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How different sounds affect bodily responses and the perception of odour, light and temperature: a pilot study on interaction effects within IEQ domains

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ABSTRACT

During perception with our senses, interactions of different environmental stressors at brain level might occur. Previous studies have shown cross-modal effects between sound and odour. To test these effects of different sounds and levels of sounds on the perception of sound, temperature, odour, and light, as well as a number of physiological indicators, sixteen students were exposed to four different sounds (two indoor: mechanical ventilation & people talking; two outdoor: quiet rural area & city centre area) and two different sound pressure levels per sound, while sitting in a semi-lab environment. Bodily responses were sampled with wearable devices. Heart rate and breathing rate were monitored using a smart watch; EEG measurements were performed to assess their attention and mental relaxation levels; Acceptability and experience were assessed through a questionnaire to assess their comfort perception. Additionally, each student took a hearing test. The outcome showed when the traffic sound level increased, the students perceived the air as more smelly and less acceptable. The other sounds did not show any cross-modal effect. Moreover, heart rate and breathing rate significantly differed during the different tests, confirming that these two indicators can help to explain the physiological effect of noise as a stressor.

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KEYWORDS
Cross-modal effects; interaction effects; lab study; different sounds; indoor environmental stressors

1. Introduction

Diseases and disorders, such as mental illnesses, obesity, cardio-vascular and chronic respiratory diseases (for example asthma in children and COPD in adults), cancer, discomfort (annoyance), building-related symptoms (e.g. headaches, nose, eyes, and skin problems, fatigue etc.), building-related illnesses (e.g. legionnaires disease), productivity loss, decrease in learning ability, and more recent COVID-19, all have been related to staying indoors (Bluyssen 2014; Morawska et al. 2020). Moreover, the consequences

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for indoor environment of climate change and the effects of the retrofitting measures we take to reduce energy consumption on health and comfort indoors, are an emerging concern (Ortiz, Itard, and Bluyssen 2020). To avoid health risks and discomfort, the European Energy Performance for building directive (EPBD) (EU 2024) mandates that 'Member states should support energy performance upgrades of existing buildings that contribute to an adequate level of indoor environmental quality achieving a healthy indoor environment.' Research has shown that, even though the indoor environmental conditions seem to comply with current standards and guidelines and those conditions seem 'comfortable' enough, staying indoors is not good for our health (Allomonte et al. 2020; Bluyssen 2014). Reasons for this discrepancy might be the fact that these guidelines (such as maximum concentrations of certain pollutants, ventilation rate, and temperature ranges) are mainly based on single-dose response relationships (dose-related indicators) determined for an average adult person, aimed at creating comfort (or neutral) (Bluyssen 2014; CEN 2019). Indoor environmental quality (IEQ)-assessment is based on effect modelling of dose-related indicators: for each parameter or indicator its effect is determined separately.

We are exposed to a mix of stressors, that can change over time, and our responses (the coping and the effects) are influenced by genetics, previous exposures and interactions between those stressors at human level (Bluyssen 2014). Indoor environmental stressors can cause their effects additively or through complex interactions: thermal factors (e.g. draught, temperature), lighting aspects (e.g. reflection, view, luminance ratios), air quality (e.g. odours, mould, chemical compounds, particulates) and acoustical aspects (e.g. noise and vibration) (Bluyssen 2014; Torresin et al. 2018). We, therefore, must acknowledge the fact that the indoor environmental quality (IEQ) is more than the sum of its parts, which requires an integrative approach (Altomonte et al. 2003; Bluyssen 2009; Rohde et al. 2020) that was recently introduced and validated (Allomonte et al. 2020; Bluyssen 2014; Bluyssen 2020; Bluyssen 2022). For further validation and completion of this model, possible interactions at and between different levels (human and environment) over time need to be explored for different scenarios and situations. We are dealing with interactions at human level that influence both our wellbeing (health and comfort) at short and long term, resulting in direct interactions with the environment (opening a window, setting the thermostat) or other behavioural responses (taking of a sweater, wearing a mask to protect yourself from particles, etc.), and in responses at human level (coping with stressors through the mechanisms we have available). Both the perceptual and physiological interactions at human level affect these responses.

The interactions at human level that occur through the mechanisms that take place in the human body to cope with the different stressors, causing the diseases and disorders, are very complex. This complexity starts already with perception and the interpretation of what our senses perceive in our brain. During perception with our senses interactions of different environmental stressors at brain level (central nervous system) might occur. This was observed for example in a study with in total 335 primary school children in the Experience room of the SenseLab (Bluyssen et al. 2018; Bluyssen et al. 2021). To test the main, cross-modal and interaction effects on the evaluation of temperature, noise, light and smell, those children were exposed to 36 different combinations of environmental conditions. The outcome showed significant relations of the perception of smell with draught, sound, and light perception. What was most interesting was the finding that when children were exposed to the sound type 'children talking' their assessment of both sound and smell, while no smell was added, was affected, indicating that children are perhaps pre-conditioned in their response by hearing children talk (Bluyssen et al. 2021). Previous studies have demonstrated a perceptual interplay between olfactory and auditory stimuli (Wesson and Wilson 2010). The olfactory tubercle has been demonstrated to be a site for olfactory and auditory convergence and that such activity is susceptible to cross-modal influences. This activity may underlie the ability of persons to relate auditory pitch with odour perceptual qualities (Belkin et al. 1997).

When we are exposed to relatively low environmental sound levels (stressors), during activities such as concentration, relaxation or sleep (Babisch 2008; Bluyssen 2014), adrenaline is produced, and the body is prepared for action by producing noradrenaline. If the stressor is limited in time and perceived intensity, in due time the balance is restored. However, with prolonged stress (chronic stress), the production of anti-stress hormones such as cortisol is increased and a chronic imbalance in the hormones released during stress can occur. From previous studies is known that cortisol plays an important role in the health effects of this chronic imbalance (McClellan and Hamilton 2010): high cortisol levels contribute to changes in carbohydrate and fat metabolism and can lead to anxiety, depression and heart disease, while a low cortisol production can lead to fatigue, allergies, asthma and increased weight. Next to the increase of hormones, other physiological indicators have been used to follow this anti-stress reaction in time, for example blood pressure (Dehghan, Bastami, and Mahaki 2017), heart rate and breathing rate (Abbasi et al. 2020), skin conductance level (Alvarsson, Wiens, and Nilsson 2010), and EEG measurements (Hamida et al. 2023). Next to asking people about their annoyance or acceptability, several physiological indicators can thus be used.

