Applied Acoustics 245 (2026) 111206

Contents lists available at ScienceDirect

Applied Acoustics

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

The effect of ventilation-related sound stimuli on 11–14 years students' cognition and soundscape assessments

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ARTICLE INFO

Keywords:
Indoor soundscape
Calculation
Reading and comprehension
Response time
Arousal theory

ABSTRACT

In previous research, ventilation-related sounds have mostly been regarded as undesirable and unwelcome noise within the school environment. Conversely, in this study, a soundscape-inspired approach was adopted, where sounds were treated as potential assets to exploit rather than mere disturbances. To test this hypothesis, this research explored the effects of various sonic environments in ventilated classrooms while students were engaged in school tasks. Five sound conditions were compared, namely, quiet, three natural ventilation sounds coming from playground, birdsongs, and traffic respectively, and finally mechanical ventilation sound. Their effects on cognitive performance in calculation and reading comprehension, as well as on participants' soundscape evaluations were assessed. A total of 229 students aged 11–14 years were tested in their own classrooms. The results (n of participants = 158) indicated that none of the sound conditions exerted a significant effect on reading comprehension, nor did they influence calculation accuracy. However, response times in calculation tasks improved in the presence of playground noise and deteriorate under mechanical ventilation noise. In terms of soundscape assessments, playground was rated as chaotic, mechanical ventilation as monotonous, whereas birdsongs is generally perceived as pleasant. The effects observed on cognitive performance were interpreted by resorting to arousal theory. In particular higher eventfulness seems to improve performance on the selected tasks. Although further research is needed to identify the most advantageous auditory stimuli, those associated with natural ventilation appear to be the most promising.

1. Introduction

School classrooms are environments in which students spend, on average, approximately 45 % of their daily time [1]. Ensuring adequate ventilation is essential to avoid impairing students' performance while in the classroom. Indeed, standards recommend a ventilation rate of approximately 10 l/s per person in settings where vulnerable individuals, such as children, are present (Class 1of EN 16798-1) [2]. Moreover, it has been observed that high ventilation rates are associated with improved cognitive performance, due to enhanced indoor air quality (IAQ) [3,4]. Adequate ventilation in educational settings can be achieved through either mechanical ventilation systems (e.g., HVAC) or natural ventilation methods (e.g., via windows). Both mechanical and natural ventilation systems result in distinctive sound stimuli that contribute to the overall acoustic environment (formally defined in ISO 12913=1 [5]) [6]. High mechanical ventilation rates are associated with louder sound levels generated by ventilation units, while opening the windows may introduce sound stimuli from the outside that would otherwise remain less audible. Such changes in the acoustic environment can, in turn, influence cognitive performance, well-being, and occupant comfort, in a similar way to how variations in indoor air quality (IAQ) impact these same aspects [7,8].

As highlighted in the review by Pellegatti et al. [7], the sound environment in educational settings can have both positive and negative impacts on cognitive abilities and comfort. The review revealed that sound stimuli from sources such as road or air traffic – which might be audible in naturally ventilated classrooms – tend to have more pronounced negative effects by decreasing cognitive performances, increasing student effort and yielding more perceived annoyance. On the other hand, natural sounds are associated with positive outcomes by

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https://doi.org/10.1016/j.apacoust.2025.111206
Received 24 July 2025; Received in revised form 9 December 2025; Accepted 11 December 2025
Available online 13 December 2025
0003-682X/

reducing annoyance and enhancing cognitive performances thanks to a restorative effect [8,9]. According to this latter finding, natural stimuli, regardless of their nature, whether visual or auditory, have the capacity to restore individuals by reducing the stress levels [8].

Notably, the review identified 32 studies, with 27 focusing on the adverse effects of sound stimuli compared to only 5 that examined the benefits of positive auditory inputs. This imbalance likely arises from a traditional noise-control view of sound stimuli as predominantly harmful, where their intensity should be limited to achieve either optimal or neutral sensory conditions.

In line with this view, traditional classroom environments, particularly in the Italian context, are predominantly designed to facilitate lecture-based instruction and thus place a strong emphasis on verbal communication. Consequently, acoustic parameters such as a high signal-to-noise ratio (SNR), short reverberation times, and elevated intelligibility indices (e.g., the Speech Transmission Index [STI] or clarity index C50) are typically prioritised [10]. The prevailing acoustic environment is largely shaped by noise from in-class equipment, student chatter, and the teacher's voice, with additional contributions from adjacent classrooms, corridors, and external sources, with the latter depending on the specific location of the school and the ventilation strategy [7]. All such sound stimuli, except for the teacher voice, are generally perceived as impediments to effective communication.

However, this perspective can be challenged by adopting a soundscape approach, which views the acoustic environment as a potentially valuable resource – one that can be leveraged to promote positive emotional conditions and address the specific needs of the occupants. In the specific context of classrooms, this latter aspect pertains to warranting effective verbal communication and supporting cognitive performance [11–13]. A similar perspective motivated the present work, whose main aim is to investigate the effects of natural and mechanical ventilation sounds in an ecological classroom context. By doing so, the relation between the sonic environment and the task performances is evaluated and a possible driving mechanism based on the arousal theory [14] is discussed.

1.1. Cognitive performances and the role of arousal

Cognitive abilities exist in various forms, as noted in the literature [7,15–17]. Broadly, these can be classified as either simple or complex cognitive abilities. The former (e.g., memory and attention) underpin learning and developmental mechanisms and are prerequisites for the latter. Complex cognitive abilities, instead, comprise tasks like reading comprehension and mathematical calculation and are more representative of examinations in educational contexts.

Several factors determine the effect of a sound stimulus on cognitive performances. They can be related to the task itself, to the auditory stimulus, to the personal characteristics of the individual or more in general to non-acoustics factors as stated in ISO 16755–1 [18]. As regards task difficulty [15,19], it is known that a task that is excessively challenging may not be impacted by sound because the available cognitive resources are already depleted by the task itself, whereas a task that is too simple may not sufficiently tax these resources to reveal any effect. Another possible reaction to a difficult task can be the mechanism of what so called "*shielding against distraction mechanism*", whereby focusing attention on the task at hand prevents external factors to be effective as interferers [20,21]. This has been observed in young adults and has also been discussed for a group of children aged 13 during a speech comprehension task [22]. Besides the difficulty of the task itself, clearly the characteristics of the auditory stimulus is crucial. In fact, its details can have a large effect on task performance because, depending on its spectro-temporal deployment, it could hinder the functioning of several memory, reasoning and attention-related cognitive systems [23]. The intensity of the auditory stimulus is most often a very relevant characteristic whereby higher sound levels are generally expected to have a more detrimental impact on task performance [7,16,24,25]. Finally, also individual characteristics, such as noise sensitivity, can play a role in shaping the task performance [26,27]. For example, students reporting higher noise sensitivity were performing with longer response times in reading and comprehension tasks compared to low sensitive ones mainly at high level of background noise [26]. Most of the aforementioned effects can be aligned with the Yerkes–Dodson law [14], which posits that performance in cognitive tasks is related to arousal[1] according to an inverted U-shaped function. Performance improves with increasing arousal up to an optimal point (top of the inverted U-shape), beyond which a further increase in arousal leads to a decline in performance. In general, different types of auditory stimuli are associated with varying levels of arousal, as demonstrated in the works of Bradley and Lang [28] and Yang et al. [29]. Similarly, higher sound levels tend to be associated with greater arousal [30]. Consequently, any sound stimulus could, in principle, enhance performance if it modulates arousal towards this optimum or conversely a sound stimulus could decrease performance if it causes an excess of arousal.

