Original Article

Acoustic Conditions and Student Perceptions in a Québec Classroom: A Case Study

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Abstract

Objective: Although several studies have reported negative impacts of classroom noise on learning, few have examined students' subjective perceptions of their acoustic environment. This cross-sectional observational case study of a single classroom explored how adolescents aged 12 to 13 years evaluated their classroom soundscape and related perceptions to objective noise measurements. **Methods:** Over 11 school days, several groups of students completed a questionnaire at the end of each class period ($N = 957$), indicating whether they felt annoyed/distracted, indifferent, or content/focused in relation to the acoustic environment, and providing free-text comments. Simultaneously, acoustic indicators (LAeq, LA10, LA90, LAmax, LA10–LA90) were recorded using calibrated sound level meters. **Results:** Periods with higher LAeq, LA10, and LAmax values were significantly associated with fewer students feeling content/focused ($r = –0.49$ to -0.59; $P < 0.05$). At the individual level, correlations between acoustic measures and evaluations were weak ($r = -0.14$ to -0.19). Qualitative analysis of students' comments identified four perceptual modes of acoustic experience: intensity, soundscape, source, and autocentric impressions. Most students used only one mode and rarely made explicit connections between sound and learning. **Conclusion:** Findings from this single-classroom case study suggest that while higher continuous and peak noise levels are modestly associated with increased annoyance and reduced focus, these effects are limited. Because some student groups visited the classroom repeatedly, the data are not fully independent; and results should be interpreted with caution. This study highlights the need for larger, multiclassroom investigations combining subjective and objective data, and for tools supporting teacher noise management and student awareness.

Keywords: Noise, acoustics, schools, students, perception

Key messages:

(1) Continuous and peak classroom noise levels (LAeq, LAmax) were significantly associated with students' self-reported ability to focus and feelings of annoyance or distraction.
(2) Students' qualitative descriptions clustered into four perceptual modes, most often focusing on noise intensity rather than source or functional impact.
(3) Reports of annoyance/distractibility increased later in the day, consistent with possible listening-fatigue effects.
(4) Subjective classroom noise evaluations are shaped by multiple acoustic, contextual, and individual factors, underscoring the need for integrated measurement approaches.

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Introduction

Excessive noise is a key acoustic factor that can negatively impact children's health, well-being, and learning in classrooms.[1-4] High noise levels impair speech perception and listening comprehension, particularly in younger learners

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whose cognitive resources for processing degraded speech are still developing.[5-7]

While the World Health Organization (WHO) recommends that background noise in unoccupied classrooms not exceed 35 dB(A) LAeq,[8] this threshold is rarely met in real teaching contexts.[9-11] In Québec, background noise in empty classrooms with regular teaching activities in neighboring classrooms has been reported between 40 and 54 dB(A),[12] exceeding WHO guidelines.

However, these recommendations apply to empty classrooms. During instruction, noise is naturally higher due to speech and student activity. Functional benchmarks have been proposed for acceptable noise during instruction. For instance, Mealings[13] suggests LAeq above 56 dB(A) in secondary classrooms indicates poor acoustic conditions, while levels below 50 dB(A) are acceptable. Real-world observations often exceed these limits, with values ranging from 56 to 77dB(A).[14-16] In Quebec, the single available study revealed mean occupied-classroom levels from 51 to 71 dB(A), with maximum levels up to 97 dB(A).[17]

Beyond objective measures, little is known about students' subjective real-time perception of their acoustic environment in naturalistic classroom settings. Most studies examine the effects of noise on performance,[2,3] but few have captured students' real-time impressions or how they interpret and react to classroom soundscapes. When explored, subjective data are usually retrospective and not temporally aligned with acoustic recordings.[9,18] This limits our understanding of how noise is experienced in real time and how it fluctuates over the day. In Quebec, a Schola group report ranked noise from student activities as the second main source of discomfort in classrooms after poor ventilation,[19] but provided no acoustic data and no student perspectives.

Subjective noise experience cannot be reduced to decibel levels alone. Annoyance, for instance, depends on emotional and contextual factors such as sensitivity, perceived control, personality, task difficulty, and sound source.[20-22] Sounds of the same intensity may be disturbing or neutral depending on these variables. Recent work confirms the multifactorial nature of classroom noise perception: students' noise sensitivity and background noise exposure can modulate task engagement and annoyance.[23] A recent scoping review highlighted the need to combine objective measures with students' subjective accounts for a fuller understanding of acoustic experience.[24]

Developmental factors also play a role. Research suggests that adolescents' noise perceptions and ability to articulate their impact on learning evolve with age. Older adolescents (14–16 years) report higher classroom noise sensitivity and annoyance than younger peers (11–13 years), who may lack the cognitive or linguistic resources to recognize and verbalize environmental noise effects.[25] Cognitive neuroscience shows that metacognitive awareness and attentional control develop into mid-adolescence, enabling more accurate self-assessment of distractions and their consequences for learning.[26] Additionally, as course material becomes more abstract and demanding, older students may find noise more disruptive.[27] These developmental differences make early adolescents a key group to study, as their subjective reports may reflect both actual acoustic conditions and age-related limitations in perception and self-report.

Most studies rely on fixed-response survey items such as multiple-choice, Likert scales, or visual analog scales (see, e.g.,[18,28]), which limit answers to predefined categories. In contrast, open-ended questions let students express experiences in their own terms, revealing dimensions of noise perception otherwise missed.[29] This aligns with the soundscape approach, which integrates subjective and objective data to better characterize acoustic experience.[30,31] While increasingly used in architectural acoustics, it remains underused in school settings.[32] A recent scoping review of school soundscape studies noted limited methodological standardization and sparse inclusion of students' perspectives in naturalistic settings, calling for integrated, real-time studies—the approach taken here.[24]

This study links students' subjective perceptions with objective classroom noise, focusing on qualitative analysis of open-ended responses. We conducted a case study in a Quebec classroom where adolescents completed brief questionnaires about the sound environment across multiple periods and days, alongside simultaneous objective noise measures (LAeq, LA10, LA90, LAmax). In addition to multiple-choice ratings of annoyance and focus, students provided open-ended descriptions, analyzed qualitatively for recurring patterns. By combining real-time subjective and objective data, this study aims to contribute to a more ecologically valid understanding of how students experience their classroom acoustically.

We hypothesized:

(1) H1: Higher LAeq, LA10, LA90, and LAmax will be associated with fewer students reporting feeling content/focused, and more reporting being Annoyed/distracted.

(2) H2: Open-ended descriptions will reveal perceptual patterns related to noise characteristics and personal experience, and these will vary by time of day and measured noise levels.

