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Guidance to investigate university students' bodily responses and perceptual assessments in sound exposure experiments

Amneh Hamida [a,*], Alessandro D'Amico [b], AnneMarie Eijkelenboom [a], Philomena M. Bluyssen [a]

[a] Chair Indoor Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Delft, the Netherlands
[b] Department of Civil, Construction and Environmental Engineering, Sapienza University of Rome, Rome, Italy

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ABSTRACT

Previous studies have shown that sound influences students both physiologically and perceptually. However, most of these studies focussed on the effects of sounds at group-level, ignoring individual differences. Therefore, we investigated which indicators can be used to identify differences in bodily responses and perceptual assessments of each individual when exposed to four different sounds. First, based on an audiometric test, the hearing acuity of 15 students (from five different profiles based on their acoustical preferences and needs) was measured. Then, two sound exposure experiments were conducted in the SenseLab: direct sound exposure using earbuds in a laboratory setting, and indirect sound exposure with speakers in a real room setting. During each experiment, the attention level (AL), mental relaxation level (MRL), heart rate (HR), and respiration rate (RR) were measured with wearable devices, and students made perceptual assessments of each condition. The percentage of change normalised the four bodily response measurements among students. Based on correlation analysis and t-tests, bodily responses, and perceptual assessments across experiments were compared, at group-level and individual-level. Six students, who suffered from mild hearing loss in low-frequency sounds, showed bodily responses such as increased HR during exposure to low-frequency sound conditions. Perceptual assessments of different sound types during both lab experiments substantiated the acoustical preferences of the students from the five profiles. Bodily responses showed no strong nor significant correlations with perceptual assessments during the direct sound exposure experiments. Differences in bodily responses and perceptual assessments between the two experiments and between group-level and individual-level were observed in AL. It is concluded that hearing acuity and type of sound (sound frequencies) are key indicators for identifying differences in bodily responses (such as HR and RR) and perceptual assessment. For future research, it is crucial to consider incorporating audiometric tests, bodily responses such as HR and RR, and perceptual assessments in this type of investigations.

1. Introduction

University students spend a significant amount of time studying indoor, whether at home or in educational buildings [1–3]. Research has shown that staying indoors for a long time can affect occupants' health due to a 'bad' indoor environmental quality (IEQ) [4,5], and thus it is important to consider the IEQ of these study places and eliminate any stressors that could affect students' health negatively. The acoustical quality is one of the IEQ factors that may positively or negatively affect students' health and comfort [6,7]. Background noise is one of the IEQ stressors that can cause nonauditory effects such as prolonged stress, caused indirectly by the anti-stress mechanism that is activated when exposed to stressors such as noise [8,9]. The anti-stress mechanism increases adrenaline and nor-adrenaline levels in the short-term, possibly leading to an increase in heart rate (HR) and respiration rate (RR) [9]. Changes in physical and/or physiological responses (including HR, RR and brainwaves) as a result of exposure to a physical stressor, such as noise, are referred to as bodily responses [10,11]. Thus, a study of occupant-related indicators, including bodily responses and perceptual assessments, might contribute to a better understanding of the effects of the acoustical environment on students' preferences and needs [12].

The effects of sound as an environmental stressor have been studied

Abbreviations: AL, attention level; HR, heart rate; IEQ, indoor environmental quality; MRL, mental relaxation level; RR, respiration rate; SPL, sound pressure level.

* Correspondence to: Faculty of Architecture and the Built Environment, Delft University of Technology, Building 8, Julianalaan 134, Delft 2628BL, the Netherlands.

E-mail address: a.b.hamida@tudelft.nl (A. Hamida).

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using bodily responses and perceptual assessments. For instance, Alvarsson et al. [13] examined university students' bodily responses, including high-frequency HR variability, when exposed to natural sounds and environmental noises. Their findings indicated no significant changes in HR during the experiment; however, the students rated the natural sounds as the most pleasant. Abbasi et al. [14] investigated university students' bodily responses to three sound pressure levels (SPL) of low-frequency sound in a lab experiment. They recorded bodily responses, including electroencephalogram (EEG) for brain wave signals and electrocardiography for HR signals. They observed that these bodily responses significantly differed among the different SPLs, and students' mental fatigue increased when the SPL increased. Tristan-Hernandez [7] found that both beta and theta brain wave amplitudes decreased when university students were exposed to background noise, resulting in reduced attention levels while performing cognitive tasks. Furthermore, Guan et al. [15] concluded that brain wave patterns differed between the perceived comfortable sound condition (music sound at 50 dB) and the perceived uncomfortable sound condition (fan noise at 80 dB). They also observed a decline in theta wave during the uncomfortable sound condition. However, correlations between bodily responses and perceptual assessments of background noise were not tested in these studies. Park and Lee [16] measured both HR, and RR of participants and asked them to assess the noticeability and annoyance of these sounds, while being exposed to six-floor impact noise (e.g., adult walking and child running) stimuli. They found that RR was correlated significantly and positively with both perceptual assessments of the standard floor impact noise. Similarly, Hume and Ahtamad [17] concluded that RR increased during the most perceived pleasant sound clips. Thus, HR, RR, and brain waves as bodily responses could be measured to explain differences in the acoustical needs of students.

Human ears are most sensitive to high frequencies (3000–5000 Hz) and generally most annoyed by low-frequency noise (20–125 Hz), which can cause stress [18,19] and negatively impact cardiovascular responses such as HR [20]. For instance, Mu et al. [21] observed that HR slightly increased among senior adults (over 60 years old) with mild or severe hearing loss up to 55 dB(A), but remained stable above that level. Keur-Huizinga et al. [22] studied the impact of hearing acuity on HR in 125 participants aged 37–72, exposed to speech sound stimuli (frequencies ranged from 330 to 6300 Hz). They found no consistent changes in HR reactivity in participants with different hearing acuity, and concluded that hearing acuity might be associated with changes in the sympathetic nervous system's reactivity. Mackersie et al. [23] examined the effects of hearing loss and noise on stress-related autonomic measures in 33 participants (18 with hearing loss, 15 with normal hearing, ages 22–79) during sentence recognition tasks. They found that the HR of participants with hearing loss decreased at lower signal-to-noise ratios, while HR of those with normal hearing did not. They highlighted that participants with hearing loss may experience increased effort and stress during speech recognition in noisy environments, which could influence the psychophysiological responses concerning the autonomic nervous system.

The above-mentioned studies [21–23] recruited senior adults, who have a lower sensitivity to low-frequency sounds compared to young adults. Although Alimohammadi and Ebrahimi [24] tested the university students' mental performance while being exposed to both low and high-frequency sounds, they excluded the students whose hearing threshold was less than 20 dB. Hence, little is known about the relationship between hearing acuity in young adults and their bodily responses to different sound types. Furthermore, while hearing acuity measured through an audiometric test has been considered in several sound exposure experiments with human subjects [13,14,18,25,26], differences in bodily responses concerning the hearing thresholds of different students at various sound frequencies have not studied.

Most of the above-mentioned lab experiments [7,13–17] considered participants' personal traits, including demographics (e.g., age and gender) and hearing acuity or noise sensitivity. However, they mainly focused on the overall bodily responses and perceptual assessment at group-level ignoring differences in preferences and needs between individuals (profiles). Profiling occupants based on their preferences and needs of a certain indoor environment is one of the methods that take into account the differences between individuals' in the indoor environment [27]. Noting that profiling of occupants in several situations (e.g., classrooms, study places, homes, and hospitals) has been addressed in previous studies [28–31]. In connection to the sound-related preferences of students, Hamida et al. [32] identified five profiles of university students based on their acoustical and psychosocial preferences for their study places, such as sounds from the outside and privacy. These five profiles are: 1) sound concerned introvert, 2) sound unconcerned introvert, 3) sound partially concerned introvert, 4) sound concerned extrovert, and 5) sound unconcerned extrovert. Moreover, they identified aspects related to the preferences of each profile through a field study, such as both students from profiles 1, 3, and 4 were concerned with the sounds from the outside because they got annoyed and lost focus by these sounds. According to these aspects, it was concluded that the study place's context, such as building location, might affect students' acoustical preferences.

Studies on bodily responses to be measured for students from different profiles when exposed to both preferable and non-preferable sounds could not be found in the literature. Also, the hearing acuity at different sound frequencies of university students was not widely studied. In addition, to advance knowledge in this area, studies on correlations between bodily responses (e.g., HR), health aspects (e.g., hearing acuity), environmental indicators (e.g., SPL and sound frequency), perceptual assessments (e.g., pleasantness), current situation of study places (e.g., existing sound sources), and preferences of university students from different profiles, are needed. Furthermore, we still need to test which of the bodily responses (including HR, RR, and brain waves that were tested in previous studies) can be measured to explain differences in the acoustical preferences of different students. Hence, the main aim of this study is to propose guidance for investigating the bodily responses that can help us better understand the differences in each student's perceptual responses to different sounds. Therefore, the main research question of this study is: Can bodily responses be used to explain differences in preferences and/or needs for different sounds, and how can we test this?

2. Methods

2.1. Study design

To study which indicators can be used to identify differences in bodily responses to different sounds and sound levels, two sound exposure lab experiments were conducted on four days in November 2023 with four students per day (except for one day with three students). All of these experiments took place in the SenseLab [33]. These two sound exposure lab experiments aim to answer the four sub-questions that answer the main research question of this study, which are:

1. To what extent is an audiometric test essential for sound exposure lab experiments?
2. Can students' perceptual assessments of sound conditions substantiate their acoustical preferences from the field study?
3. Do bodily responses correlate with perceptual assessments of different sounds?

4. Do bodily responses and perceptual assessments differ significantly when students are exposed directly or indirectly to sounds?

An audiometric test was performed to test the hearing acuity of the participating students. The first lab experiment took place in two test chambers where each participant participated individually, and the second was conducted in the Experience room of the SenseLab with four students. In the first experiment, each student was exposed to different sounds and sound levels directly in both ears via earbuds where other 'sound' stressors were eliminated since the student sat alone in the chamber and was facing the wall. Thus, the 'direct' sound exposure experiment is mainly focused on the direct effect of the sound condition on both bodily responses and perceptual assessment. In contrast, the sounds in the 'indirect' sound exposure experiment were produced by a sound-producing system (four speakers) in the ceiling that propagated in the Experience room with the presence of other 'sound' stressors, such as the presence of other students. This study aims to compare whether the bodily responses and perceptual assessments of different sounds differ significantly between the direct and indirect sound exposures. In both experiments, the other factors (lighting, indoor air, and thermal conditions) were kept as constant as possible.

2.2. Participants

Participants comprised bachelor and master students (n=15 in the test chamber with power level 1-β=0.6, and n=14 in the Experience room with power level 1-β=0.6, where β refers to beta which is type II error), from the faculty of Architecture and the Built Environment at Delft University of Technology, in the Netherlands. The power was calculated by conducting a Post hoc analysis by giving effect size=0.5, significance level=0.05, and a sample size of 15 for the first experiment, and 14 for the second experiment) using G*Power software [34]. The power level of 0.6 means that the test has a 60 % probability of correctly rejecting the null hypothesis. Students were asked not to perform any physical exercise before the experiment or smoke or drink coffee, as these activities might affect their bodily responses. Seven were female students and eight were male students. Their mean age was 21 years (standard deviation: 1.5). These students all participated in a previous questionnaire and field study performed by Hamida et al. [32]. That study resulted in five profiles based on acoustical and psychosocial preferences of their study places gathered through a questionnaire. In Fig. 1 the acoustical and psychosocial preferences of these five profiles are presented. Two students per profile (as a minimum) participated in the lab experiments: two students from Profile 1, two students from Profile 2, three students from Profile 3, four students from Profile 4, and four students from Profile 5. Additionally, to better explain both the bodily responses and the perceptual assessments of each student, part of data gathered in that previous study [32] was used, including sound sources and building-related indicators (see Appendix A).

2.3. Bodily responses

Two wearable sensors, an EEG headband (brain activity) and a smartwatch (Fig. 2), were used to measure four bodily responses: 1) attention level (AL); 2) mental relaxation level (MRL); 3) heart rate (HR); and 4) respiration rate (RR). Both HR and RR were chosen because of their possible relation with the anti-stress mechanism and their ease of measurement with smartwatches. AL was assessed to determine how certain sounds affect a student's attention, while MRL was measured to evaluate the effects of different sounds on a student's mental stress (also possibly related to the anti-stress mechanism).

The BrainLink Lite EEG headband by Macrotellect measured AL and MRL using three dry electrodes attached to the participant's forehead. EEG data were processed by the TGAM chipset from NeuroSky [35] and transmitted in real-time to a computer via Bluetooth every half-second using Python code in PyCharm 2023. The data were saved as a CSV file, including attention levels, MRLs, and various brain waves (Delta, Theta, Low-Alpha, High-Alpha, Low-Beta, High-Beta, Low-Gamma, and Mid-Gamma). Both attention and MRL were measured on a scale from 0 to 100.