In the underlying study, we asked ourselves the following questions 'Do different sounds and their levels interact with the perception of sound, temperature, odour, and light, and how do these perceptions correlate with certain physiological indicators?'

2. Methods

2.1 Study design

To test the interaction effects of different sounds and levels of sounds on the perception of sound, temperature, odour, and light, as well as a number of physiological indicators, sixteen students from the faculty, were exposed, in groups of maximum four students per test day, to four different sounds (two indoor: mechanical ventilation & people talking; two outdoor: quiet rural area & city centre area) and two different sound pressure levels per sound, while sitting in the Experience room of the SenseLab in November 2023 (see Figure 1). These four sounds (or noises) were selected, because these sounds were most experienced when sitting at their home study place (Hamida, Eijkelenboom, and Bluyssen 2024). Ventilation rate, temperature, and lighting conditions were kept constant during the experiments. No odour was added.

Heart rate, breathing rate, attention level, and mental relaxation level were chosen as physiological indicators, because they are commonly used in sound exposure lab

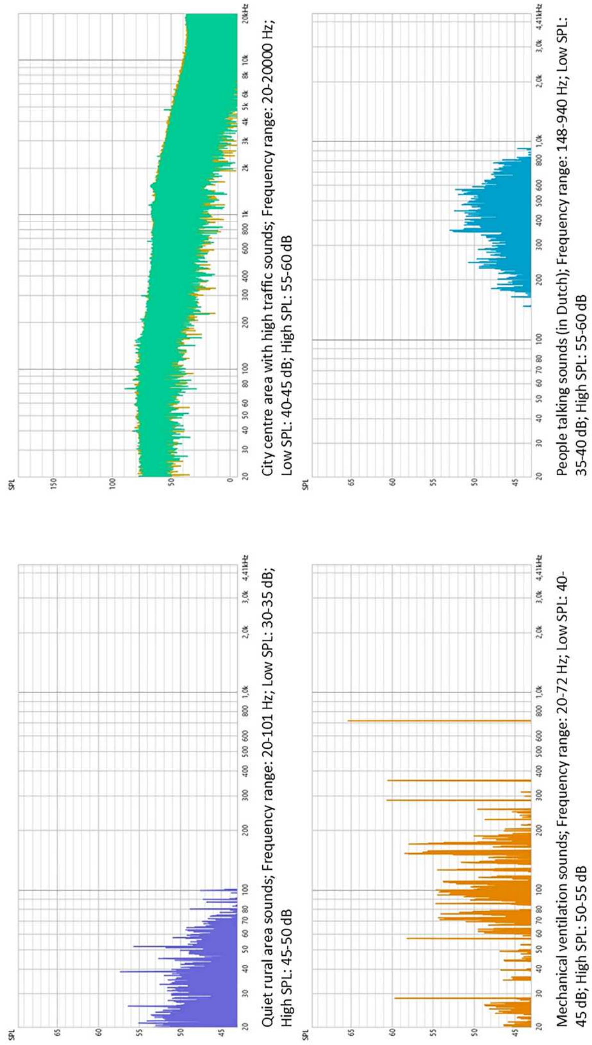

Figure 1. Sound types, sound levels, and frequencies.

experiments (Hamida et al. 2023) and interaction effects within IEQ domains (Abbasi et al. 2020; Sun, Wu, and Wu 2020). Acceptability and experience were chosen as psychological indicators (Hamida et al. 2023). Heart rate and breathing rate were monitored using a smart watch; EEG measurements were performed to assess their attention and mental relaxation levels; Acceptability and experience were assessed through a questionnaire to assess their comfort perception. Additionally, each student completed a questionnaire with personal information and took a hearing test in one of the test chambers of the SenseLab (Bluyssen 2022) as recommended by Hamida et al. (2024).

2.2 Participants

Participants comprised of bachelor and master students that participated in a previous questionnaire and field study performed by Hamida, Eijkelenboom, and Bluyssen (2024). 16 students participated in this lab experiment with power level $1\text{-}\beta = 0.7$, where β refers to beta which is type II error. The statistical power analysis was calculated through a Post hoc analysis by giving effect size of 0.5, a significance level (α) of 0.05, and a sample size of 16 using G*Power software (Universität Düsseldorf: G*Power n.d.). The power level of 0.7 means that the test has a 70% probability of correctly rejecting the null hypothesis.

Students were asked not to perform any physical exercise before the experiment, or wear perfume, or smoke or drink coffee, or eat garlic the day before the experiment, as these activities might affect their bodily responses.

2.3 The senselab

The SenseLab comprises of the Experience room, a semi-lab environment of 6.1 (l) x 4.2 (b) x 2.7 (h) = 69.2 m^3, for integrated perception of IEQ, and four test chambers (Bluyssen et al. 2018). In the Experience room, a classroom set-up was created with eight tables and five chairs. Maximum four of the eight tables were occupied by the students (see Figure 2). A researcher sat in front to instruct the students. Each test day, the ventilation

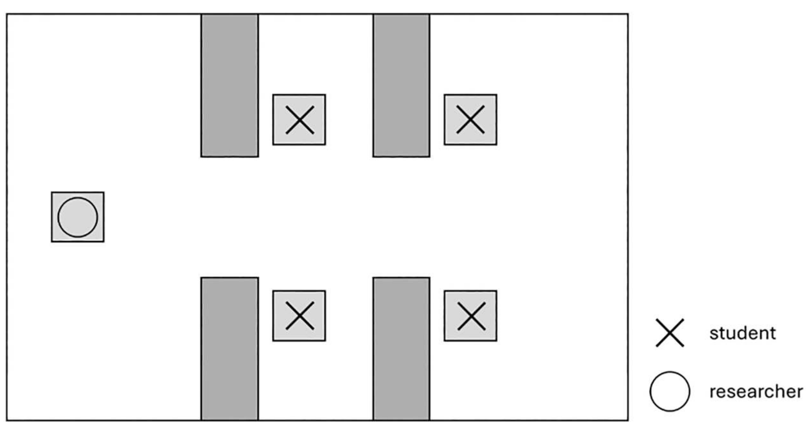

Figure 2. Test set-up in the Experience room.

