Building and Environment 288 (2026) 114005

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Combined and cross-modal effects of acoustic and indoor air quality conditions on sensory and cognitive responses of university students

Matteo Pellegatti [a,*], Chiara Visentin [a], Simone Torresin [b], Francesco Babich [c], Pawel Wargocki [d], Nicola Prodi [a]

[a] Department of Engineering, University of Ferrara, Via G. Saragat,1 44122, Ferrara, Italy
[b] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano, 77 38123 Trento, Italy
[c] Institute for Renewable Energy, Eurac Research, Via A. Volta 13/A 39100, Bolzano, Italy
[d] International Centre for Indoor Environment and Energy, Department of Environmental and Resource Engineering, Technical University of Denmark (DTU SUSTAIN), 2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Keywords:
Multi-domain
Acoustics
Indoor air quality
Cognition
Soundscape
Arousal theory

ABSTRACT

Indoor Environmental Quality (IEQ) plays a crucial role in occupant well-being, particularly in educational settings where suboptimal IEQ impacts students' cognitive abilities and ultimately their quality of learning. Although research into IEQ in educational settings has increased recently, studies that concurrently examine indoor air quality (IAQ) and acoustic domains remain scarce.

This study adopted a multi-domain approach by investigating the combined effects of these two domains on university students' cognitive abilities, as well as their cross-modal impacts on soundscape and IAQ assessments. In laboratory conditions, 29 students were exposed to two ventilation regimes which led to two bio-effluent levels represented by two CO_2 concentrations (800 and 3000 ppm), and four auditory conditions representative of both mechanical and natural ventilation conditions (Quiet, Babble noise, Mechanical Ventilation noise, and Birdsongs) while performing a calculation task and completing assessments soundscape and IAQ perception.

The results revealed a combined effect of IAQ and acoustics on calculation performance, with response times slowing down in quiet as bio-effluents increased. Moreover, only for a high bio-effluent level, response time was faster in Babble noise compared to Quiet or Birdsongs. We speculated that these effects could be explained by the arousal theory. No cross-modal effects of the two domains were found for assessments, while changes in one domain influenced the corresponding perceptual evaluation. Overall, cognitive performance seems to be mediated by an increase in sound-induced arousal, consistent with the Yerkes-Dodson law, with the arousal-performance curve further modulated by IAQ levels.

1. Introduction

Indoor Environmental Quality (IEQ) [1] describes the overall quality of an indoor environment regarding the four elements: thermal domain, indoor air quality (IAQ) domain, acoustic domain, and visual domain [1,2].

Ensuring good IEQ is essential in buildings to prevent health issues (e.g., headache, feelings of being too hot/cold, fatigue, usually referred to as Sick Building Syndrome (SBS) [3]) and enhance occupants' comfort and well-being. In the case of educational buildings, maintaining high IEQ standards becomes even more critical to avoid hindering the quality of teaching activities and students' learning, which in turn may impact their academic performance [4–6].

Traditionally, research in educational settings has mainly focused on the individual effect of each IEQ domain on students' performances (e.g., cognitive abilities, perceived performance), health and perception (e.g., comfort, acceptability) [2,7,8]. The perspective is also reflected in building standards and regulations [9]. With specific reference to the Italian regulations on indoor air quality, environments are classified into four quality grades (1, the Highest grade and 4, the lowest). Grade 2 is generally recommended, corresponding to a minimum airflow rate of 7 l/s per person, which is increased to 10 l/s per person (Grade 1) in the presence of children or other sensitive individuals [9]. The values for the highest grade coincide with those recommended during the recent

* Corresponding author.
E-mail address: matteo.pellegatti@unife.it (M. Pellegatti).

https://doi.org/10.1016/j.buildenv.2025.114005
Received 12 May 2025; Received in revised form 26 September 2025; Accepted 11 November 2025
Available online 12 November 2025
0360-1323/© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

COVID-19 pandemic, namely, an air change rate (ACH) of 6 or a ventilation rate of 10 l/s per person [10].

Regarding acoustics, instead, standards specify a maximum sound level of 34 dB(A) for the noise generated by ventilation systems [11]. Notably, these standards are developed in isolation: air quality guidelines do not take noise levels into account, while acoustic standards fail to consider variations resulting from different ventilation strategies (e.g., windows open versus closed). A slightly different approach is adopted in the UK: to encourage the use of natural ventilation via windows, noise limits are set at different values depending on whether the window is open or closed. When the window is open, these limits are increased by 5 dB [12]. However, this allowance is not supported by data in the literature, as noted in Ref. [13].

Therefore, the simple choice between natural and mechanical ventilation systems has a significant combined impact on both acoustic and air quality domains. Mechanical ventilation, for instance, allows for precise regulation of the air change rate and typically results in a predictable acoustic environment, albeit at operational costs. Conversely, natural ventilation might be more economical but produces a variable acoustic environment and offers limited control over indoor air quality. Thus, one might assume that, from an acoustic point of view, opting for mechanical ventilation is the obvious choice; however, the presence of a variable acoustic environment could, depending on the context, be advantageous. As highlighted in the review by Pellegatti et al. [14], natural sounds are generally associated with beneficial effects on students in terms of comfort and cognitive performance, whereas the sounds produced by mechanical ventilation tend to be detrimental. Furthermore, adopting solutions based on window opening could increase the perceived control of the environment.

Recently, a multidomain approach to the IEQ has been advocated for, by considering the cumulative effects of multiple domains on occupants, both in terms of combined and cross-modal effects [4–7, 15–19]. As detailed by Chinazzo et al. [15], a combined effect occurs when the joint effect of two or more domains is analysed concerning an outcome that does not directly depend on those domains. For instance, indoor air quality and acoustics may jointly influence students' cognitive abilities. Conversely, a cross-modal effect is observed when one domain influences the perceptual evaluation of another, such as how changes in indoor air quality conditions affect the acoustic pleasantness of an environment. Lastly, when the interaction between two or more domains is investigated concerning an output associated with any IEQ domain, such as how sounds and indoor air quality influence acoustic pleasantness, the phenomenon is referred to as the cross-modal interaction effect.

Literature reviews revealed that the majority of the studies focused on cross-modal effects of IEQ, with only a few examining the combined effects of different domains on cognitive abilities [19]. Furthermore, among IEQ domains, air quality and acoustics have been the least frequently studied in tandem, despite their recognised importance in educational environments [17,18]. Given this literature gap, a study was set up aiming to investigate the combined effect of the acoustics domain (i.e., the sound environment) and the indoor air quality domain on the cognitive performance and environmental assessments of university students.

1.1. Effects of sound stimuli on cognitive abilities and comfort

Acoustic stimuli possess considerable potential to influence cognitive abilities [20–23]. Anthropogenic noise, such as babble noise, has demonstrated particularly negative effects, as it captures attention owing to its richness in salient events and/or semantic content. Furthermore, negative impacts on cognitive performance have been observed with mechanical ventilation noise [14], which reduces accuracy in tasks involving reading comprehension [24,25], attention [26], and memory [26,27], whereas natural sounds, such as the sound of rain, can enhance arithmetic performance [28] and restore attention between successive tests [29]. Natural sounds were also found to improve comfort, making the classroom experience more pleasant, influencing in turn higher-order cognitive abilities and, ultimately, student performance [30]. Indeed, recent research on well-being in built environments [31] stresses the need to move forward and address the challenge of designing environments that not only maintain healthy hearing and reduce occupants' discomfort but also effectively support the well-being of the occupants in relation to the primary purpose of the facility. Acoustic-wise, it means adopting a soundscape perspective, which considers environmental sounds as potential assets, thus fostering a perspective that goes beyond noise control [32]. In indoor settings, research has established frameworks for assessing the qualitative dimensions of the sound environment in residential [33–35] and office spaces [36]. Although soundscape research in educational contexts is still in its early stages, with only a few studies available [29,37–40], a framework is also emerging for these settings, at least from the perspective of teachers [40].

1.2. Effects of IAQ on cognitive abilities and comfort

Regarding the effects of indoor air quality (IAQ), the literature presents several studies [6,41–48] that have investigated its impact on students. In relation to cognitive abilities [41], research has predominantly focused on the reduction in ventilation air changes, which results in an increase in pollutants (e.g., volatile organic compounds and bio-effluents). These studies have often employed CO_2 concentration as a proxy for air quality [49] and the associated pollutants. Henceforth, unless explicitly indicated as pure CO_2, all references to CO_2 concentrations pertain to this proxy value for IAQ as influenced by restricted ventilation in spaces occupied by people.

More specifically, the works of Zhang et al. [47,48] provided a comprehensive summary of the effects arising from elevated bio-effluent levels due to reduced ventilation, considering the nature of the task. For tasks comparable to typical office work (e.g., calculations), probable adverse effects have been observed at ventilation rates at which a CO_2 concentration was 1600 ppm [47], with effects being deemed certain only at ventilation rates at which concentrations of CO_2 were 3000 ppm or above [45]. In contrast, for more complex tasks, such as decision-making, even a pure CO_2 concentration as low as 950 ppm may be sufficient to provoke negative impacts [50]. Readers should note that, according to established guidelines [10,51], a 1000 ppm CO_2 concentration is considered to delineate good or improved IAQ from poor or reduced air quality.

Except for the effects mentioned above for taxing and complex tasks, exposure to pure CO_2 has not been shown to produce negative effects on cognitive performance, irrespective of the task [42,48], at concentrations commonly found in educational and occupational settings, which are $<$5000 ppm [52].

Regarding the effects on perceived air quality, a reduction in ventilation is associated with a decline in perceived air quality, evidenced by decreased acceptability and an increased perception of odours [45,53]. However, conflicting observations have also been reported, with some studies indicating no significant impact on perceived quality [54]. Notably, an adaptation phenomenon appears to influence perceived air quality, with acceptability increasing as exposure prolongs [45]. The effects also depend on the strength of pollution sources emitting pollutants, evoking sensory effects [55,56].