The Garmin Vivosmart 5 smartwatch monitored HR and RR per minute, known to show good accuracy during low-intensity activity [36]. Since the absolute relative error of the smartwatch showed a lower error on the left wrist compared to the right wrist during a routine activity of daily living [36], students were asked to wear the smartwatch on their left wrist during the experiment. Afterward, the smartwatch was connected to a computer via USB to transfer data using Garmin Express software, and the data were manually transferred to an Excel spreadsheet.

The audiometric test (Fig. 3) was conducted in one of the test chambers of the SenseLab using a clinical audiometer (Otometrics MADSEN Xeta) to answer the first sub-question. A monaural audiometric test with the air conduction method was conducted by producing a sound in different SPLs (starting from 0 dB) at different sound pressure levels (starting from 0 dB) across eight frequencies: 125, 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz. The student sat in front of the examiner, holding a response stick, and clicked the response button upon hearing a sound at each frequency. The examiner recorded the hearing

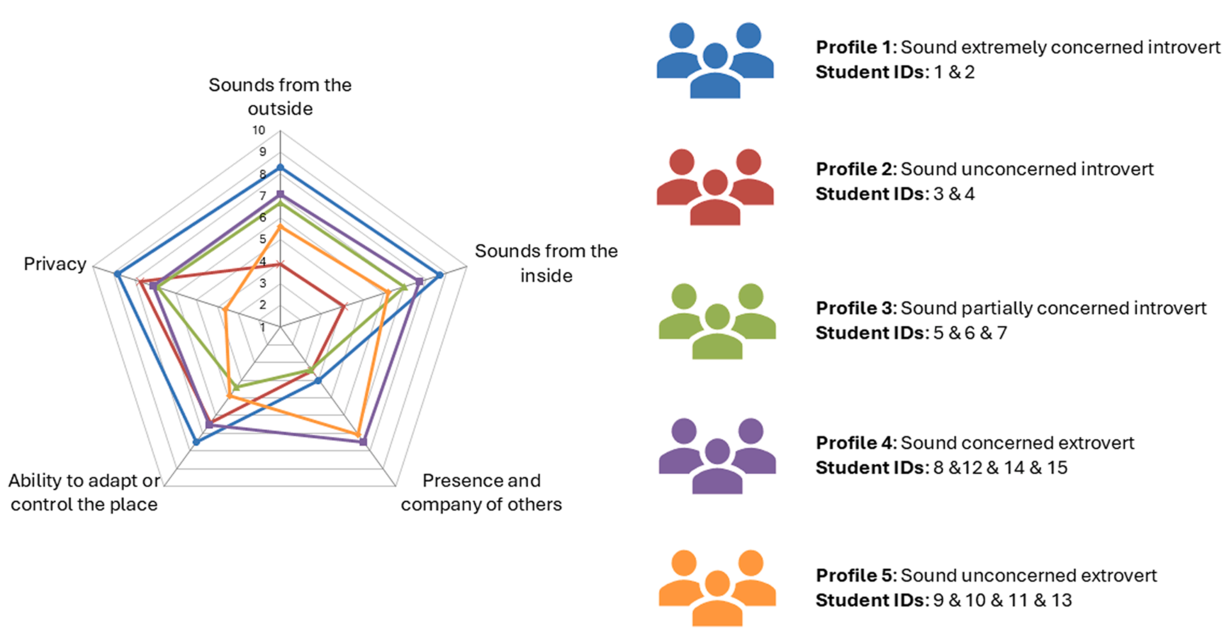

Fig. 1. Five profiles found in a previous study [32] and the participating student IDs. Note: The identified legend colour for each profile was consistently used in several figures throughout the paper.

A. BrainLink Lite EEG device. B. Vivosmart 5 smartwatch.

Fig. 2. Wearable sensor devices for measuring AL, MRL, HR, and RR.

A. Audiogram sheet.
B. Response.
C. Headset.
D. Audiometer.

Fig. 3. The audiometric test set-up using an audiometer.

threshold on an audiogram. The student sat with his/her back to the examiner to avoid visual influences on the test results. The hearing threshold was calculated according to the World Health Organization's (WHO) World Report on Hearing [37]. This involved averaging the minimum SPLs that the student could hear at 500, 1000, 2000, and 4000 Hz in the better ear.

2.4. Perceptual assessments

Perceptual assessments can contribute to a better understanding of an individual's acoustical preferences and needs in a certain context [38]. Therefore, questionnaires were used in the form of analogue scales that are easy and quick to be filled out by participants [39]. During the lab experiment in the test chamber, each student was asked to assess the sound conditions on a continuous scale from (-1) to (+1) based on three aspects: acceptability [40], pleasantness [17,26,41], and stress level [42] (see Appendix B). In the Experience room, students assessed the sound conditions based on two aspects: acceptability on a scale from (-1) to (+1) and noise level [40,43] (i.e., intensity [44]) on a continuous scale from (+1) to (+5) (see Appendix C).

2.5. Experimental setup

Previous lab experiments were carried out in a laboratory setting, such as in an audiometric room [7,16], test chamber [14,45], testing booth [25], or anechoic, semi-anechoic room [17,18,21,22,24] for direct sound exposure. As there is a lack of testing of the bodily responses of different sound types in real situations, this study designed two experimental setups: a laboratory setting in the test chambers (as a direct sound exposure), and a semi-real environment setting in the Experience room (as indirect sound exposure).

2.5.1. Test Chambers

The first sound exposure experiments were conducted in two test chambers (area 2.2*2.4 m^2) of the SenseLab. Each of these test chambers was furnished with a desk and a chair (Fig. 4). A timer device was on the wall in front of the student so that the student could track the lab experiment timeline next to the timer.

2.5.2. The Experience room

The second sound exposure experiment was conducted in the Experience room (area: 6.1*4.2 m^2 and height: 2.7 m) of the SenseLab. The floor is covered with smooth grey linoleum material, the ceiling consists of white acoustic panels, and the walls are made of laminated safety glass and covered with light green sound-absorbing panels. The reverberation time of the Experience room was 0.22 seconds [46]. The Experience room was furnished with eight tables (the top material is made of light wood laminate) and five chairs (Fig. 5); a researcher sat in front of the students to guide them with the test procedure. Each participant sat at one of the chairs in the middle of the room, where the four participants were relatively close.

2.6. Pilot tests

Several rounds of pilot tests with participants who did not take part in the main experiments were performed in October 2023. These tests

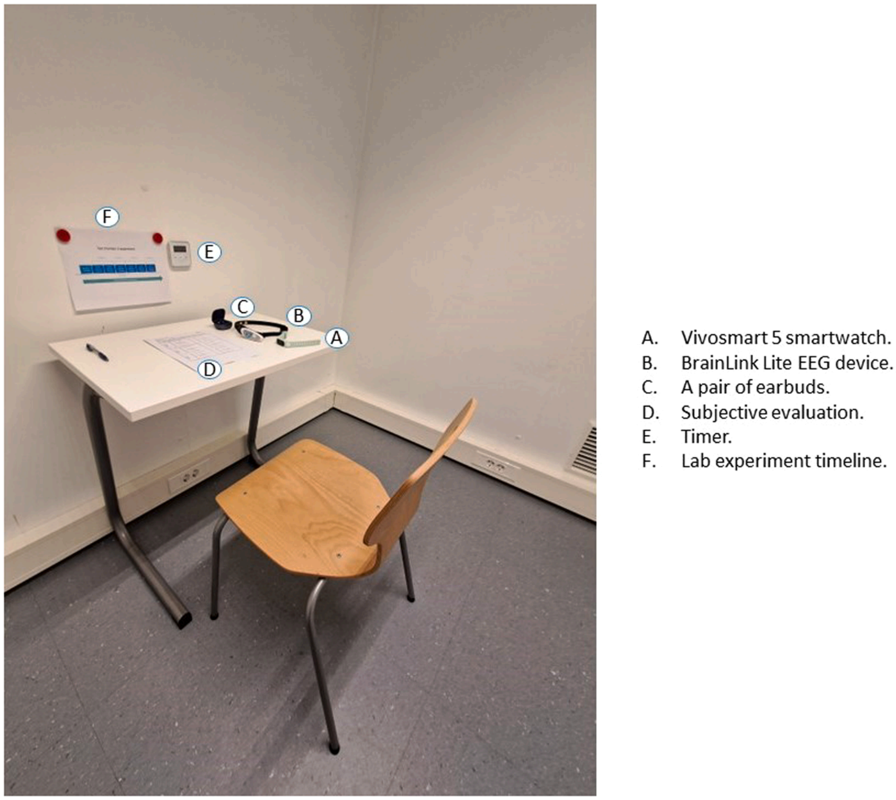

Fig. 4. Test chamber set-up as a labaratory setting.

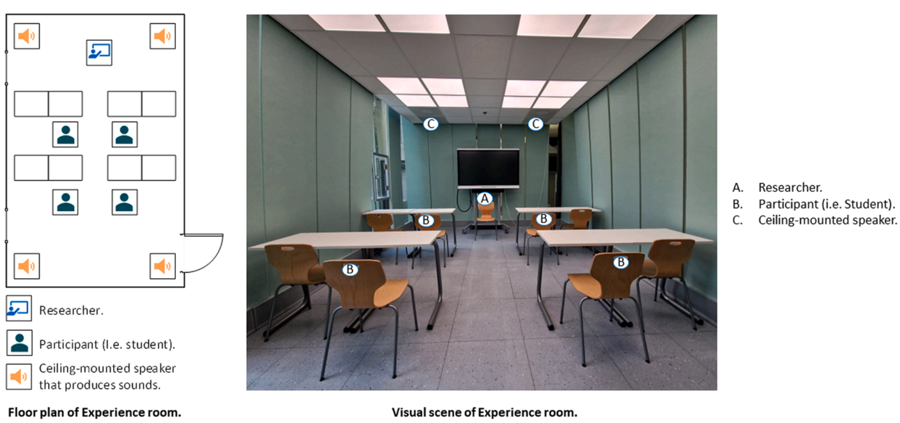

Fig. 5. Set-up in the Experience room as a real room setting.

aimed to select the sound sources, define the most suitable SPLs for each sound and determine the duration of both the baseline and sound exposure times.

- The first pilot test involved three participants to compare four bodily responses during a four-minute baseline and a four-minute break between two sound types: traffic and rural area at high SPLs, as explained in Table 1.

Table 1
Descriptions of the sounds played in both test chambers and the Experience room.

	Sound clip	Frequency (Hz)	Mean SPL (dB(A)) generated from a pair of earbuds		Mean SPL (dB(A)) generated from a the four speakers in Experience room	
			'Low' condition	'High' condition	'Low' condition	'High' condition
Outdoor sounds	Quiet rural area	20–101	22	52	33	48
	City centre area with high traffic	20–20000	38	76	43	58
Indoor sounds	Mechanical ventilation	20–721	45	56	43	53
	People talking (in Dutch)	148–940	39	53	38	58

- In the second pilot test, with four participants, differences in bodily responses within the first and second two minutes of a four-minute baseline, with a two-minute break between low and high SPLs of traffic sounds, were examined.
- In the third pilot test, five participants experienced a two-minute baseline at the beginning. Then, two sound types (rural area and traffic) were played at two SPL levels (low and high), with a two-minute break between the two SPLs of the same sound and between different sound types.
- The fourth pilot test, with three participants, was similar to the third one but the break between different SPLs of the same sound type was eliminated.
- Based on common indoor sounds at students' home study places (Appendix A), two additional sound sources were included: mechanical ventilation and people talking. The SPLs of all four sound types were set to 'bearable' levels (below 100 dB(A) as it is a short-term sound exposure for less than 15 minutes [47]) after discussion with two researchers.
- The fifth pilot test followed the complete experimental procedure with four participants (two participating simultaneously). This included four sound types (rural area, traffic, mechanical ventilation, and talking people sounds), each played at two SPLs, with two-minute baselines, two-minute breaks between different sound types, and a perceptual assessment form.

Based on the results of the first two pilot tests, subtle changes were observed in bodily responses between the first two and the second two minutes of a four-minute baseline and the break period. For example, in the second pilot test, the HR differences among the four participants were less than 5 %, with two participants showing no differences at all. Additionally, the participants indicated that the four-minute baseline was relatively too long. Consequently, the baseline period was shortened to two minutes, as was also done in the study by Park et al. [48].

The outcome of the third pilot test showed that HR differences between the two-minute baseline and the two-minute break, within the same sound type, were minimal (0 % for two participants, and 2 % and 4 % for the others). During the rural sound condition at high SPL with a break in the third pilot test, one participant's HR declined by only 1 %. In contrast, in the fourth pilot test, the HR of participants increased by 7 % during the rural area sound condition at high SPL when there was no break. Therefore, the break between the same sound type but at different SPLs was eliminated due to the observed changes in bodily responses and because participants found the number of breaks too much.