(3) H3: Reports of annoyance/distraction will increase later in the day, independently of noise levels, possibly reflecting cognitive fatigue or lowered tolerance.

Methods

This cross-sectional observational study was approved (CEREP-19-042-D; 180719; on 18 July 2019) after ethical review by the Ethical Committee for research in Education and Psychology of the University of Montreal. Informed consent was obtained from all subjects involved in the study. Participation was anonymous and optional. Subjective data were collected via a questionnaire completed by students in a secondary school classroom. Objective acoustic measurements were recorded simultaneously using a calibrated sound level meter. Analyses were conducted to relate student responses to noise levels across different periods of the school day. Missing data for particular variables were excluded pairwise from the relevant analyses; no imputation was performed.

Participants and Setting

Participants were first-year high school students (aged 12–13) attending a private French-language school in the province of Québec, Canada. A total of 957 questionnaires were collected across 30 class periods in February and March 2019; the unique number of students could not be estimated, as several groups attended this classroom, and responses were anonymous and voluntary. Students were taught various subjects (e.g., history, ethics, mathematics) in the classroom, which was shared among teachers.

Classroom Characteristics

The classroom, located on the first floor of a suburban town school located in a calm area about 1500 m from the nearest highway, measured $9 \times 7 \times 3$ m (189 m^3), with no acoustic treatment. It had two large windows on one wall and was adjacent to two other classrooms. Background noise in the unoccupied classroom, measured over a 1-hour period, was 38 dBA. Reverberation time (RT20), the time it takes for sound to decay by 20 dB in a room after the sound source has stopped (with shorter RT values indicating a clearer acoustic environment) averaged 0.7 seconds across 500 Hz, 1 kHz, and 2 kHz. Speech clarity (C50)—the ratio of early-arriving sound energy (within the first 50 ms) to late-arriving sound energy (after 50 ms), with a higher C50 value indicating better speech intelligibility as more of the sound energy reaches the listener before being masked by reverberation—was 2.9 dB. RT20 and C50 were measured using a balloon pop at 50 cm from the microphone placed at mid-room, and analyzed with the open-access software Audacity (Muse Group, Pittsburgh, Pennsylvania, USA) using the Aurora plug-in (Angelo Farina, Parma, Italy, website: http://www.aurora-plugins.com). According to American National Standards Institute (ANSI)/Acoustical Society of America (ASA) S12.60-2010 standards, reverberation exceeded the recommended 0.6 seconds for this room volume. The C50 was slightly below the optimal threshold of 3 dB for learning environments.[33]

Data Collection Procedures

Questionnaire

On 11 school days, the teachers distributed questionnaires at the start of each of the 30 class periods. Students could complete one questionnaire per period, voluntarily and anonymously. The French-language questionnaire was custom-designed by researchers and students from the publicly funded research group GRAPPE (Gestion responsable et autonome des paysages sonores en partenariat avec les écoles). It included three questions:

1. Question 1 asked students to indicate the period of the school day (1–5), each corresponding to one of the five 60-minute class periods. Periods 1 and 2 occurred before lunch; periods 3, 4, and 5 followed the lunch break.

2. Question 2 asked students to rate their experience of the sound environment using one of three illustrated options of evaluation of the acoustic environment (EAE) levels: annoyed/distracted, indifferent, or content/focused [Figure 1].

3. Question 3 was an open-ended prompt: "Why did you like the sound environment or why were you distracted by the sound environment?

Of the 957 returned questionnaires, 724 were retained for analysis based on valid responses to the EAE question, defined as selecting a single response option. Questionnaires lacking a valid response to the Period question (i.e., a number between 1 and 5) were excluded from any analysis involving that variable. Among the 724 valid questionnaires, 546 also included interpretable open-ended comments that were retained for further analysis. Only comments linked to valid EAE responses were included.

Acoustic Data

An acoustic recording station was installed on top of a bookshelf in the back of the classroom using a Raspberry Pi 3 Model B+ running NoiseStation 1.0 (Raspberry Pi Foundation, Cambridge, England) and two Umik-1 omnidirectional microphones (miniDSP, Hong Kong, China). It was calibrated and met ISO standards for a

Figure 1: Illustrations of the multiple choices for question 2 [evaluation of the acoustic environment (EAE)]. "Agacé/déconcentré" translates to annoyed/distracted, "Indifférent" translates to indifferent, and "Bien/concentré" translates to content/focused.

Class 2 sound level meter. Recordings were made during 30 occupied class periods, but six recordings were excluded due to technical issues (corrupted audio files resulting in incomplete data writes). Five acoustic metrics were computed over each 1-hour interval and processed using MATLAB R2019b (The MathWorks, Inc., Natick, Massachusetts, USA):

(1) LAeq (equivalent continuous sound level): The average sound level over a given period (here, 1 hour), representing the total energy of the noise.
(2) LA90: the sound level exceeded for 90% of the measurement time, commonly used to indicate background or ambient noise.
(3) LA10: the sound level exceeded for 10% of the measurement time, reflecting peak or intrusive noise events.
(4) LAmax: the maximum recorded sound level during the measurement period.
(5) LA10–LA90: the difference between LA10 and LA90; a measure of noise variability or fluctuation, with higher values indicating more dynamic or intermittent noise.

For each lesson, acoustic metrics were calculated over a 60-minute period corresponding to the full lesson duration. The LAeq values therefore represent the integrated noise exposure for the same time frame referenced by the end-of-lesson

Table 1: The four Perceptual Modes of Acoustic Experience themes with their respective codes and examples

Code	*Description*	*Example*
Intensity		
The student described the acoustic environment according to the intensity of the noise (in terms of quantity and quality). This PMAE consists of three codes referring to the amount of noise.		
Silence	The student mentioned in their comment that there was no noise in the classroom, there was only silence or that the students were silent.	"Because it was silent in the class"
A little noise	The student mentioned that there was some noise, a little noise, or noise that was weak or not noisy.	"There was a little noise"
A lot of noise	The student mentioned that it was loud or noisy in the classroom or that there was a lot of noise.	"Way too much noise"
Soundscape		
The student described the soundscape of the classroom by attributing qualities to the sounds other than in terms of intensity. It is constituted of four codes referring to the presence or absence of negative or positive sounds.		
Presence of negative sounds	The student mentioned that there was a disturbing sound in the environment.	"The only disturbing noise came from outside of the class"
Absence of negative sounds	The student mentioned that there were no disturbing sounds in the environment.	"Nothing disturbing"
Neutral soundscape	The student mentioned that the sound environment in the classroom is neutral, normal, usual, correct, or acceptable.	"It is as usual"
Positive soundscape	The student mentioned that the sound environment is calm, quiet, or pleasant. The sound environment is described positively.	"It's really calm"
Source		
The student identified the sound source. It is constituted of three codes referring to the type of sound.		
Sounds from students	The student identified a sound coming from their classmates laughing, whispering, chattering, etc.	"When we were reading, some students were giggling"
Sounds from material or external noise	The student identified sounds coming from school equipment or material or from outside the classroom.	"The desks always make noise or the loose sheets"
Sounds from speech	The student identified a sound coming from an activity requiring speaking, either a lecture given by the teacher, a class discussion, or a group work between classmates.	"The sound level was high during the group work"
Autocentric		
The student described the sound environment explicitly referring to its impact on themselves. It is constituted of three codes referring to whether the sound is supportive or disruptive to their learning activity.		
Disruptive effect	The student reported that they were annoyed by the sound environment or a specific noise, or that it disturbed their ability to work on their school task.	"The noise from the beads of the necklaces disturbed me"
Neutral effect	The student reported that they were indifferent to the sound environment or that they were not disturbed by the noise.	"The noise did not bother me"
Supportive effect	The student reported that they were able to concentrate or work on their school task in the sound environment or despite the presence of noise.	"There was only a few whispers, and I was able to concentrate"