1.3. Combined and cross-modal effects of acoustics and IAQ

There is a paucity of studies investigating combined and cross-modal effects of IAQ and acoustics [2,6,7]. Specifically, only two studies examined the combined effects of air quality and acoustics on cognitive performance [57,58]. In the study by Balazova et al. [57], students were exposed to two temperature conditions (23.5 °C and 28 °C), two air quality conditions (presence or not of carpet), and two levels of road traffic noise (52 vs 60 dBA) while solving mathematical problems and assessing environmental quality. No combined effect of air quality and acoustics on cognitive abilities was found. In the work by Pan et al. [58], students were instead exposed to coffee aromas and two levels of white noise (45 and 75 dBA) during generic cognitive tests. The authors reported that the environmental parameters influenced cognitive abilities.

Regarding cross-modal effects, besides the studies [57,58], further investigations have been conducted in indoor settings [59] and in outdoor environments [60,61]. Findings for indoor environments are inconsistent: both Balazova et al. [57] and Pan et al. [58] reported no cross-modal effects between the two domains, whereas Clausen et al. [59] found that an increase in traffic noise levels reduced the perception of air quality when carpets treated with mixtures of pollutants were present. Similarly, the review by Zaho et al. [62] reveal that increasing the sound level, especially of anthropogenic noise, worsened the evaluation of IAQ.

In outdoor contexts, Ba and Kang [60] and Ba et al. [61] performed soundwalks in parks with various odours and sounds, and along avenues with or without fragrant trees. They observed that the smell of food [61] and the presence of trees [60] reduced traffic-related annoyance.

1.4. Aims

To closely investigate the combined and cross-modal effects of the acoustics domain and IAQ domain on students, an experimental study was conducted in which university students were exposed to a controlled set on environmental conditions. The effects of the two domains under study were quantified through cognitive measures (accuracy and response time in a calculation task) and subjective data. Furthermore, as both IEQ and cognitive abilities are influenced not only by environmental but also by human factors (e.g., demographics, occupants' activities, social context) [33,62], personal characteristics such as noise sensitivity and introversion/extroversion were included in the study. Omitting the characterisation of personal factors could lead to less stable models in data analysis [34] or incorrect interpretation of the results [63,64]. Specifically, the following research questions were formulated:

1) What is the combined effect of acoustics and IAQ on university students' cognitive abilities in classrooms?
2) What is the cross-modal interaction effect of acoustics and IAQ on university students' soundscape assessments in classrooms?
3) What is the cross-modal interaction effect of acoustics and IAQ on university students' air quality assessments in classrooms?

2. Methods

In this research, human participants were involved in laboratory studies during which they were exposed to various IAQ and acoustic conditions while performing cognitive tests and filling in questionnaires about their perception of such conditions.

2.1. Participants

A total of 32 students from the Technical University of Denmark (DTU) participated in the experiment. They were recruited via flyers posted on noticeboards in common areas of the campus (e.g., cafeterias). Detailed information about the experiment, inclusion criteria (no known cognitive or auditory impairment), and data handling procedures was provided through informed consent forms, to be signed and returned to the researchers on the day of the experiment. All participants were rewarded with a voucher worth 300 DKK for the university bookshop.

The final number of participants included in data analyses was 29 (mean age: 22.8 years, SD: 2.5 years; 31 % female), due to technical failure with the equipment during the experiment of three participants.

The entire experiment was internally reviewed by Eurac Research's research offices and complies with the Eurac Research Core Ethics and Integrity Principles.

2.2. Facilities

The experiment was carried out in a laboratory setting, i.e., the so-called *Field Labs* at DTU (Toftum et al. [65]). The lab consists of a room with the possibility of being divided into three equally sized rooms (single volume: 55 m^3), each equipped with an independent HVAC system. During the experiment, one of the three rooms was used as a control room, whereas inside each of the other two rooms, two tables were set up, separated by a widescreen partition with a room for two participants (Fig. 1). Rooms were selected for their low pollutant levels and emissions from materials, as confirmed by previous studies [65]. Any variation in pollution levels corresponds to the experimental condition described in Section 2.3.

2.3. Experimental conditions

All participants were exposed to four listening conditions and two air quality conditions. Listening conditions were selected to represent acoustic environments typically found in university classrooms having natural or mechanical ventilation. Specifically, participants were exposed to Quiet (no added noise), Mechanical Ventilation noise, Babble noise, and Birdsongs. The latter three stimuli were recorded using binaural headphones (Head Acoustics BHS II) connected to a recording system (Head Acoustics Squadriga III).

The Mechanical Ventilation noise was recorded in a shoebox-shaped room ($4 \times 8 \times 3$ m), with a mechanical ventilation system operating at a flow rate of 160 l/s. The flow rate was calculated using 10 l/s per person and the room's maximum capacity ($n = 16$ occupants). The other two sound conditions were recorded in a university classroom with the left ear facing an open window in order to more ecological as possible.

All recordings were presented through headphones at a level of 47 dBA, calibrated using the left ear as a reference. Calibration was performed by calculating the A-weighted equivalent continuous sound level (LAeq) based on a randomly selected 60-second segment from the binaural head recording. This calibrated level corresponds to the measured level of the original stimuli, which was determined over the full duration of the original recording. The playback system comprised a laptop (HP ProBook 440 G8), an audio interface (Focusrite Scarlett Solo III), a four-channel audio amplifier (Behringer HA4700 Powerplay Pro-XL), and headphones (Sony WH-1000XM4). Since the background noise level in the laboratory was 45 dBA, active noise cancellation was enabled in the headphones, reducing the laboratory ambient noise to 29 dBA at the ear of the tester.

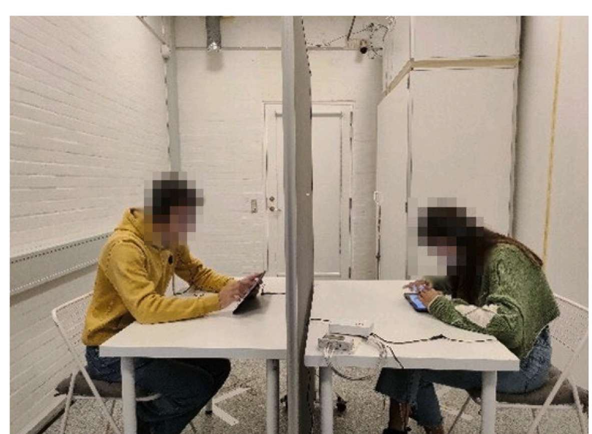

Fig. 1. Experimental setup in one of the two rooms of the Field Labs of DTU, which were used for the tests.

Fig. 2 illustrates the spectral content of the listening condition presented in 1/1 octave bands.

For air quality, two ventilation outdoor airflow rates, respectively high and low, were used. The two airflows resulted in two levels of predominantly human-produced pollutants (bio-effluents) and were represented by two levels of CO_2 concentrations, 800 and 3000 ppm. These target concentrations were selected as representing realistic scenarios of good and poor air quality that could occur in university classrooms [66]. The experimental bio-effluent concentrations were reached by having other individuals occupying the laboratory prior to the arrival of experiment participants; these other individuals left the rooms immediately prior to experiments and were not noticed by participants. During the experiment, own bio-effluent emissions from the participants allowed to keep the level of CO_2 unchanged. CO_2 was constantly monitored during the experiment. In each test room, the participants experienced only one of the two air quality conditions, and all four acoustic conditions.

Temperature (23 °*C* ± 0.5 °C) and humidity (40 % ± 10 %) were kept constant throughout the experiment and were continuously monitored to ensure stability of the environmental settings. With regard to the visual domain, no measurements were conducted. However, all tests took place in the afternoon, with the blinds closed and the laboratory illuminated by artificial lighting in order to prevent any effect from daylight.

2.4. Cognitive tasks and questionnaires

During the experiment, participants completed (i) a questionnaire for demographic information, noise sensitivity and personal traits assessment, (ii) a calculation task, to quantify the effects of environmental conditions on cognition, and (iii) two questionnaires on the perception of the air quality and the sound environment. The complete questionnaires are presented in the supplementary material.

2.4.1. Calculation task

In the calculation task, the participants were requested to determine whether the result of an equation was correct or not. They completed 24 equations for each experimental condition. Equations were presented alongside "True" and "False" buttons on a tablet (see supplementary material for an example). Each equation was displayed following a 1 s white screen and remained on the screen until a response was given or for a maximum of 20 s. Both accuracy and response time of each equation were collected.

Specifically, the equations were created following Caviola et al. papers [20,67] and involved two-digit addition and subtraction operations, both with and without carrying (addition) and borrowing (subtraction). The presence of carrying or borrowing is hereafter referred to as task difficulty (low or high), since as stated in literature the presence of borrowing and carrying is a way to modulate task difficulty [20,67–69]. The results displayed with the equations could be either correct or incorrect. All equations were required to be solved mentally, without the use of any auxiliary aids such as pen and paper or a calculator. Each operand in the operation was required to consist of two digits, and the result had to be non-zero.

Table 1 provides examples of the various combinations of operations' type along with their difficulty.

Table 1
Combination of the 24 equations solved by participants in each experimental condition. Examples of additions and subtraction with different difficulty are provided.

Difficulty	Additions	Subtractions
Easy	3 True (14+15=29)	3 True (27–15=12)
(No borrowing/carrying)	3 False (14+15=39)	3 False (27–15=14)
Difficult	3 True (18+15=33)	3 True (25–17=8)
(Borrowing/carrying)	3 False (18+15=35)	3 False (25–17=12)

2.4.2. Soundscape and air quality assessments

Method A of the ISO/TS 12,913–2 standard [70] on soundscape was employed to subjectively qualify the perception of the sound environment. Participants assessed eight attributes (pleasant, annoying, eventful, uneventful, vibrant, monotonous, calm, and chaotic) using 5-point Likert scales while listening to one of the listening conditions and being exposed to one of the IAQ conditions.

As regards IAQ assessments, participants were asked to answer three questions, respectively the first on air quality acceptability (*How acceptable do you find the indoor air quality?*), the second on ventilation acceptability (*How acceptable do you find the ventilation in the room?*), and the last one on perceived air pollution (*Do you think the air you breathe here is polluted?*). Questions were answered by using a 4-point Likert scale ranging from Clearly acceptable (Definitely not polluted) to Clearly unacceptable (Definitely polluted). Finally, participants were asked to choose between alternatives by indicating whether they generally perceived the air as dry or humid, stuffy, or fresh, and smelly or odourless. The questions were adapted from Gupta et al. [71]. The complete questionnaire can be found in the supplementary material.