2.7. Sound types and levels

Four sound clips at different frequencies were selected based on the study by Hamida et al. [32] (see Appendix A: sounds identified at students' home study places, preferred and non-preferred sounds), and the pilot tests. Two clips represented outdoor sounds and two represented indoor sounds, covering different frequencies, were downloaded from the online database 'Freesound' [49]: 1) a quiet rural area recorded in the Netherlands (covers low-frequency ranges), 2) a city center with high traffic recorded in the Netherlands (covers most frequency ranges), 3) mechanical ventilation (covers low frequencies), and 4) people talking in Dutch (covers moderate frequency ranges); and compiled into one file using Audacity 3.3.3 software [50]. These four sound clips were recorded monoaurally. The quiet rural area and the city centre area clips were recorded outdoors while the mechanical ventilation and the people talking clips were recorded indoors. The sound signal spectra of the four sound clips are illustrated in Fig. 6.

In the test chambers, the sounds were played through noise-canceling JBL Live Pro 2 earbuds. These were used because they are light on the participant's head since they wearing the BrainLink Lite EEG device. Also, other researchers, such as Guo et al. [51], indicated that earbuds are true wireless stereo devices that can be connected through Bluetooth to a hardware device, such as a computer, and can provide consistent output SPLs when they receive digital audio. In the Experience room as explained by Bluyssen et al. [33], they were played through four ceiling-mounted speakers 'near-midfield studio monitors, three-way, 2*7″ woofer, ADAM Audio A77x' and 'a subwoofer 200 W, 1*10″ MKII, ADAM Audio Sub10' from AMPTEC which are connected to a Behringer UMC404HD audio interface. Each sound clip was played at two different sound pressure levels (SPLs): low and high (Table 1). The SPLs for the earbuds were measured using a calibrated KEMAR dummy head with two Bruel & Kjaer microphones. In the Experience room, the SPLs were determined by using a Norsonic Nor 140 sound level meter and ensuring that the SPL did not exceed 100 dB(A).

2.8. Procedure

2.8.1. Test chambers experiment

The first experiment was divided into two parts, each with a duration of 14 minutes (Fig. 7). The first part focused on the sounds from the outside while the second part focused on the sounds from the inside. Two students participated simultaneously in this experiment, each in one of the test chambers. The researcher gave an introduction to the students outside the test chambers and explained to them the procedure without informing the students about the sound sources. A researcher handed each of the students the measurement devices and the pairs of earbuds. Then each student entered the test chamber, was seated, and after two minutes heard the sentence 'this is the start of the experiment' upon which the student started the experiment by pressing the start button on the timer to track the experiment timeline. Students were asked to assess acceptability, pleasantness, and stress level during each sound condition. After the end of each part, the student heard the sentence 'This is the end of the experiment'. Once the first part was finished, the students were asked to leave the test chamber and move into the other test chamber. They had a 5-minute break in between the two parts.

In the first part of the experiment the students were exposed to four conditions: 1) sounds of a quiet rural area, which were played in two SPLs (low and then high) that each lasted for two minutes, 2) no sounds 1 that lasted for two minutes, 3) sounds of a city centre area with high traffic which was played in two SPLs (low and then high) that each lasted for two minutes, and 4) no sounds 2 that lasted for two minutes. The second part of the experiment consisted again of four conditions, with different sounds than in the first experiment: 1) sounds of mechanical ventilation, which were played in two SPLs (low and then high) that each lasted for two minutes, 2) no sounds 3 that lasted for two minutes, 3) sounds of people talking sounds which was played in two SPLs (low and then high) that each lasted for two minutes, and 4) no sounds 4 that lasted for two minutes.

2.8.2. Experience room experiment

The second experiment, which was conducted in the Experience room, lasted for 24 minutes and consisted of nine conditions and three breaks (Fig. 8). Four students and a researcher were seated in the Experience room. Each student wore the same wearable sensor devices as in the test chamber test.

2.9. Data management and analysis

A dataset for the group as well as a data set for each student was created in an Excel file. Each of the datasets included the average bodily responses (heart rate, respiration rate, attention, and MRLs) of each condition in each experiment as well as the perceptual assessment of each condition. A relative change was calculated to normalised all four indicators by applying the following Eq. (1).

$$\textit{Relative change of abodily response} = \left(\frac{(C1 - C2)}{C2}\right) \times 100 \tag{1}$$

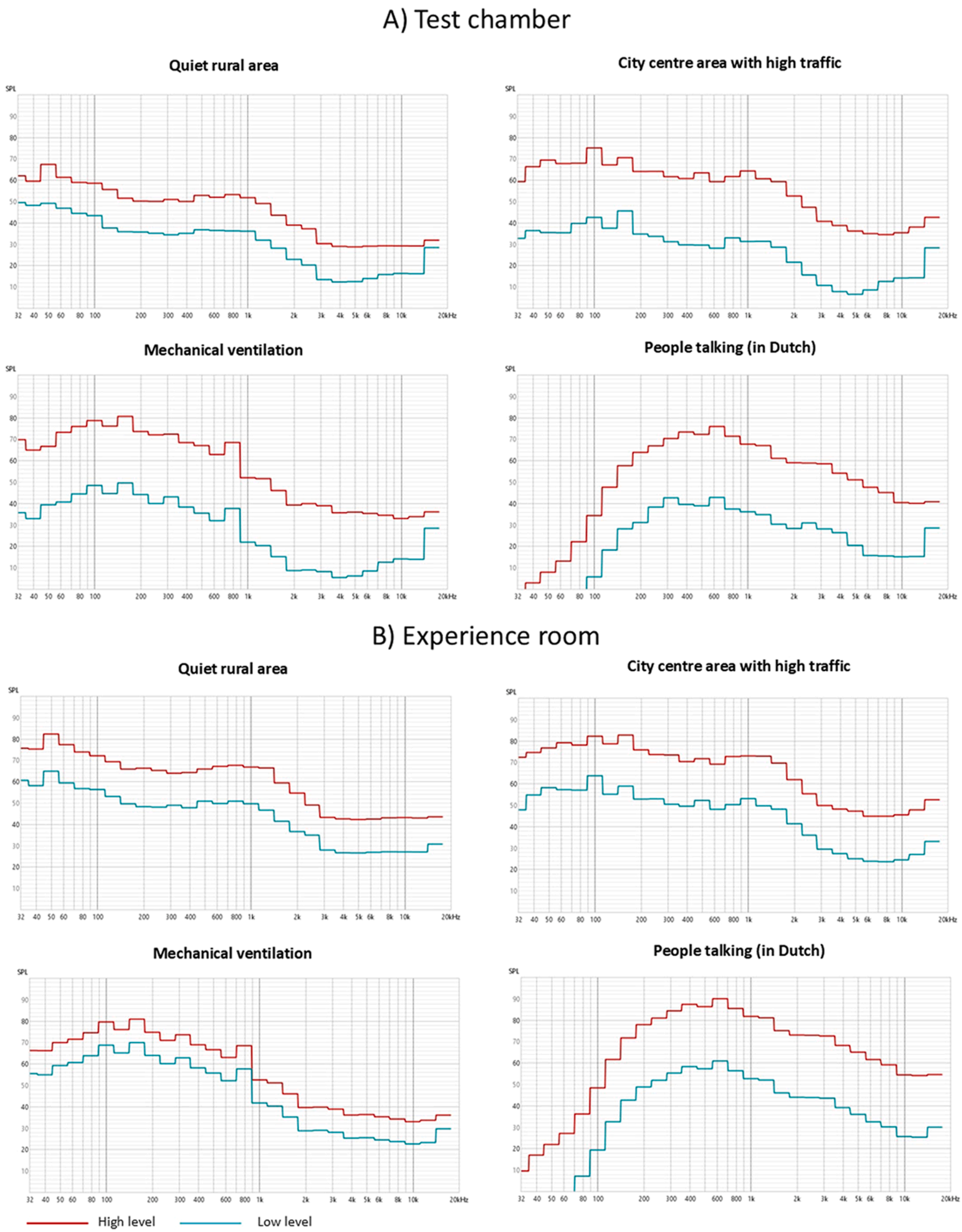

Fig. 6. Sound signal spectra for the four sound clips of the two experiments.

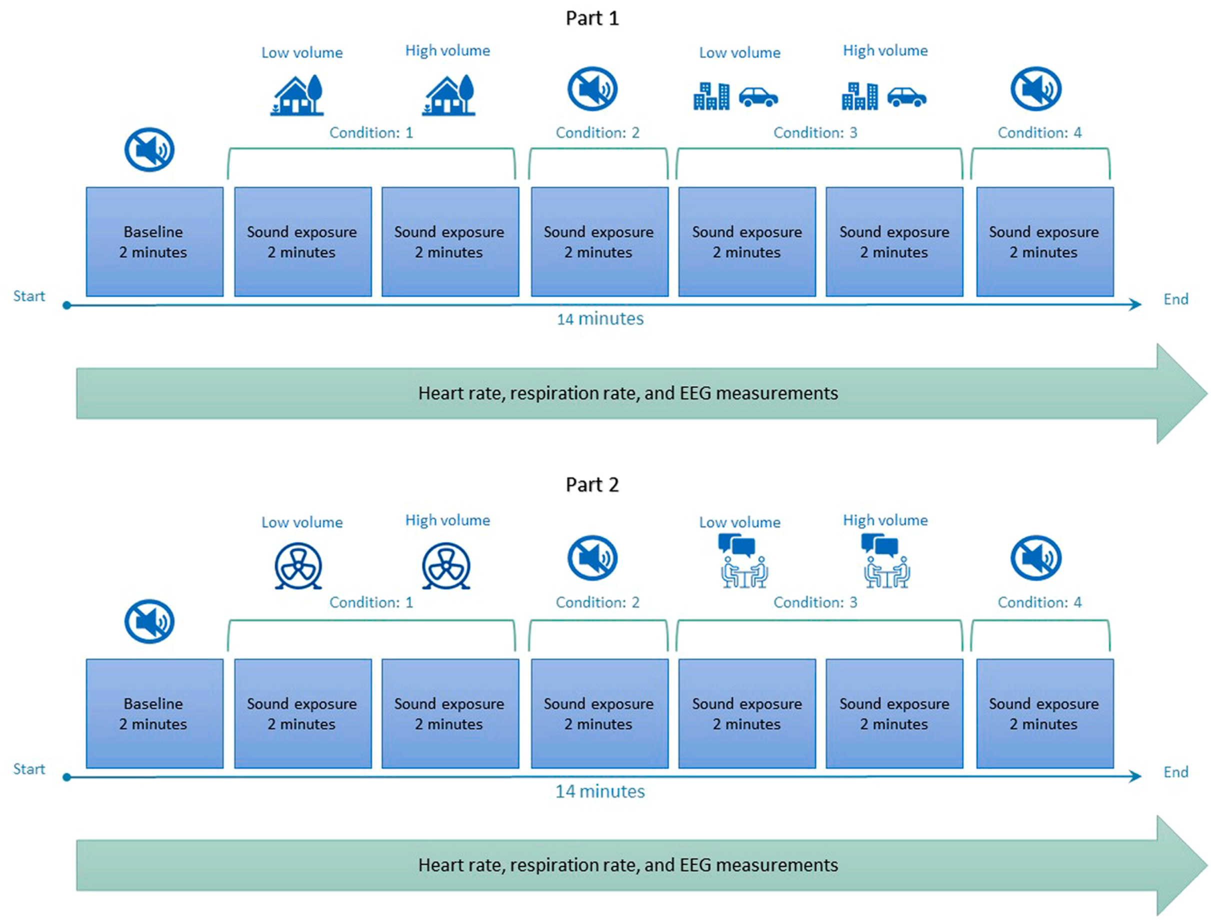

Fig. 7. Experimental procedure in the test chambers.

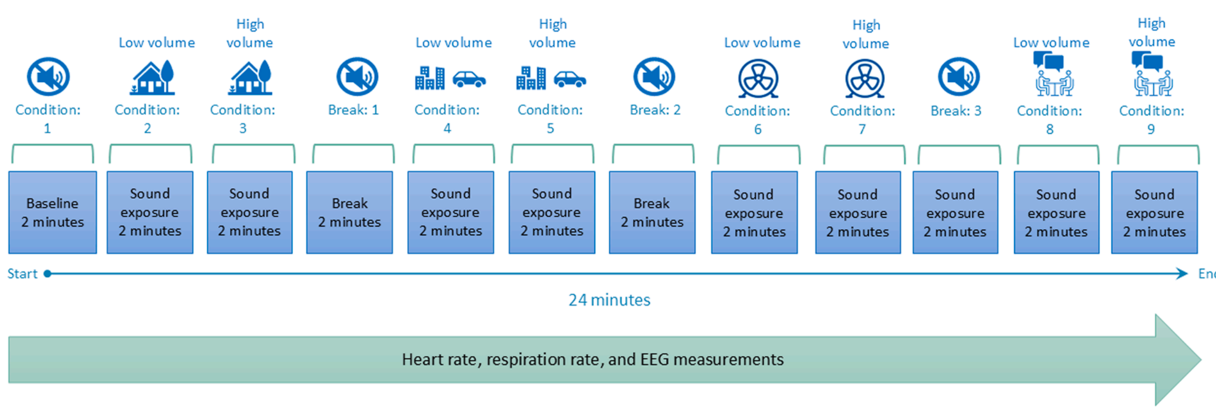

Fig. 8. Experimental procedure in the Experience room.

