.60; 0.22)	0.08 (-0.33; 0.48)	0.17 (-0.24; 0.58)	.243
MRT accuracy	0.09 (-0.35; 0.53)	-0.16 (-0.59; 0.27)	-0.10 (-0.53; 0.34)	-0.04 (-0.47; 0.39)	-0.08 (-0.51; 0.35)	.913
DSST speed	0.23 (-0.12; 0.58)	0.31 (-0.04; 0.66)	0.18 (-0.17; 0.53)	0.14 (-0.21; 0.49)	0.36 (0.0; 0.71)	.163
DSST accuracy	0.15 (-0.28; 0.58)	0.09 (-0.34; 0.51)	-0.24 (-0.66; 0.18)	-0.31 (-0.73; 0.11)	0.09 (-0.33; 0.52)	.335
BART speed	0.07 (-0.28; 0.42)	0.26 (-0.09; 0.61)	0.14 (-0.20; 0.49)	0.18 (-0.16; 0.53)	0.06 (-0.28; 0.41)	.664
BART risk score	0.14 (-0.22; 0.50)	0.04 (-0.31; 0.40)	0.06 (-0.30; 0.41)	-0.02 (-0.38; 0.33)	-0.04 (-0.39; 0.32)	.891
PVT speed	0.25 (-0.07; 0.58)	0.25 (-0.08; 0.57)	0.51 (0.19; 0.83)	0.28 (-0.04; 0.60)	0.40 (0.08; 0.72)	.175
PVT accuracy	0.13 (-0.11; 0.37)	0.25 (0.02; 0.49)	0.38 (0.14; 0.62)	0.11 (-0.12; 0.35)	0.17 (-0.07; 0.41)	.086
Overall speed	0.13 (-0.06; 0.31)	0.19 (0.01; 0.38)	0.17 (-0.01; 0.35)	0.22 (0.03; 0.40)	0.25 (0.06; 0.43)	.378
Overall accuracy	0.06 (-0.11; 0.23)	0.06 (-0.11; 0.23)	0.06 (-0.11; 0.23)	0.04 (-0.13; 0.21)	0.0 (-0.17; 0.17)	.926

4.2.8. Blood biomarkers

Different metabolites have widely different ranges of concentrations. Therefore concentrations were standardised (z-transformed) to allow comparison of the effect of noise exposure between different metabolites. Results are given in Figure 20 as differences in concentration relative to data from the Control morning. There were increases of ≥0.2, indicating at least a small effect size,[57] in concentrations of 22 (88%) circulating metabolites after the 35 dB air-filled tyre noise night. The effect sizes of other metabolites, including across all three other noise exposure conditions, were <0.2 indicating negligible effects.

Metabolite	Exposure condition (re: Control)			
	28A	28C	35A	35C
L-α-aminoadipic acid *	-.17	-.10	.44	-.16
L-α-amino-n-butyric acid	-.18	.01	.23	-.06
L-Alanine	-.06	-.13	.24	-.05
L-Arginine	-.06	-.11	.28	-.11
L-asparagine	-.12	-.03	.28	-.13
L-aspartic acid *	.07	-.17	.25	-.14
D,L-β-aminoisobutyric acid	-.18	-.04	.26	-.04
L-Citrulline	-.10	-.05	.26	-.11
L-glutamine	-.18	-.03	.26	-.05
L-glutamic acid	-.11	-.09	.28	-.08
Glycine	-.16	-.09	.32	-.06
Hydroxy-L-proline	-.17	.02	.12	.03
Isoleucine	-.14	.00	.25	-.11
Leucine	-.04	-.02	.25	-.19
Methionine	-.14	-.06	.32	-.11
Ornithine	-.17	-.08	.31	-.06
O-phosphoethanolamine	.00	-.19	.29	-.10
Phenylalanine	-.17	-.05	.37	-.15
Proline	-.04	-.04	.11	-.02
Serine	-.15	-.06	.28	-.07
Taurine	-.15	-.13	.30	-.01
Threonine	-.12	.01	.18	-.07
Tryptophan	-.16	-.06	.27	-.05
Tyrosine	-.06	-.15	.33	-.11
Valine	-.17	.02	.30	-.15

Scale (z-score) -.50 0 +.50

Figure 20 Heatmap of differences in metabolite concentrations (z-scored) relative to Control morning in Study B. 28A: 28 dB air-filled tyres; 28C: 28 dB composite tyres; 35A: 35 dB air-filled tyres; 35C: 35 dB composite tyres.

Statistical testing indicating that there were main effects of exposure condition for L-α-aminoadipic acid (p=.012) and L-aspartic acid (p=.044). However, these do not survive FDR correction for multiple testing. There were also borderline effects for ornithine (p=.061), phenylalanine (p=.071), and tyrosine (p=.062).

Exploratory post-hoc analyses of the significant (pre-adjustment) results indicate elevated levels of L-α-aminoadipic acid after the 35 dB air-filled night relative to the 28 dB composite tyre night (adjusted p=.025) and 35 dB composite tyre night (adjusted p=.034). Analysis also shows elevations of L-aspartic acid after the 35 dB air-filled night relative to the 28 dB composite tyre night (adjusted p=.046). No other post-hoc comparisons were significant after p-value adjustment.

4.2.9. Study 2 discussion

All tyre noise conditions induced event-related physiological sleep fragmentation. There were no significant effects on overall sleep macrostructure or cognitive function in the morning or the following evening. Multiple self-reported outcomes were adversely impacted by noise exposure, particularly during the 35 dB composite tyre noise night compared to the quiet Control night. Conversely, there were elevations in most circulating metabolites after the 35 dB air-filled tyre noise night, although these did not survive correction for multiple hypothesis testing.

In terms of event-related analysis, the 35 dB air-filled tyres induced the strongest sleep disturbance, indicated by higher AUC. There were also more cardiovascular arousals in this night than in the Control. Particularly noteworthy is that the AUC response was higher during 35 dB air-filled noise events than 28 dB composite noise events. This indicates that the combination of a reduction in level and change in acoustical character resulting from a shift to composite tyres may mitigate acute physiological sleep fragmentation.

The blood biomarker data further suggest that the stronger acute sleep fragmentation by air-filled tyres led to downstream perturbations in metabolic function. Elevated levels of α-aminoadipic acid, as seen after the 35 dB air-filled noise night (albeit the main effect was not significant after multiple testing adjustment) are associated with reduced levels of high-density lipoprotein cholesterol and increased risk for type 2 diabetes and atherosclerosis.[58] L-Aspartic acid is involved in glycolysis and ammonia detoxification in astrocytes,[59] and has been associated with decreases in insulin secretion and insulin sensitivity, and with increased diabetes risk.[60] Thus a shift to composite tyres could potentially benefit the cardiometabolic health of populations chronically exposed to road traffic noise.

Interestingly, the physiological data are not in complete agreement with the questionnaire data. Although both objective and subjective sleep data indicate greatest disturbance at the highest level (as expected), questionnaire data is suggestive that composite tyre noise was more disturbing than air-filled tyres. This could be due to differences in the frequency spectra of the two tyres types. Although the differences are subtle, it is possible that either the differences in spectra per se led to differential subjective response, or alternatively that the novel composite tyres were perceived as more unfamiliar. . However, the sound

pressure levels of the composite tyres were artificially high in the 35 dB L_{night} condition. The level reduction arising from a shift to composite tyres more than offsets a differential subjective disturbance.

It is worth noting that even though subjective sleep disturbance by noise was worse in the 35 dB noise nights, the point estimates of the effects are not necessarily indicative that sleep was highly disrupted universally. Typically, only a value of 8 or above on a 0-10 scale is taken to mean “highly sleep disturbed”. Three subjects (11%) gave a rating of 8 or above in the 35 dB composite tyre noise night, and only one subject (3%) gave a rating of 8 or above for 35 dB air-filled tyre noise. These data are in alignment with data from epidemiological studies, especially for the composite tyre noise condition; 35 dB corresponds to 60 dB L_{night} outdoors, and a recent meta-analysis showed that 11% of respondents are highly sleep disturbed by road noise at this outdoor level.[61] This suggests that self-reported data from the sleep studies may be broadly generalisable to the wider population, despite the laboratory setting and homogenous study sample.

In summary, a combination of both a ~7dB level reduction and change in acoustical character that are envisaged by a shift to composite tyres would therefore seem to lead to a reduction in noise-induced disturbance by road traffic.

5. Overall discussion

We observed clear event-related effects but only limited effects on overall sleep macrostructure. This is in alignment with multiple previous studies, which have found that acute alterations of sleep structure by discrete traffic noise events, including awakenings, arousals and changes of sleep stage, often occur without subsequent changes in overall sleep across the night.[62-66] This may be because there was sufficiently long time between the individual noise events for compensatory sleep to occur,[67] hence the whole-night averages would not reflect the acute noise-induced sleep fragmentation. Nevertheless, acute sleep fragmentation seems to interfere with the restorative and endogenous processes that occur during sleep. This is indicated by increased subjective disturbance and lower perceived sleep quality, and possibly also biomarkers of cardiometabolic function. Acute changes in sleep should therefore, as much as possible, be considered when evaluating the public health impact of traffic noise.

Intermittent traffic noise was generally found to be more disturbing than continuous noise of the same equivalent night-time level. This can be considered relevant because intermittent traffic is more representative of usual real world night-time traffic flow. Furthermore, intermittent noise involves exposure to single noise events during an otherwise quiet night, which, as discussed above, can lead to acute effects on sleep with downstream biological and psychological consequences. It could therefore be beneficial to consider noise metrics that capture the character of traffic flow and/or single events, such as the number of vehicles pass-bys, intermittency ratio,[68] and measures of maximum level such as $L_{AF,max}$.