However, the shape of the arousal curve is not uniquely fixed; for instance, it depend on task characteristics, such as difficulty [31,32]. Specifically for simple tasks, the curve is steeper at low levels of arousal and then flattens out for higher levels of arousal. In contrast, for complex tasks, the curve rises more gradually, with the optimal arousal level usually being reached earlier, followed by a more rapid change in slope [32]. As a result, peak performance for complex tasks may be lower compared to simple tasks, leading to the emergence of task-difficulty-dependent performance peaks. Additionally, as highlighted by Teigen [31], these relative peaks tend to shift towards lower arousal levels as task complexity increases.

The interaction between external stimuli and arousal is further complicated by individual characteristics [33]. For example, individuals who are more sensitive to noise tend to exhibit higher baseline arousal levels than those who are less sensitive [34], which may result in their arousal starting at different points along the arousal–performance curve.

1.2. The affective evaluation of the soundscape in the classroom

The standard ISO 12913–1 [5] defines soundscape as "the acoustic environment as perceived, recognised, and/or interpreted by an individual or community within a specific context." It has been shown that the perception of outdoor sound environments can be described through eight independent, affective attributes, arranged in a circumplex model (pleasantness, annoyance, calmness, monotony, chaoticity, eventfulness, uneventfulness, and vibrancy) [35,36]. Over time, circumplex models specific for residential environments [13,37,38] and offices [39] have been established. This is not yet the case for students in educational environments, although some preliminary studies have been conducted [40,41] using either the framework proposed by Bradley and Lang [28] in Ref [40], or that of Torresin [13,37,38] for residential indoor environments in Ref. [41].

On the other hand, the sound environment of classrooms was evaluated in previous literature works by resourcing to single attributes [42–45]. In particular, the review by Pellegatti et al. [7] has indicated that the focus has been predominantly on annoyance, and that natural sounds reduce annoyance, whereas mechanical sound stimuli tend to increase it. Moreover, despite an increase in sound level is not invariably associated with poorer evaluations, in general higher ratings of pleasantness have been observed at a moderate sound level of 45 dBA [46].

In this work, the ISO/TS 12913–2 [36] circumplex model was used to obtain an affective evaluation of the listening conditions under

[1] Arousal definition from the APA Dictionary of Psychology: *a state of excitement or energy expenditure linked to an emotion. Usually, arousal is closely related to a person's appraisal of the significance of an event or to the physical intensity of a stimulus. Arousal can either facilitate or debilitate performance* [82].

examination, on the premise that emotions experienced by students may influence their cognitive abilities either positively or negatively [47,48].

1.3. Research questions

In light of the preceding considerations, sound stimuli appear to be capable of influencing students' performance, with arousal potentially playing a role in this mechanism. This study wants to explore the complex interplay described above between the factors that influence performance of students when they undertake academic tasks in the classroom and are exposed to ventilation related sounds. In particular, an experiment was conducted with middle school students to assess the effects of five natural and mechanical ventilation sounds on both cognitive tasks and soundscape evaluations. Two research questions were formulated:

1) How do natural and mechanical ventilation-related sounds affect middle school students' performance in reading comprehension and calculation tasks conducted in the classroom?
2) What is the affective evaluation of the classroom soundscape while doing an exam when natural and mechanical ventilation-related sounds are present?

Furthermore, the findings related to the first research question will be examined in light of arousal theory to assess their theoretical consistency yet not properly validating the theoretical framework due to the lack of specific arousal measures in the experiment.

2. Materials and methods

2.1. Participants

A total of 229 students (11–14 yrs, M = 12.8, SD = 1.4, 47 % female) from five schools in the province of Bolzano/Bozen, Italy, took part in the experiment. Students were evenly distributed between grade VII and grade VIII (VII grade 45 %, 6 classes). Personal and demographic information (age, gender, hearing impairment, and potential neurodivergences) were provided anonymously by the school administration. Students' identities were protected by a pseudonym made of a colour identifying the classroom and a number from 1 to 30 (e.g., Red01). The connection between the student and the pseudonym was known only to the class teachers. Students with neurodivergences and hearing impairments participated in the experiment but were excluded from the analysis due to an insufficient number of respondents to be included as a cluster and compared to other students (14 students, 6.1 % of the total).

The entire experiment was internally reviewed by Eurac Research's research offices and complies with the Eurac Research Core Ethics and Integrity Principles. Written informed consent in accordance to Helsinki Declaration the was obtained from the legal guardians of the students.

2.2. Experimental stimuli

Students were exposed to five listening conditions representative of both mechanically and naturally ventilated classroom environments in different outdoor contexts. Specifically, the selection of stimuli was informed by existing literature, as highlighted in [7]. These comprised: quiet, (i.e. the baseline classroom ambient sound without any additional experimental sound stimuli), mechanical ventilation sound, playground sound generated by children playing in the schoolyard, traffic sound, and birdsongs. The authors used always the word "sound" as it is not known a priori whether the effect of the stimulus is negative or positive from a perceptual perspective in this context.

The natural ventilation sounds (i.e. birdsongs, playground activity, and traffic) were recorded using a binaural headset (Head Acoustics BHS II) attached to a recorder (Head Acoustics Squadriga III), with the left ear oriented towards an open window. The recording location was identical for all listening conditions associated with natural ventilation. Specifically, recordings were conducted in a room situated near a primary school. The building was surrounded by a courtyard with trees and was separated from the school playground by a road. All recordings were carried out during periods when a single sound source was predominantly and continuously present. The only editing performed consisted of removing events unrelated to the target sound source, e.g., the passage of cars during the playground recording.

For each sound stimulus, the sound level was calculated as the equivalent continuous level ($L_{A,eq}$ (10 min)) over the duration of the edited recording (10 min).

Regarding the recording of mechanical ventilation, this was conducted continuously inside a laboratory equipped with an HVAC system set at operational level of 160 l/s flow rate. This value corresponds to an airflow of 10 l/s per person (requirement for good IAQ [2]) for a maximum capacity of 16 individuals as estimated for using the room as a classroom. Each recording had a duration of 10 min. All listening conditions, with the exception of the quiet one, were reproduced through headphones (Sony MDR-ZX310), which were previously equalised to provide a neutral response, at 47 dB(A), referenced to the left ear. Sound levels were calculated using a binaural head (Head acoustics HMS II.3 LN HEC) by randomly selecting a 60 s segment from each recording. The reproduced sound levels were consistent with those of the original recordings. Spectral and psychoacoustical information are available in the supplementary material.