Where C1=raw bodily response to a sound exposure condition; C2= raw bodily response of a break (i.e., baseline) preceded by the sound exposure condition. Appendix C includes the raw data of both tests at an individual-level.

The average of the perceptual assessments was calculated for the group per condition, while the individual bodily responses were recorded per condition. The continuous scale of the perceptual assessment was measured using a ruler since the scale was printed in 1:1 scale in centimeters (Appendix B). The standard deviation (SD) for both bodily response and perceptual assessment was calculated for the group and per individual among the conditions of each experiment. Spearman's rank-order nonparametric correlation analysis assessed the strength between the bodily response and perceptual assessment. This strength was examined by calculating both the correlation coefficient ($r>0.5$) and the probability (p-value<0.05).

A normality test (Shapiro-Wilk) was performed on the bodily responses of the group among all the conditions of both experiments. Based on that, a two-tailed t-test (for normally distributed bodily responses and perceptual assessment variables) and Wilcoxon signed-rank test(for not normally distributed bodily responses and perceptual assessment variables) were computed to test whether the bodily response and perceptual assessment differed significantly (p-value<0.05) between the two experiments in general and per condition. More specifically, these tests aim to answer the fourth sub-question by exploring whether bodily responses significantly differ when the sound was directly exposed in the student's ears as compared to indirect sound exposure. This answer explores the potential of considering bodily responses in real environmental settings (e.g., real study places).

2.10. Ethical aspects

This study (application ID:3555) was approved by the Human Ethics Committee (HREC) of Delft University of Technology on the 15th of November 2023.

3. Results

3.1. Audiometric tests

In Fig. 9, the outcome of the audiometric tests is presented per student. According to the WHO test [37], all students had normal hearing in both ears, except for two (students 1 and 6) who suffered from mild hearing loss. Additionally, several students suffered from mild hearing loss in low frequencies (between 125 and 250 Hz). More specifically, the hearing threshold of students 3, 4, 6, 10, 11, and 13 of 125 Hz was higher than 25 dB, meaning that they have mild hearing loss at that low frequency sound. However, most of them could hear the highest frequency (8000 Hz) in the low SPL with at least one of their ears.

3.2. Bodily responses

3.2.1. Bodily responses in the test chambers

The averaged responses of the 15 students to the four indicators during the eight sound conditions of the experiments in the test chambers are presented in Fig. 10. In general, these four indicators fluctuated during the different sound conditions. AL increased mostly during the 'high rural' and 'high talking people' conditions by 15 % and 14 %, respectively. MRL increased mostly during the 'low rural' and 'low traffic' conditions by 6 % and 5 %, respectively. HR decreased mostly during the 'high ventilation' and 'low ventilation' conditions by 11 % and 10 %, respectively. RR increased mostly during the 'low traffic' condition (2 %).

At individual-level, the four bodily responses differed among the 15 participants in the test chambers (see Fig. 11). Also, bodily responses of several participants differed from the average of the group. Examples:

- AL decreased the most during both 'low rural' and 'high rural' conditions for students 2, 8, 10, and 12.
- MRL decreased the most for students 1, 3, 4, 8, 10, and 13 during 'low rural' and 'high rural' conditions, while for students 3, 14, and 15 MRL decreased the most during the 'high traffic' condition.
- HR increased the most during the 'high rural' condition for students 6, 9, and 15. RR increased the most during the 'high rural' condition for students 1, 6, and 7.
- RR increased the most during the 'high ventilation' condition for students 7, 8, and 14.

3.2.2. Bodily responses in the Experience room

Fig. 12 shows the average percentage of change of the four bodily responses of the 14 students among the eight conditions in the Experience room. AL declined during all eight conditions, especially during the 'high traffic', 'high talking people', 'low traffic', and 'low talking people' by 14 %, 11 %, 11 %, and 9 %, respectively. In contrast, MRL increased during most of the conditions, especially during the 'high ventilation', 'high traffic', and 'low talking people' by 10 %, 9 %, and 9 %, respectively. RR increased mostly during the 'low ventilation' and 'high ventilation' conditions, 5 % and 4 % respectively.

The four bodily responses differed among the 14 participants within the eight conditions in the Experience room (see Fig. 13). In addition, the bodily responses of several participants differed from the average of the group. Examples:

- AL increased the most during the 'high ventilation' condition for five students (4, 11, 13, 14, and 15).
- MRL decreased the most for four students (2, 4, 11, and 14) during the 'high talking people' condition.
- HR increased the most during the 'high rural' condition for three students (3, 5, and 6).
- RR increased the most during the 'high rural' condition for four students (2, 6, 9, and 14).

3.2.3. Differences in bodily responses between the two experiments

The normality test (Shapiro-Wilk) of the bodily responses showed that all bodily responses were normally distributed, except for MRL, which was not normally distributed in the Experience room ($p=0.01$). Therefore, a *t*-test was performed for all bodily responses, except for MRL of which a Wilcoxon signed-rank test was computed to test the differences between the bodily responses of the 14 students who participated in both tests, in general and per condition. The differences between the mean bodily responses showed that only AL significantly differed between the two tests ($p<0.001$), while other bodily responses: MRL ($p=0.16$), HR ($p=0.33$), and RR ($p=0.54$) showed no significant differences. Table 2 shows the results of the differences between the bodily responses of the 14 students per condition between the two tests. AL significantly differed between the two experiments of three conditions: 'low traffic', 'high traffic', and 'low talking people' while the MRL only differed significantly among the 'low rural' condition. HR also differed significantly between the two experiments of three conditions: 'low ventilation', 'high ventilation', and 'low talking people'. RR showed no significant differences between the two tests among the eight conditions.

Table 3 presents the differences in the bodily responses at individual-level. AL significantly differed between the two tests among seven students. MRL showed significant differences between the two tests among three students. HR significantly differed among two students only. Conversely, RR showed no significant differences between the two tests among all 14 students.

3.3. Perceptual assessment

3.3.1. Perceptual assessment in test chambers

Fig. 14 shows the average scores of three perceptual assessments for eight different conditions in the test chambers among the 15 students. It was observed that 'low rural', 'low traffic', and 'low ventilation' were the most acceptable conditions. Conversely, the 'high talking people' was perceived as the least acceptable, the least pleasant and the most stressful condition. The 'low traffic' condition was considered the most pleasant condition. Furthermore, 'low rural', 'high rural', 'low traffic', 'low ventilation', and 'low talking people' were perceived as the least stressful condition. The perceptual assessment of the eight conditions in the test chambers varied among the 15 students as shown in Fig. 15, showing several differences among the 15 students from the different profiles.

3.3.2. Perceptual assessment in the Experience room

Fig. 16 shows the average of the two perceptual assessments of the eight conditions in the Experience room for the 14 students. 'Low rural', 'low traffic', and 'low ventilation' were perceived as the most acceptable and the least noisy conditions. 'High talking people' and 'high ventilation' were perceived as the least acceptable conditions; and both 'high traffic' and 'high talking people' were perceived as the most noisy conditions. Fig. 17 shows the two perceptual assessments of the eight conditions in the Experience room at individual-level, showing some differences among the 14 students.

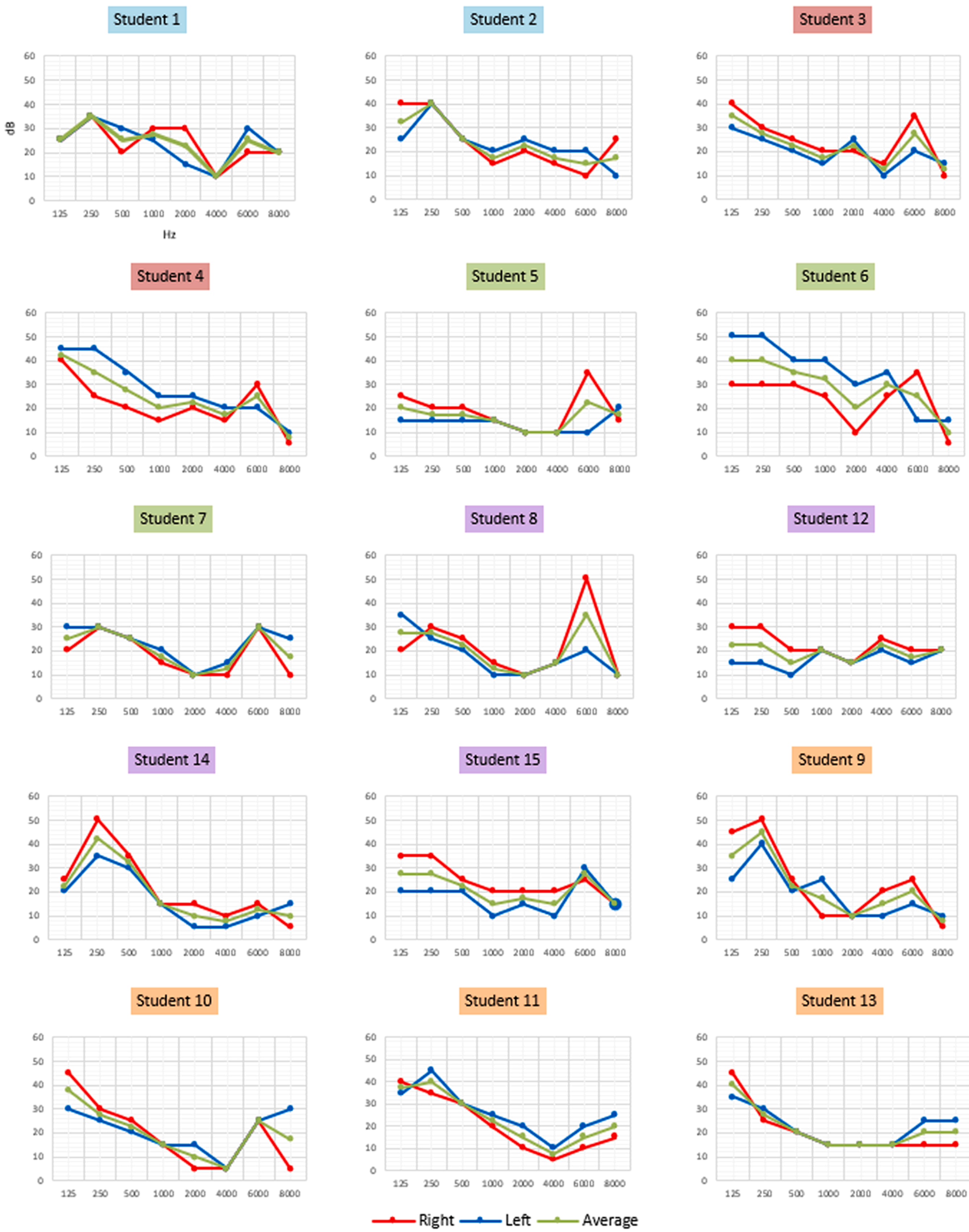

Fig. 9. The outcome of the audiometric test for each student.

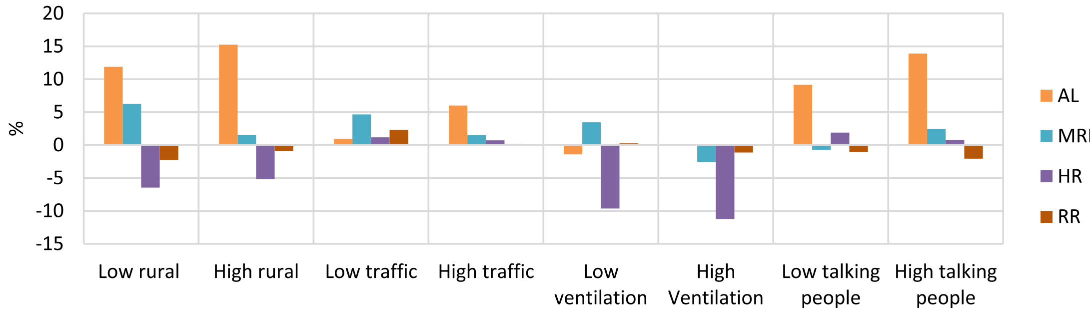

Fig. 10. Percentage of change in bodily responses of the group-level in the test chambers.