2.4.3. General questionnaire

The final questionnaire included: two questions on gender and age, the short form of the Weinstein noise sensitivity questionnaire [72] and two items derived from the Five Personality Traits framework focusing

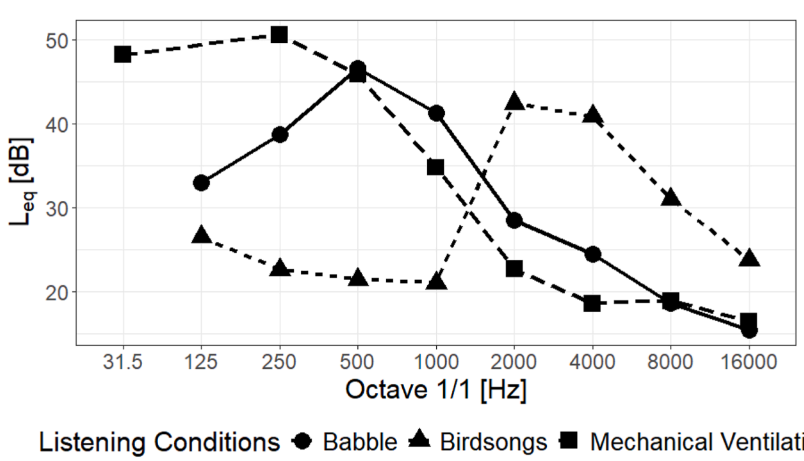

Fig. 2. The spectral content of the listening conditions was represented by the equivalent sound level (L_{eq}) across 1/1 octave bands. The L_{eq} values were calculated from a randomly selected 60-second segment of the binaural recording.

on extroversion and introversion [73]. To gauge this latter trait, two statements were evaluated on a 5-point Likert scale: “I see myself as someone who is reserved” and “I see myself as someone who is outgoing sociable”. The complete questionnaires can be found in the supplementary material.

2.5. Experimental procedure

Fig. 3 provides an overview of the whole experimental procedure. Participants started the experimental activities by completing online the general questionnaire. Afterwards a date for their experiment session was scheduled.

On the day of the experiment, participants signed the informed consent form and received training on the calculation task, soundscape, and air quality assessment while in the control room. Training was conducted while participants wore headphones in a quiet condition. Following the training, participants were directed to their assigned test room, one pair per room.

For each of the eight conditions (2 IAQ x 4 noise types) the participants were asked to firstly assess air quality, secondly to pursue the calculation task and finally to evaluate the soundscape. Each sound exposure inside a room was interspersed by a 5 min break. After completing all conditions in one room they took a 10 min break in the control room and moved to the second room with either better or worse air quality.. The entire experiment was split into two parts, each one taking place in one of the two rooms having a different bio-effluent level. The full experiment lasted approximately 2 h. The combination of listening and IAQ conditions will be hereafter referred as blocks. The order of the blocks was counterbalanced across participants using a Latin square design [74]. An illustrative table of the administration order has been added to the supplementary material. The whole experimental procedure was structured to investigate the acute exposure to the two domains in order to avoid cumulative effects that could alter both the cognitive task and the environmental assessments.

2.6. Data analysis

2.6.1. General questionnaire

Noise sensitivity and extroversion values were calculated for each participant. As regards noise sensitivity, the total score was calculated as the average of the scores of the five questions (the scale of the fifth question was reversed). Then, a median split was applied to divide participants into two groups (low and high noise sensitivity respectively).

For extroversion, the scale of the first question was reversed, and a single extroversion score for each participant was obtained as the average of the two items. The extroversion questions were answered only by a subset of 16 participants because the question was erroneously marked as optional in the general questionnaire.

2.6.2. Calculation task

Statistical analyses were conducted using *R* (ver. 4.4.2) [75] and *RStudio* (Build 563), with the *lme4* package (ver 1.1–36) [76]

General linear mixed-effect models were implemented to investigate the influence of the combined effect environmental stressors on task accuracy and response time. For the accuracy data, which could only take a value of 0 or 1, a binomial distribution was adopted in the model. For the response time of correct answers (95 % of the dataset), a Gamma distribution with a logarithmic link function was used. The GLMMs included as fixed effects: listening conditions (Quiet, Mechanical Ventilation, Birdsongs, Babble noise), bio-effluent level (categorical variable: CO_2 800, 3000 ppm), task difficulty (low, high), noise sensitivity group (low, high), the order in which the blocks were presented (1–8), and two-way interactions between listening conditions and bio-effluent levels, task difficulty and listening conditions, task difficulty and bio-effluent levels, as well as listening conditions and noise sensitivity. Participants were entered in the model as random intercepts. Post-hoc analyses were conducted using the *emmeans* package (ver1.10.6) [77], with multiple comparisons corrected according to the Benjamini-Hochberg correction criterion [78]. Effect sizes, expressed as Cohen’s d [79], were calculated only for those effects that attained statistical significance.

2.6.3. Soundscape assessments

For the assessment of the sound environment, two new variables, namely ISOPleasantness and ISOEventfulness, were calculated for each participant by combining the eight soundscape attributes evaluated in the questionnaire as specified in the standard ISO/TS 12,913–3 [80]. These two new variables range from −1 to 1, with −1 corresponding to unpleasant (uneventful) and 1 to pleasant (eventful).

Data were analysed by running two linear mixed-effects models (LMMs) with ISOPleasantness and ISOEventfulness as dependent variables to investigate the cross-modal interaction effect of the IAQ and acoustics domain. The fixed effects included in the models were: listening conditions, noise sensitivity group, bio-effluent levels, and the two-way interactions between bio-effluent levels and listening conditions, as well as between noise sensitivity group and listening conditions. Participants were included in the models as random intercepts.

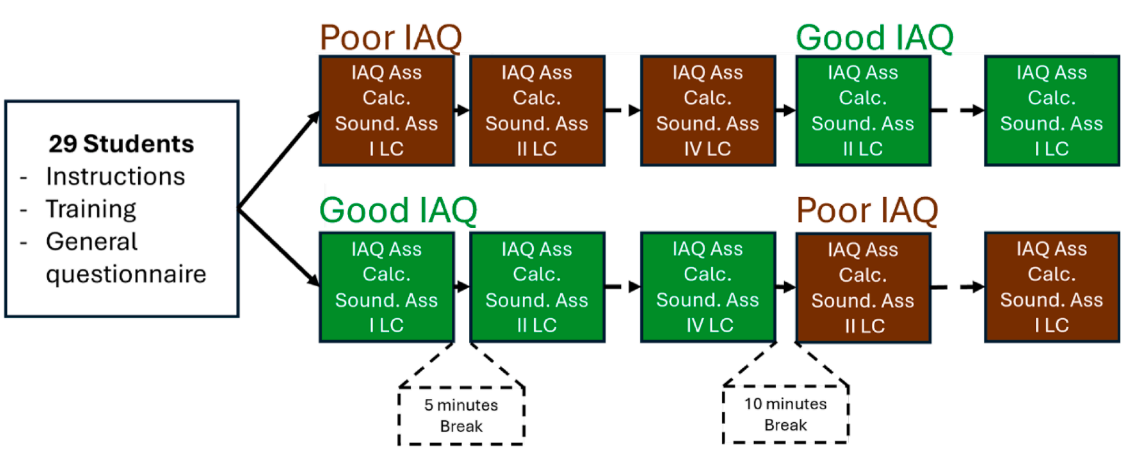

Fig. 3. Overview of the experimental procedure. The four listening conditions (LC I–IV: quiet, mechanical ventilation noise, babble noise, birdsongs) and the two air-quality conditions (low and high bio-effluent) were counterbalanced across participants. For the first IAQ exposure, three of the four possible combinations of listening condition and IAQ level are depicted; for the second exposure, two of the four combinations are shown. Dashed arrows indicate conditions that are not illustrated but were nonetheless included in the design. Identical symbols denote the same listening condition (e.g. LC *I* = Quiet, LC II = Mechanical Ventilation noise, LC III = Babble noise, LC IV = Birdsongs).

2.6.4. *Air quality assessments*

In the analysis of the air quality assessments, responses were transformed into dichotomous variables. From the question including pairs of contrasting adjectives (i.e., stuffy/fresh, smelly/odourless, and dry/humid) two variables were created by assigning to one adjective the value of 0 (fresh/odourless) and to the other the value of 1 (stuffy/smelly). The answers to the adjective pair “dry/humid” were excluded, due to difficulties of the participants in providing a reliable evaluation.

Answers to the acceptability and pollution questions were grouped into two categories: "Acceptable"/” Polluted” (including "Clearly acceptable" and "Just acceptable”) and "Not Acceptable"/” Not polluted” (including the remaining two ratings).

The answers were analysed with four generalized linear mixed-effects models, including as fixed effects: bio-effluent levels, listening conditions, the interaction between the two factors, and the presentation order of the blocks. Participants were included as random variables.

GLMM models were used rather than ordinal models due to convergence issues with the latter.

3. Results

3.1. *Calculation task*

Accuracy in the calculation task showed a strong ceiling effect, with most participants achieving the highest score in all experimental conditions. The statistical model identified a significant effect of task difficulty ($\chi^2(1)=50.7$, $p < 0.001$), indicating that accuracy was lower for complex equations ($M = 0.93$; SD=0.04) compared to simpler ones ($M = 0.97$; SD=0.02). No significant effect of air quality or listening conditions on task accuracy was observed. Graphs and detailed results are reported in the supplementary material. The identified effect size for the difficulty effect was large, as Cohens’ d was 1.05.