Note: PMAE = perceptual modes of acoustic experience questionnaire. This approach minimizes bias from short-term fluctuations while aligning with the temporal scope of the subjective evaluations.

Qualitative Analysis of Open-ended Comments

Three independent coders used inductive thematic analysis to categorize responses to question 3. Each coder created their own matrix of codes with no restrictions regarding the number of categories, and inter-coder agreement was calculated using the standard ratio formula: Intercoder reliability = (number of matches) / (number of matches + number of conflicts), "matches" representing an agreement between all judges.[34] The matrices yielded a reliability score of 87.8%, a score of at least 80% indicating acceptable reproducibility,[35] 90% and above representing highest reliability.[34] Discrepancies were resolved through discussion to create a final matrix. Final codes were grouped into four perceptual modes of acoustic experience (PMAE): intensity, soundscape description, source identification, and autocentric impact, comprising 13 distinct codes. Table 1 illustrates examples of codes and excerpts for each PMAE. The 13 final codes were not mutually exclusive, with some comments containing several response segments, each of which fell into a different PMAE or code. For example, three different response segments can be found in the following comment: "The boys were giggling really loudly and that bothered me." The first segment, "boys giggling" was coded *Sounds from students* and classified under the PMAE Source; the second segment, "really loudly" was coded *A lot of noise* and classified under the PMAE Intensity; and the third segment "bothered me" was coded *Disruptive effect* and classified under Autocentric.

Statistical Analyses

The following statistical analyses were carried out to answer the research questions:

(1) Pearson's Chi-square test of independence was used to assess dependence between:
    (1) EAE × period: does perception vary by time of day?
    (2) EAE × PMAE codes are EAE levels associated with specific impressions?

(3) To explore the association between students' EAE and objective classroom noise levels, Spearman rank-order correlations were computed between acoustic measures (LAeq, LA90, LA10, LAmax, and LA10–LA90) and EAE responses. At the individual level, separate binary variables were created for each EAE level (annoyed/distracted, indifferent, content/focused), and Spearman correlations were calculated between each binary variable and the acoustic measures. At the period level, correlations were computed between the proportion of students selecting each EAE level per classroom period and the corresponding acoustic measures. This two-level approach was used to capture both individual experiences and aggregated group trends, and to examine whether classroom-wide acoustic conditions systematically influenced collective student perceptions.

(4) One-factor analyses of variance (ANOVAs) were conducted to test if noise levels (LAeq, LA90, LA10, LA10–LA90 LAmax, 1 h) statistically differed across the five class periods.

(5) To predict students' perceptual evaluations based on acoustic conditions, a multinomial logistic regression model was conducted using GAMLj in Jamovi. The dependent variable was the three-level EAE outcome. The model compared the likelihood of reporting "indifferent" or "content/focused" relative to the reference category "annoyed/distracted," using the five continuous acoustic predictors: LAeq, LA90, LA10, LAmax, and LA10–LA90. Odds ratios (ORs) with 95% confidence intervals (CIs) were computed for each contrast, and model fit was evaluated using akaike information criterion (AIC), bayesian information criterion (BIC), and pseudo R^2. Post-hoc comparisons used Bonferroni correction.

Unless otherwise specified, all analyses were conducted with the IBM® SPSS® Statistics statistical software platform (IBM, Chicago, Illinois, United States) and supported with Microsoft Excel® (One Microsoft Way Redmond, Washington, United States).

Results

First-year high school students (aged 12–13 years) participated in the study, in a single classroom of a private French-language school in Québec. Across 30 class periods, 957 questionnaires were collected from various student groups attending the classroom, of which 724 were valid for analysis. Of the 724 valid questionnaires, 546 included interpretable open-ended comments that were retained for qualitative analysis.

Evaluation of the Acoustic Environment

Overall, 47.4% of students reported feeling content/focused, 45.6% indifferent, and 7.0% annoyed/distracted by the acoustic environment. Consistent with H3 (greater annoyance later in the day), the distribution of EAE responses varied significantly by period [Table 2], with annoyed/distracted reports peaking in period5 and content/focused highest in period1. A statistically significant association was confirmed between EAE level and period (χ^2 (8) = 29.133; $P < 0.05$).

Perceptual Modes of Acoustic Experience

In line with H2, students' open-ended descriptions clustered into distinct perceptual modes. The inductive analysis on 546 valid open-ended comments resulted in 13 final codes, grouped into four Perceptual Modes of Acoustic Experience (PMAE) related to the ways that students described their acoustic environment:

Table 2: Percentage of Evaluation of the Acoustic Environment levels according to the class period (column-wise)

EAE Levels	Periods				
	1	2	3	4	5
Annoyed/distracted (N = 51)	3.13%	4.72%	6.58%	6.82%	18.00%
Indifferent (N = 330)	41.25%	50.47%	47.37%	50.00%	40.00%
Content/focused (N = 343)	55.63%	44.81%	46.05%	43.18%	42.00%

Note: EAE = evaluation of the acoustic environment

1. Intensity (e.g., too loud, too quiet)
2. Soundscape (e.g., chaotic, calm, pleasant)
3. Source (e.g., classmates talking, construction)
4. Autocentric (e.g., personal mood, attention, stress)