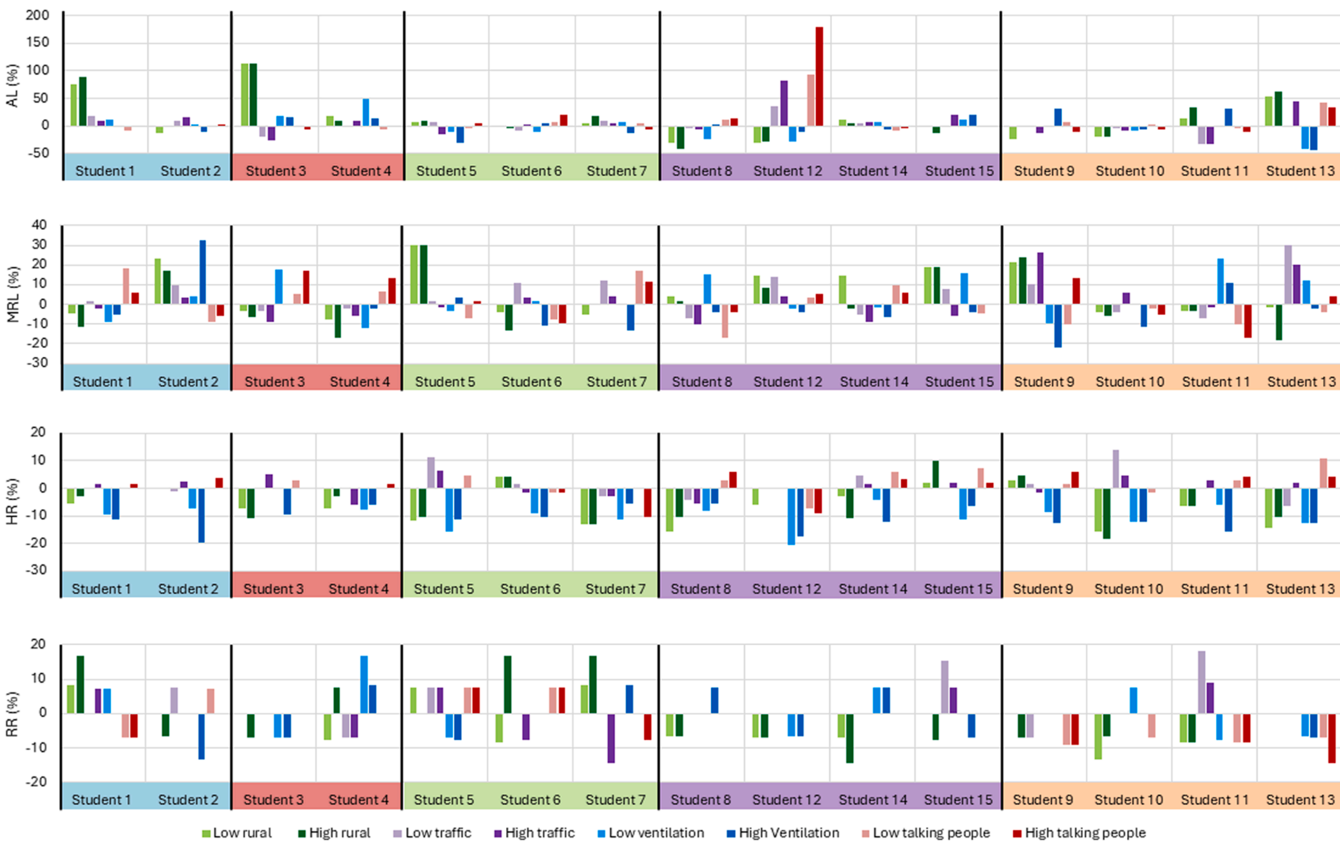

Fig. 11. Percentage of change in bodily responses per student in the test chambers.

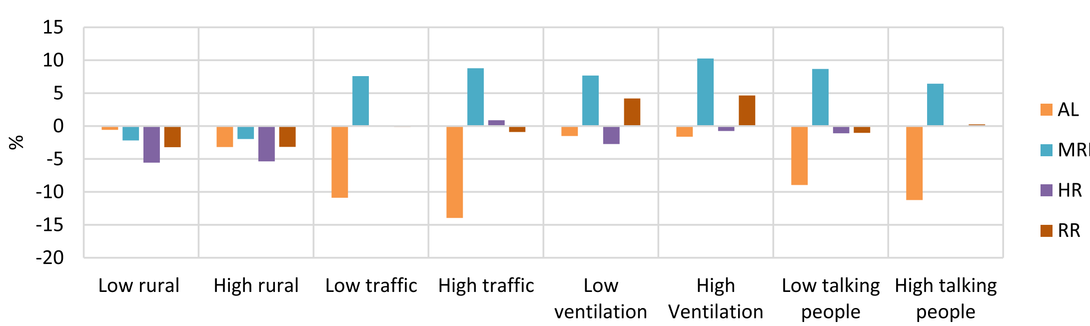

Fig. 12. Percentage of change in bodily responses of the group in the Experience room.

3.3.3. Differences in the perceptual assessment between two experiments

The means of the acceptability level among the eight conditions perceived by the 14 students showed no significant differences between the two experiments (p=0.12). The acceptability of 'high traffic' differed significantly between the two experiments (p=0.05). Other conditions showed no significant differences (Appendix D). The mean of the acceptability levels among the eight conditions between the two experiments at individual-level differed significantly for seven students:

Fig. 13. Percentage of change in bodily responses per student in the Experience room.

Table 2
The probability of differences in the bodily responses between two experiments per condition at group-level.

Condition	AL	MRL	HR	RR
Low rural	0.28	**0.05**	0.95	0.56
High rural	0.19	0.31	0.76	0.57
Low traffic	**0.03**	0.73	0.90	0.26
High traffic	**0.03**	0.11	0.79	0.72
Low ventilation	0.95	0.68	**P<0.001**	0.08
High Ventilation	0.85	0.32	**P<0.001**	0.12
Low talking people	**0.02**	0.15	**0.03**	0.86
High talking people	0.10	0.93	0.65	0.40

Table 3
The probability of differences of the bodily responses between two experiments at individual-level.

Profile	Student	AL	MRL	HR	RR
1	1	0.14	0.96	0.67	0.16
	2	0.77	**0.02**	0.72	0.98
2	3	**0.006**	**0.04**	0.20	0.25
	4	0.61	0.51	0.61	0.25
3	5	0.51	0.53	0.28	0.60
	6	**0.03**	**0.05**	0.15	0.59
	7	0.23	0.16	**0.004**	0.42
4	8	**P<0.001**	0.06	**0.04**	0.69
	12	0.08	0.09	0.56	1.00
	14	**P<0.001**	0.80	0.53	0.82
	15	**P<0.001**	0.08	0.36	0.67
5	9	**P<0.001**	0.58	0.15	0.91
	11	**P<0.001**	0.95	0.53	0.31
	13	0.21	0.47	0.65	0.17

student 3 (p=0.05), student 6 (p=0.03), student 7 (p=0.01), student 8 (p=0.04), student 13 (p=0.01), student 14 (p=0.03), and student 15 (p=0.01).

3.4. Correlations between bodily responses and perceptual assessments

3.4.1. Correlations between responses in the test chambers

The results of the correlations between each of the four bodily responses and three perceptual assessments at group-level are shown in Table 4. No strong nor significant correlations between the three bodily responses AL, HR, and RR and the three perceptual assessment were found. MRL showed strong and positive but not significant correlations with acceptability, pleasantness, and stress level.

The correlations between the four bodily responses and the three perceptual assessments in the test chamber at individual-level differed among the students (see Appendix E).

3.4.2. Correlations between responses in the Experience room

Table 5 shows the correlations between each of the four bodily responses with the two perceptual assessments at group-level. AL was strongly, positively, and significantly correlated with both perceptual assessments: acceptability and noise level. HR showed a strong and negative as well as a significant correlation with noise level, meaning that HR increased when the condition was perceived as a loud noise. In addition, HR was strongly and negatively correlated with acceptability, although this correlation was not statistically significant. MRL and RR did not show strong nor significant correlations with the two perceptual assessments.

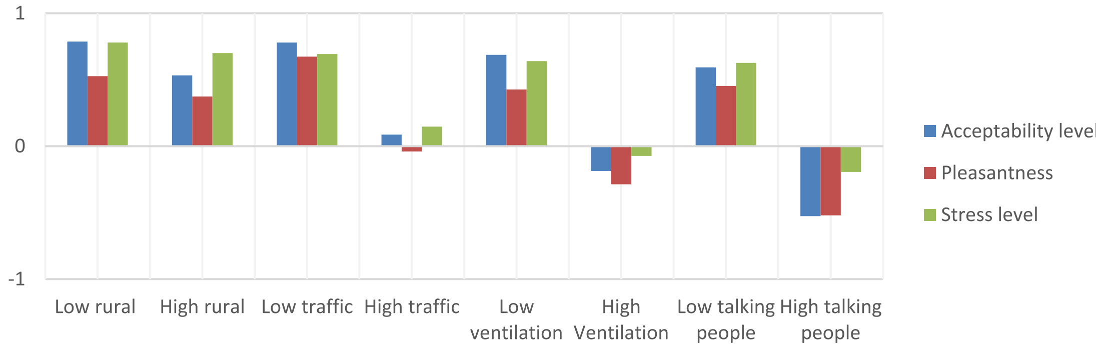

Fig. 14. Average perceptual assessments of the group during the eight conditions in the test chambers.

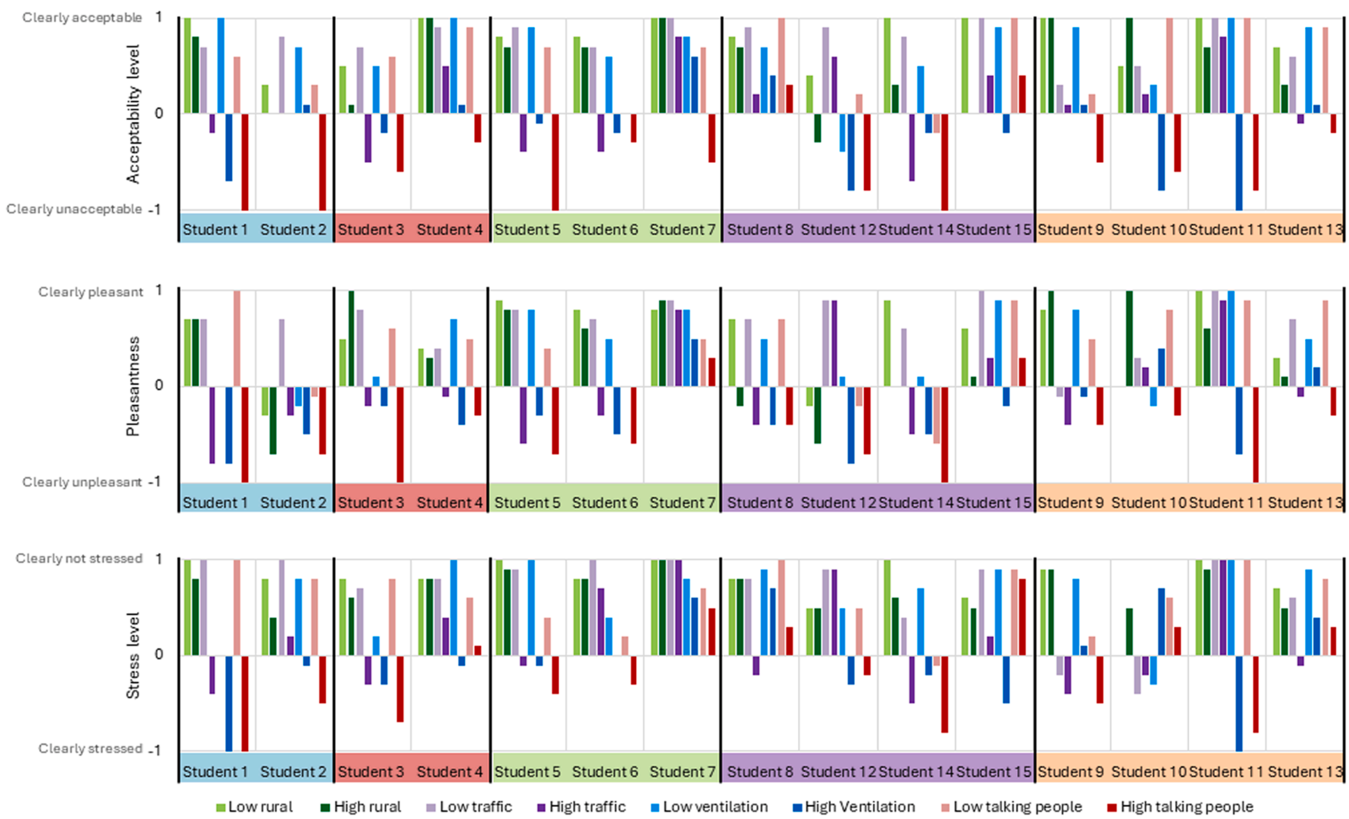

Fig. 15. Perceptual assessments per student in the test chambers.

4. Discussion

4.1. *Key findings*

In the present study, it was investigated which bodily responses can be measured to explain differences in preferences and/or needs of university students from different profiles while being exposed to different sounds in two settings. Four main findings are discussed below: the audiometric test, the perceptual assessments of the different profiles, correlations between bodily responses and perceptual assessments, and direct and indirect sound exposure.