The statistical analysis of response time data indicated a significant main effect of listening conditions ($\chi^2(3)=11.23$, $p = 0.01$), order of the blocks ($\chi^2(7)=15.28$, $p < 0.001$), task difficulty ($\chi^2(1)=1049$, $p < 0.001$), and a significant interaction between listening conditions and bio-effluent levels ($\chi^2(3)=9.75$, $p = 0.02$). Post hoc analyses revealed that response times were shorter for low-difficulty equations ($M = 3.67$ s, SD=0.98 s) compared to more difficult ones ($M = 5.4$ s, SD=1.9; $z = 32.38$, $p < 0.001$, $d = 0.82$ – large effect size). Moreover, response times decreased continuously during the first four blocks of the experiment. The later the block (only 1 to 4), the shorter the response time ($p < 0.001$). Please check the supplementary material for the graphical results.

Fig. 4 displays the significant interaction between listening conditions and bio-effluent levels. Pairwise comparisons showed that only for Quiet the difference in the response time between the bio-effluent levels was significant. Response times were longer in the poor ($M = 4.54$ s) compared to the good air quality condition ($M = 3.74$ s; $z = 2.65$, $p = 0.04$, $d = 0.13$ – small effect). In addition, for the high bio-effluent level exposure to Babble noise shortened response time compared to Quiet ($z = 3.04$, $p = 0.02$, $d = 0.16$ – small effect size) and Mechanical Ventilation noise ($z = 3.57$, $p = 0.006$, $d = 0.15$ – small effect size).

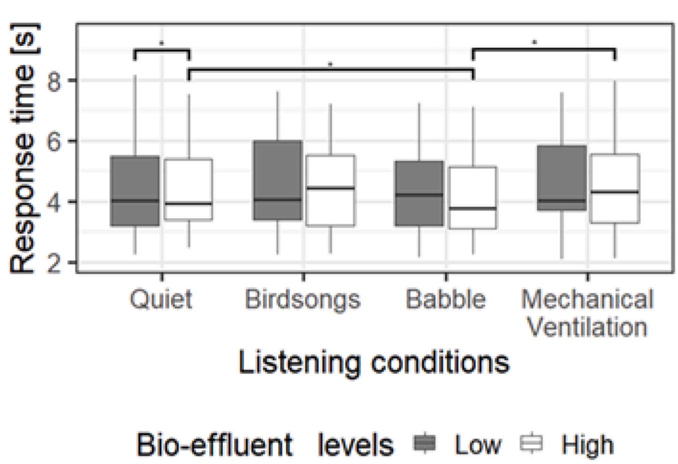

Fig. 4. Response times for correct responses only, plotted as a function of listening and IAQ conditions. For each participant, the median response time was calculated across all correct trials, irrespective of equation difficulty.

3.2. *Soundscape assessments*

Fig. 5 shows a visualisation of the distribution of soundscape assessments for each listening conditions (averaged across the bio-effluent levels) using 50th percentile contours [69]. The figure can be divided into two main axes, corresponding to ISOPleasantness and ISOEventfulness, and two secondary axes. According to the circumplex model [81], these secondary axes represent the chaotic–calm and monotonous–vibrant dimensions, which are respectively associated with the II and IV quadrants and the III and I quadrants. In this framework, chaotic sounds exhibited negative ISOPleasantness and positive ISOEventfulness, whereas calm sounds scored positive on pleasantness and negative on eventfulness; monotonous sounds registered negative on both scales, while vibrant sounds registered positive on both. Babble noise was perceived as chaotic, Birdsongs generally as pleasant, Mechanical Ventilation as monotonous, and Quiet as calm.

The analysis of ISOPleasantness revealed a significant effect of the listening condition ($\chi^2(3)=125$, $p < 0.001$). Post-hoc tests indicated that pleasantness was significantly lower for Babble noise compared to Mechanical Ventilation noise ($t = 2.36$, $p = 0.02$, $d = 0.45$ – medium effect size). Both stimuli were rated with a significantly lower pleasantness than Quiet and Birdsongs (Mech. Vent.<Birdsongs, $t = 7.42$, $p < 0.001$, $d = 1.41$ – large effect size; Mech. Vent.<Quiet, $t = 5.55$, $p < 0.001$, $d = 1.05$ – large effect size; Babble<Birdsongs, $t = 9.79$, $p < 0.001$, $d = 1.85$ – large effect size; Babble<Quiet, $t = 7.92$, $p < 0.001$, $d = 1.5$ – large effect size). No significant difference in pleasantness was found between Quiet and Birdsongs conditions ($p = 0.6$).

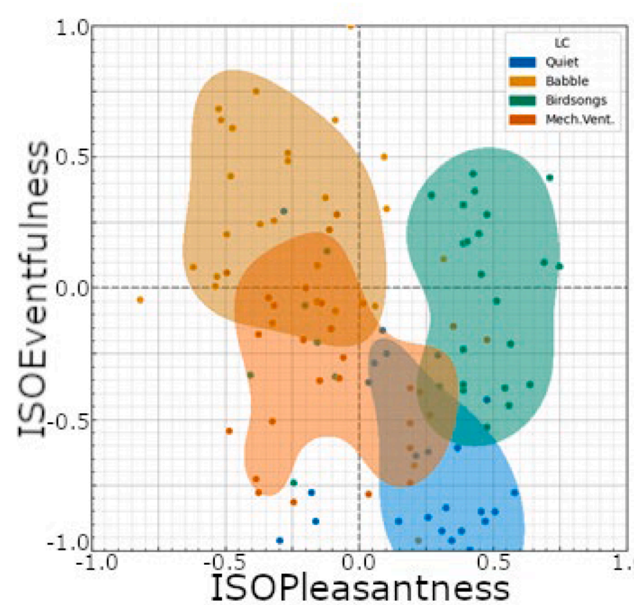

Fig. 5. Graphical representation of the combined distributions of ISOPleasantness (X axis) and ISOEventfulness (Y axis across all listening conditions (LC). The curve represents the median distribution, while the dots correspond to individual participants. The figure was generated using the Soundscapy package for Python [82].

The analysis of eventfulness similarly indicated a significant effect of the listening conditions ($X^2(3)=165$, $p < 0.001$), with all sound stimuli differing significantly in their perceived eventfulness ($p < 0.001$). In descending order from most to least eventful, the listening conditions were Babble, Birdsongs, Mechanical Ventilation, and Quiet. The minimum effect size, calculated as Cohen's d, was 0.6, corresponding to a medium effect

3.3. Air quality assessments

Table 2 summarises the results of the five statistical models referred to the air quality assessment. For all the investigated quantities, the analyses indicated a significant effect only of the bio-effluent levels, consistently lower ratings (lower acceptance, more polluted air, smellier and stuffier air) in the condition with 3000 ppm CO_2 compared to the condition with 800 ppm CO_2. No effect was found due to noise for both interactions.

4. Discussion

4.1. Calculation task: accuracy

Two performance metrics were evaluated for the calculation task: accuracy and response time.

Accuracy was not influenced by environmental stressors. Only task difficulty had a significant effect, with a small difference of four percentage points between the less and the more difficult equations. The results would therefore suggest a complete absence of environmental stressors affecting accuracy. However, the authors do not consider this to be plausible for three reasons. First, a strong ceiling effect was found for the task accuracy, even for the most difficult equations, meaning that the task turned out to be easy to elicit any performance differences between the conditions for a university population. A similar phenomenon was also observed by Proverbio et al. [28], who employed an experimental paradigm very similar to that used in the present experiment.

Second, the experimental design was structured to target the effects of acute exposure to bio-effluents (exposure time: 10 min). To the best of the Authors' knowledge, this is the only study employing such short exposures, whereas previous studies have investigated the effects of much longer ones (from 2 to 4 h) [41,42,45,54,83] with a minimum exposure time of 40 min [84]. Increasing the exposure time would probably lead to the presence of an effect on accuracy, but at the same time, it would affect the environmental assessments as well. The topic is furthermore discussed in the limitations section. Third, the lack of significant effects of the listening conditions on accuracy may be attributed to the combination of sound levels and the modality of how equations were presented to the students. In the present study, equations were displayed visually on a screen; had they been delivered auditorily (for example, read aloud), it is plausible that background noise would have exerted a greater influence on accuracy. Indeed, studies with primary-school children have shown that irrelevant speech and multi-talker babble at 60 dBA do not impair accuracy in visual tasks [85].

Table 2
Summary of significant effects from the five statistical models examining indoor air quality. The 1st column lists each dependent variable (with scale endpoints in brackets), the 2nd column details the significant effects of the independent variables and their statistical outputs, and the final columns report the mean (and standard deviation) ratings under the two air-quality conditions.

Dependent variable	Significant effects	Bio-effluent level (CO_2 concentration) Low (800 ppm)	High (3000 ppm)
Stuffy (0 Fresh, 1 Stuffy)	bio-effluents: $X^2(1)=15.68$, $p < 0.001$	0.20 (0.32)	0.46 (0.39)
Smelly (0 Odourless, 1 Smelly)	bio-effluents: $X^2(1)=8.24$, $p = 0.004$	0.34 (0.39)	0.52 (0.42)
IAQ Acceptability (0 Not acceptable, 1 Acceptable)	bio-effluents: $X^2(1)=7.18$, $p < 0.007$	0.88 (0.26)	0.7 (0.38)
Ventilation Acceptability (0 Not acceptable, 1 Acceptable)	bio-effluents: $X^2(1)=14.85$, $p < 0.001$	0.86 (0.25)	0.66 (0.39)
Pollution (0 Not polluted, 1 Polluted)	bio-effluents: $X^2(1)=6.72$, $p = 0.009$	0.23 (0.34)	0.38 (0.40)

4.2. Calculation task: response time

Regarding response time, a significant two-way interaction between bio-effluents and listening conditions and a main effect of the order of the blocks was found. This provides preliminary evidence suggesting that indoor air quality and acoustic conditions should be investigated and designed using an integrated approach rather than considered separately, at least when assessing their effects on cognitive performance in contexts where cognitive abilities play a crucial role, such as educational environments.