2.3. Calculation task

In the calculation task, students were asked to determine whether an equation was true or false. For each listening condition, students solved a set of 24 two-digit equations. Specifically, these comprised 12 additions and 12 subtractions, with equally probable true or false outcomes (50 %). Half of the operations involved carrying (additions) or borrowing (subtractions), while the other half did not. This latter aspect defined the task difficulty: specifically, equations involving carrying or borrowing were classified as difficult, whereas those without were considered easy. All possible combinations of the three parameters were included within the set of 24 equations. Examples of equations combination are reported in Table 1. All the operations and results used in this work were taken from the works of Caviola et al. [15,49].

Each equation was displayed on a tablet screen along with the two response options for a maximum of 20 s, or until the student provided an answer. Trials were interleaved with a white screen lasting 100 ms. The presentation of the equivalence task took place while the auditory stimulus was played in the background. The playback of the stimulus began 1 s prior to the first equation and ended simultaneously with the 24th response.

Accuracy of each trial (0 for an incorrect response, 1 for a correct response) and response time, namely the time elapsed from equation presentation to response selection, were retrieved. The entire task was implemented on the online platform gorilla.sc [50]. The order of the equations in a set was randomised for each participant, while the combination of listening conditions and set of equations, hereafter referred as blocks, was counterbalanced between participants using a Latin Square design. The average duration of sound exposure, from the

Table 1
Double-entry table showing examples of all combinations of operation type (addition, subtraction), task difficulty (easy, difficult) and result correctness (True, False).

Operation type	Difficulty	True result	False result
Addition	Easy	24 + 12 = 36	24 + 12 = 38
	Difficult	24 + 17 = 41	24 + 17 = 31
Subtraction	Easy	27 – 14 = 13	27 – 14 = 23
	Difficult	34 – 17 = 17	34 – 17 = 23

beginning of the first listening condition to the end of the last one during the calculation task, was 18 min.

2.4. Reading and comprehension task

A test analogous to that proposed by Connolly et al. [16] was implemented in this study to investigate students' reading and comprehension abilities. Under each listening condition, students read a set of three stories and answered five multiple-choice questions per story. The stories were children's scientific articles in Italian, adapted to be 150 words long. In the absence of Italian readability scales such as the Flesch–Kincaid Readability Test [51], equivalent difficulty across the stories was ensured by employing a lemma frequency list. Each story contained similar numbers of low and high frequency lemmas. The stories were further divided into segments of approximately 50 words, each followed by one or two questions. Students were allowed to read each segment for as long as they wished; however, once they proceeded to the question section, they could no longer return to the text. Regarding the questions, two factual questions (answers stated in the text), two inferential questions (answers requiring deduction from the text), and one question concerning the meaning of an unfamiliar novel word were posed. The novel word was explicitly mentioned in the text. Each question was provided with three alternative choice answers. Reading times for each story segment, as well as comprehension accuracy and response times were recorded. The test was implemented on gorilla.sc. The order of the block as well as the order of the stories inside a block was counterbalanced across the participants. The average duration of sound exposure during the reading and comprehension task, from the start to the end of the experiment, was 20.6 min.

2.5. Soundscape assessments

Soundscape assessments were also carried out by using tablets and headphones on gorilla.sc. The ISO/TS 12913–2 standard [36] Method A was used. Specifically, students rated the eight adjectives of the circumplex model (pleasant, annoying, calm, chaotic, vibrant, monotonous) using a 5-point Likert scale ranging from "*not at all*" to "*very much*." They were instructed to evaluate the listening conditions as if they were taking a classroom test. Playback of each listening condition started five seconds prior to the questions and ended concurrently with their completion. The order of the listening conditions was randomised across participants, while the order of the adjectives remained constant for all the listening conditions.

2.6. Proficiency questionnaires

Students were also administered two pen-and-paper tasks to assess their proficiency in calculation and in reading and comprehension.

Regarding mathematical proficiency, the Calculation Fluency Test by Caviola et al. [52] was administered. The test comprised three pages, each containing 20 operations arranged in columns. Students were instructed to solve the equations in order, without using a calculator or omitting any operations. They had a two-minute time limit per page to solve as many operations as possible within this period. One point was assigned to each correct answer.

The reading and comprehension proficiency task, instead, involved reading a story and answering multiple-choice questions (each with four options). The students' baseline score of each task was calculated as the percentage of correct responses. Finally, a median split was applied to the proficiency scores of each task to categorise participants into two groups: high and low.

2.7. Noise sensitivity questionnaire

The short Italian version of the Weinstein Noise Sensitivity Questionnaire [53] was used for the assessment. This self-assessment instrument comprises five items, each rated on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). A single value for each participant was obtained as expressed [53]. Finally, the students were divided into three groups of noise sensitivity (low, medium, and high) using tertile cut-offs. This categorisation was based on the distributions of task and questionnaire results in relation to noise sensitivity. The distributions revealed a U-shaped pattern, with better performance observed for intermediate levels of noise sensitivity and poorer performance for both low and high levels. This trend in the data directly motivated the three-group division. The Supplementary Material includes the corresponding distribution graphs, as well as a summary of all experimental tasks and questionnaires.

2.8. Experimental procedures

Tests and questionnaires were administered directly in students' classrooms over the course of three separate days; each spaced one week apart. Data collection took place between early November 2022 and late December 2022. On the first two days, students completed the mental arithmetic task and the soundscape questionnaire on one day, and the reading comprehension task on the other. The order in which the two tasks were performed was counterbalanced across classes. On the third and final day, students completed the reading and calculation proficiency tasks followed by the noise sensitivity questionnaire. All classrooms were naturally ventilated via windows; however, all tasks and questionnaires were carried out with the windows closed. The acoustic environment was not monitored, which has been acknowledged as a limitation in the relevant section.

2.9. Data analysis

2.9.1. Calculation task

Data were cleaned to ensure that the dataset consisted of results from participants who were sufficiently motivated in task pursuing. Data cleaning consists in several passages. First, all trials with response times that were identified as outliers in the gamma distribution of response times, as defined in Ref. [54] were excluded. This resulted in the exclusion of all participants with response times shorter than 1.5 s, accounting for 5 % of the dataset. The graphical representation of the distribution is available in the supplementary material.

Secondly, for each participant, blocks with a global accuracy of the block lower than 50 % (chance level) as well as blocks with fewer than 50 % of trials left at each difficulty level were removed. The former criterion was applied because when accuracy is equal or lower of the chance level it is impossible to determine if the effect is related to environmental stressor or if participants guess randomly. The latter was adopted to ensure that a sufficient and representative amount of data was available for both difficulty levels.

Finally, participants with less than two remaining blocks were also excluded. In the end, 63 % of the original dataset was retained after data cleaning.

Data analysis was performed in R (ver. 4.4.2) [55] with lme4 package (ver 1.1–37) [56]. A generalised mixed-effects model (GLMM), based on a binomial distribution, was fitted to the accuracy data. Listening conditions, equation difficulty, and their interaction were included as fixed effects. Noise sensitivity (three levels), math proficiency (two levels), and the order to the blocks (five levels) were included as covariates, along with the interaction between listening conditions and noise sensitivity. Specifically, block order referred to a numerical index ranging from 1 to 5, indicating for each participant the progression of blocks completed during the experiment, irrespective of the listening condition performed. Participants were included as a random intercept.[2]

A GLMM based on a Gamma distribution with a logarithmic link was fitted to the response times of the correct answers (81 % of the accuracy dataset). Post-hoc comparisons for both accuracy and response time were conducted using the emmeans package (ver 1.11.0) in R [57] with adjustments for multiple comparisons applied via the Benjamini–Hochberg criterion [58].

