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Let's get loud: How classroom activities influence speech and noise levels during lessons

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ABSTRACT

Student activity noise is the dominant sound source in primary school classrooms. While it reflects the dynamic and interactive nature of learning, excessive noise can disrupt speech perception, impair concentration, and affect well-being. This study analysed the acoustic environment of 26 classrooms during real lessons, separating speech and activity noise using Gaussian Mixture Models. Ninety-three periods of homogeneous activities across Grades II–V were examined to assess the effects of activity type, student age, and classroom acoustic characteristics.

Results indicated that the type of activity in the class is an important source of acoustic variability, with teacher-led lessons and group work producing the highest overall levels and quiet work the lowest. Activity noise averaged 50 dB(A) across activities, with large variability linked to class-specific behavioural dynamics, and speech levels were consistently higher in more interactive settings. Student age significantly affected speech levels, showing a nearly 5 dB decline from Grade II to Grade V, and, together with activity type, influenced the speech–noise relationship. Noise level analyses revealed a 10 dB increase from unoccupied to baseline conditions (occupied but inactive) and an additional rise of over 5 dB during activities. Classrooms with higher speech clarity had lower activity noise, highlighting the role of early reflections control in mitigating noise from student movement and interaction. The findings underscore the importance of integrating acoustic ergonomics into school design and refurbishment, through multidisciplinary collaboration, to support effective communication and learning—particularly for younger children.

1. Introduction

1.1. Acoustics for learning: why the sound environment matters

Acoustics represent a fundamental aspect of learning environments, directly impacting students' learning and well-being—particularly for younger children, still developing their cognitive, linguistic, and auditory skills, and vulnerable student populations. Addressing this topic is therefore essential to advancing the aims of Sustainable Development Goal 4, which calls for inclusive and effective learning environments for all [1].

Good acoustic conditions in primary school classrooms ensure optimal speech intelligibility [2], support performance [3], and reduce listening effort [4]. From a long-term perspective, there is growing evidence that appropriate acoustic conditions significantly sustain students' learning and, consequently, enhance their life chances - that is, their opportunities to achieve positive outcomes in education, employment, health, and overall social participation throughout their lives [5–8].

1.2. Activity noise in active classrooms

Following a recent review [9], *good acoustic conditions* are generally defined in national and international standards based on two factors assessed under unoccupied conditions: reverberation time and background noise (or ambient noise) level. Reverberation time is primarily determined by the room volume and surface materials, while ambient noise is influenced by the sound insulation of façade and internal partitions, as well as by internal sources like HVAC systems and audio-visual equipment. Measures of speech intelligibility (e.g., speech clarity – C_{50}, Speech Transmission Index - STI) are typically used as validation tools for the overall acoustic performance of the learning spaces.

However, existing standards do not (explicitly) account for a key

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factor that significantly shapes the sound environment during actual classroom use: activity noise by occupants. This refers to the sounds generated directly by students, including speech, movement, the handling of objects, and the shifting of chairs and desks [10]. Shield and Dockrell [11] found that during lessons in primary schools, external and background noises were generally inaudible, with internal noise mainly stemming from the students and varying according to the diverse activities they undertake. Similarly, Visentin et al. [12] reported that classmates' voices and movements were not only the most frequently perceived sounds, but also the most disturbing—significantly impacting perceived loudness, pleasantness and arousal. Unlike ambient noise, activity noise is dynamic and highly variable over time, often reflecting the nature and structure of the learning activity [13]. While it may indicate high engagement and participation, excessive or unmanaged activity noise can compromise speech intelligibility and overall acoustic quality [14]. Indeed, numerous studies have shown that children—especially those in early developmental stages —are particularly sensitive to some features of the activity noise (i.e., semantic content, salient acoustic features, or deviant acoustic patterns), all of which disrupt attention and cognitive processing [15].

Therefore, it appears that to better understand how classroom acoustics affect learning—and to develop relevant criteria for classroom design and use—it is essential to study classrooms during occupancy and actual lessons, i.e., in active conditions. This need has long been recognized, with early studies dating back to the 2000s [16–18] seeking to relate overall sound levels in active classrooms to occupancy, acoustic parameters, and student grade levels. These studies typically use A-weighted, equivalent sound levels (L_{Aeq}), statistical levels (L_{A90}, or other percentiles), with monitoring durations ranging from just a few minutes [11] to several hours [13], and even full school days [19].