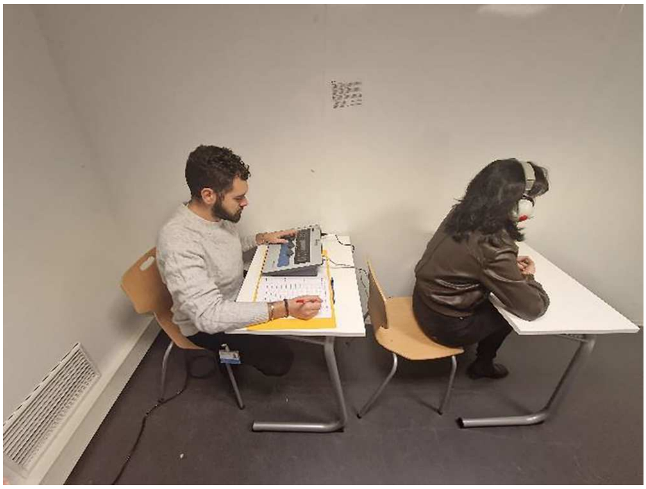

Figure 3. Organisational scheme of seats during the hearing test.

rate was kept at 1200 m^3/h with a temperature of 21°C. The hearing test was performed in one of the test chambers (Figure 3).

2.4 Physiological measurements

A headband BrainLink Lite EEG device, comprising three electrodes that record EEG data, was used to measure the attention and mental relaxation levels. This device was connected to a computer via Bluetooth of which real-time measurement data were recorded per second using a Python code that ran in PyCharm 2023. The raw data were saved as CSV file, which includes attention levels, mental relaxation levels, Delta waves, Theta waves, Low-Alpha waves, High-Alpha waves, Low-Beta waves, High-Beta waves, Low-Gamma waves, and Mid-Gamma waves. A Vivosmart 5 smartwatch by Garmin was used to measure the heart rate. An Otometrics MADSEN Xeta clinical audiometer was used for the hearing test. A monaural test with the air conduction method was conducted. An audiogram was used to record the measurement results of the frequencies 125, 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz.

2.5 Perception

A one-page questionnaire was developed to assess the perception of sound, temperature, odour, and light for each of the conditions the students were exposed to (Figure 4). The assessments were based on the level of acceptability and the perception of intensity.

2.6 Procedure

Upon arrival of the students, they were informed about the test procedure, completed the consent form, and were asked to take the hearing test in the test chamber. After the

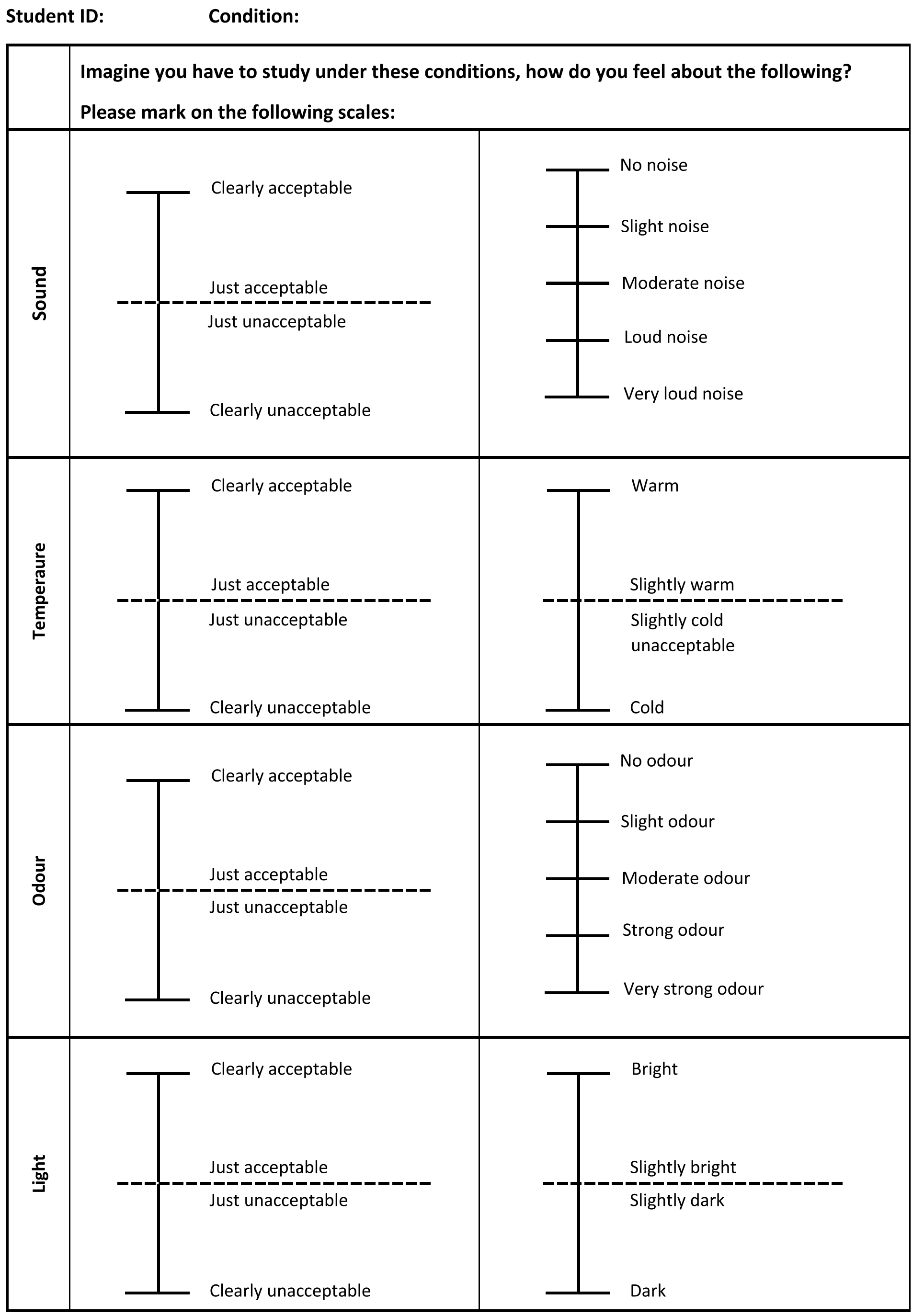

Figure 4. One page questionnaire.

hearing test, they received the brain link and the smart watch. Then they were asked to enter the Experience room.