2.9.2. Reading and comprehension task

A data cleaning similar to the calculation task was performed also for the reading and comprehension task. All questions with a response time of less than 1.5 s were removed. The same criterion based on the distribution outlier used for calculation was also applied here. Please see supplementary material for the distribution. Next, all the stories with fewer than three valid comprehension responses left, as well as those with a comprehension accuracy below the chance level of 33 % were excluded from the analysis. Additionally, any story, and all the relative questions, with at least one segment registering a reading time of less than 4 s was eliminated. Blocks with fewer than two remaining stories were removed. Finally, all participants with fewer than two blocks left were excluded as well.

Once the cleaning procedure was completed, the reading time of each story was calculated by summing the reading time of each passage. Then the reading time of the block was calculated as an average between the stories. GLMMs[3] were fitted for accuracy (using 48 % of the initial dataset), reading time (51 % of the initial dataset), and response time for correct answers only (72 % of the accuracy dataset). In the accuracy model, listening conditions, the type of questions (factual, inferential, new word), and the interaction between these factors were included as fixed variables. Covariates comprised the order of the blocks, noise sensitivity group, proficiency group in reading and comprehension tasks, and the two-way interaction between noise sensitivity and listening conditions. Participants were included as random intercepts. The model for comprehension response time mirrored that for accuracy, while the model for reading time did not include question type or its interaction with sound stimuli, as this variable was not applicable to the reading time data. Post-hoc multiple comparisons were adjusted by Benjamini–Hochberg [58] correction.

2.9.3. Soundscape assessments

Data from the assessments were converted into ISOPleasantness and ISOEventfulness values, as defined by ISO/TS 12913–3 [59]. Specifically, the assessments were transformed into pleasantness and eventfulness metrics, which were then normalised to a range from –1 (completely annoying/uneventful) to 1 (completely pleasant/eventful).

The two new variables were analysed with linear mixed-effects models (LMM)[4] with listening condition, noise sensitivity group, and the two-way interaction as fixed variables. Participants were included as random intercepts.

3. Results

3.1. Calculation task

The accuracy model revealed significant effects of students' proficiency ($\chi^2(1) = 34.7$, $p < 0.001$) and task difficulty ($\chi^2(1) = 669$, $p < 0.001$), while no significant effects were observed for other parameters (ps > 0.1) or interactions (ps > 0.55). Post-hoc comparisons indicated that accuracy was higher for easier (M = 87.2 %) compared to more difficult equations (M = 71 %) (z = 25.88, $p < 0.001$) and for students with high (M = 84.2 %) compared to low (M = 76.3 %) math proficiency (z = 5.87, $p < 0.001$).

Regarding response time of correct answers, significant effects were found for listening condition ($\chi^2(4) = 21.7$, $p < 0.001$), task difficulty ($\chi^2(1) = 1762$, $p < 0.001$), order of the blocks ($\chi^2(4) = 416.8$, $p < 0.001$), as well as for the interactions between listening condition and difficulty ($\chi^2(4) = 11.3$, $p = 0.02$) and between listening condition and noise sensitivity ($\chi^2(8) = 36.4$, $p < 0.001$).

Response times decreased as long as the sequence of listening conditions was progressing (all ps < 0.05). The interaction between listening condition and difficulty is displayed in Fig. 1. It was found that students consistently performed faster on easy than on difficult calculations across all listening conditions (all ps < 0.0001). Investigating the

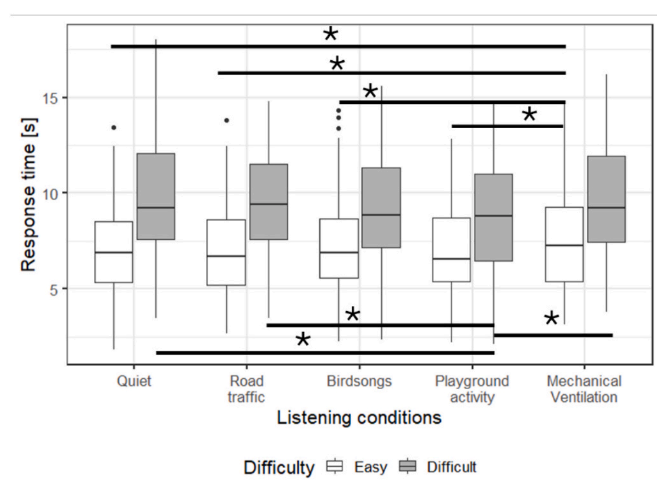

Fig. 1. Boxplot of the response time for individual correct answers in the calculation task. The interaction between listening conditions and task difficulty is depicted within the graph. Significant differences between listening conditions (p values < 0.05) are reported with bars and asterisks (*).

[2] The formulas for the accuracy and response time model on calculation according to Wilkinson notation [83].

Accuracy ~ Listening conditions + Difficulty + Proficiency calc. + Noise sensitivity + Order of the blocks +Listening conditions:Difficulty + Listening conditions:Noise sensitivity + (1|ID),data=data, family=binomialResponse time ~ Listening conditions + Difficulty + Proficiency calc. + Noise sensitivity + Order of the blocks +Listening conditions:Difficulty + Listening conditions: Noise sensitivity + (1|ID), data=data, family=Gamma(link="log").

[3] The formulas for the reading and comprehension models (accuracy comprehension, response time comprehension, reading time) according to Wilkinson notation [83].

Accuracy ~ Listening conditions + Type of the question + Noise sens. + Proficiency reading + Order of the blocks +Listening conditions: Noise sens. + Listening conditions:Type of the questions + (1|ID),data=data, family=binomialResponse time ~ Listening conditions + Type of the question + Noise sens. + Proficiency reading +Order of the blocks +Listening conditions: Noise sens. + Listening conditions:Type of the questions + (1|ID), data=data, family=Gamma(link="log")Reading time ~ Listening conditions+ Noise sens. + Proficiency reading + Order of the blocks + Listening conditions: Noise sens. + (1|ID), data=data, family=Gamma(link="log").

[4] The formulas for the ISOPleasantness and ISOEventfulnes models according to Wilkinson notation [83].

ISOPleasantness ~ Listening conditions*Noise sensitivity + (1|ID), data=dataISOEventfuness ~ Listening conditions*Noise sensitivity + (1|ID), data=data.

effect of the listening conditions at fixed difficulty, when solving difficult equations students responded faster while listening to playground activity compared to Quiet, Mechanical Ventilation and Road Traffic (ps < 0.03), but not to Birdsongs ($p = 0.06$). Conversely, for easier equations, students' response times were slower when exposed to mechanical ventilation compared to all other sounds (ps < 0.04). Table 2 provides a detailed summary of the statistical information for the significant comparisons in the interaction between listening condition and difficulty.