1.3. How activities change the overall levels

Although studies on active classroom acoustics (see previous subsection) represented a significant step forward, they assumed the acoustic conditions to be uniform across all teaching periods, overlooking the fact that specific activities —such as lecturing, group discussions, individual tasks, or hands-on work—can produce markedly different acoustic scenarios. Despite long-standing recognition in educational research, studies that directly investigate how different types of classroom activity influence the sound environment remain limited [13].

Shield and Dockrell [11] demonstrated that sound levels can vary by up to 20 dB across activities in British classrooms, with $L_{Aeq,2\ min}$ values ranging from 56.3 dB(A) during silent reading to 76.8 dB(A) during group work involving movement. Their findings also indicated that sound levels were more strongly correlated with the number of students in the classroom than with pupil age.

Similarly, Radun et al. [20] confirmed that activity type significantly affects classroom sound levels and pupil perceptions. Measurements in a traditional Finnish classroom (reverberation time: 0.54 s) across four activity categories—quiet work, individual speaking, group work, and activity-based work—showed $L_{Aeq,30\ min}$ values ranging from 52.7 to 71.6 dB(A). In a refurbished classroom (reverberation time: 0.32 s), reductions of 2–13 dB were observed depending on the activity, alongside decreased annoyance from peer noise and improved concentration and speech perception reported by students. In line with these findings, Radun et al. [21] also observed that sound levels in enclosed classrooms ranged from 63.8 dB(A) during calm activities to 66.7 dB(A) during lively ones.

To better describe the relationship between classroom activity and acoustic conditions, Seitz and Fels [22] introduced the concept of activity-based acoustic situations (ABAS), emphasizing how different educational activities shape the acoustic environment and influence teacher-student communication. Measurements in German primary schools reported A-weighted sound levels ranging from 55.5 dB(A) during silent work to 69.3 dB(A) during breakfast breaks, with both $L_{Aeq,15\ min}$ and loudness levels higher among younger (first grade) than older (fourth grade) pupils.

Building on this perspective, the recently introduced L3 Assessment Framework [23] relies on a multidisciplinary approach to classroom design, that explicitly incorporates the role of classroom activity in shaping the perceptual setting. It identifies three core activity types - lectures (teacher-led instruction), group learning (collaborative or peer-led discussion), and independent work (individual consolidation of knowledge) – each prompting specific changes in factors related to speech intelligibility (e.g., sound levels, signal-to-noise ratio SNR, sensory distractions).

1.4. Disentangling activity noise and speech levels in active classrooms

Most studies on active classrooms focus on overall sound pressure levels without disentangling the contributions of the two main sources: speech and student activity. These sources coexist in the same space and overlap in both time and frequency domains. Disentangling their individual contributions is challenging, as only a single measure is typically available, in which the two contributions are mixed. Technological limitations, such as sampling time, further constrain this process. As a result, any method used can only provide an approximation of each source's actual contribution.

Two main approaches have been proposed to address this methodological challenge. The first uses two acoustic indicators—the A-weighted equivalent continuous sound level (L_{Aeq}) and the 90th percentile level (L_{A90})—to approximate teacher speech and student activity noise, respectively [6]. The second relies on model-based methods. Hodgson et al. [10] introduced Gaussian Mixture Models (GMM) to separate contributions from teacher speech, student activity, and background noise in university lectures. Subsequent studies applied GMM in primary classrooms [17,24] and across school levels [25], though limited samples and the dominance of plenary teaching restricted analyses of activity-related effects. K-means clustering (KM) has also been used and compared with GMM in large-scale classroom surveys [19]. Comparative analyses show that L_{Aeq} levels match speech levels only in the case of frontal teaching, and L_{A90} tends to underestimate student activity noise, potentially leading to an overestimation of SNR values and, consequently, an inaccurate representation of speech intelligibility conditions [19]. The inaccuracy of L_{A90} in matching activity noise further suggest that *a priori* fixed percentiles may not reliably capture activity-related sounds, that also depends on social and contextual dynamics [26]. GMM and KM methods yield broadly consistent results [14], though GMM may also slightly underestimate non-speech levels [19].

These findings reflect the inherent uncertainty in any separation method and the lack of a formal uncertainty model tailored to this type of context.