4.1.1. *The audiometric test*

Six students (3, 4, 6, 10, 11, and 13) suffered from mild hearing loss in low-frequency sounds (Fig. 8). Interestingly, these students belong to the profiles who are sound partially concerned or sound unconcerned (students 3 and 4 are sound unconcerned introverts, student 6 is a sound partially concerned introvert, and students 10, 11, and 13 are sound unconcerned extroverts). Moreover, student 6's HR increased the most while being exposed to the low-frequency sound stimuli: the 'low rural' condition in the test chamber's experiment but found it most acceptable. Similarly, student 13, had the highest HR increase in the same condition in the Experience room's experiment but perceived it as slightly noisy and acceptable. These observations could mean that even though the student could not hear the sound source at a certain SPL, the body responded physiologically. Mackersie et al. [23] highlighted that participants with hearing loss may experience increased effort and stress during speech recognition in noisy environments, which could influence the psychophysiological responses concerning the autonomic nervous system. This might explain the increased HR in students 6 and 13, who likely expected to hear a sound during the 'low rural' condition but did not, leading to stress and a rise in HR. Therefore, hearing acuity seems an essential indicator to consider in sound exposure experiments that could explain a person's acoustical preferences and needs.

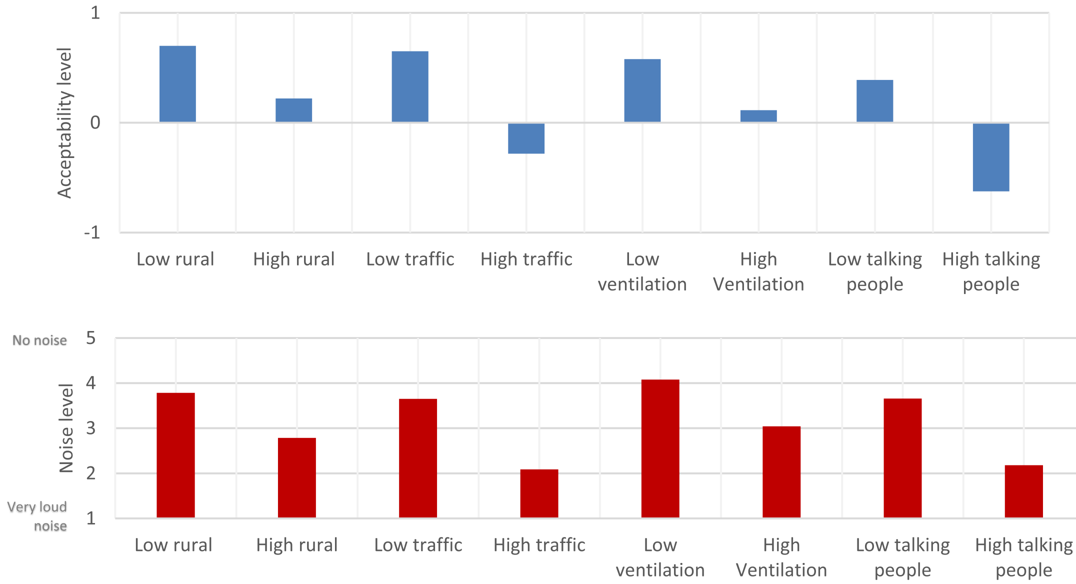

Fig. 16. Average perceptual assessments of the group in the Experience room.

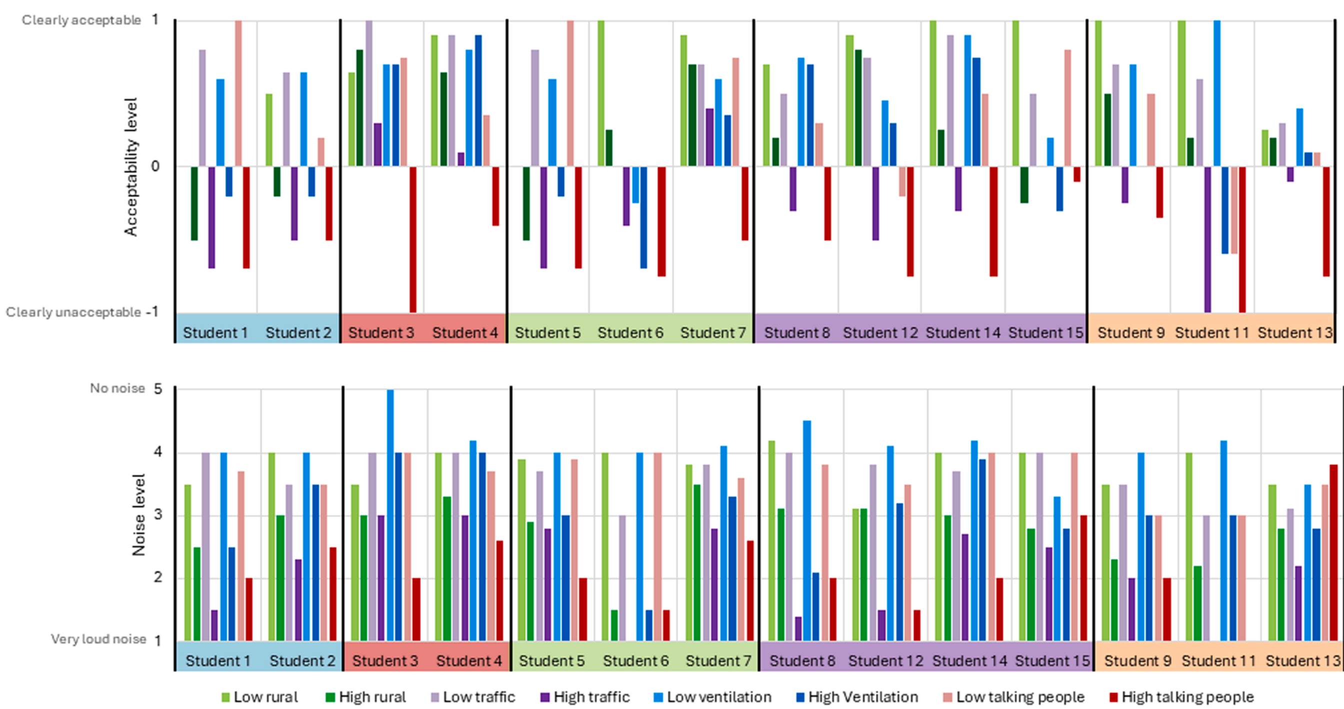

Fig. 17. Perceptual assessments per student in the Experience room.

4.1.2. *Perceptual assessments and the five profiles*

Several differences in perceptual assessments were observed at group, individual, and profile levels. For example, in the test chamber (as illustrated in Fig. 15), six students (1, 3, 5, 6, 13, and 14) deemed the 'high traffic' condition as unacceptable, noting that four of these students are from profiles 1, 3, and 4 who are sound concerned. In terms of pleasantness, students 2, 8, and 12 (from profiles 1 and 4) perceived the 'high rural' condition as unpleasant, confirming that these students are sound concerned. Conversely, five students (7, 10, 11, 12, and 15) found the 'high traffic' condition as pleasant. Interestingly, these students are exposed to traffic sounds at their home study place (Appendix A), which might result in the habituation of this sound type. Another example, concerning stress levels, six students (4, 7, 8, 10, 13, and 15) perceived the 'high talking people' condition as not stressful, of which four of them belong to the extrovert profiles: 4 and 5. Pertaining to the perceptual assessments in the Experience room (Fig. 17), both students 1 and 2 who belong to the 'sound extremely concerned introvert' profile perceived the 'high rural' condition as unacceptable, which confirms that these two students are extremely sound concerned. Hence, these findings substantiate the conclusions of Hamida et al. [32]: students from different profiles differ in their acoustical preferences.

4.1.3. *Correlations between bodily responses and perceptual assessments*

Bodily responses did not show strong or significant correlations with perceptual assessments at the group-level in the test chamber experiment, except for MRL. Although MRL showed a strong and positive

Table 4
Correlations between bodily responses and perceptual assessments in the test chambers at group-level.

Bodily responses vs perceptual assessments	R	P-value
AL vs Acceptability	−0.2	0.69
AL vs Pleasantness	−0.1	0.74
AL vs Stress level	0.2	0.65
MRL vs Acceptability	**0.7**	0.06
MRL vs Pleasantness	**0.6**	0.14
MRL vs Stress level	**0.6**	0.10
HR vs Acceptability	0.0	0.91
HR vs Pleasantness	0.3	0.49
HR vs Stress level	−0.1	0.87
RR vs Acceptability	0.2	0.57
RR vs Pleasantness	0.3	0.42
RR vs Stress level	0.1	0.74

Table 5
Correlations between bodily responses and perceptual assessments in the Experience room at group-level.

Bodily responses vs perceptual assessments	R	P-value
AL vs Acceptability	**0.6**	**0.03**
AL vs Noise level	**0.8**	**P<0.001**
MRL vs Acceptability	−0.4	0.22
MRL vs Noise level	−0.2	0.57
HR vs Acceptability	**−0.5**	0.10
HR vs Noise level	**−0.6**	**0.04**
RR vs Acceptability	−0.4	0.25
RR vs Noise level	0.0	0.89

The correlations between the four bodily responses indicators and the two perceptual assessments differed among the 14 students (see Appendix F).

correlation with the three perceptual assessments, this correlation was not statistically significant. At the individual-level, only two students (students 6 and 12) displayed a strong and positive correlation between their MRL and acceptability. Additionally, student 6's MRL was strongly, positively, and significantly correlated with pleasantness. Conversely, student 4's MRL was strongly and significantly, but negatively, correlated with the perceptual stress level. Since MRL is not significantly correlated with perceptual assessments, it could be used as an independent bodily response alongside the other three bodily responses which did not show strong nor significant correlations, separate from perceptual assessments.

In the Experience room experiment, AL was strongly, positively, and significantly correlated with both acceptability and noise levels at group-level. It implies that when the sound condition was perceived as 'acceptable' and 'no noise', AL increased, and vice versa. Similarly, for individual students 6 and 7, AL showed strong, positive, and significant correlations with acceptability perceptual assessments. Furthermore, student 8's AL was strongly, positively, and significantly correlated with the perceived noise level. Additionally, HR was strongly, negatively, and significantly correlated with noise levels during the Experience room experiment at group-level: HR increased as the noise level was perceived as loud of which SPL was set at a high level. This finding aligns with Lorenzino et al. [52], who concluded that noise levels ranging from 30 to 55 dB(A) significantly impacted acoustical comfort, with higher noise levels correlating with increased HR and psychological discomfort. It also corroborates Abbasi et al. [14], who found that HR significantly differed among various sound levels of low-frequency noise. Moreover, Latini et al. found a strong association between pulse rate and soundscape response of which the pulse rate decreased with perceived pleasant sounds and increased with perceived unpleasant sounds [53]. Thus, HR is a significant bodily response indicator associated with the noise level and sound type (i.e., soundscape).

In summary, the four bodily responses are generally independent of the perceptual assessments. This indicates that perceptual assessments cannot be reliably predicted from bodily responses, nor can bodily responses be predicted from perceptual assessments. This also confirms the study by Erfanian et al. [54] that soundscape studies should consider both bodily responses and perceptual assessments (i.e., psychological) to understand better how and why individuals experience the sound environment in such way. However, our study shows that HR is an exception, as it can explain the perceptual assessment related to the perception of the noise level corresponding to the SPL as a physical indicator. In addition, AL is an exception that could explain both acceptability and noise level.

4.1.4. Direct sound exposure vs indirect sound exposure

The present study compared bodily responses and perceptual assessment between two experimental settings: direct sound exposure (laboratory setting in the test chambers) and indirect sound exposure (semi-real life setting in the Experience room). At group-level, the mean AL among the eight conditions varied significantly between the two experiments, particularly under the 'low traffic', 'high traffic', and 'low talking people' conditions. These significant changes were also observed at individual-level for seven students. Conversely, the acceptability assessments did not show significant differences between the two experiments. Given the significant differences in AL between the two experiments at both group and individual levels (among seven students), it appears that this bodily response might be affected by the differences in the experimental setup between the two experiments. Additionally, MRL differed significantly between the two experiments among three students and differed in the first condition 'low rural' at group level, which showed decreases in the second experiment. These differences might be linked to the experimental procedure. It can be also noted that the sound exposure time for both experiments lasted two minutes per condition. Thus, both AL and MRL could be more reliable bodily responses for longer sound exposure durations, such as 5 [14,51] or 10 min [7]. Furthermore, these two bodily responses could be measured in sound exposure experiments that involve performance tasks, such as testing mental fatigue [14] or attention based on a cognitive task [7], which could explain differences in performances. Both HR and RR showed no significant differences between the two experiments at group level. However, HR did show significant differences under 'low ventilation' and 'high ventilation' conditions with a greater decrease observed in the first experiment. This difference may be related to the fact that the student moved between chambers prior to these two conditions. Also, significant HR differences were only observed in two individual students. Moreover, HR was significantly correlated with the noise level. Therefore, HR and RR seem applicable for explaining differences in acoustical preferences and needs within short-term sound exposure experiments. These two bodily responses can be measured in real-life situations, such as a study place, since no differences were observed between the two experiments as well as they were normally distributed among students in both experiments.