During the hearing test in the test chamber, the student was invited to wear headphones and hold the button of the test instrument. It was explained that they would have to press the appropriate button when they heard a sound coming from the headphones, that different frequencies would be tested at different sound pressure levels and that the right ear would be tested first and then the left ear. The test was carried out in frequency increases from 100 to 6000 Hz, increasing the sound pressure from 0 in successive steps of 10 dB until the student indicated that he/she had heard the sound. The data were reported on special forms for the audiometric examination compiled by the researcher who conducted the test. During the test, the student sat with his/her back to the researcher so that he/she was not influenced by manual operations on the instrument during the change of frequency and sound pressure (Figure 3).

In the Experience room the students were invited to take sit at the four organised seats (Figure 2), instructed on how to complete the one-page questionnaire, and then on how the experiment would take place. It was explained to them that they would experience nine different conditions (C1 to C9) lasting two minutes each, interrupted with some breaks, in which the IEQ factors would change and which they would have to assess each time using the appropriate questionnaire (see Figure 5).

The two-minute exposure time was chosen because no differences in physiological measurements were identified between the two – and four-minute exposure time during the pilot testing. From those tests, reported in (Hamida et al. 2024) it was concluded that 2 min was enough to recover.

A researcher sitting in the room with the students communicated the beginning of a new environmental condition. They were asked not to immediately start with completing the questionnaire when the condition changed, but to wait 30 s to evaluate it on all aspects and then complete the questionnaire. The researcher sitting in the room communicated the end of the initial 30 s of evaluation.

2.7 Ethical aspects

The students were sent an email with the information letter and a copy of the consent letter one week before the test day. At the day of the tests, they were asked to sign the consent form before conducting the tests. In addition, a subject could always decide not to continue and stop with the test. Each student received a voucher for their efforts. The Ethics Committee approved the study on November 15, 2023.

2.8 Data management and analysis

All questionnaire data were manually typed and stored in an Excel database. The smart watch and EEG data were downloaded from the appropriate sensor management software and reported according to the temporal sequence of the conditions analysed for each participant. For each condition, minimum, maximum, mean and standard deviation values were calculated. Boxplots and line graphs were produced for data evaluation. For the physiological data, the percentages of variation in each environmental condition compared to the baseline value, i.e. condition C1 before each sound type exposure, were also calculated. T-tests (2-tailed, paired) were performed to check whether the

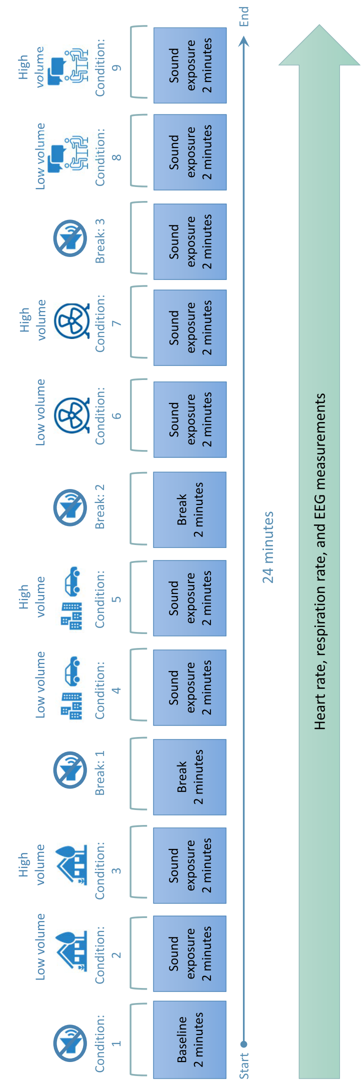

Figure 5. Test schedule interaction tests.

difference in assessment between the two sound level conditions per sound type statistical differ. ANOVA tests were performed for all perceptual assessments and physiological responses (including the baseline responses for the raw data) during the tests to check whether the responses differed. Correlations were established between noise assessments and both perceptual and physiological responses.

3. Results

3.1 Participants

The outcome of the hearing tests is presented in Table 1. According to WHO (WHO 2021) the hearing threshold is the average of the minimum SPL that a person can hear on the average of frequencies 500, 1000, 2000, and 4000 Hz in the better ear. Based on their grading (see Table 2) all the students have normal hearing, except for student 6 (hearing threshold is 22.5 dB) and student 16 (hearing threshold is 21 dB), who have mild hearing loss.

3.2. Perception

Figure 6 shows the mean perception votes for sound, temperature, odour and light when exposed to different sound conditions. Table 3 shows the t-test of the assessment between the two sound level conditions per sound type, and the ANOVA of all assessments (sound, temperature, odour and light), to check whether there was a difference in the mean of each assessment.

3.3. Smart watch and EEG

Figure 7 shows the average attention level, relaxation level, heart rate, and breathing rate scores of each exposure condition, without correction (i.e. raw data). Table 4 presents the t-tests of the physiological assessments between the two sound levels per sound type, and the ANOVA test of all physiological responses during the tests, after correction to the baseline value preceding the sound type exposure (expressed in % of change compared to the baseline response in the two minutes before each sound exposure).