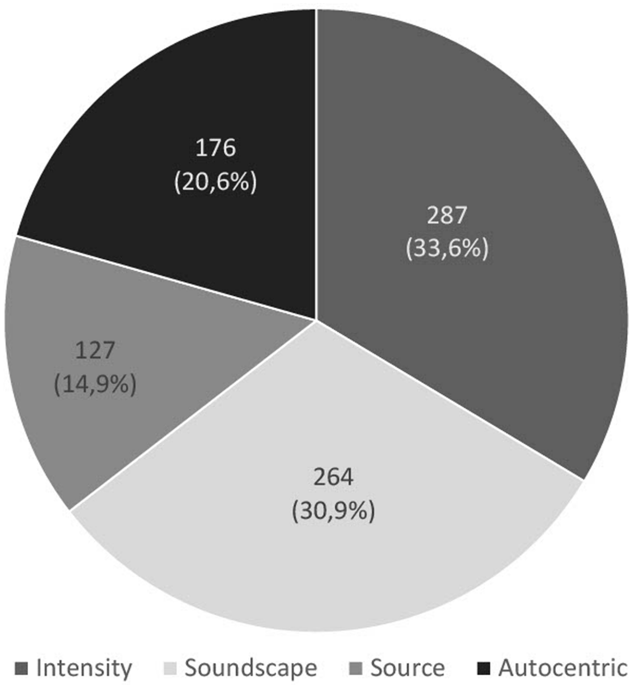

Figure 2: Percentage of response segments according to perceptual modes of acoustic experience.

In total, the 546 valid comments contained 854 coded segments.

Most students (57.3%) used only one PMAE in their comments, 33.2% used two PMAEs, and only a minority used three (8.1%) or four (0.7%) PMAEs. The frequency of occurrence varied across PMAEs, with intensity-related codes being the most common and source-related codes were least frequent [Figure 2].

Code-Level Descriptions and Links to Evaluation of the Acoustic Environment

Figure 3 shows the frequency distribution of each of the 13 codes among the 546 valid comments. The most common were positive indicators such as Silence, Positive soundscape, and A little noise. Negative indicators, such as A lot of noise, were less common. Only 3.5% of valid comments reported the sound environment as having a disruptive effect.

The variables EAE and the codes were statistically related [χ^2 (24) = 475.89; P < 0.05] . Code frequencies varied across EAE levels:

1. Among annoyed/distracted students (N = 44), the most frequent codes were Sounds from students (29.1%), A lot of noise (22.8%), and Presence of negative sounds (17.7%).

2. Among content/focused students (N = 262), frequent codes included Silence (32.0%), Positive soundscape (17.9%), and Supportive effect (16.9%). No students in this group mentioned A lot of noise.

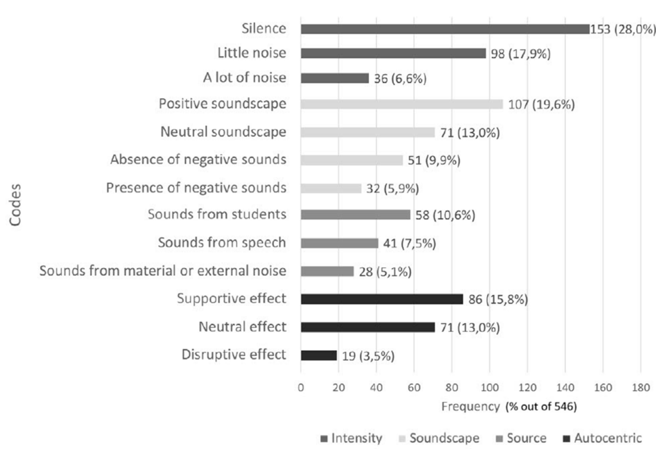

Figure 3: Number of response segments according to code.

Table 3: Mean values of acoustic metrics (in dBA) per class period, with standard deviations in parentheses. All values computed over 1-hour intervals

Acoustic Metric	Period 1 (N = 4)	Period 2 (N = 7)	Period 3 (N = 6)	Period 4 (N = 4)	Period 5 (N = 3)
LAeq	66.7 (3.5)	61.2 (4.4)	67.8 (2.7)	66.4 (4.4)	62.0 (6.1)
LA90	44.3 (3.1)	43.1 (4.6)	47.8 (4.6)	47.2 (7.9)	43.1 (5.1)
LA10	70.7 (3.8)	62.0 (6.5)	70.5 (2.7)	68.2 (7.2)	63.2 (7.3)
LAmax	84.7 (3.7)	82.6 (4.4)	88.5 (6.1)	88.3 (3.2)	84.7 (5.0)
LA10–LA90	26.4 (1.1)	18.9 (2.4)	22.7 (1.9)	21.0 (2.5)	20.1 (2.2)

3. No dominant code pattern emerged among indifferent students, suggesting diverse interpretations of the sound environment.

Acoustic Analyses

Table 3 shows descriptive statistics for each acoustic metric by period. The number of measurement points per period was very small ($N = 3–7$), which makes inferential testing underpowered. While an exploratory ANOVA indicated no statistically significant differences, these results should be interpreted with caution. No systematic variation across periods can be inferred from this dataset given the limited sample size. Table 4 shows the Spearman correlations between acoustic metrics and students' EAE, both at the individual and period levels. Supporting H1, at both levels, higher LAeq (continuous sound level), LA10 (intrusive noise), and LAmax (peak noise) values were significantly associated with a lower proportion of students reporting being content/focused. At the individual level, higher LAeq, LA10, and LAmax values were also significantly associated with an increased likelihood of reporting being annoyed/distracted. LA10 further showed a positive association with indifferent responses. Although statistically significant, these associations were modest in magnitude ($|r| \approx 0.11–0.19$), suggesting a weak but consistent trend across individual

Table 4: Spearman correlations between acoustic measures and students' Evaluation of the Acoustic Environment, at both individual and period levels

Acoustic Measure	Annoyed/Distracted	Indifferent	Content/Focused
Individual-level correlations (binary) (N = 546)†			
LAeq, 1 h	**0.15*** (P < 0.001)**	**0.11* (P = 0.020)**	**–0.19*** (P = 0.001)**
LA90, 1 h	0.08 (P = 0.096)	0.02 (P = 0.589)	–0.07 (P = 0.134)
LA10, 1 h	**0.11* (P = 0.018)**	**0.12** (P = 0.008)**	**–0.18*** (P < 0.001)**
LA10–LA90, 1 h	**0.12** (P = 0.007)**	0.01 (P = 0.865)	–0.08 (P = 0.084)
LAmax, 1 h	**0.16*** (P < 0.001)**	0.05 (P = 0.311)	**–0.14** (P = 0.002)**
Period-level correlations (proportion) (N = 24 periods)			
LAeq, 1 h	0.24 (P = 0.25)	**0.42* (P = 0.04)**	**–0.59** (P = 0.002)**
LA90, 1 h	0.02 (P = 0.91)	0.15 (P = 0.48)	–0.24 (P = 0.27)
LA10, 1 h	0.20 (P = 0.34)	**0.45* (P = 0.03)**	**–0.56** (P = 0.005)**
LA10–LA90, 1 h	0.30 (P = 0.16)	0.13 (P = 0.55)	–0.31 (P = 0.14)
LAmax, 1 h	0.11 (P = 0.63)	0.24 (P = 0.26)	**–0.49* (P = 0.016)**

Note: Individual-level correlations were computed using binary coding for each EAE level (0/1). Period-level correlations are based on the proportion of students selecting each EAE level per classroom period; † n: Annoyed/distracted = 44, indifferent = 240; content/focused = 262; $^{*}P < 0.05$ $^{**}P < 0.01$ $^{***}P <$ 0.01; statistically significant results are in bold.