The sample sizes of N=15 and N=30 for Studies 1 and 2 respectively, while rather large for experimental sleep studies (for Study 2 especially), limit the statistical power to detect significant results. By adjusting for multiple testing with both Type III main effects and also post-hoc pairwise tests despite possible power issues, we have adopted a conservative statistical approach. As a result, we may miss small but clinically relevant results. Nevertheless, the fact that we find multiple significant outcomes across a range of biological and psychological domains, despite this conservative approach, provides weight to the argument that these results reflect true effects and are unlikely chance findings.

There are known dose-response relationship between the sound pressure level of single traffic noise events and cortical and autonomic arousal,[50,69] and between average night-time levels and the likelihood of reporting high levels of sleep disturbance.[61] Composite tyres, if successful in their design, could reduce self-reported and physiological sleep disturbance and cardiovascular response by way of their much reduced sound pressure level.

We have only considered short-term response, over a one week period per study subject. It remains unclear how these short-term physiological changes translate to risk for cardiometabolic diseases and disorders in the long term. To answer this questions, longitudinal cohort studies over an extended period are needed. Nevertheless, many of the short-term responses investigated are considered to be risk factors for health. Repeated cardiovascular arousal may reflect increased sympathetic activity and/or reduced parasympathetic activity, which has been suggested to be important in the long term for the development of cardiovascular disease.[28] Elevations of metabolite concentrations could indicate disturbance of metabolic function, which has important implications for increased cardiometabolic disease risk.[70-72] Fragmented sleep has been associated with insulin resistance, diabetes and hypertension,[73,74] although underlying pathophysiology remains poorly understood. It could be that it is metabolic consequences of disrupted sleep, rather than sleep disturbance *per se*, influencing the disease risk.

5.1. Limitations

Study participants were young and had normal good sleep. This needs to be kept in mind when considering the representativeness of the results in the wider population. The study sample may on the one hand represent a population particularly resilient to external influences on sleep, who may have reacted less strongly to the noise exposure than individuals of different ages or with pre-existing sleep problems. Conversely, populations exposed to noise at home may partially habituate over time, having fewer arousals, awakenings and sleep stage changes,[75] or may become accustomed to physiologically poor sleep and consequently upwardly adjust their perceived sleep quality,[76] and may be less affected than the group in the present study. It is likely however that the study population were resilient sleepers, which could partially explain the absence of effects of sleep macrostructure and cognitive function.

Due to the nature of the exposure, i.e. tyre noise that the participants would perceive once playback started, it was not possible to fully blind the participants to the experimental conditions. We cannot exclude that this may have influenced the outcomes, particularly for the self-reported measures.

6. Conclusion

Intermittent/impulsive traffic flow was generally more disturbing for sleep than continuous traffic flow of the same noise level. The data for this conclusion were however suggestive rather than conclusive, perhaps due to limited statistical power in Study 1.

Single tyre noise events induced acute physiological sleep fragmentation. These acute responses only translated into changes in overall sleep macrostructure at high average noise levels (40 dB L_{night} in the bedroom). Even in the absence of changes in sleep macrostructure, there was some limited evidence for downstream changes in metabolic function following acute physiological sleep fragmentation.

A shift to composite tyres could lead to reduced physiological sleep fragmentation and reduced cardiovascular arousal. This is primarily due to a 7 dB reduction in level.

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9. Appendices

9.1. Appendix A: Annex: Results on perceptual and physiological response to selected tyre sound stimuli

Research and Innovation action

NUMBER — 955387 — LEON-T

LEON-T

Low particle Emissions and lOw Noise Tyres

Deliverable No.	D4.3 Annex A	
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Revision history

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
		First complete version of the deliverable Annex	Thibaut Marin-Cudraz and Etienne Parizet (INSA)

A1 Executive summary

This annex presents the third set of listening test experiments conducted at INSA Lyon. The goal of these experiments was to study the relationship between self-assessed short-term noise annoyance and fatigue and the physiological response to different sound parameters of tyre noises, as previously identified (see D4.2). The results can also be compared with the results of experiments on noise effects on sleep conducted at UGOT.

In a previous experiment (cf. deliverable D4-2), participants were asked to assess the unpleasantness of sounds. They were placed in an active listening situation - their attention was entirely focused on the sounds. In the experiment described below, the focus was on annoyance. This means that the participants had to perform a task with their attention not focused on the sounds (passive listening situation). The exposure was longer (10 minutes for each sound condition). At the end of each condition, the participants were asked to evaluate whether the noise had disturbed them in their task. We chose a simple and relaxing task (reading a magazine, playing crossword puzzles, etc.) to represent the situation experienced by someone living near a traffic lane experience.

Four different artificial traffic exposure conditions were synthesised from the artificial tyre pass-by noises used in D4.2 at a given speed of 70 km/h. The traffic flow was based on public data taken from the flow of vehicles in the ring road of Paris at night. Each condition was a combination of two values of tonality and sound pressure level. We focused our attention on these parameters as previous experiments showed that they could explain the unpleasantness evaluations given by participants (see D4.2).

Sounds were then filtered in order to simulate the isolation of a typical building façade (the filtering characteristics are the same as those mentioned in D4.2). Filtered sounds were presented to two groups of 24 listeners (two age groups: below 31 years and over 40 years) in a relaxing situation (e.g. reading, or doing crosswords or sudoku). Participants wore a medical grade wristband that recorded some physiological data (heart rate, skin conductance and body temperature). At the end of each traffic noise exposure, the participants had to assess their perceived annoyance and their fatigue level.

Data were analysed in random intercept linear mixed models (random subject effect) adjusted for age, noise sensitivity and order of presentation of the stimuli in the study. The results showed that short-time exposure to traffic noise based on tyre noises only affected the self-assessed parameters while having no physiological effects on the participants, with a prominent effect of the tonality.

Parallels will be drawn with the rest of the deliverable (UGOT sleep experiment) and the results will provide a comparison between several ways to evaluate annoyance.

A2 – Synthesis of traffic noise

A2.1 – Selected psychoacoustics parameters used to synthesise the sounds

Based on results presented in D4.2, we decided to focus mainly on sound pressure level and tonality (amplitude of an emerging tone) as these two sound parameters had a major influence on unpleasantness. The minimum and maximum values of each parameter were selected so as to maximize the difference between the four traffic conditions (Tab.A1).

Tonality factor	Level (L_{eq})
0	40 dB(A)
0.5	52 dB(A)

Table A1: Summary of the different parameters and their different values

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A2.2 – Generating the traffic flow

We aggregated real traffic flow data from the open data of Paris ring road [1] to imitate a real night-time traffic. The data were available from October 2021 to June 2022. We filtered the daily traffic data between 10 pm and midnight. We could then have access to the duration between two passing vehicles. To simulate a dense traffic, we only took the periods between two vehicles with values superior or equal to the third quartile of the distribution (q75). The resulting dataset could be modelled as a log-normal distribution with the following parameters: $\mu = e^{1.66}$ and $\sigma = e^{0.49}$ using the R language 4.1.2 [2] and the *fitdistrplus* library [3]. This distribution was chosen from several other types of distribution as it presented the best goodness-of-fit statistics and criterion values (Tab.A2). Figure A1 represents the actual distribution and its representation.

Goodness-of-fit	Gamma	Normal	Log-Normal	Weibull

Kolmogorov-Smirnov	0.044	0.065	0.074	0.045
Cramer-von Mises	0.88	1.91	2.73	0.76
Anderson-Darling	6.86	12.70	18.12	5.28
AIC (Akaike's Information Criterion)	9085.84	9155.67	9234.24	9040.21
BIC (Bayesian Information Criterion)	9096.99	9166.82	9245.39	9051.37

Table A2: Goodness-of-fit comparison of the gamma, normal, log-normal and Weibull distributions. Three goodness-of-fit statistics (Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling) and two criteria (AIC and BIC) were used to evaluate the distribution best fitting the traffic flow data.

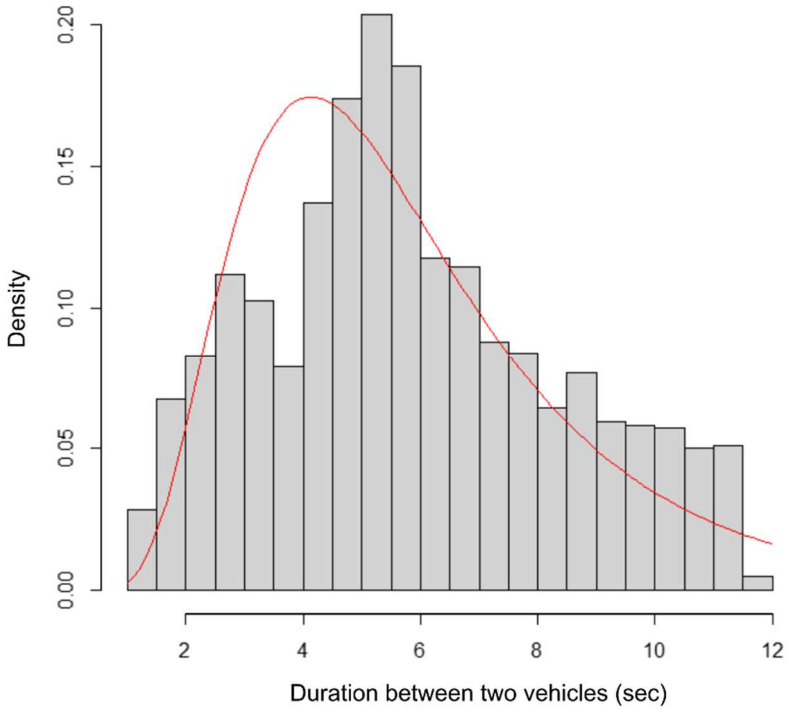

Figure A1: Representation of the real (histogram) and fitted (red curve) distribution of the periods between two vehicles passing by in the Paris ring road during the night.

This theorical distribution allowed to generate automatically the synthetic traffic noises. For each value of level and tonality, we generated artificial tyre noises to imitate the pass-by noise of vehicles using the same process as described in D4.2. Each individual pass-by lasted 17 s. For conditions corresponding to non-null tonality, the fundamental frequency of the tone was randomly selected between 300 Hz and 500Hz to avoid the same exact tones. The interval between each passing noise was randomly generated using the theorical distribution to imitate real traffic flow.