4.2. Strengths and limitations

This study represents a first attempt to investigate university students' bodily responses and perceptual assessments, accounting for their varying acoustical and psychosocial preferences and needs, across multiple levels: group, individual, and profile levels. Through lab experiments, it enhanced the understanding of students' acoustical preferences, previously classified into five profiles [32]. Another notable strength of this study is the audiometric test conducted with 15 students, in which hearing thresholds at different frequencies (for both ears) were examined, based on the WHO guidelines [37]. Additionally in this study, bodily responses and perceptual assessments in two distinct settings were compared: a laboratory setting in test chambers and a semi-real life setting in the Experience room.

Despite the novel contributions of this study, it has some limitations. First, the sample size is relatively small, comprising 15 students (power:

1-β=0.6) from the Faculty of Architecture and the Built Environment, all of whom had participated in a previously conducted study [32]. Second, the distribution of students across the five profiles was uneven, though a minimum of two students per profile were included. Third, one student (student 10) did not participate in the Experience room experiment, reducing the sample size for the comparative analysis to 14 students. While perceptual assessments supported the acoustical preferences associated with each profile, the small sample size limits the generalisation of these findings. Fourth, the measured SPL of the same sound type differed between the earbuds (direct exposure) and the speakers (indirect exposure) which might be related that sounds in the Experience room diffused and absorbed within the room. Fifth, the sound conditions of both experiments were not randomised among the different groups of students due to the small sample size per group (3 or 4 students) and only four groups. Finally, the bodily responses data were calculated as mean values for the two-minute exposure time rather than the real-time measurements per second due to the limitations of the Garmin smartwatch that exports the HR and RR data per two-minutes.

4.3. Implications and future research

The interpretation of the key findings of this study (as detailed in Section 4.1) provides insights for future researchers in the design and set-up of sound exposure experiments aimed at investigating participants' bodily responses to and perceptual assessments of sounds.

First, the audiometric test is a critical procedure with the potential to elucidate participants' bodily responses and perceptual assessments when exposed to specific sound types. Second, profiling participants (e.g., students) based on their acoustical preferences could provide a clear understanding of their perceptual assessments of different sounds. Third, HR and RR are reliable and robust indicators of bodily responses that can be effectively measured using simple wearable devices, demonstrating clear reactions to short-term sound exposure. Lastly, given the lack of strong or significant correlations between bodily responses and perceptual assessments, it is imperative to consider both independently in sound exposure research.

Because of the sample size limitations as this is a follow-up study of a specific pool of students, it is recommended for future research to recruit at least 26 students per profile (of which the power level is 1-β=0.8, as indicated by Park et al. [48]). This could better present the results per profile rather than per individual, such as performing the correlations between the bodily responses and perceptual assessments per profile and testing whether the profile is a significant variable. Furthermore, it is recommended for future sound exposure experiments to randomise the sound conditions to acquire comprehensive results in explaining how bodily responses can be used to explain differences in sound perceptions and preferences. Given the fact that the HR and RR showed no significant differences between the two experiments, it is encouraged to also measure them in a real-life situation, such as a real study place.

5. Conclusion

This study conducted two sound exposure experiments with 15 university students from five profiles who differ in their acoustical preferences of their study places. Each experiment included four bodily responses (AL, MRL, HR, and RR) and five perceptual assessments (acceptability, pleasantness, stress level, and noise level), while students were exposed to four sound types varying in frequencies and SPLs in two different settings. The key findings are summarised as follows:

1. The relationship between hearing acuity and bodily responses (such as HR) and sound perception seems to be essential for better understanding how our body responds to sound. It was observed that although students suffered from mild hearing loss in low frequency, their bodies physiologically responded when they were exposed to a low-frequency sound condition.
2. The outcomes from this study showed that the perceptual assessment in a lab experiment setting confirmed the acoustical preferences of the five profiles of university students.
3. This study found that both HR and RR were not strongly nor significantly correlated with perceptual assessments during direct sound exposure in the test chamber. HR was strongly and significantly related to the perceptual assessment of noise level in the Experience room.
4. Both HR and RR showed no significant differences between the two experiments of this study. This implies that they are reliable for explaining acoustical preferences and can be measured in real environments as well since they showed no differences between the two settings: a laboratory setting in test chambers and a semi-real life room setting in the Experience room. In contrast, AL and MRL were affected by the experimental setting and procedure in this study, which could be more reliable for a longer sound exploration of experiments and/or involve performance tasks.

CRediT authorship contribution statement

Philomena M. Bluyssen: Writing – review & editing, Supervision, Methodology, Conceptualization. **AnneMarie Eijkelenboom:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Alessandro D′Amico:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Amneh Hamida:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix A
Home study place characteristics of the students.

Student (profile)	Building type			Home study place location				Sound sources at home study place		Sound is noise	Sound source preference
	Student housing	Private housing with roommate (s)	Private housing with parents	Private studio	Private bedroom	Private office room	Shared living room	From outside	From inside		
1(1)	X			X				-Construction -Truck loading	-Mechanical ventilation	-Continuous sounds	-Silence -People studying at the library -Music
2(1)	X			X				-Doorbell from the other building -Truck loading	-Footsteps from neighbours upstairs -Refrigerator	-Distracting sounds -Not constant sounds -Loud sounds	-Music -Winds sounds -Rain sounds
3(2)	X				X			-Nearby school in the morning -Winds	-People talking in the living room	-Distracting sounds -Noticeable sounds -Not normal sounds -Vacuum sounds -Loud sounds	-Music -people walking sounds
4(2)		X				X		-Traffic (cars)	-Radio -People talking in the living room	-Louds sounds (e.g., washing machine)	-Music
5(3)			X		X			-Birds -Traffic sounds in previous home study place	-People talking in the living room -TV -Washing and drying machines	-Louds sounds (e.g., vacuum machine)	-Quiet sound environment -Rain sounds
6(3)			X		X			-Birds - People playing at the soccer field (when the window is opened) - Neighbour sounds from the garden (only during summer when the window is opened)	-People talking in the living room	-People sounds	-Quiet sound environment
7(3)		X			X			-Café' -Birds -Electric saw -Traffic (cars, tram) -Sirens	-Neighbours talking	-Continuous sounds (too long sound duration) -Neighbours talking -Electric saw sounds	-Music (piano) -Listening to podcast
8(4)			X		X			-Winds and rain when the window is opened -Traffic (cars) when the window is opened -Children playing outside when the window is opened	-People talking in the same house -Washing and drying machines -Parot talking	-When student's mood is negative, all sounds are considered noise -Inconstant sounds	-Music (piano and with known lyrics)

(continued on next page)

Appendix A (*continued*)

Student (profile)	Building type			Home study place location				Sound sources at home study place		Sound is noise	Sound source preference
	Student housing	Private housing with roommate (s)	Private housing with parents	Private studio	Private bedroom	Private office room	Shared living room	From outside	From inside		
9(5)	X				X			-People working in the garden -Birds -Rains	-Music sounds from neighbour upstairs (not often. happens once or twice a month) -It is a quiet home study place in general	-Continuous sounds (too long sound duration) -Loud sounds	-Different types of music (classical. pop. soul) in a low level as a background
10(5)	X						X	-Traffic (cars)	-People talking in the same apartment -Washing machine -Footsteps from neighbours upstairs	-Inconstant sounds -Distracting sounds	-Quiet sound environment
11(5)		X			X			-People walking -Traffic (cars and tram)	-Plumbing system -People walking and talking from the same apartment	-All sounds are noise -People walking sounds are not noise. it is a pleasant sound	-Music (e.g. rock. hip-hop. electronic).
12(4)	X				X			-Goose -Sirens from police and ambulance stations (the student get used to these sounds)	-Music played by other students in the same apartment	-Inconstant sounds -Loud sounds	-Music without lyrics -People studying sounds (e.g. paper-flipping sounds) -Constant sounds such as rain
13(5)			X			X		-Winds and rain -Traffic (cars, trains but not often, and planes)	-Door tapping sounds when it is a windy day -It is a quiet home study place from the inside	-Loud sounds -Unusual sounds -Scooter sounds	-Wind sounds -Birds sounds
14(4)	X			X				-It is a quiet home study place from the outside -Truck loading sounds	-It is a quiet home study place from the inside -Ventilation in the bathroom (when the door is open)	-Loud sounds -Irregular sounds -Any sounds that cannot be filtered out	-Depends on studying task -Music -Rainfall sounds
15(4)	X				X			-People talking -Traffic sounds in previous home study place	-People talking -Mechanical ventilation	-Continuous sounds -Party sounds	-Quiet study place while studying -Listening to music during drawing

Profile 1: Sound extremely concerned introvert, profile 2: sound unconcerned introvert, profile 3: sound partially concerned introvert, profile 4: sound concerned extrovert, profile 5: sound unconcerned extrovert

Appendix B. Perceptual assessment form

B.1. Test in the test chamber.
B.2. Test in the Experience room.

Appendix C
Raw data of bodily responses

AL in test chamber

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Baseline 1	17	42	23	43	50	40	51	66	54	55	42	58	24	45	59
Low rural	30	37	49	51	53	39	54	46	41	44	48	40	37	50	58
High rural	32	41	49	47	55	38	60	39	53	44	56	42	39	47	52
Baseline 2	37	40	60	39	49	39	51	41	52	53	50	28	32	48	52
Low traffic	44	44	48	39	52	36	56	39	51	51	34	38	32	50	52
High traffic	40	46	44	43	42	40	53	38	45	48	34	51	46	51	63
Baseline 3	55	56	33	39	63	37	57	63	48	54	38	47	55	49	44
Low ventilation	61	57	39	58	56	33	61	48	48	50	37	34	32	52	49
High Ventilation	54	50	38	44	44	39	50	65	63	51	50	42	31	46	53
Baseline 4	61	60	55	49	42	40	52	58	55	52	52	15	30	53	58
Low talking people	56	59	54	46	40	43	55	65	59	53	50	29	43	49	58
High talking people	60	62	51	48	44	48	49	66	49	49	47	42	40	51	58

AL in Experience room

	1	2	3	4	5	6	7	8	9	11	12	13	14	15
Baseline 1	71	42	45	58	61	46	58	39	50	48	49	42	45	54
Low rural	63	43	35	51	48	56	58	39	58	52	43	38	44	56
High rural	57	45	26	51	38	40	57	49	47	53	50	43	46	58
Baseline 2	57	47	32	59	42	60	55	55	49	68	49	47	44	59
Low traffic	47	53	26	59	41	56	60	60	44	34	40	31	38	52
High traffic	43	56	30	56	41	55	54	36	40	36	31	47	37	51
Baseline 3	40	60	60	45	41	63	53	42	54	40	45	34	45	50
Low ventilation	44	54	38	44	49	51	48	45	51	62	22	37	47	54
High Ventilation	45	62	36	57	39	26	50	40	39	64	34	40	52	54
Baseline 4	45	61	51	51	58	61	51	70	49	66	40	51	51	52
Low talking people	48	56	27	44	51	53	54	57	46	60	47	42	50	48
High talking people	60	53	23	59	42	45	47	49	48	61	33	44	50	50

MRL in test chamber

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Baseline 1	63	47	62	54	43	54	56	69	42	54	61	48	60	49	43
Low rural	60	58	60	50	56	52	53	72	51	52	59	55	59	56	51
High rural	56	55	58	45	56	47	56	70	52	51	59	52	49	48	51
Baseline 2	55	62	58	51	56	54	49	71	49	52	57	51	40	55	50
Low traffic	56	68	56	50	57	60	55	66	54	50	53	58	52	52	54
High traffic	54	64	53	48	55	56	51	64	62	55	56	53	48	50	47
Baseline 3	55	49	57	51	55	65	60	52	74	62	47	49	42	63	43
Low ventilation	50	51	67	45	53	66	60	60	67	62	58	48	47	62	51
High Ventilation	52	65	57	50	57	58	52	50	58	55	52	47	41	59	59
Baseline 4	49	69	58	46	56	65	53	53	60	55	60	59	53	53	49
Low talking people	58	63	61	49	52	60	62	44	54	54	54	61	51	58	41
High talking people	52	65	68	52	57	59	59	51	68	52	50	62	55	56	39

MRL in Experience room

	1	2	3	4	5	6	7	8	9	11	12	13	14	15
Baseline 1	63	43	58	51	57	51	34	56	82	48	67	56	47	51
Low rural	54	45	59	45	61	45	41	62	70	46	59	60	41	53
High rural	56	48	57	52	65	47	36	52	69	52	61	49	43	56
Baseline 2	51	49	58	48	60	44	37	45	45	48	61	48	47	65
Low traffic	55	51	65	49	50	57	37	50	56	56	58	50	53	67
High traffic	58	49	64	50	55	54	40	53	62	57	48	49	58	61
Baseline 3	57	55	46	49	53	40	42	53	50	61	47	56	57	56
Low ventilation	53	48	55	56	50	44	48	59	66	50	71	55	56	57
High Ventilation	51	52	51	58	51	65	46	54	71	55	71	54	53	49
Baseline 4	48	66	54	59	54	31	51	38	54	52	65	47	57	53
Low talking people	54	55	68	58	56	43	57	54	57	50	61	48	58	56
High talking people	53	59	59	53	63	43	58	57	55	46	60	53	47	50