Table 5: Multinomial logistic regression predicting students' Evaluation of the Acoustic Environment based on classroom noise levels. Values are odds ratios (OR) with 95% confidence intervals in brackets

Predictor	Indifferent vs. Annoyed	Content vs. Annoyed	LRT (χ^2,P)
LAeq	1.450 [0.89, 2.37] (P = 0.138)	0.929 [0.57, 1.51] (P = 0.767)	**13.25****, P = 0.001
LA90	0.924 [0.82, 1.04] (P = 0.187)	1.007 [0.90, 1.13] (P = 0.910)	<0.001, P = 1.000
LA10	0.852 [0.70, 1.04] (P = 0.107)	0.979 [0.81, 1.19] (P = 0.830)	<0.001, P = 1.000
LAmax	**0.833 [0.72, 0.97]** (P = 0.015)	0.927 [0.80, 1.07] (P = 0.309)	**9.33****, P = 0.009
LA10–LA90	0.922 [0.83, 1.02] (P = 0.116)	0.972 [0.88, 1.08] (P = 0.592)	<0.001, P = 1.000

Note: $^{**}P < 0.01$; statistically significant results are in bold; LRT = likelihood ratio test statistic for each predictor across both contrasts; for A vs. B, OR < 1 indicates higher predictor values favor B over A.

students. At the period level, LAeq and LA10 were also positively correlated with the proportion of students reporting feeling indifferent. In contrast, LA90 (background noise) and LA10–LA90 (noise variability) showed no significant associations with any of the EAE levels.

The multinomial logistic regression [Table 5], conducted to examine whether classroom noise levels predicted students' EAE, further supported H1. It converged successfully but showed low explanatory power (pseudo $R^2 = 0.038$, AIC = 868.99, and BIC = 910.56). Among the predictors, LAeq [χ^2 (2) = 13.25; $P = 0.001$] and LAmax [χ^2 (2) = 9.33; P =< 0.009] significantly improved model fit. LA90, LA10, and LA10–LA90 did not contribute significantly ($P = 1.000$).

In the comparison between the "indifferent" and "annoyed/distracted" categories, higher LAmax was significantly associated with decreased odds of being indifferent [OR = 0.83, 95% CI (0.72, 0.97), $P = 0.015$). None of the predictors significantly distinguished between "content/focused" and "annoyed/distracted," although the effects for LAeq and LAmax were consistent with reduced odds of reporting positive evaluations under higher noise levels.

Noise Monitored During a Typical School Day

Figure 4 provides an illustrative example of real-time noise fluctuations during one representative school day, with overlaid EAE ratios for periods 1, 2, and 5. During this day, the classroom was occupied for full-class lessons during four class periods of the day, out of five (periods 1, 2, 4, and 5), the third period only including a smaller group of students. EAE levels were unavailable for periods 3 and 4. As can be seen in the graph, noise started at around 9:20, the start of the first period. There is a dip at around 11:28, which is the start of lunch break. Noise increases again at 12:35, corresponding to the start of the third period with the smaller group, but stays at a lower level than during full-class periods. An increase in noise is observed again at 13:42, coinciding with the start of the fourth class period. Noise decreased toward 15:50, which was the time of class dismissal. Noise levels fluctuated across the school day, but the absence of clear changes in average noise across periods during this illustrative day suggests that the time-of-day differences in EAE (see SectionA) are unlikely to be explained by objective noise variation on that day. This pattern is consistent with the descriptive averages across all measured days [Table 3], which similarly did not show systematic differences in mean noise levels across periods, supporting H3.

Discussion

This study explored how adolescents perceive their classroom acoustic environment in relation to objective noise levels. Three hypotheses were tested: (1) higher noise levels would be associated with increased reports of annoyance and fewer of feeling content or focused; (2) students' open-ended descriptions would reflect diverse perceptual modes; and (3) annoyance would increase later in the day, independent of noise levels.

Subjective Perception and Objective Noise

Hypothesis 1 was partially supported. Higher LAeq, LA10, and LAmax were significantly associated with fewer students feeling content/focused and more reporting annoyed/distracted. These acoustic indicators—representing continuous, intrusive, and peak noise—appear to negatively affect students' perceptions of their acoustic environment, aligning with past research.[5,6] However,

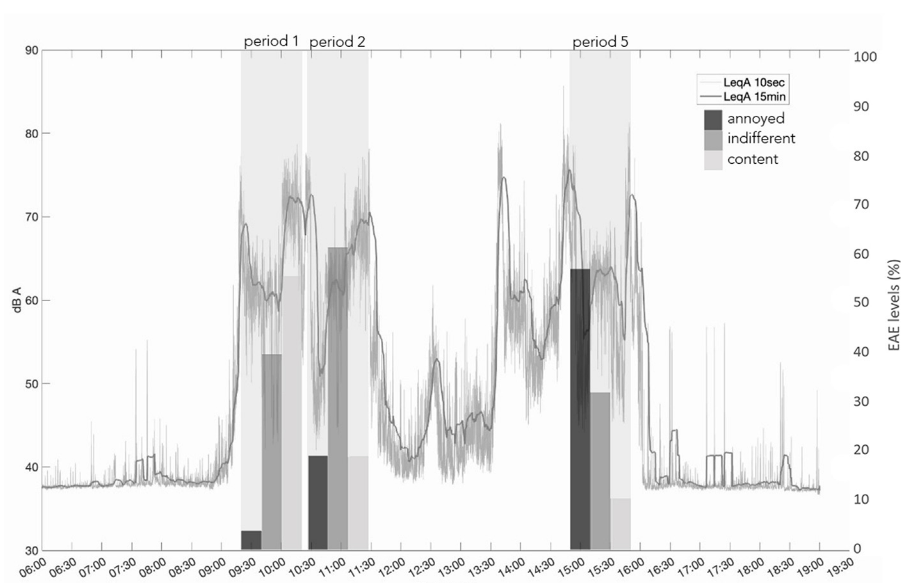

Figure 4: Time history of the noise monitored during a typical school day with overlaid EAE ratios for periods 1, 2, and 5. Period 3 was not occupied for a full-class lesson; EAE levels were unavailable for period 4 as students were not provided with the questionnaire.

these correlations were weak ($r = 0.11–0.19$), suggesting that despite a consistent trend across individuals, noise accounts for only a small portion of the variance. Other factors, such as task engagement, noise sensitivity, or familiarity with the environment, likely modulate students' responses to noise. This highlights the limitations of relying solely on acoustic metrics to predict subjective experience.