Thus, four sound sequences were synthesised, in a complete experimental design (2 factors at 2 levels). The duration of each sequence was 10 minutes.

A3 – Material and methods of the psychoacoustic experiment

A3.1 – Participants

48 participants were recruited, in two groups:

- the '20-31' age class was composed of 24 students between 20 and 31 years old (Mean +/- SD: 22.25 +/- 2.71 years, 11 women, 13 men) recruited at INSA Lyon (Mechanical Engineering department);
- the '40+' age class was composed of 24 participants between 41 and 60 years old (Mean +/- SD: 50.0 +/- 6.2 years, 20 women, 4 men) recruited by an external company.

During the recruitment phase, participants were informed that they should to stay in a relaxing activity during the experiment and that they could bring with them a book, a magazine or a relaxing game (sudoku or crosswords).

The hearing threshold of each participant was measured using a computer (Dell optiplex 9020), the Eolys Piston XP software, and 3M PELTOR Optime II headphones, in the sound proof booth of the Laboratoire Vibrations Acoustique at INSA Lyon (see deliverable D4.1 for a photo of the booth). The threshold was measured according to the ISO 8253-1:1989 standard (tonal audiometry, 7 frequencies between 125 and 8000 Hz) and showed that all participants had normal hearing (i.e. their hearing threshold was below 20 dB HL at all tested frequencies).

A3.2 – Listening test procedure

The experiment took place at the LVA soundproof booth (Fig.A2). It used a DELL computer, linked to an USB audio interface (Echo Gina) and loudspeakers (Focal Alpha 50). The experimental setup was calibrated beforehand, with a calibration microphone (PCB Piezotronics 378B02) linked to an OROS OR38 system, so that the levels of the displayed noises corresponded to the one chosen when designing the sounds.

A chair (model Pello from Ikea) was placed approximately 2 meters from the loudspeakers.

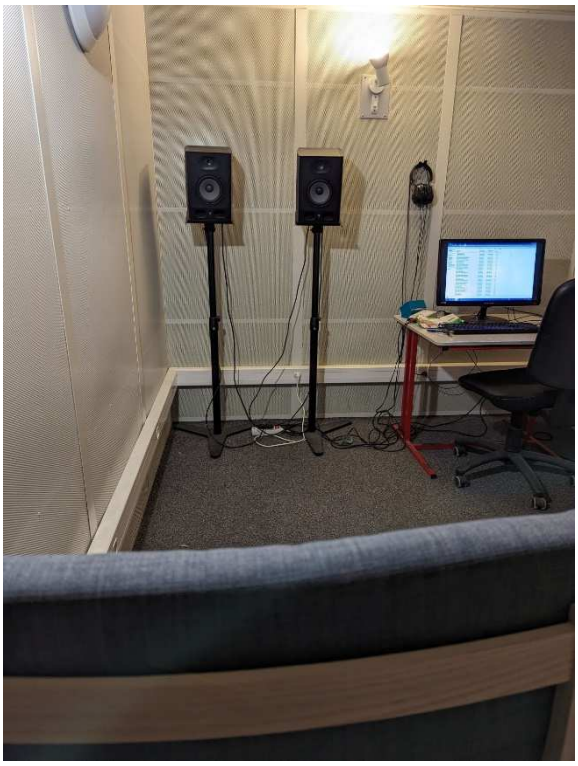

Figure A2: Photo of the experimental room, with the chair in the foreground, the loudspeakers on the left of the background and the computer on the right.

The experiment used an interface made in-house (using Python [4] and tKinter [5]). On arrival, the participant was asked a few questions in order to get general information which can be related to the upcoming physiological measurements: the time since the last caffeinated drink (coffee or tea), since the last physically demanding activity and whether he or she had any known cardiovascular disease. Then the participant answered the NoiSeQ-R questionnaire [6], composed of 12 questions about noise tolerance at work, at home and during sleep. This gives a global noise sensitivity score between 0 (not sensitive) and 3 (very sensitive). Then, the French Canadian MFI20 questionnaire [7] was used to evaluate the initial level of fatigue of the participant. This questionnaire is composed of 15 sentences related to different kinds of fatigue. The participant had to give his/her level of agreement to 15 statements using a 7-point scale: ranging from 1 (totally disagree) to 7 (totally agree) for different context: general/physical fatigue, reduced activity, reduced motivation and mental fatigue. The global fatigue score is obtained by summing up all scores corresponding to the statements of each context. The higher the score, the higher the self-assessed fatigue.

In a next step, the participant was asked to sit in a chair and to relax for 15 minutes. Several magazines were made available to the participant, who could read one of them (or some other book he or she had brought), or play to some quiet game (e.g. sudoku or crosswords). This took place in silence. After 15 minutes, the participant was asked to fill again the MFI questionnaire – this represented the *baseline* condition. He or she was also asked to evaluate the noise annoyance (even if the condition was silent). The same

graphical interface developed for D4.2 was used: answers were given by moving a slider on a continuous scale from 0 ('not at all annoying') to 1000 ('extremely annoying').

The next stage of the experiment consisted of repeating 5 phases which were organized in random order. Each phase consisted of the following steps (Fig. A3):

- the first 2 minutes were silent, designed to put the participant in a relaxing situation; he or she resumed the relaxing activity (reading, or playing cross-words or sudoku);
- the next 5 minutes were also silent. In the meantime, reference values of some physiological parameters were recorded by a medical grade wristband (Empatica E4, see Tab.2 in section A5 for a complete list of the physiological parameters);
- during the next 10 minutes, the loudspeakers could play one of the four traffic conditions (or stay silent), while the participant continued the relaxing activity;
- after this exposure phase, the participant had to go back to the computer and evaluate the annoyance caused by the noise situation. The participant then completed the fatigue questionnaire again.

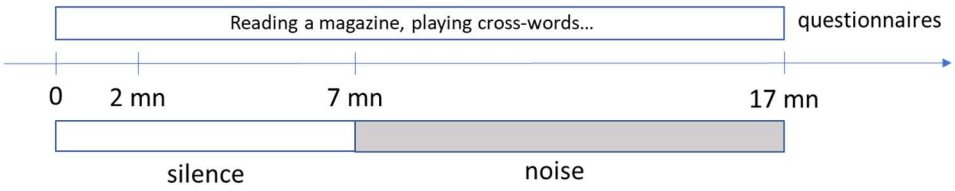

Figure A3 : timeline of one of the 5 noise conditions

The participant could take a short break in the booth between two phases. All in all, he or she had to go through 6 phases (the initial silent one plus the 5 randomly arranged). The overall duration of the experiment was approximately 150 Minutes (6x17 minutes, plus hearing threshold measurement, preliminary explanations).

A3.3 – Ethics

The only personal data collected were the participant's age, sex and hearing threshold. Their personal information was treated to respect their privacy: in the computer running the experiment, participants are referred to as numbers only. The table relating numbers to participants' names and personal information is stored as one file, recorded in a secured computer (different from the one running the experiment) and will be erased at the end of Leon-T project. Sound stimuli were presented at a level lower than 60 dB(A), i.e., the level of a normal speech conversation for a participant. Our exposure time is short as a stimulus does not last more than 10 minutes. Thus, the combination of a short exposure time and the low level of the stimuli ensures no risk of hearing damage.

Particular care was taken in consideration of the current Covid-19 situation: the sound booth was disinfected and ventilated for at least 5 minutes between participants. The interior dimensions of the booth were large enough so that participants would feel at ease (3.4 m long, 2.4 m wide and 2.2 m high). A window allowed the experimenter to check that everything was fine with the participant. Participants signed a consent form before starting the experiment (Appendix I) and were informed that they could stop at any time (see the instructions in Appendix II).

The experiment was approved by the Ethic Comity of Lyon University (Comité Ethique de l'Université de Lyon) under the number 2022-06-23-003.

A4 – Effect of traffic tyre noise on self-assessed annoyance and fatigue

A4.1 – Differences of noise sensitivity between age classes and sex

No influence of gender on the results of the NoiSeQ-R questionnaire could be found (Student's t-test, p = 0.151. Note that the two groups had different sizes : 31 women and 17 men).
On the other hand, it appeared that 40+ age class had a higher noise sensitivity (Fig.A4), as shown by a Student's t-test ($t_{(45.90)} = 2.95$, $p = 0.0025$)). The means are relatively close (2.32 for the 20-31 class versus 2.66 for the 40+ class) and indicate that both age classes have a mild sensitivity to noise. In the existing literature, contradictory results can be found about an age effect on noise sensitivity: as an example, the effect was significant in [8], and not in [9]. Thus, those differences might be a sampling effect.

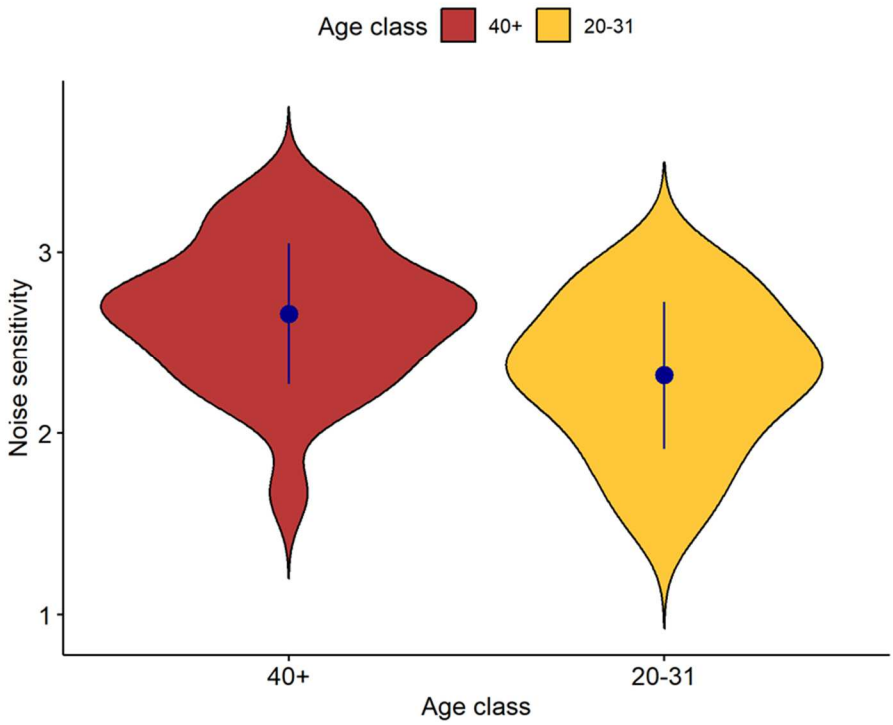

Figure A4: Violin plot and Mean +/- SD (in dark blue) of the comparison of noise sensitivity across the age classes.