4. Discussion

4.1 Hearing and sensitivity

Humans are in general able to hear frequencies between 20 Hz and 20 kHz. Our ear is most sensitive in the range of 3000–5000 Hz and annoyed most with frequencies between 20 and 125 Hz (Bluyssen 2009). From the hearing tests is clear that most students were indeed less sensitive to lower frequencies (see Table 1) and more sensitive to the higher frequencies except for 6000 Hz on the right ear. Considering the sound level and sound acceptability assessments, the students seemed to be most annoyed with the high 'talking' sound level, followed by the high 'traffic' sound level,

Table 1. Audio test outcome: minimum SPL (dB) a person can hear at different frequencies (Hz).

	Left ear								Right ear							
ID	125 Hz	250 Hz	500 Hz	1000 Hz	2000Hz	4000 Hz	6000 Hz	Av[1] Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000Hz	4000 Hz	6000 Hz	Av[1] Hz
1	25	35	30	25	15	10	30	20	25	35	20	30	30	10	20	22.5
2	25	40	25	20	25	20	20	22.5	40	40	25	15	20	15	10	19
3	30	25	20	15	25	10	20	17.5	40	30	25	20	20	15	35	20
4	45	45	35	25	25	20	20	26	40	25	20	15	20	15	30	17.5
5	15	15	15	15	10	10	10	12.5	25	20	20	15	10	10	35	14
6	50	50	40	40	30	35	15	36	30	30	30	25	10	25	35	22.5
7	30	30	25	20	10	15	30	17.5	20	30	25	15	10	10	30	15
8	35	25	20	10	10	15	20	14	20	30	25	15	10	25	50	19
9	25	40	20	25	10	10	15	16	45	50	25	10	10	20	25	16
10	25	30	30	20	20	5	5	19	20	25	25	15	20	5	5	16
11	35	45	30	25	20	10	20	21	40	35	30	20	10	5	10	16
12	15	15	10	20	15	20	15	16	30	30	20	20	15	25	20	20
13	35	30	20	15	15	15	25	16	45	25	20	15	15	15	15	16
14	20	35	30	15	5	5	10	14	25	50	35	15	15	10	15	19
15	20	20	20	10	15	10	30	14	35	35	25	20	20	20	25	21
16	45	40	35	25	15	15	25	22.5	35	40	30	25	20	10	30	21

Note: 1: average hearing threshold for frequencies 500, 1000, 2000, and 4000 Hz.

Table 2. Grading of hearing according to WHO (WHO 2021).

Grade	Hearing threshold in the better hearing ear in dB
Normal hearing	< 20 dB
Mild hearing loss	Between 20 to < 35 dB
Moderate hearing loss	Between 35 to < 50 dB
Moderately severe hearing loss	Between 50 to < 65 dB

Table 3. T-test of the assessments between the two sound levels per sound type (+ANOVA of all responses).

	Low vs. high rural	Low vs high traffic	Low vs. high system	Low vs. high people	ANOVA
All students					
Sound Acc.	**<0.001**	**<0.000001**	**<0.01**	**<0.000001**	***P*<0.001**
Sound level	**<0.0001**	**<0.0000001**	**<0.0001**	**<0.000001**	***P*<0.001**
Temp Acc.	0.65	0.91	0.85	0.51	0.99
Temp. level	0.77	0.08	1	0.54	0.51
Odour acc.	0.33	**0.04**	0.25	0.33	**0.017**
Odour level	0.30	**0.05**	0.22	0.53	0.17
Light acc.	0.63	0.35	0.61	1	0.99
Light level	0.29	0.26	0.14	0.17	0.99
Without students 6 and 16					
Sound Acc.	**0.001**	***P* < 0.001**	**0.003**	***P* < 0.001**	***P* < 0.001**
Sound level	***P* < 0.001**	***P* < 0.001**	***P* < 0.001**	***P* < 0.001**	***P* < 0.001**
Temp Acc.	0.70	1	0.85	1	0.99
Temp. level	1	0.08	0.79	0.55	0.10
Odour acc.	0.39	**0.03**	0.25	0.34	**0.01**
Odour level	0.30	**0.05**	0.22	0.53	0.14
Light acc.	0.79	0.43	0.52	1	0.99
Light level	0.29	0.12	**0.003**	0.39	0.99

*: $p < 0.05$ are in bold.

Table 4. Mean (SD) of the physiological assessments and t-test of the assessments between the two sound levels per sound type, expressed in percentage of change (+ANOVA of all responses).

	Attention level		Relaxation level		Heart rate		Breathing rate	
	Mean (SD) % (%)	t-test *p**	Mean (SD) % (%)	t-test *p**	Mean (SD) % (%)	t-test *p**	Mean (SD) % (%)	t-test *p**
Low rural	−1 (13)	0.34	0 (12)	0.67	−7 (9)	0.92	−4 (6)	1
High rural	−4 (18)		−1 (10)		−6 (10)		−4 (10)	
Low traffic	−11 (16)	0.54	7 (11)	0.54	0 (3)	0.79	1 (6)	0.08
High traffic	−13 (17)		9 (14)		1 (5)		−2 (7)	
Low system	−1 (24)	0.77	5 (18)	0.77	−3 (5)	**0.02**	4 (7)	1
High system	−2 (28)		7 (24)		0 (4)		4 (8)	
Low talking	−8 (14)	0.68	8 (16)	0.38	−1 (4)	0.35	−1 (5)	0.22
High talking	−10 (20)		6 (18)		0 (4)		1 (8)	
ANOVA (*p)**	0.46		0.52		**0.001**		**0.012**	

*: $p < 0.05$ are in bold.

and assessed both levels the highest (see Table 5) (the SPL level for both was 55–60 dB(A), see Figure 1).

Excluding the two students with mild hearing loss, the assessments did not substantially change. In general, both the mean perceived sound level and the mean acceptability slightly increased with respectively 0.02 and 0.01, which is negligible. This means that excluding students based on the hearing test, in this study, did not affect the outcome of the sound perception tests.