At the class period level, correlations with annoyed/distracted ratings were slightly higher but not statistically significant, possibly due to interpersonal variability in noise sensitivity or coping strategies that are averaged out in the aggregated data, or reduced statistical power resulting from a smaller number of data points. Conversely, the negative associations between noise levels and reports of feeling Content/focused were stronger and more consistent at the period level, particularly for LAeq, LA10, and LAmax.[13]

Interestingly, LA10–LA90 (noise variability) showed a weak association with annoyance/distraction at the individual-response level, but this effect disappeared in period-level and multivariate analyses. This suggests that while fluctuations in background noise may influence individual perceptions in the moment, their contribution is less robust than overall or peak noise levels when data are aggregated or modeled jointly.

These findings highlight the value of analyzing both individual and group-level data to uncover both immediate perceptual impacts and broader trends. Beyond statistical associations, the absolute noise levels observed in this study are themselves concerning. The measured background noise of 38 dBA already exceeded the WHO guideline of 35 dBA for unoccupied classrooms, suggesting that even in "quiet" conditions, the acoustic baseline was suboptimal. More strikingly, during instruction, all mean LAeq values ranged from 61.2 to 67.8 dBA—well above the 50 dBA "acceptable" benchmark and surpassing the 56 dBA threshold that Mealings[13] characterizes as acoustically "poor." These findings indicate that students were consistently exposed to noise environments that international standards and empirical guidelines regard as detrimental to learning. In practical terms, this means that the observed weak statistical associations between measured noise and reported annoyance may actually underestimate the true pedagogical risks, as students in this study may never have been exposed to what would be considered an acoustically "good" or "acceptable" classroom. Rather, their responses may reflect adaptation to persistently adverse conditions. This underscores the need for school-level interventions targeting noise reduction and for policies that enforce compliance with established acoustic guidelines.

In addition to the bivariate correlations, the multinomial logistic regression provided further insight. Both LAeq and LAmax significantly improved model fit. However, the model's explanatory power was very low (R^2=0.038), indicating that acoustic indicators do not have a practical predictive value. Nonetheless, this indicates that continuous and peak noise levels might play a role in shaping students' subjective experiences. In contrast, LA90, LA10, and LA10–LA90 did not significantly contribute, suggesting that background or variability-based indicators are even less relevant to perceived focus or annoyance. Together, these findings confirm that high and intrusive noise levels are linked to more negative perceptions, but also highlight that most of the variation in perception remains unexplained by acoustic metrics alone.

The weak association between noise levels and annoyance reflect the complex and multifactorial nature of noise annoyance. It is influenced not only by sound intensity, but also by psychological and contextual factors such as perceived control, source attribution, noise sensitivity, and task demands.[21,22,36] For example, Massonnié *etal*.[37] reported that students with attentional control difficulties were more disturbed by similar noise levels than their peers. Renaud *et al.*[11] demonstrated that noise can provoke emotional responses like fatigue or tension independently of measured sound intensity. Thus, student characteristics, emotions, and task context must be considered alongside acoustic metrics to fully understand noise perception.

In this study, students rarely referenced noise sources in their comments—focusing instead on overall intensity. This contrasts with Connolly *et al.*,[20] who observed that students were particularly disturbed by external or mechanical sounds. In real-time natural classroom settings, students may be less likely to consciously identify sound sources or may normalize peer-related noise to the extent that it is underreported as a distraction.

These findings underscore that subjective noise perception is shaped by a wide range of influences beyond measured sound levels, including individual differences such as mood, motivation, task engagement, as well as social dynamics and contextual influences such as the nature of classroom activities or classroom management strategies. The complexity of these interactions highlights the importance of integrating acoustic data with individual and contextual variables, as recently recommended for multidimensional assessment of environmental quality in educational settings.[23,24]

In addition to the occupied noise levels, fixed acoustic characteristics of the classroom also provide relevant context. Speech clarity (C50) was measured at 2.9dB, just below the 3dB benchmark for learning environments.[33] A change of 1.1 dB in C50 was found to be a just notable difference[38]; in Bradley and Sato,[39] a 3 dB change in C50 roughly corresponded to a 5% difference in measured speech intelligibility. By simple proportional scaling, the 0.1 dB deviation observed in our study would correspond to well under a 1% change in intelligibility—a negligible difference, which could still slightly increase listening effort when combined with the high occupied classroom noise levels.

The predominance of "indifferent" responses, despite objectively suboptimal acoustic conditions, likely reflects the developmental considerations outlined earlier. Most participants were 12 to 13 years old, an age in which students may lack the metacognitive awareness to connect noise with learning. Research shows that older adolescents (14–16) are more sensitive to noise than younger ones.[25] As cognitive and linguistic skills mature, students become better at recognizing and reporting acoustic impacts.[4,27,37]

PMAE coding supported this. The code silence was most frequently cited by students who felt content/focused, supporting the well-established link between low noise levels and improved concentration.[5,6] In contrast, sounds from students was frequently associated with reports of being annoyed/distracted, consistent with studies identifying peer-generated noise—chatter, scraping chairs—as the most disruptive.[18,40] Unlike external or infrastructural noise, peer-generated noise is manageable, making it a potential intervention target.

Qualitative responses further supported a developmental interpretation, showing a limited perceptual vocabulary. Most students used only one perceptual mode, typically sound intensity. This may reflect both linguistic limitations and a still-developing awareness of the effects of sound. Educational or participatory interventions aimed at increasing acoustic awareness could help students develop a more nuanced understanding of how sound affects their concentration, comfort, and learning.