HR in test chamber

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Baseline 1	71	89	84	67	68	69	70	77	68	76	78	49	48	74	51
Low rural	67	89	78	62	60	72	61	65	70	64	73	46	41	72	52
High rural	69	89	75	65	61	72	61	69	71	62	73	49	43	66	56
Baseline 2	67	90	76	65	62	72	65	72	72	65	73	50	46	66	56
Low traffic	67	89	76	65	69	73	63	69	73	74	73	50	43	69	56
High traffic	68	92	80	61	66	71	63	68	71	68	75	50	47	67	57
Baseline 3	72	97	83	66	71	77	70	72	80	73	82	63	56	75	62
Low ventilation	65	90	83	61	60	70	62	66	73	64	77	50	49	72	55
High Ventilation	64	78	75	62	63	69	66	68	70	64	69	52	49	66	58
Baseline 4	62	82	74	61	64	73	68	68	69	64	69	54	47	65	56
Low talking people	62	82	76	61	67	72	68	70	70	63	71	50	52	69	60
High talking people	63	85	74	62	64	72	61	72	73	64	72	49	49	67	57

HR in Experience room

	1	2	3	4	5	6	7	8	9	11	12	13	14	15
Baseline 1	66	68	62	76	57	67	53	72	64	73	55	56	69	67
Low rural	56	69	63	61	60	68	52	68	63	67	45	60	57	55
High rural	58	69	66	62	63	71	54	65	66	63	44	55	55	54
Baseline 2	60	68	66	63	62	69	56	68	66	62	45	72	56	53
Low traffic	61	68	65	62	62	71	55	71	63	62	46	70	54	56
High traffic	59	69	65	60	66	74	56	70	66	65	46	63	55	58
Baseline 3	59	73	65	61	64	72	60	72	67	67	48	54	55	56
Low ventilation	57	71	67	63	61	70	59	68	60	68	48	46	56	55
High Ventilation	60	76	67	60	62	72	59	70	62	66	51	48	57	56
Baseline 4	58	79	68	63	62	70	57	67	67	69	50	47	59	60
Low talking people	58	73	69	64	60	70	58	69	63	69	47	50	59	56
High talking people	59	72	68	62	62	71	60	70	68	69	49	49	58	57

RR in test chamber

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Baseline 1	12	15	14	13	13	12	12	15	14	15	12	14	14	14	13
Low rural	13	15	14	12	14	11	13	14	14	13	11	13	14	13	13
High rural	14	14	13	14	13	14	14	14	13	14	11	13	14	12	12
Baseline 2	14	13	13	14	13	13	14	13	14	14	11	13	14	13	13
Low traffic	14	14	13	13	14	13	14	13	13	14	13	13	14	13	15
High traffic	15	13	13	13	14	12	12	13	14	14	12	13	14	13	14
Baseline 3	14	13	14	12	14	13	13	13	11	13	13	15	15	13	14
Low ventilation	15	13	13	14	13	13	13	13	11	14	12	14	14	14	14
High Ventilation	14	13	13	13	12	13	13	14	11	13	13	14	13	14	13
Baseline 4	14	14	13	13	13	13	13	13	11	14	12	14	14	13	13
Low talking people	13	15	13	13	14	14	13	13	10	13	11	14	13	13	13
High talking people	13	14	13	13	14	14	12	13	10	14	11	14	12	13	13

RR in Experience room

	1	2	3	4	5	6	7	8	9	11	12	13	14	15
Baseline 1	15	13	13	14	12	13	14	13	13	13	14	14	13	13
Low rural	14	13	13	13	10	14	13	12	13	13	13	13	13	13
High rural	13	15	13	12	9	14	13	12	14	12	13	13	14	13
Baseline 2	14	14	14	12	9	15	13	13	14	11	13	13	14	13
Low traffic	13	14	14	13	10	14	13	13	13	11	13	13	14	13
High traffic	13	13	13	13	11	14	13	13	12	10	13	14	13	14
Baseline 3	13	14	12	13	9	14	13	14	11	10	13	13	13	13
Low ventilation	14	13	12	15	10	14	13	14	10	11	13	14	14	15
High Ventilation	13	14	13	15	11	14	13	13	10	12	13	13	13	15
Baseline 4	13	14	12	14	11	14	14	13	10	13	13	13	13	14
Low talking people	13	13	12	14	11	13	14	14	10	13	13	14	12	13
High talking people	13	13	12	15	13	13	13	14	11	13	12	15	13	13

Appendix D

Differences in perceptual assessments (acceptability) between the two experiments

D.1 At group-level per condition

Condition	P-value
Low rural	0.03
High rural	0.12
Low traffic	0.0.9
Low ventilation	0.27
High ventilation	0.09
Low talking people	0.29
High talking people	0.34

D.2 At individual-level

Student	P-value
1	0.40
2	0.51
4	0.50
5	0.32
9	0.74
11	0.11
12	0.40

Appendix E

Correlations between bodily responses and perceptual assessments at individual-level: tests in test chambers.

Physiological vs perceptual	R 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AL vs Acceptability	**0.7**	0.0	0.2	0.4	0.4	**−0.8**	**0.8**	−0.1	−0.1	−0.1	−0.3	−0.1	0.0	0.4	−0.3
AL vs Pleasantness	0.2	0.3	0.4	0.1	0.5	**−0.7**	**0.9**	−0.2	0.2	0.2	−0.2	−0.1	−0.2	**0.7**	−0.1
AL vs Stress level	0.4	0.0	0.4	0.4	0.4	0.4	**0.7**	−0.2	0.1	0.1	−0.5	0.0	−0.1	0.5	−0.3
MRL vs Acceptability	−0.5	0.2	0.0	**−0.8**	0.0	**0.8**	−0.1	−0.1	0.2	0.2	0.0	**0.6**	−0.1	0.3	0.1
MRL vs Pleasantness	0.1	−0.2	−0.4	−0.3	0.4	**0.9**	−0.1	0.0	0.0	−0.3	0.3	0.3	0.0	0.1	0.1
MRL vs Stress level	0.2	0.0	−0.1	**−0.7**	0.2	0.4	−0.1	0.1	0.0	−0.5	0.0	0.4	−0.1	0.4	0.2
HR vs Acceptability	−0.5	**-0.7**	0.0	**−0.6**	−0.3	0.4	−0.4	0.0	0.1	−0.3	0.2	**0.8**	−0.2	−0.1	0.1
HR vs Pleasantness	−0.2	−0.4	−0.3	−0.3	−0.4	0.5	−0.3	−0.2	0.1	−0.3	−0.1	0.5	0.0	−0.2	−0.2
HR vs Stress level	0.0	−0.4	0.0	−0.4	−0.5	0.1	−0.2	−0.1	0.1	−0.5	0.3	**0.7**	−0.3	−0.3	−0.1
RR vs Acceptability	**0.7**	**0.6**	0.1	0.0	−0.2	−0.2	0.4	−0.3	0.2	**−0.6**	0.0	0.2	0.1	−0.2	**0.6**
RR vs Pleasantness	0.2	**0.8**	−0.1	0.0	−0.1	−0.5	0.4	−0.4	0.1	−0.4	0.3	0.4	0.1	−0.2	**0.7**
RR vs Stress level	0.2	**0.7**	0.2	0.0	−0.1	**−0.8**	0.2	−0.2	0.3	−0.4	0.2	0.3	0.0	−0.3	0.4

Physiological vs perceptual	P-value 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
AL vs Acceptability	0.06	0.88	0.64	0.27	0.19	0.07	**P<0.001**	0.82	0.71	0.82	0.34	0.87	0.93	0.15	0.38
AL vs Pleasantness	0.56	0.36	0.23	0.78	0.07	0.02	**P<0.001**	0.48	0.55	0.63	0.50	0.89	0.57	**0.02**	0.76
AL vs Stress level	0.35	1.00	0.22	0.37	0.20	0.04	**0.01**	0.60	0.71	0.66	0.13	0.95	0.78	0.10	0.43
MRL vs Acceptability	0.20	0.63	0.88	**0.02**	0.90	0.33	0.75	0.77	0.50	0.63	0.89	0.14	0.73	0.34	0.70
MRL vs Pleasantness	0.86	0.45	0.25	0.46	0.25	**0.02**	0.86	0.94	0.97	0.29	0.39	0.53	1.00	0.80	0.82
MRL vs Stress level	0.68	0.94	0.71	0.07	0.63	**P<0.001**	0.86	0.65	0.97	0.07	0.90	0.28	0.74	0.16	0.62
HR vs Acceptability	0.23	**0.02**	0.88	0.15	0.43	0.38	0.24	0.91	0.68	0.38	0.59	**0.02**	0.58	0.68	0.73
HR vs Pleasantness	0.68	0.25	0.35	0.46	0.21	0.29	0.41	0.58	0.71	0.41	0.67	0.26	0.91	0.45	0.62
HR vs Stress level	0.93	0.23	0.88	0.27	0.12	0.25	0.52	0.65	0.85	0.14	0.41	**0.04**	0.51	0.41	0.79
RR vs Acceptability	0.06	0.06	0.73	0.98	0.61	0.76	0.16	0.40	0.44	**0.04**	0.90	0.60	0.73	0.47	**0.03**
RR vs Pleasantness	0.68	**P<0.001**	0.73	0.99	0.80	0.57	0.26	0.18	0.69	0.16	0.35	0.39	0.83	0.47	**0.01**
RR vs Stress level	0.63	**0.02**	0.48	0.98	0.67	0.17	0.53	0.48	0.39	0.18	0.56	0.49	0.95	0.38	0.16

Appendix F

Correlations between bodily responses and perceptual assessments at individual-level: tests in the Experience room.

Physiological vs perceptual	R														P-value													
	1	2	3	4	5	6	7	8	9	11	12	13	14	15	1	2	3	4	5	6	7	8	9	11	12	13	14	15
AL vs Acceptability	0.1	−0.1	0.1	0.5	0.3	**0.8**	**0.7**	0.5	0.4	0.3	0.2	0.1	0.1	−0.4	0.89	0.80	0.86	0.20	0.30	**0.03**	**0.01**	0.15	0.27	0.41	0.61	0.87	0.83	0.24
AL vs Noise level	0.1	−0.3	0.2	0.1	0.4	0.2	0.3	**0.6**	0.2	0.4	−0.2	−0.4	0.4	−0.1	0.82	0.30	0.54	0.75	0.18	0.63	0.43	**0.03**	0.54	0.23	0.69	0.34	0.27	0.79
MRL vs Acceptability	−0.1	0.0	0.3	0.2	−0.4	**−0.7**	0.1	−0.4	−0.3	−0.2	0.0	−0.2	0.0	0.5	0.87	0.94	0.39	0.60	0.28	**0.04**	0.75	0.17	0.43	0.50	0.98	0.63	0.89	0.16
MRL vs Noise level	−0.2	−0.1	**0.8**	0.4	−0.3	−0.3	0.2	−0.2	0.1	−0.4	**0.8**	**0.7**	0.1	0.5	0.57	0.75	**0.01**	0.31	0.37	0.55	0.50	0.48	0.80	0.17	**0.02**	0.07	0.78	0.11
HR vs Acceptability	−0.1	−0.1	0.2	−0.2	**−0.6**	0.3	−0.4	−0.5	−0.4	−0.3	−0.4	−0.2	0.0	−0.1	0.78	0.77	0.50	0.64	**0.05**	0.54	0.17	0.14	0.27	0.37	0.32	0.65	0.94	0.68
HR vs Noise level	−0.2	0.0	0.2	0.3	**−0.6**	**−0.6**	**−0.7**	−0.4	**−0.7**	−0.1	0.2	0.5	0.3	−0.3	0.65	0.91	0.52	0.54	**0.05**	0.11	**0.02**	0.26	**0.01**	0.74	0.66	0.22	0.31	0.40
RR vs Acceptability	0.3	0.2	0.3	0.3	−0.1	**0.6**	**−0.6**	−0.4	0.0	0.3	−0.1	−0.3	0.2	−0.3	0.51	0.53	0.41	0.53	0.83	0.14	0.07	0.23	0.89	0.30	0.82	0.44	0.47	0.30
RR vs Noise level	0.3	0.2	0.4	0.5	−0.1	0.1	−0.2	−0.2	−0.2	**0.6**	0.6	0.1	0.1	−0.4	0.48	0.59	0.23	0.24	0.82	0.81	0.58	0.51	0.48	**0.03**	0.11	0.72	0.69	0.18

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