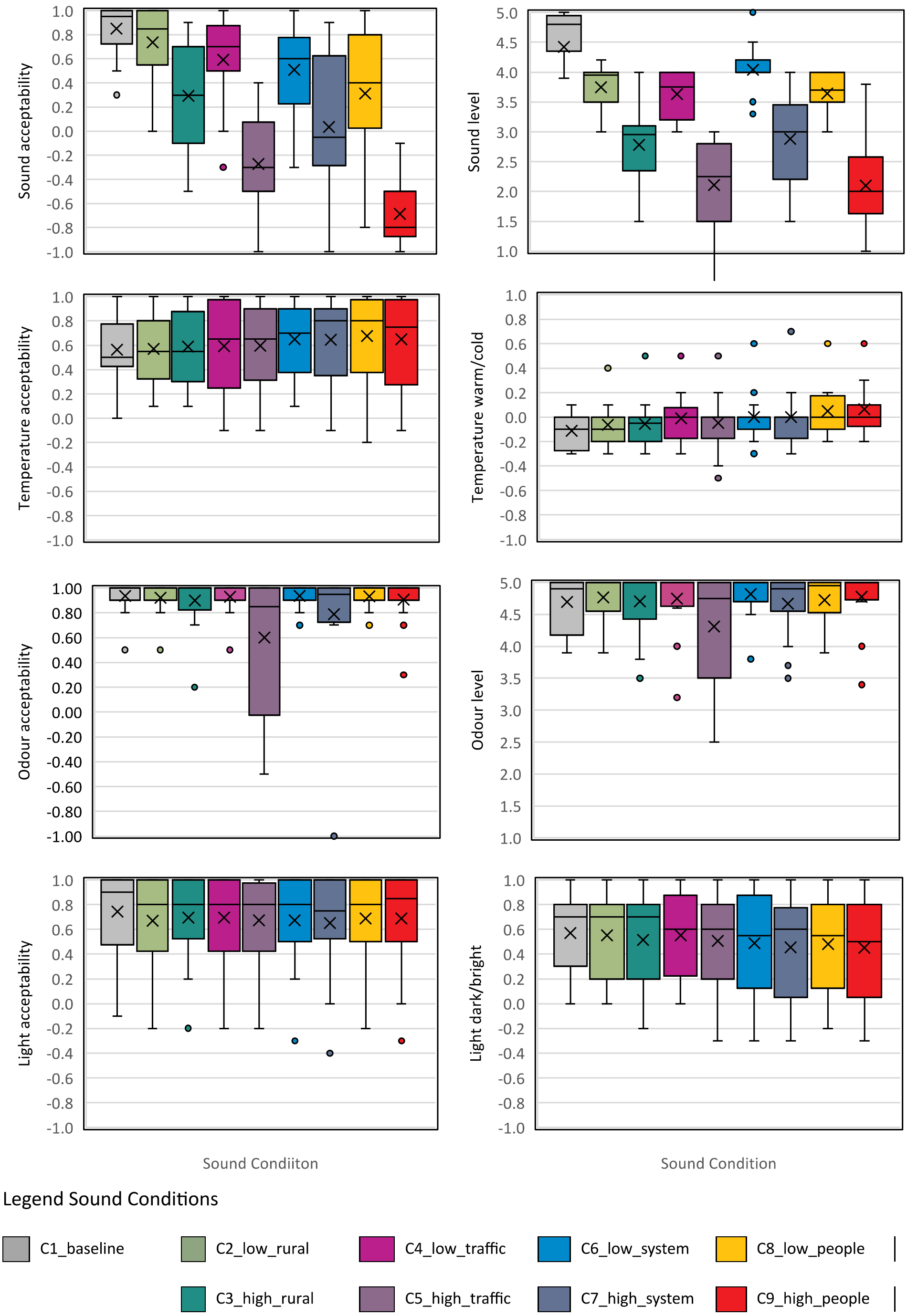

Figure 6. Perception results. The colours of C2 and C3 presenting low and high sound level of rural sound, respectively; C4 and C5 low and high sound level of traffic sound, respectively; C6 and C7 low and high sound level of mechanical ventilation system sound, respectively; C8 and C9 low and high sound level of talking people, respectively. C1 represents the baseline condition.

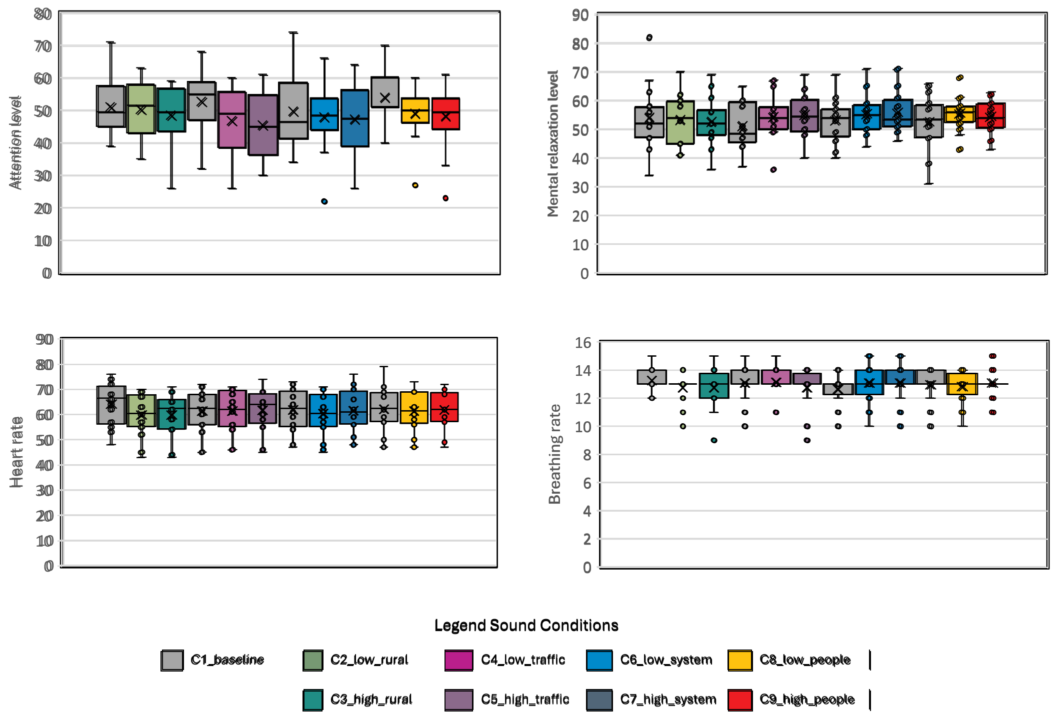

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Table 5. Mean sound level and sound acceptability assessments.