Students' Descriptions and Learning Context

Findings from the PMAE analysis supported hypothesis 2. Students described the acoustic environment using four modes:

intensity, soundscape, source, and autocentric impressions. These categories reflect a range of sensory and cognitive dimensions and provide a framework to better interpret subjective reports. However, most students made limited links between acoustic environment and learning effects, even when annoyed or distracted—highlighting the need for tools to support acoustic awareness in schools.[30,32]

Listening Effort and Time-of-Day Effects

In line with hypothesis 3, students reported greater annoyance later in the day and more focus in the morning. Importantly, this pattern was not paralleled by clear differences in measured noise across periods: descriptive averages across all recorded days [Table 3] and illustrated intraday fluctuation for one representative day [Figure 4] showed broadly similar mean noise levels, though the very small number of samples per period ($N = 3–7$) limited the robustness of the statistical comparison. These results point to cognitive fatigue as a factor. The Framework for Understanding Effortful Listening framework suggests prolonged listening in difficult acoustic environments can lead to fatigue and reduced performance.[41] Wingfield's cognitive-behavioral theory[42] also proposes that effortful listening diverts cognitive resources away from higher-level learning.[41]Classrooms often impose high listening demands due to poor acoustics. Over time, this can deplete cognitive resources and reduce focus. In this study, students felt more focused in the morning and more distracted in the afternoon, even though LAeq levels remained stable. For instance, the second-highest LAeq was recorded during the first period, while the fifth showed one of the lowest. This supports the idea that factors beyond measured noise levels, such as cumulative listening effort or cognitive fatigue, may contribute to decreased focus later in the day. While this remains speculative without physiological data or performance measures, it suggests scheduling demanding tasks earlier in the day or introducing structured breaks may help mitigate the effects of listening fatigue.[41]

Limitations and Future Directions

This case study presents several limitations that also offer avenues for future research. It was conducted in a single classroom, limiting generalizability. The exact number of individual students contributing to the questionnaires is unknown, as the classroom was attended by several groups across the study duration, some of which may have visited repeatedly. This likely led to some students completing the questionnaire multiple times, thereby reducing the independence of the 957 responses. Such nonindependence may cause statistical tests to overestimate the effective sample size, as repeated responses from the same individuals are likely correlated. Consequently, findings should be interpreted with caution, as they reflect repeated sampling of a relatively small pool rather than a large independent cohort. Future studies should adopt designs that track individual-level identifiers to avoid pseudoreplication.

We lacked data on hearing status, attention-deficit/hyperactivity disorder, or language disorders—factors that may affect noise sensitivity.

The visible presence of the questionnaire and equipment may have influenced behavior (Hawthorne effect),[43] possibly lowering LAmax values. Moreover, microphones were placed at the back of the room, potentially resulting in conservative noise estimates, which could explain why LAeq values were lower than in other studies.[12,14] Spatial variability in reverberation and clarity may also have been underestimated due to a single measurement point.

Although LAeq values were calculated over the same 60-minute period referenced in the questionnaires, students' perceptions could have been influenced by specific parts of the lesson (e.g., noisy group discussion or particularly quiet individual task), weakening correlations. Some students selected multiple EAE categories within the same class period, suggesting fluctuating experiences. Future studies could ask students to identify their dominant experience or use real-time sampling methods.

The EAE scale combined annoyance and concentration, which may have introduced ambiguity. Separating these constructs could improve clarity. Finally, although we know the school was francophone, private, and mixed-gender, we had no sociodemographic data, which may influence noise sensitivity and reporting.

Future research should expand to multiple classrooms, gather more detailed individual data, and explore ways to support students in developing acoustic awareness. This would improve generalizability, and help develop classroom management strategies that enhance learning in noisy environments.

Conclusion

This study explored adolescents' perceptions of their classroom's acoustic environment in relation to objective noise indicators. While noise levels, particularly LAeq, LA10, and LAmax, were modestly associated with students' self-reported annoyance and focus, the correlations were relatively weak, underscoring the complexity of subjective acoustic experience. Qualitative data further revealed that students often relied on a limited perceptual vocabulary, with most referencing sound intensity alone. This, combined with a predominance of "indifferent" responses, suggests that younger adolescents may be less sensitive or less equipped to articulate how soundscapes affect their learning. Notably, students reported greater annoyance later in the day, despite consistent noise levels across periods, supporting the role of listening fatigue. Together, these findings demonstrate the value of combining objective and subjective approaches to better understand how classroom acoustics influence students. They also point to the importance of age-appropriate tools that foster acoustic awareness and help educators create learning environments conducive to sustained attention and well-being.

Availability of Data and Materials

The data collected in this study will be made available upon reasonable request, in respect to research ethics.

Author Contributions

Timothy Pommée: Formal analysis; data curation; writing—original draft; writing—review and editing; visualization. **Rachel Bouserhal**: Conceptualization; methodology; writing—original draft; resources; supervision; funding acquisition. **Tiffany Chang**: Conceptualization; methodology; data curation; project administration; writing—original draft. **Florence Renaud**: Investigation. **Cecilia Maria Ferreira Borges**: Conceptualization; methodology; resources; supervision; funding acquisition. **Annelies Bockstael**: Conceptualization; methodology; resources; supervision; funding acquisition. **Ingrid Verduyckt**: Conceptualization; methodology; writing—original draft; resources; supervision; funding acquisition.

Ethics Approval and Consent to Participate

The study was approved (CEREP-19-042-D; 180719; on July 18, 2019) after ethical review by the Ethical Committee for research in Education and Psychology of the University of Montreal. Informed consent was obtained from all subjects involved in the study. Participation was anonymous and optional.

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Conflicts of Interest

No conflict of interests exist for any author regarding the material presented in this manuscript. This study was approved by the Université de Montréal's ethics committee.

References

1. Minelli G, Puglisi GE, Astolfi A. Acoustical parameters for learning in classroom: A review. Build Environ 2022;208:108582.
2. Pellegatti M, Torresin S, Visentin C, Babich F, Prodi N. Indoor soundscape, speech perception, and cognition in classrooms: a systematic review on the effects of ventilation-related sounds on students. Build Environ 2023;236:110194.
3. Lamotte A-S., Essadek A, Shadili G, Perez J-M., Raft J. The impact of classroom chatter noise on comprehension: a systematic review. Percept Mot Skills 2021;128:1275–91.
4. Gheller F, Spicciarelli G, Scimemi P, Arfé B. The effects of noise on children's cognitive performance: a systematic review. Environ Behav 2023;55:698–734.
5. Woolner P, Hall E. Noise in schools: A holistic approach to the issue. Int J Environ Res Public Health 2010;7:3255–69.
6. Klatte M, Bergström K, Lachmann T. Does noise affect learning? A short review on noise effects on cognitive performance in children. Front Psychol 2013;4:578.
7. Fretes G, Palau R. The impact of noise on learning in children and adolescents: a meta-analysis. Appl Sci 2025;15:4128.
8. World Health Organization. Guidelines for community noise. Geneva: WHO; 1999.
9. Goldschagg P, Bekker T, Cockcroft K. Perceived effects of background noise on the learning experiences of English first- and second-language female learners. S Afr J Educ 2023;43:1–8.
10. Choi Y-J. An acoustic survey of Korean school classrooms: the necessity for Korean acoustic standards and design guidelines. Appl Acoust 2025;231:110548.