A4.2 – Annoyance.

Figure A5 shows the self-assessed annoyance obtained in the five conditions, for the two groups of participants.

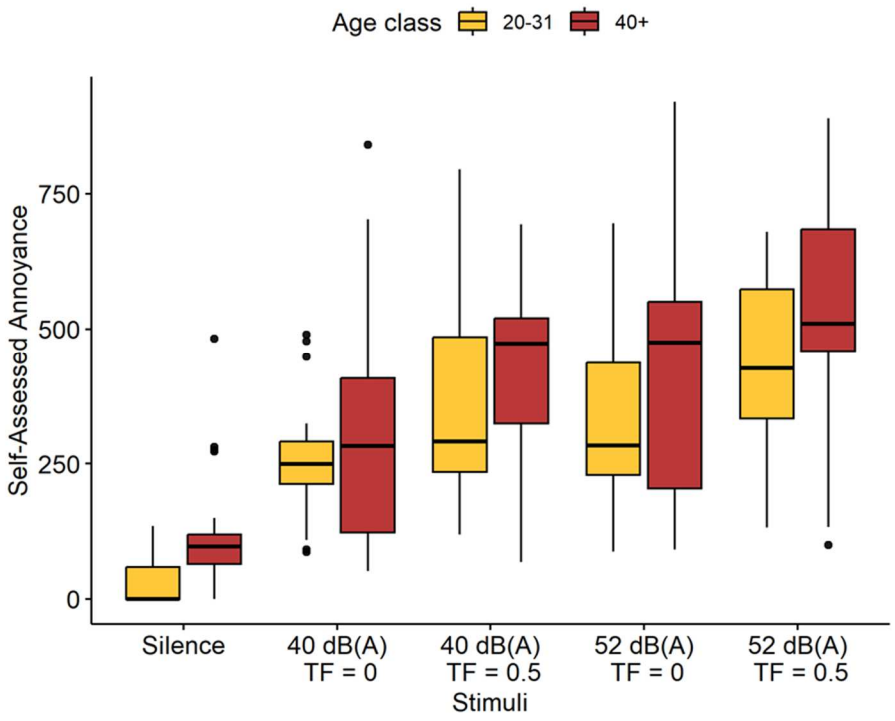

Figure A5: Boxplot showing the effect of the age class and the stimuli on the self-assessed annoyance. The level (in dB(A)) and the tonality factor (TF) is indicated for each stimulus.

Results obtained in the four noisy conditions were analysed by a three-factor analysis of variance (ANOVA) for repeated measures. The three factors were the age class, the level and tonality factor of the stimuli presented. The model significantly explained the data (comparison with the null model: $\chi_{(9)}^2 = 182.58$, $p << 0.001$). A step wise model selection showed that there were no significant interactions between factors (comparison model with versus without interaction: $\chi_{(5)}^2 = 0.77$, $p = 0.98$). All factors (Level: $\chi_{(2)}^2 = 153.45$, $p << 0.001$; Tonality: $\chi_{(1)}^2 = 34.29$, $p << 0.001$; Age class: $\chi_{(1)}^2 = 4.26$, $p=0.039$) were statistically significant. Figure A5 shows that noises with higher level and higher tonality factor caused the highest annoyance. It also showed that the 40+ age class was usually more annoyed than the students by the noises.

Following these results, the data obtained for exposure with no noise (silence) were excluded to analyse the importance of each timbre parameter on the annoyance. As in D4.2., we first centred the annoyance ratings to eliminate the individual variability and also the age class effect. The unpleasantness scores for each participant *i* and each traffic noise *j* were corrected by mean normalisation: the average of all scores given by the participant *i* was subtracted and the global mean of the data was added (eq. 1):

$$(1)\ Centered\ score_{i,j} = score_{i,j} - \frac{1}{n_j}\sum_{j} score_{i,j} + \frac{1}{n_j \times n_i}\sum_{i,j} score_{i,j}$$

With *nj*, the number of different traffic noises evaluated by a given participant *i*, i.e $n_j = 4$; n_i, the number of participants, i.e. $n_i = 48$.

The centred annoyance scores were then used in a linear model without interactions to perform an importance evaluation similar to D4.2, using the R library *vip* [10] (see deliverable D4.2 for the description of "importance"). The tonality factor and the level variables were centred and scaled beforehand. The results of this analysis showed that the linear model was significant ($F_{(2,188)} = 30.36$, $p < 0.001$, $R^2 = 0.24$) and that the tonality factor had more importance than the sound pressure level on the annoyance (Tab.A3).

Variable	Coefficient Estimate	Standard error	P-value	Importance
Tonality	52.44	7.73	<0.001	100
Level	38.83	7.73	< 0.001	74

Table A3: Effect of the Tonality factor and the level on the centred annoyance. The importance was normalised so that the maximum importance equals 100.

A4.3 – Self-assessed fatigue

A first step showed that the age classes presented different fatigue scores - calculated from the MFI20 - during the experiment (Fig.A6, Wilcoxon rank sum test: W = 19615, *p* << 0.001).

Figure A6: Violin plot and Mean +/- SD (in dark blue) of the comparison of self-assessed fatigue across the age classes.

A repeated-measure ANOVA was conducted, using a within-subject factor (5 conditions, including the silent one) and one between-subject factor (age group). Although there was a tendency for fatigue to increase after the noisy phases (especially those where the tonality was maximum, see Fig. A7), no significant effect was detected for the "noise condition factor" ($F(3.28, 147.7) = 2.45$, $p = 0.06$ after using the Greenhouse sphericity correction). It can be hypothesised that the exposure time was not long enough and the task not complex enough to show an effect.

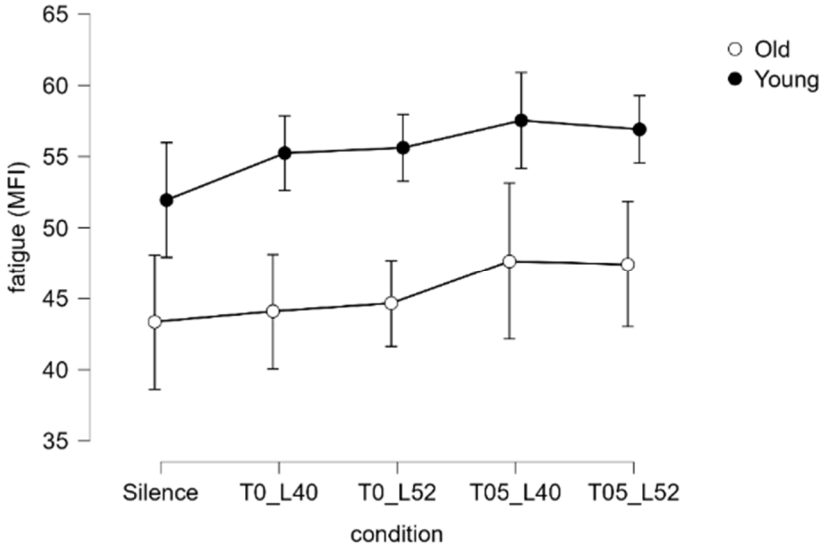

Figure A7: averaged fatigue evaluations after each exposure, for the two groups of listeners (means in their 95% confidence intervals)

A5 –Physiological parameters

A5.1 – Summary of the selected physiological parameters

The Empatica E4 [12] is a wristband device used for the acquisition of several physiological signals during the experiment. The movements of the arm and wrist are quantified using a 3-axes accelerometer. The wrist temperature is measured by an infrared thermopile. The electrodermal activity (EDA) of the skin is measured by two electrodes in contact with the wrist skin. The heart-rate variables are calculated from the temporal evolution of the blood volume pressure (BVP) using the photoplethysmography technique (see A5.5 for a short description of the technique). A total of 24 parameters were measured and presented in Tab.A4. The rest of this section gives more details for each parameter. Parameters were measured during the 5 min preceding sound exposure (or the silent condition) and the 10 minutes during exposure. The difference between the exposure and the preceding period was used in a statistical analysis to evaluate the effect of the stimuli on the measured parameters. Linear mixed models were used to test those effects; parameters of the models were the age class, the phase (stimuli used during the relaxing phase), if the participants had a caffeine beverage (tea or coffee) in the last 7 hours and if he/she did sports or any physically demanding activity before coming to the experiment.

Table A4: Summary of the different physiological taken during the noise exposure.