Sound	Rural low	Rural high	Traffic low	Traffic high	System low	System high	Talking low	Talking high
All students								
Level								
Mean	3.75	2.78	3.63	2.11	4.04	2.88	3.64	2.10
St dev	0.36	0.66	0.40	0.79	0.4	0.8	0.37	0.7
Acc.								
Mean	0.74	0.29	0.59	−0.27	0.51	0.03	0.31	−0.69
St dev	0.30	0.43	0.35	0.41	0.35	0.56	0.52	0.26
Without students 6 and 16								
Level								
Mean	3.71	2.79	3.65	2.16	4.04	3.04	3.59	2.15
St dev	0.37	0.51	0.38	0.67	0.43	0.71	0.37	0.73
Acc.								
Mean	0.71	0.25	0.61	−0.29	0.59	0.11	0.3	−0.66
St dev	0.31	0.43	0.33	0.43	0.26	0.56	0.53	0.27

4.2 Interaction effects

The T-tests show a clear (statistically relevant) difference between perception assessments of the two sound levels per sound (Table 3). Additionally, a difference is seen between the odour level and odour acceptability of low and high traffic sound levels. This implies that when the traffic sound level increases, the students perceived the air as more smelly and less acceptable. For the other sounds, this effect was not seen. To check whether this phenomenon is still observed when we take out the two students that have, according to the WHO grading (Sun, Wu, and Wu 2020), a mild hearing loss (students 6 and 16), we repeated the t-tests excluding students 6 and 16. The same effect is seen (plus an interaction effect with the light level in low vs. high system noise). Moreover, the ANOVA of all perceptual assessments showed that only the odour acceptability assessments statistically differed, in both cases (all students and without students 6 and 16). This confirms earlier findings of the perceptual interplay between olfactory and auditory stimuli in the brain (Bluyssen et al. 2018; Wesson and Wilson 2010), to be exact the olfactory tubercle that has been demonstrated to be a site for olfactory and auditory convergence and thus susceptible to cross-modal influences (Belkin et al. 1997). Why in this study, this interplay only occurred with traffic noise, and not with people talking could be related to previous exposures and experiences of the subjects. Mechanical ventilation noise and rural area sounds, in general do not smell bad, and therefore the odour assessments make sense for those.

While, as expected, the assessment of the noise level and the acceptance of a noise for all conditions assessed, were highly correlated (Table 6), correlations between odour acceptability and noise level as well as noise acceptability also showed a strong

Table 6. Correlation (r) between means of different assessments.

	Noise	Odour		Heart rate		Breathing rate	
	acc.	level	acc.	raw	% change	raw	% change
All students							
noise level	**0.91**	0.48	**0.63**	0.08	−0.42	0.10	0.15
noise acc.	–	0.35	**0.51**	−0.13	**−0.59**	−0.07	−0.15
Without students 6 and 16							
noise level	**0.93**	**0.54**	**0.61**	0.36	−0.24	0.47	0.17
noise acc.	–	0.44	**0.53**	0.12	−0.47	0.19	−0.15

Note: r > 0.50 in bold represents a strong correlation.

correlation. The odour level had a strong correlation with the noise level, for the assessments excluding students 6 and 16.

4.3 Physiological assessments

For the physiological assessments during the exposure of the two levels of each sound type, the t-tests showed a statistically relevant difference in heart rate for the exposure to low versus high system sound, and a trend towards a statistical difference in breathing rate for low vs. high traffic sound (Table 4). Also, the ANOVA of all assessments for the different sounds and levels, showed that both heart rate and breathing rate differed significantly (Table 4), confirming that these two indicators can help to explain the physiological effect of noise as a stressor. The EEG measurements did not show a statistical difference between the two levels of sound for any of the sound types and did not show a difference in all of the assessments. The latter finding indicates that exposure of 2 min to different sounds and levels with 2 min break, the attention level and the relaxation level were not affected.

Correlating the noise assessments with the heart rate and breathing rate assessments, the noise acceptability assessment showed a strong correlation with heart rate. This confirms the effect of noise exposure on heart rate found in previous studies (Dehghan, Bastami, and Mahaki 2017).

5. Conclusions and recommendations

A lab study was performed with 16 students in the SenseLab, to answer the questions 'Do different sounds and their levels interact with the perception of sound, temperature, odour, and light, and how do these perceptions correlate with certain physiological indicators?'

Answering the first question, the outcome showed a clear (statistically relevant) difference between perception assessments of the two sound levels per sound, as well as a statistically relevant difference between the odour level and odour acceptability of low and high traffic sound levels. This implies that when the traffic sound level increased, the students perceived the air as more smelly and less acceptable. For the other sounds, people talking, mechanical ventilation system noise, and rural sounds, this effect was not seen. Excluding the two students based on the hearing test, did not affect the outcome of the sound perception tests, nor did it affect the cross-modal effect with odour level and odour acceptability.

With regards to the physiological indicators, while the EEG measurements did not differ, both heart rate and breathing rate differed significantly during the different tests, confirming that these two indicators can help to explain the physiological effect of noise as a stressor. Moreover, heart rate showed a strong correlation with noise acceptability assessment, confirming the effect noise exposure can have on our heart rate.

Based on the outcome of this pilot study, several future studies can be pursued to further explore the interaction effects within IEQ domains between sensory perceptions and physiological responses. First, to validate the conclusions, a follow-up study with a larger and more diverse sample of participants is required, including individuals from various ages, backgrounds, and sensory impairments. Second, a study on how prolonged exposure to different sound levels affects perception and the physiological indicators over time, could provide insights into chronic stress responses and habitation to noise. Finally, examining the cross-modal interactions between sound perception and other sensory modalities through controlled experiments, i.e. controlling odour, temperature and light in conjunction with sound levels to examine how they interact to influence perception.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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References

Abbasi AM, Motamedzade M, Aliabadi M, Golmohammadi R, Tapak L (2020) Combined Effects of Noise and air Temperature on Human Neurophysiological Responses in a Simulated Indoor Environment, Applied Ergonomics 88(June):103189.