Regarding the interaction between listening condition and noise sensitivity, displayed in Fig. 2, pairwise comparisons indicated that students with low noise sensitivity took shorter to respond when listening to playground (M = 7580 ms) compared to mechanical ventilation (M = 8143 ms, $z = 4.23$, $p < 0.001$), road traffic (M = 8005 ms, $z = 4.86$, $p < 0.001$) and birdsongs (M = 8126 ms, $z = 3.41$, $p = 0.007$). No differences were present for the mid and highly sensitive to noise students.

3.2. Reading and comprehension task

The statistical analysis of reading times in the comprehension task revealed only a significant main effect of the order of the blocks($\chi^2(4) = 59.29$, $p < 0.001$), indicating that the reading times of the stories shortened as the sequence of the conditions progressed (from 8.2 s to 7.0 s). Regarding the statistical model for the comprehension accuracy, significant effects were found for proficiency level ($\chi^2(1) = 18.00$, $p < 0.001$) and question type ($\chi^2(2) = 95.20$, $p < 0.001$), while no significant effect of listening conditions was observed. Students with higher proficiency demonstrated greater comprehension accuracy (M = 73.4 %) than those with lower proficiency (M = 66.4 %) ($p < 0.001$). Furthermore, responding to factual questions (M = 77.8 %) was associated with higher accuracy than responding to inferential questions from the text (M = 65.3 %) ($p < 0.001$) or questions that required understanding novel words meaning (M = 65.8) ($p < 0.001$).

Finally, the analysis of response times in the comprehension task indicated a significant main effect of both the order of the blocks ($\chi^2(4) = 44.15$, $p < 0.001$) and the question type ($\chi^2(2) = 274$, $p < 0.001$). Pairwise comparisons indicated that factual questions had the lower response time, followed by questions involving new words. Inferential questions showed instead the slowest response. (Factual > Inferential, $z = 16.40$, $p < 0.001$; Factual > New word, $z = 3.89$, $p < 0.001$; New word > Inferential, $z = 9.12$, $p < 0.001$). Regarding the effect of order, students were significantly faster in the final listening condition compared with all previous conditions (all ps < 0.001). Since the primary aim of this paper is to investigate the effects of acoustic stressors, and no impact on calculation accuracy was observed, the corresponding result graphs have been included in the supplementary material to enhance the readability of the main text.

Table 2
Pairwise significant comparisons for the interaction between listening condition and difficulty at fixed difficulty for response time in the calculation task. In the listening condition values between brackets represent the mean response time between all the participants in ms.

Difficulty	Listening condition	Difference [ms]	Z ratio	P value
Difficult	Quiet (9709) > Playground (8827)	882	3.74	< 0.001
	Mec. Ventilation (9846) > Playground (8827)	1019	3.94	< 0.001
	Road traffic (9480) > Playground (8827)	653	2.44	= 0.03
Easy	Mec. Ventilation (7367) > Quiet (7104)	263	2.69	= 0.02
	Mec. Ventilation (7367) > Playground (7047)	320	2.30	= 0.04
	Mec. Ventilation (7367) > Road traffic (7039)	328	3.46	= 0.002
	Mec. Ventilation (7367) > Birdsongs (7243)	124	2.46	= 0.03

3.3. Soundscape assessments

The students' perceptual evaluations of the listening conditions are displayed in Fig. 3. According to the soundscape circumplex model developed by Axelsson et al [35] playground and road traffic are located in the chaotic quadrant, whereas mechanical ventilation is neutral with respect to the ISOPleasantness axis with a slight tendency towards the monotony region. Quiet aligns more closely with the secondary axis of calmness. In this experiment, birdsongs is primarily perceived as pleasant, its distribution being approximately even along the positive pleasantness axis.

Statistical analysis of the ISOPleasantness model indicated that the effect of listening condition ($\chi^2(4) = 514$, $p < 0.001$), noise sensitivity ($\chi^2(1) = 9.58$, $p = 0.008$), as well as their interaction ($\chi^2(4) = 23.58$, $p = 0.003$) were significant. Further investigation of the interaction revealed that, as noise sensitivity increases, perceived pleasantness of the playground condition decreases. Students with low noise sensitivity perceived playground as more pleasant than those with medium ($t = 2.72$, $p = 0.01$) or high sensitivity ($t = 4.86$, $p < 0.001$), while those with medium sensitivity rated it as more pleasant than those with high sensitivity ($t = 2.24$, $p = 0.04$).

The latter effect subsequently influences the pleasantness ratings of the various auditory stimuli at a fixed level of noise sensitivity. Indeed, individuals with higher noise sensitivity perceived birdsongs as the most pleasant condition, followed by quiet. Mechanical ventilation and traffic are ranked equally unpleasant after quiet, whereas the playground was rated as the most unpleasant sounds. Conversely, for individuals with mid noise sensitivity road traffic and playground were rated equally pleasant, while for low noise sensitivity students, no difference in pleasantness was found between mechanical ventilation, traffic, and playground. Fig. 4 presents the pleasantness rating graphs. A table reporting p-values and the significant differences is provided in the supplementary material.

The ISOEventfulness statistical model indicated only a main effect of listening condition ($\chi^2(4) = 187$, $p < 0.001$). Post-hoc comparisons indicated that quiet and mechanical ventilation were the least eventful listening conditions, followed by birdsongs, road traffic and, finally, playground activity, which was perceived as the most eventful (Fig. 5). All the comparisons were significant except between quiet and mechanical ventilation (ps < 0.001).

4. Discussions

4.1. Performance in the calculation task

The results of the study indicated that the listening conditions had no significant effect on accuracy when students are performing a calculation task presented in the visual domain. The finding is in contrast with previous literature which, for similar tasks, has reported a decreased accuracy under exposure to traffic [61,62] and improvements when natural sounds were presented [63]. However, the present outcomes are consistent with studies on mechanical ventilation, which have shown that ventilation does not affect students' mathematical performance [64].

The discrepancy between these results and those reported in the literature may be attributed to two main reasons.