Physiological category	Abbreviation	Description
Acceleration	*ACC*	Root mean square of the acceleration
Temperature	*MeanTemp*	Mean of the temperature
	SDTemp	Standard deviation of the temperature
	MaxMinTemp	Difference between the maximum and minimum temperature
	dTemp	Mean of the derivative of the temperature
Electrodermal activity	*MeanEDA*	Mean of the total EDA response

	TonicMean	Mean of the tonic part of the EDA
	TonicSD	Standard Deviation of the tonic part of the EDA
	TonicDeriv	Mean of the derivative of the tonic part of the EDA
	PhasicMean	Mean of the phasic part of the EDA
	PhasicNumPeaks	Number of peaks present in the phasic part of the EDA
	PhasicMeanPeriodPeaks	Mean period between two peaks in the phasic part of the EDA
Heart Rate Variability	*HrMean*	Mean heart rate
	HrSDNN	Standard deviation of interbeats intervals
	HrRMSSD	Root mean square of successive RR interval differences
	HrVLF	Power spectrum of the heart rates corresponding to the very low frequency range [0.0033-0.04 Hz]
	HrLF	Power spectrum of the heart rates corresponding to the low frequency range [0.04-0.15 Hz]
	HrHF	Power spectrum of the heart rates corresponding to the low frequency range [0.15-0.4 Hz]
	HrLFHF	Ratio of Low frequency to High frequency power
	HrLFn	Normalized low frequency power
	HrHFn	Normalized high frequency power
	HrSD1	Poincaré plot standard deviation perpendicular the line of identity
	HrSD2	Poincaré plot standard deviation along the line of identity
	HrSD1SD2	Ratio of SD1 to SD2

A5.2 – Temperature

The wrist temperature is measured using an infrared thermopile with a 4 Hz sampling frequency. The mean, standard deviation, the difference between the extrema and the mean of the temperature were then calculated. The temperature variables showed little variability according to the stimuli. The statistical model of the mean temperature was not significant when tested against a null model ($\chi^2_{(80)}$ = 85.53, p = 0.32) and showed no differences between stimuli (Fig.A8).

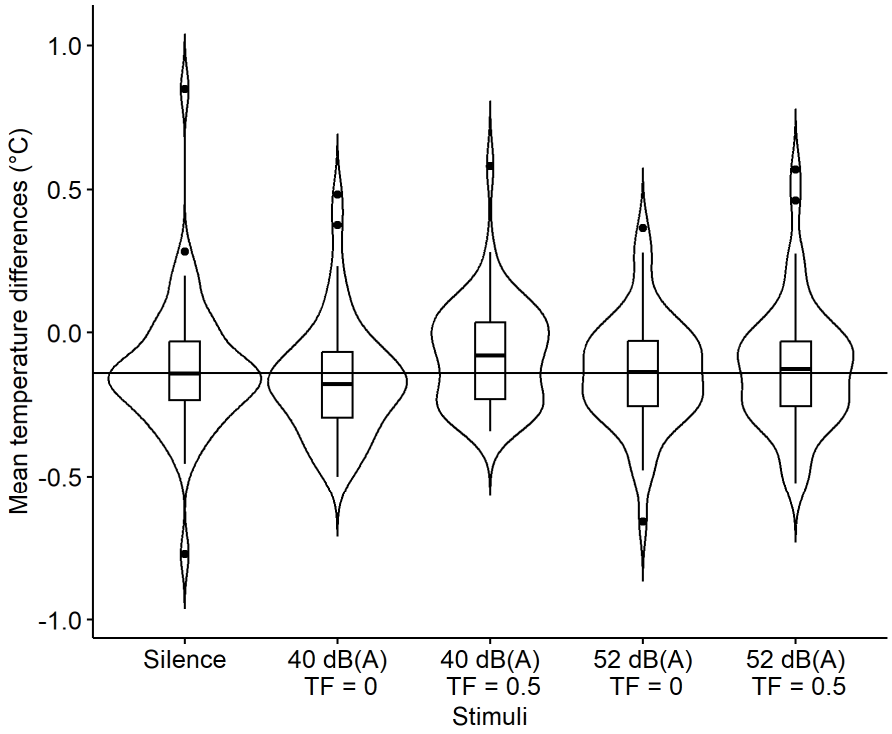

Figure A8: Violin plots with boxplots showing no modification of the mean temperature differences (calculated between the exposure period and the period before) across the different type of stimuli of the experiment. The horizontal black line represents the global median of the data.

A5.3 – Acceleration

The 3-axis accelerometer of the wristband captures the acceleration forces (in g) for the 3-dimensional axes *x*, *y* and *z* with a sampling frequency of 32 Hz. The total acceleration is deduced by (3):

$$(3)\ Acceleration = \sqrt{x^2 + y^2 + z^2}$$

The root mean square (RMS) of the acceleration was used as a proxy to evaluate the amount of movement of the participant. The acceleration showed little variability according to the stimuli: the statistical model showed no significant difference with a null model ($F_{(39)}$ = 1.13, p = 0.29) and showed no differences between stimuli (Fig.A9).

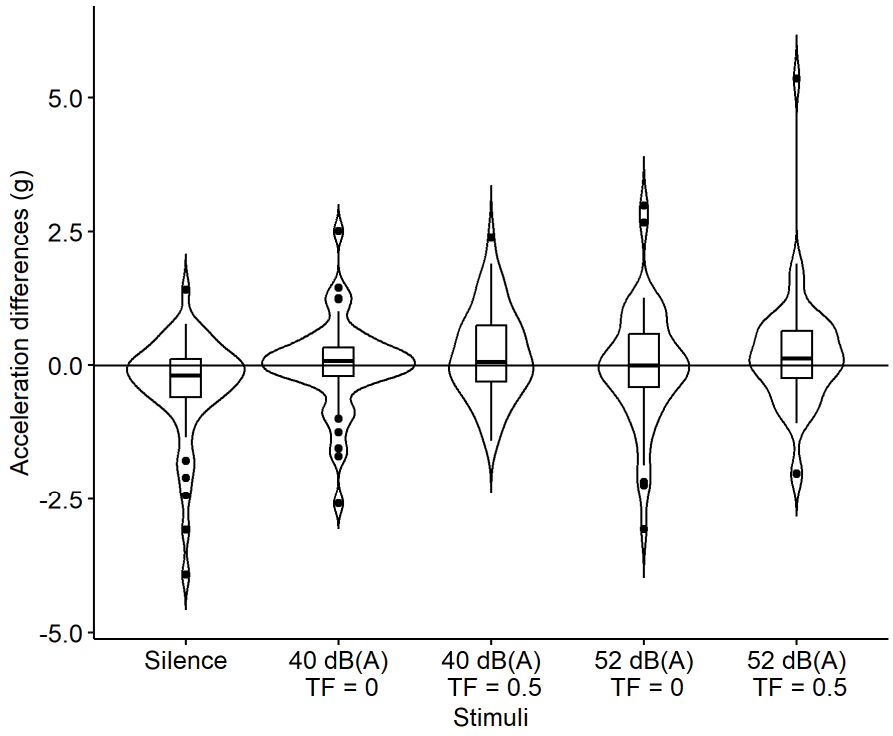

Figure A9: Violin plots with boxplots showing no modification of the acceleration RMS differences (calculated between the exposure period and the period before) across the different type of stimuli of the experiment. The horizontal black line represents the global median of the data.

A5.4 – Electrodermal activity (EDA)

The electrodermal activity (EDA) corresponds to the skin conductance (in µSiemens) measured between the two electrodes of the wristband with a 4 Hz sampling frequency. The conductance is proportional to the amount of sweat produced by the sweat glands under the skin, considered to be a marker of the sympathetic nervous activity on sweat glands [13]. The EDA signal can be separated in two parts: the phasic electrodermal activity and the tonic electrodermal activity (Fig.A10). The tonic part refers to long-term and slow changes, usually provoked by non-specific responses like internal thoughts whereas the phasic part corresponds to rapid changes in the signal in the form of peaks and are elicited by external stimuli [14]. The mean was calculated on the total EDA response and then the signal was separated in its two components: a 451 points (equivalent to 112 s.) moving mean was applied to the signal to get the tonic part. The phasic part was then obtained by subtracting the tonic part from the original signal.

The mean, standard deviation and mean of the derivative were calculated for the tonic part of the EDA. The mean of the phasic part was calculated, and the number of peaks was detected with the python library *NeuroKit2* [15]. The mean of the period between two peaks was calculated to evaluate whether the occurrence of peaks tended to speed up or slow down.

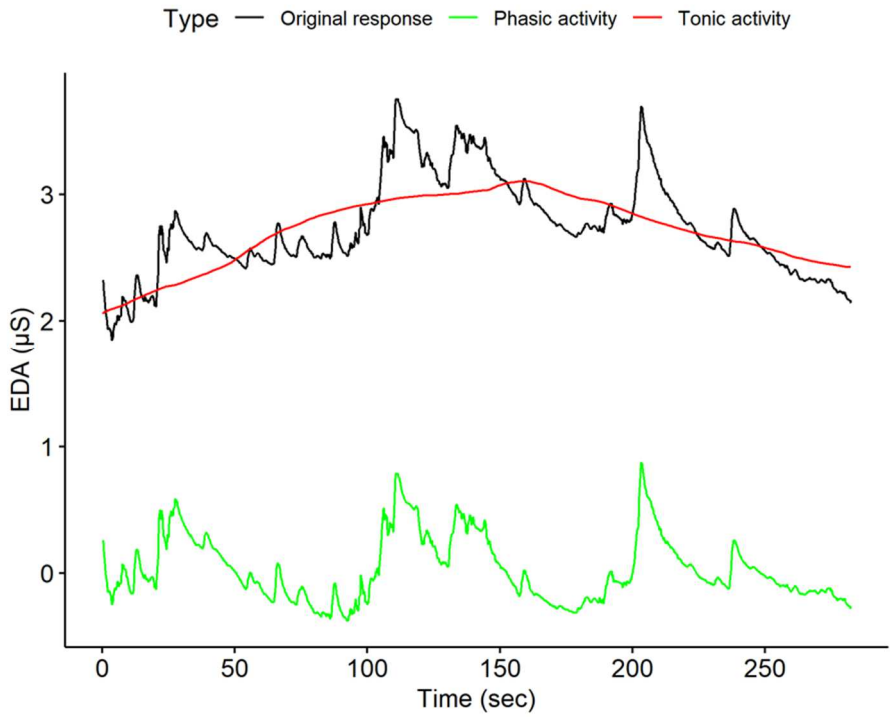

Figure A10: An extract of an electrodermal activity signal, with the original signal in black, the tonic activity in red and the phasic activity in green.