Allomonte S, Allen J, Bluyssen PM, Brager G, Heschong L, Loder A, Schiavon S, Veitch J, Wang L, Wargocki P (2020) Ten Questions Concerning Well-Being in the Indoor Environment, Building and Environment 180:106949 https://doi.org/10.1016/j.buildenv.2020.106949.

Altomonte S, Kacel S, Wegertseder Martinez P, Licina D (2024) What is NExT? A new Conceptual Model for Comfort, Satisfaction, Health, and Well-Being in Buildings, Building and Environment 252:111234.

Alvarsson JJ, Wiens S, Nilsson ME (2010) Stress Recovery During Exposure to Nature Sound and Environmental Noise, International Journal of Environmental Research and Public Health 7(3):1036-1046.

Babisch W (2008) Road Traffic Noise and Cardiovascular Risk. Noise and Health, 10, pp 27-33.

Belkin K, Martin R, Kemp SE, Gilbert AN (1997) Auditory Pitch as a Perceptual Analogue to Odor Quality, Psychological Science 8:340-342.

Bluyssen PM (2009) *The Indoor Environment Handbook*, Taylor & Francis, London, UK.

Bluyssen PM (2014) *The Healthy Indoor Environment, How to Assess Occupants' Wellbeing in Buildings*, Taylor & Francis, London, UK.

Bluyssen P.M. (2020) Towards an Integrated Analysis of the Indoor Environmental Factors and its Effects on Occupants. Intell. Build. Int. 12(3):199-207.

Bluyssen, PM (2022) Patterns and Profiles for Understanding the Indoor Environment and its Occupants. In CLIMA 2022, REHVA 14th World congress, paper 1504, Rotterdam, the Netherlands, May 22–25 https://doi.org/10.34641/clima.2022.417.

Bluyssen PM, van Zeist F, Kurvers S, Tenpierik M, Pont S, Wolters B, van Hulst L, Meertins D (2018) The Creation of Senselab: A Laboratory for Testing and Experiencing Single and Combinations of Indoor Environmental Conditions, Intelligent Buildings International 10:5-18.

Bluyssen PM, Zhang D, Kim DH, Eijkelenboom A, Ortiz-sanchez M (2021) First SenseLab Studies with Primary School Children: Exposure to Different Environmental Configurations in the Experience Room, Intelligent Buildings International 13(4):275-292.

CEN (2019) *EN 16798-1, Energy Performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6.* CEN-CENELEC Management Centre, Brussels, Belgium.

Dehghan H, Bastami MT, Mahaki B (2017) Evaluating Combined Effect of Noise and Heat on Blood Pressure Changes among Males in Climatic Chamber, Journal of Education and Health Promotion 6(1):39.

EU (2024) Directive (EU) 2024/1275 of the European Parliament and of the council of 24 April 2024 on the energy performance of buildings. Assessed June 25, 2024 from Official Journal of the European Union https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri = OJ:L_202401275.

Hamida A, D'Amico A, Eijkelenboom A, Bluyssen PM (2024a) Guidance to investigate university students' bodily responses and perceptual assessments in sound exposure experiments, Indoor Environments 1(4): 100066.

Hamida A, Eijkelenboom A, Bluyssen PM (2024b) Profiling university students based on their acoustical and psychosocial preferences and characteristics of their home study places, Building and Environment: 111324.

Hamida A, Zhang D, Ortiz MA, Bluyssen PM (2023) Indicators and Methods for Assessing Acoustical Preferences and Needs of Students in Educational Buildings: A Review, Applied Acoustics 202: 109187.

McClellan S and Hamilton B (2010) *So Stressed, A Plan for Managing Women's Stress to Restore Health, joy and Peace of Mind*, Simon & Schuster, London, UK.

Morawska L, Tang J, Bahnfleth W, Bluyssen PM, Boerstra A, Buonanno G, Cao J, Dancer S, Floto A, Franchimon F, Haworth C, Hogeling J, Isaxon C, Jimenez JL, Kurnitski J, Li Y, Loomans M, Marks G, Marr LC, Mazzarella L, Melikov AK, Miller S, Milton D, Nazaroff W, Nielsen PV, Noakes C, Peccia J, Querol X, Sekhar C, Seppänen O, Tanabe S, Tellier R, Tham KW, Wargocki P, Wierzbicka A, Yao M (2020) How Can Airborne Transmission of COVID-19 Indoors be Minimised? Env. Int. 142:105832.

Ortiz M, Itard L, Bluyssen PM (2020) Indoor Environmental Quality Related Risk Factors with Energy-Efficient Retrofitting of Housing: A Literature Review, Energy and Buildings 221:110102 https://doi.org/10.1016/j.enbuild.2020.110102.

Rohde L, Steen-Larsen T, Lund Jensen R, Kalyanova Larcen O (2020) Framing Holistic Indoor Environment: Definitions of Comfort, Health and Well-Being, Indoor and Built Environment 29(8):1118-1136.

Sun X, Wu H, Wu Y (2020). Investigation of the Relationships among Temperature, Illuminance and Sound Level, Typical Physiological Parameters and Human Perceptions. Building and Environment 183: 107193.

Torresin S, Pernigotto G, Cappelletti F, Gasparella A (2018) Combined Effects of Environmental Factors on Human Perception and Objective Performance: A Review, Indoor Air 28:525-538.

Universität Düsseldorf: G*Power (n.d.). Accessed April 3, 2025 from https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower.

Wesson DW and Wilson DA (2010) Smelling Sounds: Olfactory – Auditory Sensory Convergence in the Olfactory Tubercle, The Journal of Neuroscience 30(8):3013-3021.

WHO (2021) World report on hearing, March 2021, World health Organization. Assessed on June 30, 2024: https://www.who.int/publications/i/item/9789240020481.