Specifically in our results, in the quiet condition, poor air quality was associated with longer response times. The result might be explained by the ability of the stressor to affect the arousal level of the participants. The Dictionary of Psychology of the American Psychological Association [86] defines arousal as "A state of physiological activation or cortical responsiveness, associated with sensory stimulation and activation of fibres from the reticular activating system". The relationship between arousal and cognitive performance is described by the Yerkes-Dodson law [87,88]. Specifically, cognitive performance, measured in terms of task accuracy or response/execution times, exhibits an inverse U-shaped relationship with arousal. Moderate levels of arousal optimise performance, while too little or too high arousal yields drowsiness or overactivation. In this study, no measures of arousal or stress were collected. However, it can be speculated that the poor air quality condition increased arousal state in participants, which in turn impaired their cognitive performance by increasing the response time. This interpretation is consistent with the literature, which suggests that poor air quality tends to increase arousal and stress responses [41,45,46,89]. In addition to the effect of IAQ on performance, the results of the study showed that exposure to Babble noise prompted faster response times when the air quality was poor. Similarly to the effects of air quality, certain sounds could be more effective than others in elevating arousal [90–93]. The latter results, however, do not seem to align with the hypothesis of only a synergistic effect of acoustics and IAQ conditions on increasing arousal.

Indeed, if the mechanism described above were purely synergistic, the additional increase in arousal caused by auditory stimuli in an already over-aroused condition, such as that induced by poor air quality, would lead to a further decline in performance. This would manifest as longer response times, particularly for auditory stimuli like Babble noise, which are known in the literature to induce higher levels of arousal compared to Quiet or Mechanical Ventilation noise [93,94]. Yet, our results demonstrated the reverse pattern. It is therefore plausible that reduced air quality not only elevated arousal (which we did not measure directly) but also altered perceived task difficulty: poor IAQ may have rendered the equations subjectively more challenging, whereas good IAQ made them seem easier, thereby overriding any simple arousal-driven effects on performance. As suggested by Sörens et al. [95] the perceived difficulty of a task can modify the shape of the Yerkes–Dodson curve. According to this view, easy tasks exhibit a steeper slope at low arousal levels before reaching a plateau or a less steep portion, whereas difficult tasks, despite overall poorer performance, display a clearly defined inverted U-shaped curve.

Fig. 6 was created solely for illustrative purposes, in order to highlight the discussed effects. The features have been deliberately exaggerated to better convey and facilitate understanding of the underlying theoretical considerations. In this study, the low bio-effluents condition, listening conditions would fall within the "flat" region of the curve, as no significant differences between the listening conditions were observed. In contrast, under high bio-effluent levels, differences in the sound effect could be observed due to the more pronounced inverted-U shape of the curves. This hypothesis is also consistent with the observed effects under quiet conditions as the steeper inverted-U shape leads to an overall deterioration in performance. In conclusion, although an increase in arousal due to a deterioration in indoor air quality cannot be excluded, the results appear instead to be driven by a change in the shape of the performance curve, likely due to an altered perception of task difficulty. Future studies should consider broadening the range of air quality and acoustic conditions, such as exploring additional or alternative sound levels, to gain a more comprehensive understanding of how these variables interact, both in terms of arousal shifts and potential reshaping of the performance curve, and to identify the most suitable type of ventilation for different contexts..

Finally, an effect of the order of the blocks was identified, indicating the presence of a learning effect across the first four and the last four experimental blocks. To avoid or at least reduce learning effects, in the experimental design, an extensive practice session was held before the main test. Nevertheless, learning still occurred, which may have diminished the model's overall sensitivity to interactions between listening conditions and air quality. Future studies might employ a longer and more thorough familiarisation phase to prevent such order effects.

4.3. Direct and cross-modal effects on soundscape assessments

In this study, the soundscape framework was used for the assessment of the sound environment, adopting a human-centred viewpoint and exploiting the tools developed to characterise the complex interrelationship between listener, environment, and context [96].

Concerning the second research question, which addressed the presence of cross-domain effects on acoustic perception, the results of the study indicated that indoor air quality did not influence soundscape assessments, with the effects being solely attributable to the acoustic domain. The findings align with the results of the previous literature investigating the cross-modal effect of air quality on the acoustic domain with adults [5,7,57,59]. Even though this cross-modal effect is rarely reported, findings consistently suggest that the effect of a change in indoor air quality (e.g., odour and olfactory comfort, pollutants) on acoustic perception and comfort is non-significant. For instance, air pollution was found not to influence noise acceptability [57]. Pan et al. [58] found that additions of odour had neither synergistic nor antagonistic effects on the perception of noise, and changes in air quality, indicated by CO_2 concentrations, did not affect the acoustic comfort of university students [97].

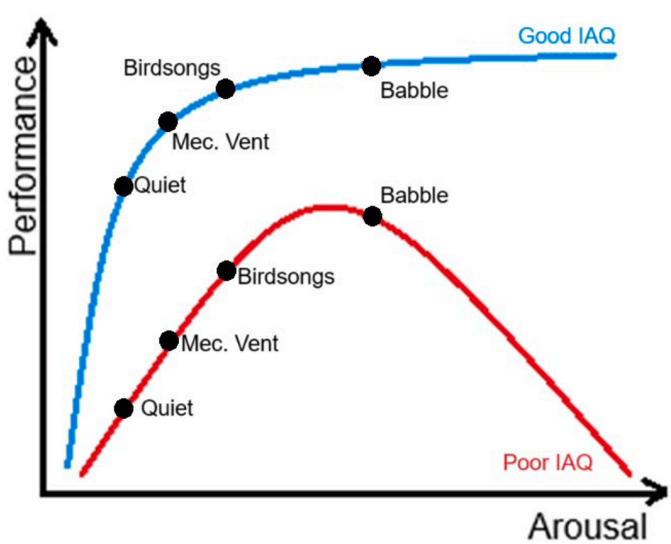

Fig. 6. Illustrative example of the interaction between bio-effluent concentration and acoustic conditions. Low bio-effluent levels (good IAQ) are indicated by the blue line, while high bio-effluent levels (poor IAQ) are shown by the red line. Differences between listening conditions that are indistinguishable under good IAQ (blue line) become apparent under poor IAQ (red line). The pattern depicted is purely hypothetical and intended for illustrative purposes only.

Focusing therefore solely on the effects of the acoustic domain, the results of this study confirm, as expected, that acoustic perception is strongly influenced by the type of background noise [81], even when sound pressure level is kept constant. In this study, the sound stimuli are clearly distributed across the soundscape quadrants, with Birdsongs and Quiet being deemed as most pleasant, with the former being in the vibrant region and the latter in the calm. On the other hand, Mechanical Ventilation and Babble noise were deemed, respectively, as monotonous and chaotic. The result matches literature suggesting that increasing the percentage of natural features or decreasing human and mechanical components determine the perceived soundscape quality (especially in terms of tranquillity) [98]. In addition, the pleasantness values is largely consistent with the literature in showing that noise sources, such as speech [14], are perceived as unpleasant by students, whereas natural sounds tend to have a positive effect [14,29,99].

Regarding eventfulness, the highest value was associated with Babble noise, followed by Birdsongs and Mechanical Ventilation, with Quiet being the least eventful sound. Also, these findings are in line with the literature [35,81], which indicates that sounds of human origin tend to be perceived as more eventful, technological sounds such as mechanical ventilation are considered less eventful, and natural sounds show only a partial association with eventfulness.

In summary, the results confirm what has been reported in the literature: the absence of cross-modal effects of air quality variation on acoustic perception, and a general tendency for greater comfort to be associated with natural sounds.

4.4. Direct and cross-modal effects on IAQ assessments

Concerning the third research question, our results indicated that acoustics had no cross-modal effects on IAQ assessments, with the observed effects being solely attributable to variations in bio-effluents. These findings align with those reported by Pan et al. [58], who investigated the interaction between the perception of noise and odour by exposing participants to conditions with and without a coffee-aroma constituent at sound levels of 45 and 75 dBA. However, the results stand in contrast to other literature in the field. Indeed, Clausen et al. [59] reported significant cross-modal effects, with increased traffic noise being associated with a reduction in perceived air quality. Similarly, several studies have highlighted a significant negative association between noise levels and IAQ comfort, with quieter conditions being linked to better IAQ perception [62].

However, a main issues prevent a straightforward comparison of the present results with the literature. Firstly, in our experimental paradigm, the type of sound stimuli was manipulated instead of the sound level. It might be speculated that it is sound intensity rather than its spectro-temporal characteristics that impact the perception of the other environmental factors. However, a role for the characteristics of the sound stimuli was outlined by Bluyssen et al. [18,100], with reference to primary school children. Both in the lab and in the field, children were found to be more sensitive to smell (worst perception) when exposed to the sound of "children talking".

Limiting the analysis to a unidimensional approach, the CO_2 concentrations targeted in the experiment were sufficiently distinct to induce differences in the perception of IAQ, with higher bio-effluent levels consistently associated with a decline in perceived IAQ. These findings align with those of Zhang et al. [45], regarding bio-effluents, but in contrast with Tang et al. [101]. This discrepancy likely arises from differences in exposure duration. In Zhang et al. study, the questionnaire on air quality and odour perceptions was administered at the outset of exposure—before sensory adaptation to bio-effluents, which occurs within the first few minutes. In Tang et al. work, however, evaluations were conducted after 120 and 180 min of exposure, well beyond the adaptation period. In the present study, ratings were obtained immediately after each exposure, with a rest interval between conditions to minimise the effects of sensory adaptation. From a perceptual standpoint, an integrated approach does not seem to be required for these two domains. Nonetheless, evaluations across different contexts are essential to ascertain whether variations in the context might yield different outcomes, especially since the literature suggests potential cross-modal effects.

5. Limitations

This study has many limitations. Firstly, although the concentration of CO_2 was continuously monitored, minor variations in CO_2 levels were present across the different exposure sessions, as the ventilation system was not directly linked to CO_2 levels and had to be operated manually.

Secondly, as stated in the discussion, the calculation task was easy for participants familiar with scientific subjects. The task was selected for continuity across various experiments, involving different age groups. For future studies, more complex tasks could be considered, for instance, complicating the present task by removing the predefined outcome.