The EDA variables showed little variability according to the stimuli. For example, the statistical model of the mean of the total/original EDA signal showed no significative differences with a null model ($\chi^2_{(79)} = 70.17$, $p = 0.75$) and showed no differences between stimuli (Fig.A11).

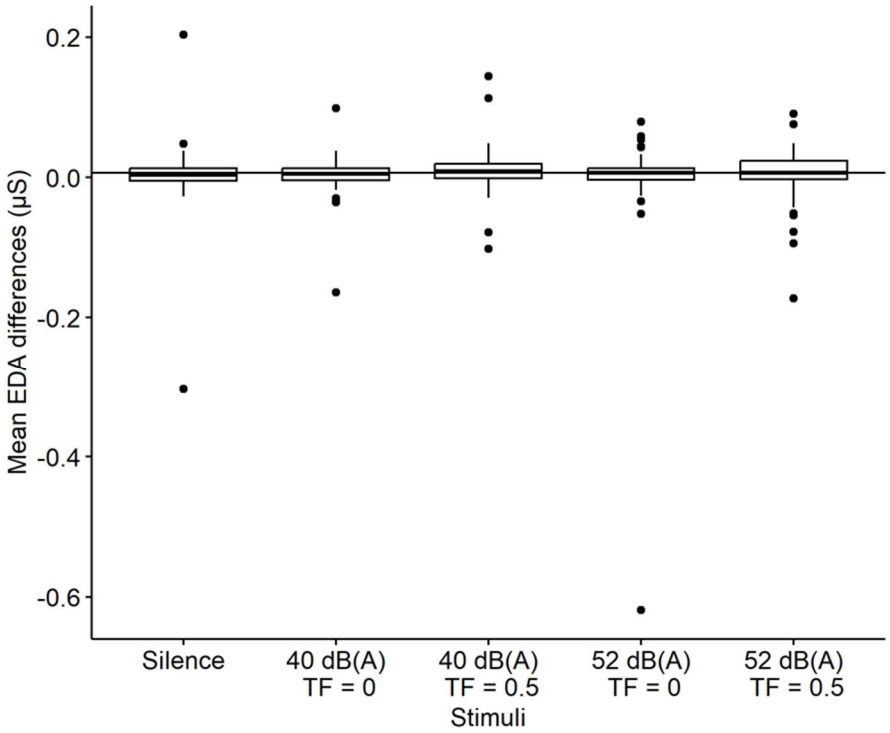

Figure A11: Boxplots showing no modification of the mean EDA differences (between the exposure and the beginning of the phase) across the different type of stimuli of the experiment. The horizontal black line represents the global median of the data.

A5.5 – Heart rate variability

The heart rate variability is calculated from the blood volume pressure, which is deduced from the photoplethysmography sensor (sampling frequency: 64 Hz). The sensor emits flashing red and green lights towards the skin and a light receiver in the device captures the reflected lights coming back from the tissues underneath the skin. The general hypothesis of the technique is that all tissues will have the same light absorbance over time, except for the pulsatile component of arterial blood [16]. The absorbance is then only modulated by the volume of fresh blood coming from the heart. The comparison of the power of the emitted lights with the power of the received lights allows thus to monitor the blood volume pressure inside the arteries of the wrist. Such signal contains specific pulse patterns, corresponding to a heartbeat, with an increase of blood pressure followed by a gradual decrease, with a second, small increase (Fig.A12).

We used the pattern matching method to detect such pulses in the signal: a cross-correlation was performed between the blood volume signal of the device and a template with a shape close to a blood volume pulse (part of a sinus, Fig.A13) to obtain the similarity between the two signals. A pulse detection algorithm of the python library *scipy* [17] was used to detect maximum values in the similarity signal, to locate where the blood volume pressure was the closest to the pattern, i.e. where the heart beat pulses were

located in the original signal. The duration between two consecutive pulses had to be greater than 0.3 seconds, otherwise it was classified as false positive. We used this threshold since it is the minimum refractory period of cardiac muscle for normal sinus rhythm [18].

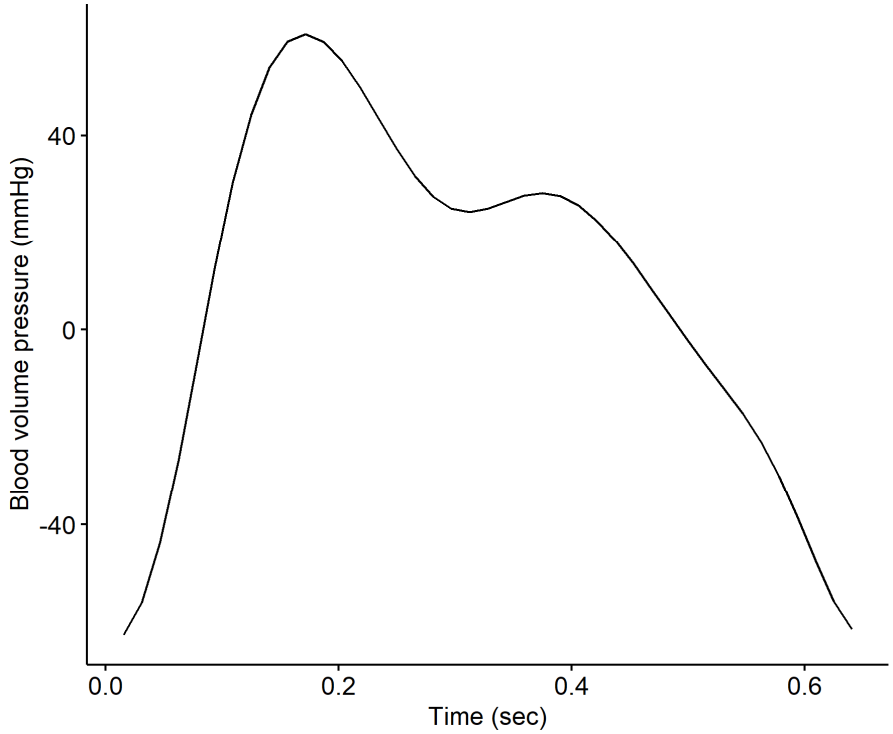

Figure A123: An example of blood volume pressure pulse indicating a heartbeat.

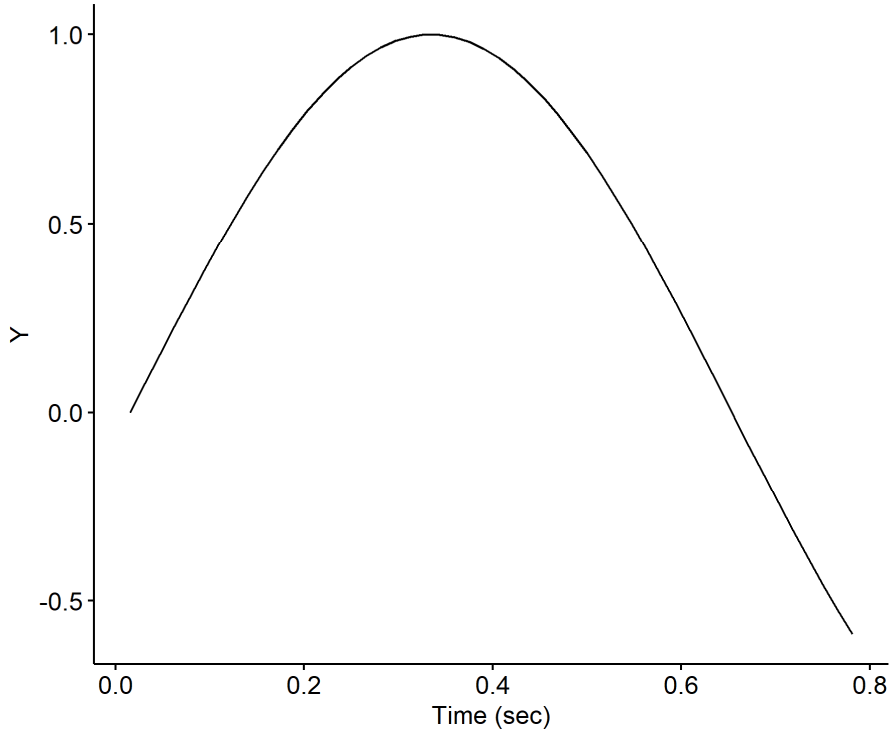

Figure A13: The template used in the pattern matching technique: a sinus calculated for values ranging from 0 to 1.2 x π.

The intervals between successive heartbeats, called RR intervals, were then calculated and cleaned before analysis. First, we identified all RR intervals that were superior to twice the z score of the RR intervals series. Those outliers were replaced by the median of the RR intervals series. Secondly, we used the python library *hrvanalysis* [19] (developed for the aura project [20]) to clean up the signal from the remaining outliers and false positives. Those RR-intervals were deleted and replaced other ones computed by a linear interpolation. Finally, the same library was used to detect ectopic beats. Those spontaneous arrhythmias of the heart can occur a few times a day: the heart might be contracting too soon, skip a beat, increase suddenly for a very short period, etc Although usually harmless, they can nonetheless influence the results and create supplementary undesirable variability in the signal and thus needed to be corrected. *Hrvanalysis* uses the technique explained in [21] to detect such beats. They are then erased and replaced by values obtained from a linear interpolation.