The former, there were considerable differences in the sound levels used. For instance, in the study by Proverbio et al. [63], although a task administration system similar to that of the present study was employed, participants were exposed to the sound of rainfall as high as 89 dB. Similarly, Ljung et al. [62] and Papanikolau et al. [61] employed higher or much higher sound levels compared to the present realistic levels; in the former, students were exposed to two sound levels equal respectively

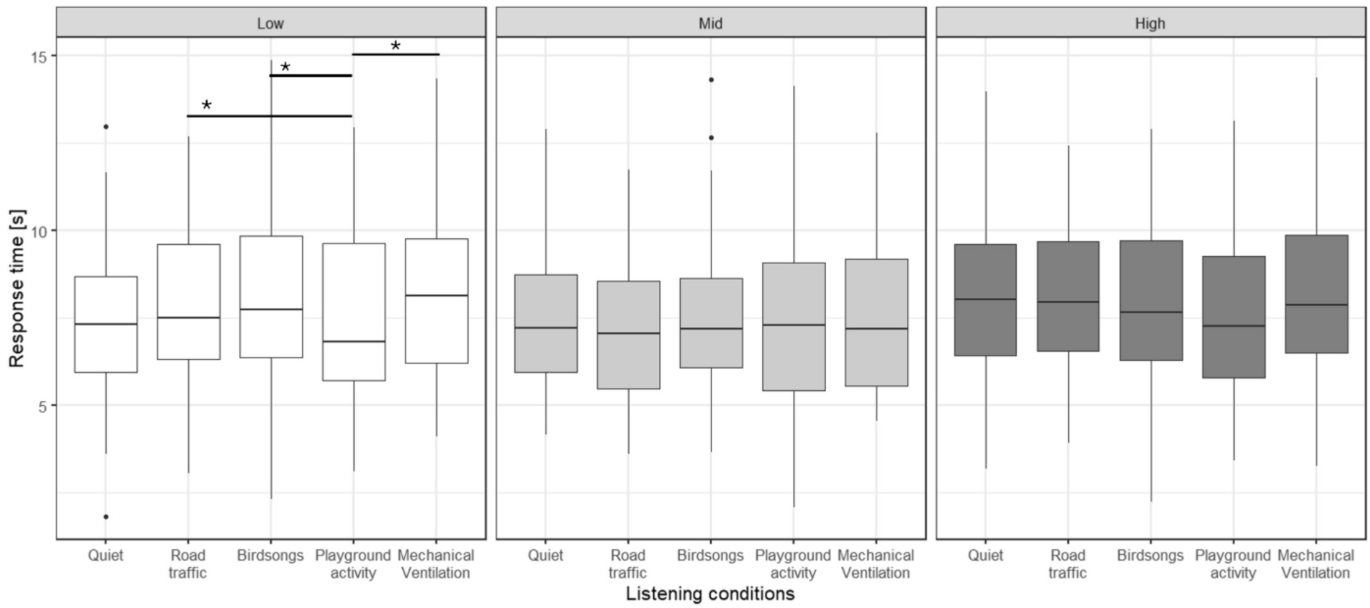

Fig. 2. Boxplot of the response time for individual correct answers in the calculation task. The interaction between listening conditions and noise sensitivity group is depicted within the graph. Significant differences between listening conditions (p values < 0.05) are reported with bars and asterisks (*).

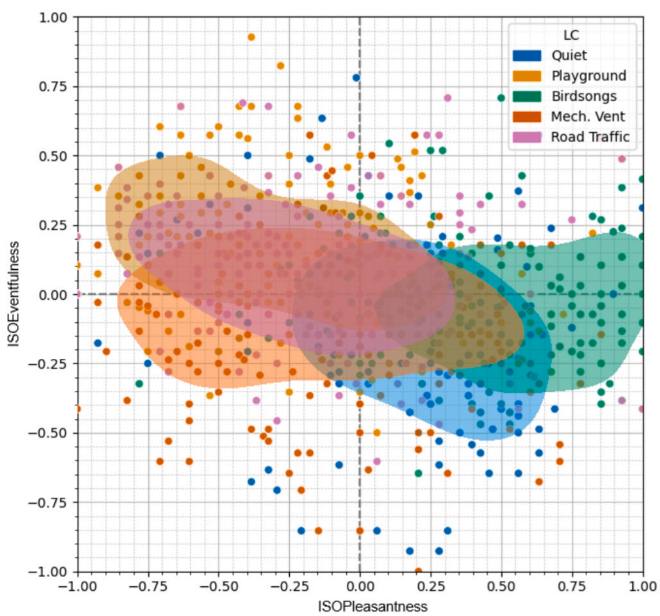

Fig. 3. Graphical representation of the distributions (field) of the 50th percentile ISOPleasantness and ISOEventfulness for all the listening conditions (LC). Dots represents the single participants response. Graphs were realised by using Python package soundscapy [60].

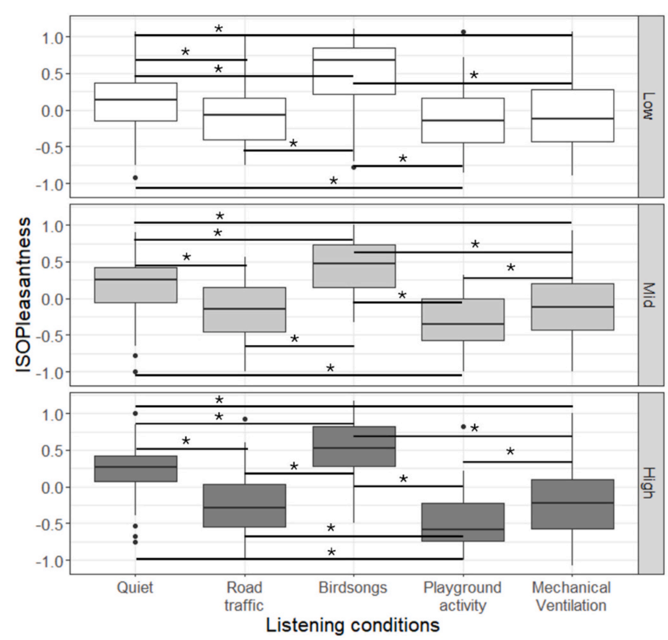

Fig. 4. Boxplot of the ISOPleasantness values as a function of both the listening conditions (X axis) and the noise sensitivity group: Low (Low_NS) and High (High_NS). Bars ans asterisks (*) shows the signifcant differences between listeninin conditions for a fixed noise sensitivity group (p values < 0.05).

to 55 and 62 dBA, whereas in the latter, the range extended up to 80 dBA. In all cases, the sound levels were far from the 47 dBA used in the present study. As mentioned in the introduction, higher sound levels have a greater capacity to affect arousal than lower ones [30] and potentially imply a stronger impact on the task, hence it is not surprising that no effect was recorded here on the accuracy variable. It is pertinent to highlight that the 47 dBA utilised in this study was deliberately chosen as it corresponds to the actual measured ambient sound level, with the intention of recreating conditions as ecologically valid as possible.

Secondly, the modality in which the task was presented differs from previous studies. In fact, here a visual presentation of the task, rather than an auditory one, was employed. In auditory presentations a signal masking may occur, either of an energetic or informational nature. For a detailed explanation of these phenomena, the reader is referred to Refs [65–67]. In brief, the auditory message may not be perceived due to masking by background noise, thereby introducing the possibility of an incorrect response—either because the message was simply not heard, or because reconstructing the message reduces the cognitive resources available [68]. In contrast, such phenomena do not occur in the case of the visual modality used in the present study because the visual input channel is not directly masked by the auditory signal at least at the encoding phase.