Thirdly, extroversion data were collected in the study; questions had been mistakenly set as optional and, as a result, could not be directly used due to the limited number of responses relative to the total sample size (16 out of 29 participants). Furthermore, the subset was composed of only extroverted students. Controlling this personal factor in data analysis might have helped in understanding the interaction between IAQ and acoustics upon performance. Notably, extroverted individuals generally exhibit lower baseline arousal levels than introverts [28,102,103]. As a result, the arousal increase induced by auditory stimuli may bring their performance closer to optimal levels. Proverbio et al. [28], who divided participants based on their Eysenck's extroversion test scores [104], found that exposure to natural sounds rich in acoustic events, such as rain, significantly reduced response times in extroverts, thereby eliminating the performance gap observed between groups under quiet conditions. A more detailed questionnaire on extroversion and a larger dataset will be needed to fully explore the implications of extroversion/introversion in future studies.

Fourthly the choice of investigation the acute exposure, might have hindered the results of the study as concerns the math task. Indeed, for cognitive tasks, effects of the air quality conditions become apparent only after an exposure period of at least 40 min [84] . Future studies should tackle the issue of balancing acute/chronic exposure in order to assess simultaneously the effects of IAQ on cognition and perception. Lastly, the three research questions were analysed separately, and no attempt was made to link the soundscape and indoor air quality assessment with cognitive performance. The relationship between hearing sounds and emotions has been relatively underexplored in the literature; however, it seems well established that, when individuals experience positive emotions elicited by pleasant sounds, they tend to perform better in a given task, due to improved self-motivation [105]. On the contrary, when experiencing negative emotions, they will tend to perform more inefficiently in the task, lacking to maintain the desired mind-state [106]. Andringa and Lanser [106] proposed that the calm-chaotic axis in the circumplex model represents the extent to which the soundscape acts as an external motivator; specifically, how much mental effort is required to process and monitor the (auditory) environment. Increasing the degree of external monitoring will then affect the amount of attention directed toward the task. Likewise, arousal can be empirically related to task performance through the Yerkes-Dodson law. Even though “arousal” and “eventfulness” are two distinct constructs, they were positively related in the literature [81], as it seems plausible that more eventful soundscapes will be more arousing and activating than less eventful soundscapes. Future studies shall investigate the direct and indirect relationships between environmental factors, affective assessment, and cognitive performance, focusing on how different environmental conditions influence emotional responses and, in turn, affect cognitive processes such as attention, memory, and decision-making.

6. Conclusions

This study examined the existence of a combined effect of IAQ and ventilation sounds on students' calculation abilities. Besides, cross-modal interactions of the two domains on soundscape and air quality evaluations were examined as well. The findings indicate the presence of a combined effect on the calculation response time only. Poor air quality due to elevated bio-effluent levels, as indicated by high CO_2 concentration, caused the test to be performed more slowly in Quiet. The Babble noise increased the pace at which the task was solved when IAQ was poor, but not mechanical ventilation noise. We speculated that the observed effects could be explained by the Yerkes-Dodson Law, but neither arousal nor stress of participants was measured.

No cross-modal effects were observed; evaluations were influenced solely by factors specific to each respective domain. Listening conditions significantly affected both pleasantness and eventfulness, clearly distinguishing the four acoustic scenarios across the four quadrants of the circumplex model, in line with findings reported in the literature.

The air quality assessments depended exclusively on bio-effluent levels, with higher levels invariably leading to reduced responses with respect to the quality of air poorer conditions.

These findings provide an initial framework for combined analyses of IAQ and acoustics in educational settings. They tentatively suggest that, when air quality is compromised, natural ventilation may outperform mechanical systems by supporting cognitive performance as indicated by slower response time and creating more dynamic environments. However, this remains speculative; future research should employ broader IAQ and acoustic manipulations, alongside subjective and physiological measures of arousal, to validate and extend these conclusions.

CRediT authorship contribution statement

Matteo Pellegatti: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Chiara Visentin:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Simone Torresin:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Francesco Babich:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Pawel Wargocki:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Nicola Prodi:** Writing – review & editing, Supervision, Methodology, 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.

Acknowledgement

The Authors gratefully acknowledge HEAD Acoustics, and Stefan Zillekens in particular for making this study possible by lending the HATS for binaural recordings.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.buildenv.2025.114005.

Data availability

Data will be made available on request.

References

[1] Ashrae terminology IEQ, (2025). https://terminology.ashrae.org/?entry=indoor%20environment%20quality%20(IEQ) (accessed March 6, 2025).
[2] H.W. Brink, M.G.L.C. Loomans, M.P. Mobach, H.S.M. Kort, Classrooms' indoor environmental conditions affecting the academic achievement of students and teachers in higher education: a systematic literature review, Indoor Air 31 (2021) 405–425, https://doi.org/10.1111/ina.12745.
[3] A. Mendes, J.P. Teixeira, Sick building Syndrome, in: encyclopedia of Toxicology, Elsevier (2014) 256–260, https://doi.org/10.1016/B978-0-12-386454-3.00432-2.
[4] O. Toyinbo, Indoor Environmental quality, pupils' Health, and academic performance—A literature review, Buildings 13 (2023) 2172, https://doi.org/10.3390/buildings13092172.
[5] M. Schweiker, E. Ampatzi, M.S. Andargie, R.K. Andersen, E. Azar, V. M. Barthelmes, C. Berger, L. Bourikas, S. Carlucci, G. Chinazzo, L.P. Edappilly, M. Favero, S. Gauthier, A. Jamrozik, M. Kane, A. Mahdavi, C. Piselli, A.L. Pisello, A. Roetzel, A. Rysanek, K. Sharma, S. Zhang, Review of multi-domain approaches to indoor environmental perception and behaviour, Build Environ 176 (2020) 106804, https://doi.org/10.1016/j.buildenv.2020.106804.
[6] C. Wang, F. Zhang, J. Wang, J.K. Doyle, P.A. Hancock, C.M. Mak, S. Liu, How indoor environmental quality affects occupants' cognitive functions: a systematic review, Build Environ 193 (2021), https://doi.org/10.1016/j.buildenv.2021.107647.
[7] S. Torresin, G. Pernigotto, F. Cappelletti, A. Gasparella, Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works, Indoor Air 28 (2018) 525–538, https://doi.org/10.1111/ina.12457.
[8] F. Babich, G. Torriani, J. Corona, I. Lara-Ibeas, Comparison of indoor air quality and thermal comfort standards and variations in exceedance for school buildings, Journal of Building Engineering 71 (2023), https://doi.org/10.1016/j.jobe.2023.106405.
[9] European Committee for Standardization, CEN EN 16798-1:2019 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, (2019).
[10] REHVA, REHVA COVID-19 guidance document how to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces, 2021.
[11] Ente Italiano di Normazione, UNI 11532-2:2020 - caratteristiche acustiche interne di ambienti confinati - Metodi di progettazione e tecniche di valutazione - parte 2: settore scolastico, 2020.
[12] R. Daniels, A. Bodkin, Acoustic design of schools: performance standards, Building bulletin 93 (2015).
[13] S.Y. Dicle, F. Aletta, J. Kang, A framework for developing adaptive acoustic comfort: insights from expert interviews, Applied Acoustics 235 (2025) 110642, https://doi.org/10.1016/j.apacoust.2025.110642.
[14] M. Pellegatti, S. Torresin, C. Visentin, F. Babich, N. Prodi, Indoor soundscape, speech perception, and cognition in classrooms: a systematic review on the effects of ventilation-related sounds on students, Build Environ 236 (2023) 110194, https://doi.org/10.1016/j.buildenv.2023.110194.
[15] G. Chinazzo, R.K. Andersen, E. Azar, V.M. Barthelmes, C. Becchio, L. Belussi, C. Berger, S. Carlucci, S.P. Corgnati, S. Crosby, L. Danza, L. de Castro, M. Favero, S. Gauthier, R.T. Hellwig, Q. Jin, J. Kim, M. Sarey Khanie, D. Khovalyg, C. Lingua, A. Luna-Navarro, A. Mahdavi, C. Miller, I. Mino-Rodriguez, I. Pigliautile, A. L. Pisello, R.F. Rupp, A.-M. Sadick, F. Salamone, M. Schweiker, M. Syndicus, G. Spigliantini, N.G. Vasquez, D. Vakalis, M. Vellei, S. Wei, Quality criteria for multi-domain studies in the indoor environment: critical review towards research guidelines and recommendations, Build Environ 226 (2022) 109719, https://doi.org/10.1016/j.buildenv.2022.109719.
[16] P.M. Bluyssen, Health, comfort and performance of children in classrooms - new directions for research, Indoor and Built Environment 26 (2017) 1040–1050, https://doi.org/10.1177/1420326x16661866.
[17] P.M. Bluyssen, D.H. Kim, A. Eijkelenboom, M. Ortiz-Sanchez, Workshop with 335 primary school children in The Netherlands: what is needed to improve the IEQ in their classrooms?. Build Environ Elsevier Ltd, 2020 https://doi.org/10.1016/j.buildenv.2019.106486.
[18] P.M. Bluyssen, D. Zhang, S. Kurvers, M. Overtoom, M. Ortiz-Sanchez, Self-reported health and comfort of school children in 54 classrooms of 21 Dutch school buildings, Build Environ 138 (2018) 106–123, https://doi.org/10.1016/j.buildenv.2018.04.032.
[19] H. Wu, Y. Wu, X. Sun, J. Liu, Combined effects of acoustic, thermal, and illumination on human perception and performance: a review, Build Environ 169 (2020), https://doi.org/10.1016/j.buildenv.2019.106593.
[20] S. Caviola, C. Visentin, E. Borella, I. Mammarella, N. Prodi, Out of the noise: effects of sound environment on maths performance in middle-school students, J Environ Psychol 73 (2021), https://doi.org/10.1016/j.jenvp.2021.101552.
[21] C. Visentin, M. Pellegatti, M. Garraffa, A. Di Domenico, N. Prodi, Be quiet! effects of competing speakers and individual characteristics on listening comprehension for primary school students, Int J Environ Res Public Health 20 (2023), https://doi.org/10.3390/ijerph20064822.
[22] B.M. Shield, J.E. Dockrell, The effects of environmental and classroom noise on the academic attainments of primary school children, J Acoust Soc Am 123 (2008) 133–144, https://doi.org/10.1121/1.2812596.
[23] J.E. Dockrell, B.M. Shield, Acoustical barriers in classrooms: the impact of noise on performance in the classroom, Br Educ Res J 32 (2006) 509–525, https://doi.org/10.1080/01411920600635494.
[24] D.L. Valente, H.M. Plevinsky, J.M. Franco, E.C. Heinrichs-Graham, D.E. Lewis, Experimental investigation of the effects of the acoustical conditions in a simulated classroom on speech recognition and learning in children, J Acoust Soc Am 131 (2012) 232–246, https://doi.org/10.1121/1.3662059.
[25] Q. Chen, D. Ou, The effects of classroom reverberation time and traffic noise on English listening comprehension of Chinese university students, Applied Acoustics 179 (2021), https://doi.org/10.1016/j.apacoust.2021.108082.
[26] S. Sepehri, M. Aliabadi, R. Golmohammadi, M. Babamiri, The effects of noise on human cognitive performance and thermal perception under different air temperatures, J Res Health Sci 19 (2019).
[27] P.J. Lee, J.Y. Jeon, Relating traffic, construction, and ventilation noise to cognitive performances and subjective perceptions, J Acoust Soc Am 134 (2013) 2765–2772, https://doi.org/10.1121/1.4818776.
[28] A.M. Proverbio, F. De Benedetto, M.V. Ferrari, G. Ferrarini, When listening to rain sounds boosts arithmetic ability, PLoS One 13 (2018) e0192296, https://doi.org/10.1371/journal.pone.0192296.
[29] S. Shu, H. Ma, Restorative effects of classroom soundscapes on children's cognitive performance, Int J Environ Res Public Health 16 (2019) 293, https://doi.org/10.3390/ijerph16020293.
[30] R.S. Ulrich, Stress reduction theory, in: D. Marchand, E. Pol, K. Weiss (Eds.), 100 Key Concepts in Environmental Psychology, Routledge, 2023, pp. 143–146.
[31] S. Altomonte, J. Allen, P.M. Bluyssen, G. Brager, L. Heschong, A. Loder, S. Schiavon, J.A. Veitch, L. Wang, P. Wargocki, Ten questions concerning well-being in the built environment, Build Environ 180 (2020) 106949, https://doi.org/10.1016/j.buildenv.2020.106949.
[32] S. Torresin, F. Aletta, F. Babich, E. Bourdeau, J. Harvie-Clark, J. Kang, L. Lavia, A. Radicchi, R. Albatici, Acoustics for supportive and healthy buildings: emerging themes on indoor soundscape research, Sustainability 12 (2020) 6054, https://doi.org/10.3390/SU12156054, 2020, Vol. 12, Page 6054.
[33] S. Torresin, R. Albatici, F. Aletta, F. Babich, J. Kang, Assessment methods and factors determining positive indoor soundscapes in residential buildings: a systematic review, Sustainability (Switzerland) 11 (2019), https://doi.org/10.3390/su11195290.
[34] S. Torresin, F. Aletta, T. Oberman, V. Vinciotti, R. Albatici, J. Kang, Measuring, representing and analysing indoor soundscapes: a data collection campaign in residential buildings with natural and mechanical ventilation in England, Build Environ 243 (2023), https://doi.org/10.1016/j.buildenv.2023.110726.
[35] S. Torresin, R. Albatici, F. Aletta, F. Babich, T. Oberman, S. Siboni, J. Kang, Indoor soundscape assessment: a principal components model of acoustic perception in residential buildings, Build Environ 182 (2020), https://doi.org/10.1016/j.buildenv.2020.107152.
[36] B. West, A. Deuchars, I. Ali-MacLachlan, Office soundscape assessment: a model of acoustic environment perception in open-plan offices, J Acoust Soc Am 156 (2024) 2949–2959, https://doi.org/10.1121/10.0034230.
[37] C. Visentin, S. Torresin, M. Pellegatti, N. Prodi, Indoor soundscape in primary school classrooms, J Acoust Soc Am 154 (2023) 1813–1826, https://doi.org/10.1121/10.0020833.
[38] H.K. Kurukose Cal, J. Kang, F. Aletta, Methodological approaches and main factors considered in school soundscape studies: a scoping review, Building Acoustics 31 (2024) 75–90, https://doi.org/10.1177/1351010x231216016.
[39] Y.-N. Chan, Y.-S. Choy, W.-M. To, T.-M. Lai, Influence of classroom soundscape on learning attitude, International Journal of Instruction 14 (2021) 341–358, https://doi.org/10.29333/iji.2021.14320a.
[40] H. Kurukose Cal, F. Aletta, J. Kang, Perception of indoor and outdoor school soundscapes: a large-scale cross-sectional survey with UK teachers, Applied Acoustics 227 (2025), https://doi.org/10.1016/j.apacoust.2024.110219.
[41] B. Du, M.C. Tandoc, M.L. Mack, J.A. Siegel, Indoor CO2 concentrations and cognitive function: a critical review, Indoor Air 30 (2020) 1067–1082, https://doi.org/10.1111/ina.12706.
[42] Y. Fan, X. Cao, J. Zhang, D. Lai, L. Pang, Short-term exposure to indoor carbon dioxide and cognitive task performance: a systematic review and meta-analysis, Build Environ 237 (2023) 110331, https://doi.org/10.1016/j.buildenv.2023.110331.
[43] P. Wargocki, Effects of classroom air quality on learning in schools. Handbook of Indoor Air Quality, Springer, Singapore, 2022, pp. 1–13, https://doi.org/10.1007/978-981-10-5155-5_65-1.
[44] P. Wargocki, D.P. Wyon, Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork, Build Environ 112 (2017) 359–366, https://doi.org/10.1016/j.buildenv.2016.11.020.