The parameters of heart rate variability are calculated from the cleaned signal (Tab.2). Those parameters are known to be markers of emotions, especially short-term stress [22-25]. For temporal parameters, we chose the mean heart rate (in beats per minutes), the standard deviation and the RMSSD (root mean square of the difference between adjacent intervals) of the RR intervals series. For spectral parameters, the Welch power spectrum of the interval series is calculated and divided in different sub bands (see Tab.2 for their values). The power of each sub-band is reported. Ultra-low frequencies (< 0.0033 Hz) were initially added in the analysis but removed after inspection of the dataset as they were absent in our data. For low and high frequencies, we reported also the power in each sub-band normalised by the total spectral power. The ratio between those two sub-bands frequencies was finally added. Another way to look at the heart rate variability is to derive parameters from the Poincaré plot, i.e. plotting an interval with respect to the following one (Fig.A14). SD1 is defined by the authors of *Hrvanalysis* and in [26] as “the standard deviation of projection of the Poincaré plot on the line perpendicular to the line of identity.” It is “is a measure of the short-term beat-to-beat changes influenced by the sympathetic to parasympathetic tonus ratio (comparable to RMSSD and HF)”. They defined SD2 as “the standard deviation of the projection of the Poincaré plot on the line of identity (y=x)” and “a measure of the overall dispersion of the RR intervals, and reflects long-term changes (comparable to LF)” (see Fig.A12 for a visual representation of SD1 and SD2). The ratio between SD2 and SD1 was also obtained in our analysis.

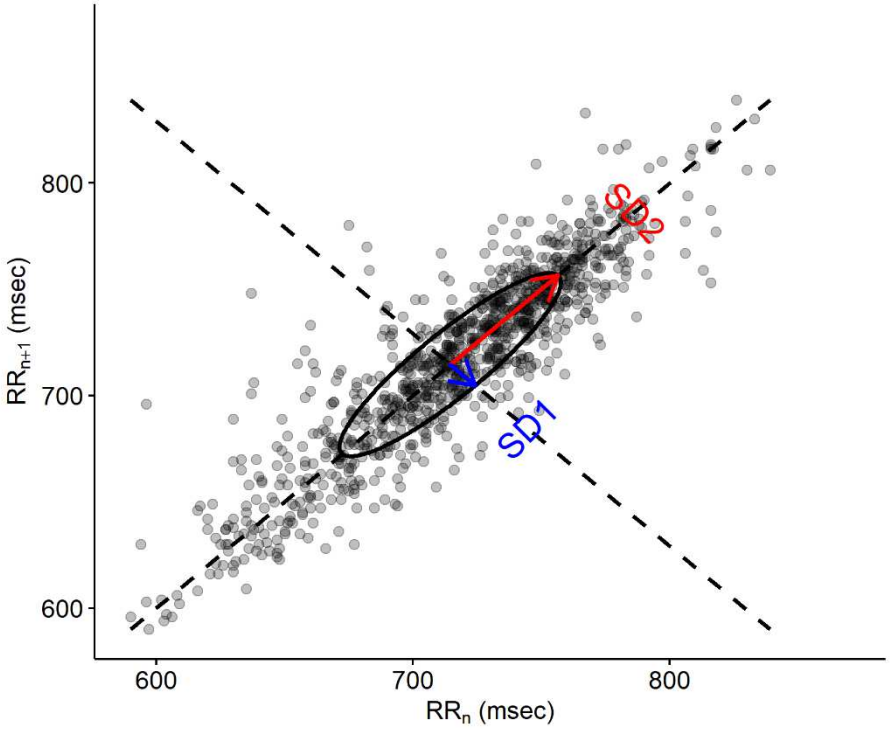

Figure A14: Poincaré plot of an example of a RR interval series (taken from hrvanalysis) and the associated value of SD1 and SD2.

The heart rate parameters showed little variability depending on the stimuli used during the exposure. For example, the statistical model of the mean heart rate showed no significative differences with a null model ($\chi^2_{(39)}$ = 39.43, p = 0.45) and showed no differences between stimuli (Fig.A15).

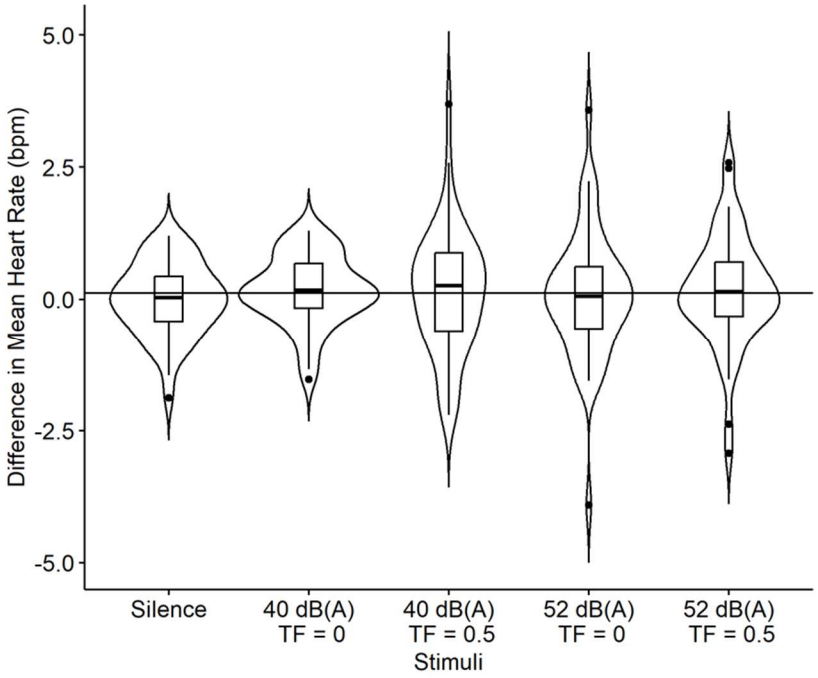

Figure A15: Boxplots showing no modification of the mean heart rate beat rate (in beats per minutes) differences (between the exposure and the beginning of the phase) across the different type of stimuli of the experiment. The horizontal black line represents the global median of the data.

A6 – Conclusion

The experiment showed that short-time exposure to traffic noise based on tyre noise only affected the self-assessed parameters while having no effects on the physiological parameters measured.

The self-assessed annoyance was affected by tonality and overall level, the highest effect being attributed to tonality. Though a general tendency, no effect could be seen in fatigue assessments, no significant effect of sound parameters could be identified. The same holds for physiological parameters, which did not significantly vary during the experiment. This can be due to the short exposure duration (10 min) and the fact that participants were not engaged in a demanding task.

Given the prominent effect of tonality found in our experiments, this work suggests that tonality should be included in future regulations regarding tyre noise.

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A8.a Appendix I: Consent form signed before the listening test (Originally in French)

Laboratoire Vibrations Acoustique

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

Consent form

Last name :
First name :
Address :

I declare that I do not have any hearing problem that could alter the tests or have an impact on my health.

I agree to participate freely with the help and assistance of the INSA Lyon vibration and acoustics laboratory in a listening test experiment.

This experiment is safe and has no consequences for hearing.

The noise level is controlled by the laboratory and does not exceed that experienced in everyday life or in the vicinity of certain common appliances.

The duration of the tests is also controlled by the laboratory.

This experiment takes place in specially equipped booths or in the presence of everyday sound objects.

I have been informed that I am free to stop the experiment at any time, temporarily (to rest) or permanently.

I agree to assist without remuneration and to answer the questionnaire at the end of the experiment.

The questionnaire and the results of the experiment are the exclusive property of the laboratory, which is free to use them as it wishes, provided that it does not reveal the identity of the person involved.

As a compensation, the laboratory will give me the sum of 50 Euros (fifty Euros) corresponding to travel expenses, loss of time, etc. (please attach a bank details form).

Date :

Signature of the participant

Signature of the experimenter

A8.b Appendix II: Information letter received by the participants during the recruitment process (Originally in French)

Laboratoire Vibrations Acoustique
INSA de Lyon
Bâtiment St. Exupéry 25 bis av. Jean Capelle
69621 Villeurbanne cedex – France

Low Particle Emissions and Low Noise Tyres (LEON-T)

Why do I receive this letter?

You have responded to a public advertisement and expressed interest in participating in a laboratory study on the unpleasantness of tire noises based on listening tests. This letter provides more information about this study. You can read through the letter in peace and quiet and you are most welcome to call or email with any questions. You can also ask any questions during your visit to the laboratory before you decide to participate.

The purpose of the study?

The Road traffic noise accounts for the majority of perceived urban environmental noise and has important health consequences. The rolling noise of vehicle tires is a major contributor to perceived road noise. The European project LEON-T aims to minimize the nuisance of heavy vehicle tires, especially noise. Prior to a study of the effects of tire noise on sleep, this experiment is conducted to know how the timbre parameters of such noises influence the self-assessed short-term unpleasantness and fatigue perceived by listeners. Furthermore, physiological parameters will be measured to see if the noises elicit any physiological reaction. The stimuli were synthetized to combine all values of the parameters known to influence the short-term unpleasantness as established in a previous study.

How does the study work?

The experiment was approved by the Ethic Comity of Lyon University (Comité Ethique de l'Université de Lyon)

The study involves you coming to the laboratory for 2 hours and 15 minutes during the day and entering a soundproof booth to complete the following tasks: hearing threshold measurement and self-evaluating the unpleasantness of synthetized tire noises.

Your hearing threshold will be measured using headphones and a button that you will need to push whenever sounds is eared. A computer graphic interface will be used to evaluate the unpleasantness. Loudspeakers will be used throughout the duration of the experiment to display the sounds.

You will stay in a soundproof booth during the experiment under the supervision of an experimenter. You are free to leave the room at any time, without any reason. There is never a good or wrong answer for the unpleasantness or the assessment of the fatigue. However, when a response is validated, it is definitive.

Risks or benefits of participating?