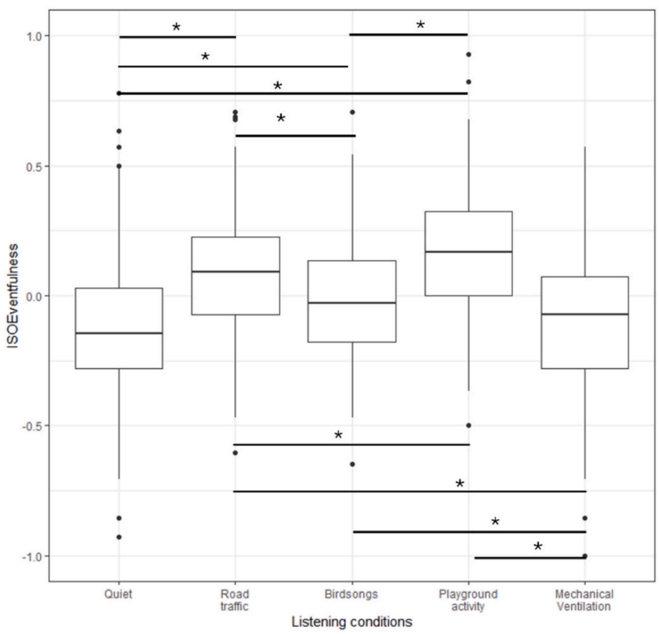

Fig. 5. Boxplotof the ISOEventfulness values as a function of the listening conditions (X axis). Bars and asterisks (*) shows the signifcant differences between listeninin conditions (p values < 0.05).

Contrary to accuracy, a significant effect of listening condition was identified for the variable response time. Both interactions of listening conditions respectively with task difficulty and noise sensitivity were significant. The findings for response time can be reasonably framed within the Yerkes–Dodson law [14,69].

It has to be recalled that no measurement of arousal was undertaken in this experiment so what is discussed below is a working hypothesis, not a validation of a theoretical model. Such validation calls for a more specific assessment of arousal, which could be done for instance by means of both physiological measurements (e.g., salivary cortisol or heart rate) or psychological assessments (e.g., perceived arousal [28]) [70].

That said, one can observe that children in the low noise sensitivity group responded faster when exposed to playground compared to other sound conditions. In contrast, children with mid high noise sensitivity exhibited no differences between the listening conditions. According to the literature [34], individuals with lower noise sensitivity tend to exhibit lower baseline levels of arousal compared to those with moderate or high sensitivity. In the context of the present experiment, it is possible that participants with low noise sensitivity were positioned on the ascending branch of the Yerkes–Dodson curve. For them, the increase in arousal induced by the playground sounds may have led to improved performance. Conversely, participants with moderate or high sensitivity might have already been closer to the peak of the curve, and therefore the variation in auditory stimuli may not have produced noticeable differences in their performance.

Fig. 6 provides an illustrative example of the interaction between sound stimuli and noise sensitivity, as described in the preceding paragraphs.

A similar argument may be applied to discuss the effect of task difficulty. In fact, this factor can distort the Yerkes–Dodson curves as proposed by Sörensen [32], and shown in Fig. 7. In the case of easier tasks, only the effects of mechanical ventilation are evident, as this

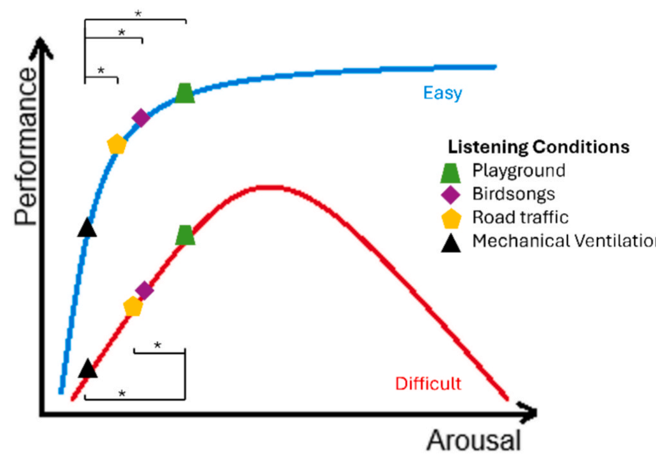

Fig. 7. An illustrative example of possible Yerkes–Dodson curves for the calculation task, showing the potential influence of task difficulty on the arousal–performance relationship. The outcome related to performance is response time. The red curve represents difficult task, while the blue curve represents the easy task. The hypothetical positions of the listening conditions are also indicated on the curves and significant differences between listening conditions (p values < 0.05) were highlighted with bars and asterisks (*). Differences in performance between difficulty levels under fixed listening conditions were all significant (p values < 0.05) with lower performance for the more difficult equations.

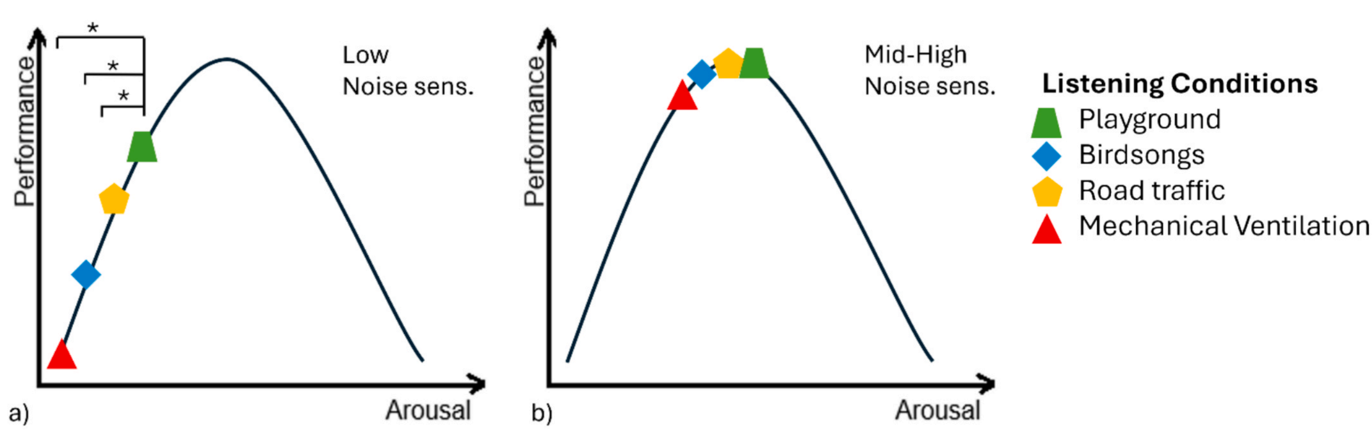

Fig. 6. An illustrative example of possible Yerkes–Dodson curves for the calculation task, showing the potential influence of noise sensitivity on the arousal–performance relationship. In this case the outcome considered is response time, for which a better performance is obtained with shorter values. Panel a) show the possible response for the Low noise sensitivity group, while panel b) show the possible response for Mid and High noise sensitivity group. The hypothetical positions of the listening conditions are also indicated on the curves and significant differences between listening conditions (p values < 0.05) were highlighted with bars and asterisks (*).

condition would ideally fall on the steeper segment of the Yerkes–Dodson curve, while the other conditions would lie on its flatter portion. Conversely, with more demanding tasks, the differences elicited by playground become more pronounced. Fig. 7 illustrates also the hypothetical positioning of the listening conditions along these curves.