[45] X. Zhang, P. Wargocki, Z. Lian, C. Thyregod, Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance, Indoor Air 27 (2017) 47–64, https://doi.org/10.1111/INA.12284.

[46] P. Wargocki, J.A. Porras-Salazar, S. Contreras-Espinoza, W. Bahnfleth, The relationships between classroom air quality and children's performance in school, Build Environ 173 (2020) 106749, https://doi.org/10.1016/j.buildenv.2020.106749.

[47] X. Zhang, A. Mishra, P. Wargocki, Effects from exposures to Human bioeffluents and carbon dioxide, in: Handbook of Indoor Air Quality, Springer Singapore, Singapore, 2022, pp. 1–12, https://doi.org/10.1007/978-981-10-5155-5_63-1.

[48] X. Zhang, P. Wargocki, Z. Lian, J. Xie, J. Liu, Responses to Human bioeffluents at levels recommended by ventilation standards, Procedia Eng 205 (2017) 609–614, https://doi.org/10.1016/j.proeng.2017.10.415.

[49] D. Zhang, P.M. Bluyssen, Exploring the possibility of using CO2 as a proxy for exhaled particles to predict the risk of indoor exposure to pathogens, Indoor and Built Environment (2022), https://doi.org/10.1177/1420326x221110043.

[50] J.G. Allen, P. MacNaughton, U. Satish, S. Santanam, J. Vallarino, J.D. Spengler, Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments, Environ Health Perspect 124 (2016) 805–812, https://doi.org/10.1289/ehp.1510037.

[51] Ashrae epidemic task force, (2021).

[52] J.L. Scott, D.G. Kraemer, R.J. Keller, Occupational hazards of carbon dioxide exposure, J Chem Health Saf 16 (2009) 18–22, https://doi.org/10.1016/j.jchas.2008.06.003.

[53] P. Wargocki, The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity, Indoor Air 10 (2000) 222–236, https://doi.org/10.1034/j.1600-0668.2000.010004222.x.

[54] R. Maddalena, M.J. Mendell, K. Eliseeva, W.R. Chan, D.P. Sullivan, M. Russell, U. Satish, W.J. Fisk, Effects of ventilation rate per person and per floor area on perceived air quality, sick building syndrome symptoms, and decision-making, Indoor Air 25 (2015) 362–370, https://doi.org/10.1111/ina.12149.

[55] P. Wargocki, Measurements of the effects of air quality on sensory perception, Chem Senses 26 (2001) 345–348, https://doi.org/10.1093/chemse/26.3.345.

[56] P. Wargocki, Sensory pollution sources in buildings, Indoor Air 14 (2004) 82–91, https://doi.org/10.1111/j.1600-0668.2004.00277.x.

[57] I. Balazova, G. Clausen, D.P. Wyon, The influence of exposure to multiple indoor environmental parameters on human perception, performance and motivation, in: CLIMA 2007.WellBeing Indoors: Proceedings Congress., FINVAC, Helsinky, 2007.

[58] Z. Pan, S.K. Kjaergaard, L. Mølhave, A chamber-experiment investigation of the interaction between perceptions of noise and odor in humans, Int Arch Occup Environ Health 76 (2003) 598–604, https://doi.org/10.1007/s00420-003-0464-3.

[59] G. Clausen, L. Carrick, P.O. Fanger, S.W. Kim, T. Poulsen, J.H. Rindel, A comparative study of discomfort caused by indoor air pollution, thermal load and noisec, Indoor Air 3 (1993) 255–262, https://doi.org/10.1111/j.1600-0668.1993.00006.x.

[60] M. Ba, J. Kang, Effect of a fragrant tree on the perception of traffic noise, Build Environ 156 (2019) 147–155, https://doi.org/10.1016/j.buildenv.2019.04.022.

[61] M. Ba, Z. Li, J. Kang, The multisensory environmental evaluations of sound and odour in urban public open spaces, Environ Plan B Urban Anal City Sci 50 (2023) 1759–1774, https://doi.org/10.1177/23998083221141438.

[62] Y. Zhao, D. Li, Multi-domain indoor environmental quality in buildings: a review of their interaction and combined effects on occupant satisfaction, Build Environ 228 (2023) 109844, https://doi.org/10.1016/j.buildenv.2022.109844.

[63] M.M. HAINES, S.A. STANSFELD, R.F.S. JOB, B. BERGLUND, J. HEAD, Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children, Psychol Med 31 (2001) 265–277, https://doi.org/10.1017/S0033291701003282.

[64] M. Klatte, K. Bergström, T. Lachmann, Does noise affect learning? A short review on noise effects on cognitive performance in children, Front Psychol 4 (2013), https://doi.org/10.3389/fpsyg.2013.00578.