This experiment is safe for you and has no consequences for your hearing. The noise level is controlled by the laboratory and does not exceed that experienced in everyday life or in the vicinity of certain common appliances. Sound stimuli are presented through loudspeakers, with a level lower than 60 dB(A), i.e. the level of a normal speech conversation for a participant. Our exposure time is short as all exposure sequence does not last more than 30 minutes and there are breaks between exposure. Thus, the combination of a short exposure time and the low level of the stimuli ensures no risk of hearing damage. Particular care was taken in consideration of the current Covid-19 situation: the sound booth was disinfected and ventilated for at least 5 minutes between participants. You will be equipped with a medical apparatus in the form of a wristband. It will be tight enough to keep it in contact with your skin throughout the whole experiment that will be loose enough so that you will not feel uncomfortable in any case. The plastic of the wristband is of medical grade. Thus, you should not feel any irritation nor discomfort.

The inside dimensions of the booth are large enough so that you would feel at ease (3.4 m long, 2.4 m large and 2.2 m high). A window allows the experimenter to check on everything that could happen to you.

Insurance and compensation

You will receive 50€ after completing the experiment as a financial compensation for your time. You will receive the compensation if you finish the experiment or if you stop before the end for valid reasons, confirmed by the experimenter (e.g. discomfort, medical urgency, …).

How is the information collected handled?

Your responses to the experiment will be processed so that no unauthorised persons can access them and the access is restricted only to authorized researchers at the LVA. Results are stored in the computer used in the experiment but your name or other personal data are not stored in that computer, as participants are labelled as ID numbers only. There will only be one file with the relationship between your ID and your personal information. This file will have limited access and will be stored inside the experimenter's computer for the duration of the LEON-T project (36 months) and then destroyed.

All personal data is processed in accordance with the EU General Data Protection Regulation (GDPR). According to the EU Data Protection Regulation, you have the right to access the information about you handled in the study free of charge, and if necessary to have any errors corrected. You can also request that data about you be deleted and that the processing of your personal data be restricted. To access the information, please contact the project manager: Etienne Parizet, who can be reached by phone: +33 (0)4 72 43 81 21 / by email: etienne.parizet@insa-lyon.fr.

Data Protection Officer at INSA Lyon can be reached by e-mail: dpo@insa-lyon.fr. If you are dissatisfied with how your personal data is processed, you have the right to lodge a complaint with the French Authority for Privacy Protection, which is the supervisory authority.

How do I get information about the results of the study?

The results of the project will be reported in scientific journals and at conferences. A summary of the results will also be published on the department's website (https://recherche.insavalor.fr/)

and the project's website (www.leont-project.eu/) once the results are compiled. All reporting takes place at the group level where individual answers cannot be determined.

Volunteering

Participation in the project is voluntary. You can cancel your participation at any time, without having to provide any specific explanation. You can also ask to have collected data and personal data deleted or anonymised by competent researchers. You can do this by contacting the project manager – see below.

Responsible

The research principal is the INSA de Lyon. The responsible researcher is Etienne Parizet, Professor at the Laboratoire Vibrations Acoustique at the INSA de Lyon. The principal experimenter is Thibaut Marin-Cudraz, PhD, post-doctoral researcher at the Laboratoire Vibrations Acoustique at the INSA de Lyon.

With kind regards,

Etienne Parizet
Professor, Responsible Researcher
etienne.parizet@insa-lyon.fr
+33 (0)4 72 43 81 21

9.2. Appendix B: UGOT sleep study questionnaires

Frågor att besvara på morgonen

Besvara frågorna inom 15 minuter från det att du blivit väckt kl. 7.00 på morgonen

OBS att formulären är två-sidiga

1. **Hur skulle du vilja bedöma din sömnkvalitet under natten?** Markera med ring runt lämplig siffra

Mycket dålig 0 1 2 3 4 5 6 7 8 9 10 Mycket bra

Ange även ditt svar på nedanstående verbala skala:

2. **Hur skulle du vilja bedöma din sömnkvalitet under natten?**
   - [ ] Mycket bra
   - [ ] Ganska bra
   - [ ] Inte särskilt bra
   - [ ] Dålig
   - [ ] Mycket dålig

3. **Markera rutan bredvid det påstående som bäst beskriver hur sömnig du känner dig just nu…**
   - [ ] Extremt pigg
   - [ ] Mycket pigg
   - [ ] Pigg
   - [ ] Ganska pigg
   - [ ] Varken pigg eller sömnig
   - [ ] Första tecknen på sömnighet
   - [ ] Sömnig, men ej ansträngande vara vaken
   - [ ] Sömnig, viss ansträngning vara vaken
   - [ ] Mycket sömnig, ansträngande vara vaken, kämpar mot sömnen

Hur känner du dig just nu? *Markera med en ring runt lämplig siffra*

4.	Mycket trött	0	1	2	3	4	5	6	7	8	9 10	Mycket utvilad
5.	Mycket spänd	0	1	2	3	4	5	6	7	8	9 10	Mycket avspänd
6.	Mycket irriterad	0	1	2	3	4	5	6	7	8	9 10	Mycket glad

7. **Hur lång tid tog det för dig att somna igår kväll?** Minuter: _____

8. **Hur många gånger uppskattar du att du vaknade under natten?** [ ] Vaknade inte Vaknade ___ gånger

9. **Hade du svårt att somna om när du vaknat?** [ ] Vaknade inte [ ] Nej [ ] Ja

Hur upplevde du natten och din sömn? *Markera med en ring runt lämplig siffra*

10.	Lätt att somna	0	1	2	3	4	5	6	7	8	9	10	Svårt att somna
11.	Sov bättre än vanligt	0	1	2	3	4	5	6	7	8	9	10	Sov sämre än vanligt
12.	Sov djupt	0	1	2	3	4	5	6	7	8	9	10	Sov ytligt
13.	Vaknade aldrig	0	1	2	3	4	5	6	7	8	9	10	Vaknade ofta

14. **Störddes din sömn av buller under natten?**
Markera med en ring runt lämplig siffra

Inte alls	0	1	2	3	4	5	6	7	8	9	10	Oerhört mycket

Anser du att buller under natten störde din sömn så att du:

		Inte alls	Inte särskilt mycket	Ganska mycket	Mycket	Oerhört mycket
15.	sov dåligt?	[ ]	[ ]	[ ]	[ ]	[ ]
16.	väcktes?	[ ]	[ ]	[ ]	[ ]	[ ]
17.	hade svårt att somna om?	[ ]	[ ]	[ ]	[ ]	[ ]
18.	var trött på morgonen	[ ]	[ ]	[ ]	[ ]	[ ]

Om du blev störd i din sömn, beskriv här vad du stördes av.

Lista över positiva och negativa affekter
PANAS

Nedan finns en lista med ord som beskriver olika känslor. Läs varje ord och skriv sedan på raden bredvid ordet den siffra som bäst beskriver hur **Du känner Dig just nu**. Använd följande skala för att fylla i Dina svar.

1	2	3	4	5
Väldigt lite eller inte alls	**Lite**	**Måttligt**	**Mycket**	**Väldigt mycket**

____	1. Intresserad	____	11. Lättretlig
____	2. Bekymrad	____	12. Pigg
____	3. Ivrig	____	13. Skamsen
____	4. Upprörd	____	14. Inspirerad
____	5. Stark	____	15. Nervös
____	6. Skuldmedveten	____	16. Beslutsam
____	7. Skräckslagen	____	17. Uppmärksam
____	8. Fientligt inställd	____	18. Skakis
____	9. Entusiastisk	____	19. Aktiv
____	10. Stolt	____	20. Rädd

Frågor att besvara på kvällen

Besvara frågorna strax innan du går och lägger dig.

1. **Markera rutan bredvid det påstående som bäst beskriver hur sömnig du känner dig just nu……**

[ ] Extremt pigg
[ ] Mycket pigg
[ ] Pigg
[ ] Ganska pigg
[ ] Varken pigg eller sömnig
[ ] Första tecknen på sömnighet
[ ] Sömnig, men ej ansträngande vara vaken
[ ] Sömnig, viss ansträngning vara vaken
[ ] Mycket sömnig, ansträngande vara vaken, kämpar mot sömnen

Hur känner du dig just nu? *Markera med en ring runt lämplig siffra*

2.	Mycket trött	0	1	2	3	4	5	6	7	8	9 10	Mycket utvilad
3.	Mycket spänd	0	1	2	3	4	5	6	7	8	9 10	Mycket avspänd
4.	Mycket irriterad	0	1	2	3	4	5	6	7	8	9 10	Mycket glad

5. **Om du tänker på de senaste 8 timmarna innan du lade dig idag (mellan 15:00-23:00), har du…**

a) Tränat (fysisk ansträngning så att du blivit andfådd)? ☐ Ja ☐ Nej

Om ja, ungefär mellan vilka tider?
Startade:
_____
Slutade:
_____

b) Druckit koffein (t.ex. kaffe, te, energidryck)? ☐ Ja ☐ Nej

Om, ja, hur många koppar_____ ☐ Ja ☐ Nej

c) Använt nikotin (tex, cigaretter, snus, e-cigarett)? ☐ Ja ☐ Nej

d) Använt läkemedel (inklusive p-piller)? ☐ Ja ☐ Nej

Om, ja, vilka? ☐ Ja ☐ Nej
_____

e) Druckit alkohol? ☐ Ja ☐ Nej

Lista över positiva och negativa affekter
PANAS

Nedan finns en lista med ord som beskriver olika känslor. Läs varje ord och skriv sedan på raden bredvid ordet den siffra som bäst beskriver hur **Du känner Dig just nu**. Använd följande skala för att fylla i Dina svar.

1	2	3	4	5
Väldigt lite eller inte alls	**Lite**	**Måttligt**	**Mycket**	**Väldigt mycket**

____	1. Intresserad	____	11. Lättretlig
____	2. Bekymrad	____	12. Pigg
____	3. Ivrig	____	13. Skamsen
____	4. Upprörd	____	14. Inspirerad
____	5. Stark	____	15. Nervös
____	6. Skuldmedveten	____	16. Beslutsam
____	7. Skräckslagen	____	17. Uppmärksam
____	8. Fientligt inställd	____	18. Skakis
____	9. Entusiastisk	____	19. Aktiv
____	10. Stolt	____	20. Rädd