The results obtained in the present study appear to differ from those reported in the existing literature, which has consistently shown negative effects of anthropogenic noise on response times [15,19,71]. However, in contrast to previous studies, this work employed lower sound levels, 47 dBA compared to at least 60 dBA in earlier research [15,19]. It is therefore possible that, in those studies, the increase in arousal induced by both the sound level and the nature of the noise exceeded the optimal performance peak *so that representative performance points would be placed in the right, descending past of an hypothetical Yerkes-Dodson curve.* On the contrary in the present study the peak of the curve may not have been surpassed. To confirm this hypothesis, future studies incorporating direct measurements of arousal will be necessary.

4.2. Reading and comprehension task

In the context of reading and comprehension tasks, no effects of listening conditions were observed. However, effects related to proficiency in the comprehension tasks were found, particularly in the accuracy of responses. Additionally, the type of questions had an impact accuracy and response time, while the order of the block affected almost reading time. However, the literature has reported the presence of effects due to acoustic conditions on reading and comprehension tasks [72–75]. As discussed for the calculation task, previous studies typically used higher sound levels (e.g., 64 and 70 dBA) [16] and the same consideration as above do apply here. Secondly, unfortunately a loss of statistical power in the experiment could have affected the data on reading and comprehension. In fact in the panning of the experiment the number of participants was determined to achieve a medium effect size (ca. 0.5 according to Cohen's scale [76]) with a power of 0.8. However, effect size was calculated post-hoc for all pairwise comparisons and the effects of the listening conditions were not medium-sized but, being the highest effect size equal to 0.12, they could be rated between "small" and "very small" according the Cohen's scale. Based on this post-hoc effect size and a desired power of 0.8, a minimum of 171 participants would have been required, as calculated using the software G*Power [77,78]. However, the current results included only 158 participants instead of the 229 scheduled at the beginning because a strict data cleaning was necessary due to reading and comprehension tests which were either dropped while incomplete or misperformed.

4.3. Soundscape assessments

Soundscape assessments were consistent with existing literature, where natural sounds are generally perceived as pleasant, and any kind of noise, especially anthropogenic ones as unpleasant [7].

However, in the present study, a mediating effect of noise sensitivity was identified, significantly influencing the perceived pleasantness of playground. This mediating effect may be attributed to findings reported in the literature [79,80], which suggest that increased noise sensitivity is associated with higher levels of reported annoyance. A similar trend was observed in this study, where playground was associated with a lower ISOPleasantness score. It is worth noting that playground consistently yielded negative values on the pleasantness axis, indicating an evaluation of annoyance according to the circumplex model of soundscape perception.

The results also revealed a loss of significance in the differences in pleasantness ratings between the three sounds of mechanical ventilation, traffic and playground in cases of low noise sensitivity. In other words, a difference is observed when noise sensitivity is high. This finding is consistent with the study by Park et al. [79], which found that as noise sensitivity increases, so does the perceived annoyance, and the gap between a ball impact noise and traffic noise becomes wider. In contrast, for low noise sensitivity individuals, the gap between the two stimuli shrinks.

With regard to eventfulness, ratings were influenced solely by the listening condition, as anticipated, given that participants' evaluations closely reflected the acoustic characteristics of the recorded stimuli. Specifically, the sound stimuli that exhibited a greater number of events were those almost entirely characterised by repeated salient occurrences, such as children playing or traffic marked by the passage of individual vehicles. In contrast, birdsongs contained both periods of high event density and prolonged silences, thereby closely mirroring the distribution along the axis of ISOPleasantness. Finally, mechanical ventilation was perceived as a fully stationary sound, lacking temporal variability.

Interestingly, it is worth noting how eventfulness might also be related to performance in the mathematical task. Indeed, according to Axelson et al. [35], an increase in eventfulness could be associated with a corresponding increase in arousal, and therefore with performance according to the above mentioned Yerkes–Dodson relationship. To examine this hypothesis, multiple correlations were conducted using the rmcorr package [81], revealing a trend suggesting that higher eventfulness may be linked to improved task performance. The corresponding graphs are included in the Supplementary Material. This topic is further elaborated in the following paragraph, which discusses the study's limitations and directions for future research.

5. Limitations and future works

This study presents four principal limitations. The first is the stringent data–cleaning procedures used. While it ensured that only sufficiently motivated participants were retained, it resulted in a reduced sample size and incomplete coverage of trials and listening conditions, since a more permissive approach might have preserved additional data but at the risk of including responses of questionable validity.

The second, we did not collect any direct measures of arousal (either physiological or psychological), so our invocation of the Yerkes–Dodson framework—though grounded in prior literature—remains inferential rather than empirically validated within this experiment. Future studies could address this by incorporating objective or subjective measures of arousal in student populations to validate the proposed theoretical link.

Thirdly, the sound environment was not monitored during the administration of tests and questionnaires. However, any potential effect is expected to be minimal, as students consistently wore closed headphones and the classrooms remained closed (windows and doors) during the activities.

Finally, although participants rated each soundscape along the dimensions of pleasantness and eventfulness, we did not deeply investigate how these subjective evaluations might interact with cognitive performance. This leaves a significant avenue for future research. Indeed, combined analyses—for example, through structural equation modelling (SEM)—would be of considerable interest, as they may reveal a dual effect of soundscape characteristics on cognitive functioning.

Another interesting follow up of the present research is that soundscape analysis may partly elucidate the way by which auditory environments influence cognition through affective and emotional pathways. That is, soundscapes may foster either positive or negative emotional responses in students, thereby modulating cognitive performance accordingly. This line of investigation calls for both theoretical and experimental developments.

6. Conclusions

Natural and ventilation sounds presented at modest and ecologically valid sound level affected response time but not accuracy in calculations. Results could be framed within the Yerkes-Dodson law. In fact, the effects depend on the ability of the sound variables to either increase or not the students' arousal levels, possibly up to the peak of performance (i.e. shortest response time). However, the effects were modulated by noise sensitivity; we discussed and hypothesized that noise sensitivity might alter baseline arousal levels and, by this mechanism, the effect of the sound could became peculiar for an individual.

Regarding reading and comprehension, no effects of the listening conditions were found, likely due to the low power of the experiment.

As regards the soundscape assessments, students preferred hearing birdsongs or quiet, while traffic, anthropogenic sounds, and mechanical ventilation were found to be bothersome. The evaluations were affected by noise sensitivity, but this influence was only observed for sounds perceived as unpleasant. For individuals with low noise sensitivity, no significant differences were observed between mechanical ventilation, playground, and traffic. Regarding eventfulness, only the listening conditions had an effect, with eventfulness ratings aligning with the recorded stimuli.

In conclusion, the results of this study suggest that sounds related to natural ventilation may be preferable to sounds related to mechanical ventilation, as they prompt an increase in performance in a calculation tasks (shorter response time) and with birdsongs also a more pleasant sound environment. However, these outcomes depend on the personal characteristics of the students (i.e., noise sensitivity) and the context (e.g., the task that students were doing).

Creating an optimal environment that is both pleasant and conducive to improved performance could represent a promising direction for future studies, focusing on optimising the sound environment for enhanced performance without compromising the affective reactions of the occupants.

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. **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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apacoust.2025.111206.

Data availability

Data will be made available on request.

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