11. Renaud F, Verduyckt I, Chang T, *et al.* Students' self-reported experience of soundscape: the link between noise, psychological and physical well-being. Int J Environ Res Public Health 2024;21:84.
12. Hetu R, Truchon-Gagnon C, Bilodeau SA. Problems of noise in school settings: a review of literature and the results of an exploratory study. J Speech Lang Pathol Audiol 1990;14:31–8.
13. Mealings K. Classroom acoustic conditions: Understanding what is suitable through a review of national and international standards, recommendations, and live classroom measurements. 2nd Australasian Acoustical Societies Conference, ACOUSTICS 2016, 2, 1047–1056.
14. Kristiansen J, Lund SP, Persson R, Shibuya H, Nielsen PM, Scholz M. A study of classroom acoustics and school teachers' noise exposure, voice load and speaking time during teaching, and the effects on vocal and mental fatigue development. Int Arch Occup Environ Health 2014;87:851–60.
15. Wang LM, Brill LC. Speech and noise levels measured in occupied K-12 classrooms. J Acoust Soc Am 2021;150:864–77.
16. Degotardi S, Sharma M, Sweller N, Djonov E, Kelly M, Ng J. Noise levels in infant-toddler early childhood classrooms: individual variation and relationships with social and physical features of the room. Australas J Early Child 2025;50:305–18.
17. Riel J. Analyse de l'activité de travail des enseignantes et enseignants du secondaire [Master's thesis]. Montreal (QC) : Unversité du Québec à Montréal; 2009.
18. Lundquist P, Holmberg K, Landström U. Annoyance and effects on work from environmental noise at school. Noise Health 2000;2:39–46.
19. Schola. L'ABC de la rénovation scolaire au Québec. Fascicule A : De l'analyse des bâtiments scolaires et de leurs usages [Internet]. Québec: Schola; 2022 [cited 2025 Aug 29]. Available from: https://www.schola.ca/telech/ABC_fasciculeA_2022.pdf.
20. Connolly DM, Dockrell JE, Shield BM, Conetta R, Cox TJ. Students' perceptions of school acoustics and the impact of noise on teaching and learning in secondary schools: findings of a questionnaire survey. Energy Procedia 2015;78:3114–9.
21. Francis AL, Chen Y, Medina Lopez P, Clougherty JE. Sense of control and noise sensitivity affect frustration from interfering noise. J Acoust Soc Am 2024;156:1746–56.
22. Cai J, Kwan M-P., Kan Z, Huang J. Perceiving noise in daily life: how real-time sound characteristics affect personal momentary noise annoyance in various activity microenvironments and times of day. Health Place 2023;83:103053.
23. Bhandari N, Tadepalli S, Gopalakrishnan P. Investigation of acoustic comfort, productivity, and engagement in naturally ventilated university classrooms: role of background noise and students' noise sensitivity. Build Environ 2024;249:111131.
24. Kurukose Cal HK, Kang J, Aletta F. Methodological approaches and main factors considered in school soundscape studies: a scoping review. Build Acoust 2024;31:75–90.
25. Connolly D, Dockrell J, Shield B, Conetta R, Cox T. Adolescents' perceptions of their school's acoustic environment: the development of an evidence-based questionnaire. Noise Health 2013;15:269–80.
26. Dumontheil I, Hassan B, Gilbert SJ, Blakemore S-J. Development of the selection and manipulation of self-generated thoughts in adolescence. J Neurosci 2010;30:7664–71.
27. Ambrose S, Bridges M, DiPietro M, Lovett M, Norman M, Mayer R. How learning works: Seven research-based principles for smart teaching. San Francisco: Jossey-Bass 2010.
28. Radun J, Lindberg M, Lahti A, Veermans M, Alakoivu R, Hongisto V. Pupils' experience of noise in two acoustically different classrooms. Facilities 2023;41:21–37.
29. Reja U, Manfreda KL, Hlebec V, Vehovar V. Open-ended vs. close-ended questions in web questionnaires. Dev Appl Stat 2003;19:159–77.
30. Torresin S, Aletta F, Babich F, *et al.* Acoustics for supportive and healthy buildings: emerging themes on indoor soundscape research. Sustainability 2020;12:6054.
31. van Kamp I, Klæboe R, Brown A, Lercher P. Soundscapes, human restoration, and quality of life. In Kang J, Schulte-Fortkamp B, eds. Soundscape and the Built Environment. Boca Raton, FL: CRC Press 2015. p.43–68.
32. Hamida A, Zhang D, Ortiz MA, Bluyssen PM. Indicators and methods for assessing acoustical preferences and needs of students in educational buildings: a review. Appl Acoust 2023;202:109187.
33. Rakerd B, Hunter EJ, Berardi M, Bottalico P. Assessing the acoustic characteristics of rooms: a tutorial with examples. Perspect ASHA Spec Interest Groups 2018;3:8–24.
34. O'Connor C, Joffe H. Intercoder reliability in qualitative research: debates and practical guidelines. Int J Qual Methods 2020;19:1–13.
35. Blick B, Nakabugo S, Garabedian LF, Seru M, Trap B. Evaluating inter-rater reliability of indicators to assess performance of medicines management in health facilities in Uganda. J Pharm Policy Pract 2018;11:11.
36. Hagen M, Kahlert J, Hemmer-Schanze C, Huber L, Meis M. Developing an acoustic school design: Steps to improve hearing and listening at schools. Build Acoust 2004;11:293–307.
37. Massonnié J, Frasseto P, Mareschal D, Kirkham NZ. Learning in noisy classrooms: Children's reports of annoyance and distraction from noise are associated with individual differences in mind-wandering and switching skills. Environ Behav 2022;54:58–88.
38. Bradley JS, Reich R, Norcross SG. A just noticeable difference in C50 for speech. Appl Acoust 1999;58:99–108.
39. Bradley JS, Sato H. The intelligibility of speech in elementary school classrooms. J Acoust Soc Am 2008;123:2078–86.
40. Enmarker I, Boman E. Noise annoyance responses of middle school pupils and teachers. J Environ Psychol 2004;24:527–36.
41. Pichora-Fuller MK, Kramer SE, Eckert MA, *et al.* Hearing impairment and cognitive energy: the framework for understanding effortful listening (FUEL). Ear Hear 2016;37:5S–27.
42. Wingfield A. Evolution of models of working memory and cognitive resources. Ear Hear 2016;37:35S–43.
43. McCambridge J, Witton J, Elbourne DR. Systematic review of the Hawthorne effect: new concepts are needed to study research participation effects. J Clin Epidemiol 2014;67:267–77.