[65] J. Toftum, G. Langkilde, P.O. Fanger, New indoor environment chambers and field experiment offices for research on human comfort, health and productivity at moderate energy expenditure, Energy Build 36 (2004) 899–903, https://doi.org/10.1016/j.enbuild.2004.02.001.

[66] M. Magoni, A. Rossi, F. Tralli, P. Bernardoni, B. Fabbri, A. Gaiardo, S. Gherardi, V. Guidi, Novel chemoresistive sensors for indoor CO2 monitoring: validation in an operational environment, ACS Sens 9 (2024) 2999–3008, https://doi.org/10.1021/acssensors.4c00171.

[67] S. Caviola, I.C. Mammarella, C. Cornoldi, D. Lucangeli, The involvement of working memory in children's exact and approximate mental addition, J Exp Child Psychol 112 (2012) 141–160, https://doi.org/10.1016/j.jecp.2012.02.005.

[68] D. Heathcote, The role of visuo-spatial working memory in the mental addition of multi-digit addends, Cahiers de Psychologie Cognitive/Current Psychology of Cognition 13 (1994) 207–245.

[69] D.A. Kalaman, J.-A. Lefevre, Working memory demands of exact and approximate addition, European Journal of Cognitive Psychology 19 (2007) 187–212, https://doi.org/10.1080/09541440600713445.

[70] International Organization for Standardization, ISO - ISO/TS 12913-2:2018 - Acoustics — Soundscape — Part 2: Data collection and Reporting Requirements, 2018. https://www.iso.org/standard/75267.html. accessed July 21, 2022.

[71] A. Gupta, G. Torriani, S. Torresin, L. Pistore, M. Pellegatti, L. Piazza, F. Miorin, W. Pasut, A. Belleri, R. Lollini, F. Babich, Thermal comfort and perceived air quality (PAQ) using automatic ceiling fans in residential buildings, Energy Build 330 (2025) 115317, https://doi.org/10.1016/j.enbuild.2025.115317.

[72] V.P. Senese, F. Ruotolo, G. Ruggiero, T. Iachini, The italian version of the weinstein noise sensitivity scale: measurement invariance across age, sex, and context, European Journal of Psychological Assessment 28 (2012) 118–124, https://doi.org/10.1027/1015-5759/a000099.

[73] B. Rammstedt, O.P. John, Measuring personality in one minute or less: a 10-item short version of the Big Five Inventory in English and German, J Res Pers 41 (2007) 203–212, https://doi.org/10.1016/j.jrp.2006.02.001.

[74] D.A. Preece, Latin squares, Latin cubes, Latin rectangles, etc. Encyclopedia of Statistical Sciences, Wiley, 2004, https://doi.org/10.1002/0471667196.ess1400.

[75] R Core Team, R: a language and environment for statistical computing, (2025).

[76] D. Bates, M. Mächler, B. Bolker, S. Walker, Fitting linear mixed-effects models using **lme4**, J Stat Softw 67 (2015), https://doi.org/10.18637/jss.v067.i01.

[77] R.V. Lenth, emmeans: estimated Marginal means, aka Least-Squares means, (2025).

[78] Y. Benjamini, Y. Hochberg, Controlling the false discovery rate: a practical and powerful approach to multiple hypothesis testing, J R Stat Soc B 57 (1995).

[79] J. Cohen, Statistical Power Analysis For the Behavioral Sciences, Routledge, 2013, https://doi.org/10.4324/9780203771587.

[80] International Organization for Standardization, ISO - ISO/TS 12913-3:2019 - acoustics — Soundscape — Part 3: data analysis, (2019).

[81] Ö. Axelsson, M.E. Nilsson, B. Berglund, A principal components model of soundscape perception, J Acoust Soc Am 128 (2010) 2836–2846, https://doi.org/10.1121/1.3493436.

[82] A. Mitchell, F. Aletta, J. Kang, How to analyse and represent quantitative soundscape data, JASA Express Lett 2 (2022) 037201, https://doi.org/10.1121/10.0009794.

[83] U. Satish, M.J. Mendell, K. Shekhar, T. Hotchi, D. Sullivan, S. Streufert, W.J. Fisk, Is CO2 an indoor pollutant? Direct effects of low-to-moderate CO2 concentrations on human decision-making performance, Environ Health Perspect 120 (2012) 1671–1677, https://doi.org/10.1289/ehp.1104789.

[84] S. Petersen, K.L. Jensen, A.L.S. Pedersen, H.S. Rasmussen, The effect of increased classroom ventilation rate indicated by reduced CO2 concentration on the performance of schoolwork by children, Indoor Air 26 (2016) 366–379, https://doi.org/10.1111/ina.12210.

[85] J. Massonnié, D. Mareschal, N.Z. Kirkham, Individual differences in dealing with classroom noise disturbances, Mind, Brain, and Education 16 (2022) 252–262. https://doi.org/10.1111/mbe.12322.

[86] https://www.apa.org/science/about/psa/2012/02/emotional-arousal, (n.d.).

[87] R.M. Yerkes, J.D. Dodson, The relation of strength of stimulus to rapidity of habit-formation, Journal of Comparative Neurology and Psychology 18 (1908) 459–482, https://doi.org/10.1002/CNE.920180503.

[88] K.H. Teigen, Yerkes-Dodson: a law for all seasons, Theory Psychol 4 (1994) 525–547, https://doi.org/10.1177/0959354394044004.

[89] J. Toftum, B.U. Kjeldsen, P. Wargocki, H.R. Menå, E.M.N. Hansen, G. Clausen, Association between classroom ventilation mode and learning outcome in Danish schools, Build Environ 92 (2015) 494–503, https://doi.org/10.1016/J.BUILDENV.2015.05.017.

[90] M.M. Bradley, P.J. Lang, Affective reactions to acoustic stimuli, Psychophysiology 37 (2000) 204–215, https://doi.org/10.1111/1469-8986.3720204.

[91] W. Yang, H.J. Moon, Combined effects of sound and illuminance on indoor environmental perception, Applied Acoustics 141 (2018) 136–143, https://doi.org/10.1016/j.apacoust.2018.07.008.

[92] W. Yang, J.Y. Jeon, Effects of lighting and sound factors on environmental sensation, perception, and cognitive performance in a classroom, Journal of Building Engineering 76 (2023), https://doi.org/10.1016/j.jobe.2023.107063.

[93] A.P. Soares, A.P. Pinheiro, A. Costa, C.S. Frade, M. Comesaña, R. Pureza, Affective auditory stimuli: adaptation of the international Affective Digitized Sounds (IADS-2) for European Portuguese, Behav Res Methods 45 (2013) 1168–1181, https://doi.org/10.3758/s13428-012-0310-1.

[94] W. Yang, K. Makita, T. Nakao, N. Kanayama, M.G. Machizawa, T. Sasaoka, A. Sugata, R. Kobayashi, R. Hiramoto, S. Yamawaki, M. Iwanaga, M. Miyatani, Affective auditory stimulus database: an expanded version of the International Affective Digitized Sounds (IADS-E), Behav Res Methods 50 (2018) 1415–1429, https://doi.org/10.3758/s13428-018-1027-6.

[95] L.K.A. Sörensen, S.M. Bohté, H.A. Slagter, H.S. Scholte, Arousal state affects perceptual decisionmaking by modulating hierarchical sensory processing in a large-scale visual system model, PLoS Comput Biol 18 (2022), https://doi.org/10.1371/journal.pcbi.1009976.

[96] International Organization for Standardization, ISO 12913-1:2014 acoustics — Soundscape — Part 1: definition and conceptual framework, (2014).

[97] I. Pittana, F. Morandi, F. Cappelletti, A. Gasparella, A. Tzempelikos, Within- and cross-domain effects of environmental factors on students' perception in educational buildings, Sci Technol Built Environ 29 (2023) 678–697, https://doi.org/10.1080/23744731.2023.2239080.

[98] R. Pheasant, K. Horoshenkov, G. Watts, B. Barrett, The acoustic and visual factors influencing the construction of tranquil space in urban and rural environments tranquil spaces-quiet places? J Acoust Soc Am 123 (2008) 1446–1457, https://doi.org/10.1121/1.2831735.

[99] J. Ha, H.J. Kim, The restorative effects of campus landscape biodiversity: assessing visual and auditory perceptions among university students, Urban For Urban Green 64 (2021), https://doi.org/10.1016/j.ufug.2021.127259.

[100] P.M. Bluyssen, D. Zhang, D.H. Kim, A.M. Eijkelenboom, M. Ortiz-Sanchez, First SenseLab studies with primary school children: exposure to different environmental configurations in the experience room, Intelligent Buildings

International 13 (2021) 275–292, https://doi.org/10.1080/17508975.2019.1661220.
[101] H. Tang, Y. Ding, B. Singer, Interactions and comprehensive effect of indoor environmental quality factors on occupant satisfaction, Build Environ 167 (2020), https://doi.org/10.1016/j.buildenv.2019.106462.
[102] S. Dornic, B. Ekehammar, Extraversion, neuroticism, and noise sensitivity, Pers Individ Dif 11 (1990) 989–992, https://doi.org/10.1016/0191-8869(90)90283-W.
[103] S.B.C. Eysenck, H. Eysenck, The biological basis of personality, The Biological Basis of Personality (2017) 1–399, https://doi.org/10.4324/9781351305280/BIOLOGICAL-BASIS-PERSONALITY-HANS-EYSENCK/ACCESSIBILITY-INFORMATION.
[104] H.J... Eysenck, S.B.G. Eysenck, Eysenck personality inventory, (1994). https://search.worldcat.org/title/803404693 (accessed October 31, 2024).
[105] H. Choi, H. Kim, T. Hong, J. An, Examining the indirect effects of indoor environmental quality on task performance: the mediating roles of physiological response and emotion, Build Environ 236 (2023) 110298, https://doi.org/10.1016/j.buildenv.2023.110298.
[106] T. Andringa, J. Lanser, How pleasant sounds promote and annoying sounds impede health: a cognitive approach, Int J Environ Res Public Health 10 (2013) 1439–1461, https://doi.org/10.3390/ijerph10041439.