1.5. Aims of the present study

As summarized so far, substantial evidence supports the need to better characterize classroom acoustics during actual lessons. Meanwhile, over the past three decades, pedagogical practices have shifted away from traditional lecture-based formats toward more dynamic, student-centred approaches [27–29] . This shift prompts the need for further research into how different teaching and learning scenarios influence the acoustic conditions in classrooms. Moreover, understanding not just average sound levels but the distinct contributions of speech and activity noise is of interest, as the nature of classroom activity—whether it involves whole-class instruction, group collaboration, or independent work—can significantly affect both the desired signal (typically the teacher's speech) and the noise produced by the students themselves.

The present study aims to address these gaps by focusing on primary schools and considering the type of classroom activity as a key factor influencing acoustic conditions. By applying Gaussian Mixture Models to disentangle speech and activity noise levels during various teaching scenarios, this study seeks to provide a more detailed and ecologically valid account of how the sound environment of the classroom changes in real use. Specifically, we investigated whether speech and activity noise levels varied according to: (i) the type of classroom activity, (ii) the age of the students, and (iii) the acoustic characteristics of the classroom.

2. Materials and methods

This study is part of the activities conducted within a national Italian research project (LearN: Learning in Noise), which focuses on the causal analysis of the relationship between the acquisition of reading and writing skills and both students' individual characteristics (e.g., cognitive skills, auditory sensitivity) and the acoustic features of the learning environment.

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the University of Padova (Italy). The study was preliminarily approved by the management of the five schools. The guardians of the children provided written informed consent for their children to participate.

2.1. Schools and classrooms

Five primary schools in Ferrara and Padova (Italy) were involved in the study, that was conducted during spring and autumn 2024. The schools belonged to distinct urban context (modern city and outskirts), even though they were all located far from main roads and surrounded by the schoolyard. The schools included students from diverse socio-economic backgrounds, ensuring a representative sample across different income levels and social contexts. Within each school, classes were recruited on a voluntary basis resulting in a total number of 26 classes distributed from grade II to V (age of the students: 7 to 11 years).

2.2. Acoustic measurements in unoccupied classrooms

In each classroom, acoustic measurements were performed in unoccupied conditions outside school hours, according to the Italian standard on classroom acoustics UNI 11532–2 [30] and the standard ISO 3382–2 [31]. The measurement chain consisted in a ½ inch microphone (B&K 4189), a signal conditioner (B&K Type 5935), a B&K Type 4231 calibrator, an RME Fireface UC full-duplex sound card, an omni-directional sound source (LookLine D303), and a laptop. Impulse responses were obtained with a sine-sweep technique and used to calculate reverberation time (T_{30}) and speech clarity (C_{50}) as the spatial average of the source-receiver combinations. The reverberation time measured in unoccupied conditions (two source positions X three receiver positions) was corrected to consider an 80 % occupancy and compared to the optimal range defined in the Italian standard [30], referring to category A3 (learning spaces with simultaneous and concurrent talkers). For the measure of speech clarity, one source positions was defined close to the desk or the whiteboard (where the teacher usually stands while doing lessons, at a height of 1.50 m), and four receivers (h = 1.20 m) were placed in the area where students sit. The background noise level (A-weighted equivalent level, L_{amb}) was measured with the door and the windows closed in the same four positions (2 min acquisition for each position).

Table 1 reports the acoustic parameters measured in the classrooms, obtained by calculating a single value for each position (frequency average — T_{30}: 0.5–1 kHz; C_{50}: 0.5–2 kHz) and arithmetically averaging the values at the four positions. Table 2 displays geometrical, acoustic and occupancy data pooled by grade. The results indicate that in 23 out of 26 classrooms, T_{30} was higher than the optimal value defined in the Italian standard [30] and higher than the reference interval defined in the frequency range 125–4000 Hz. The three classrooms complying with the standard belonged to the same school where all learning spaces were acoustically treated with a sound absorbing ceiling. Speech clarity was higher than the threshold value of 2 dB in 6 out of 26 classrooms, while ambient noise in unoccupied conditions (composed by sounds from the outdoors and the HVAC system) was lower than the reference value of

Table 1
Acoustic parameters measured in the unoccupied classrooms: background noise with windows closed (L_{amb}), reverberation time T_{30} (measured in unoccupied conditions, and estimated for 80 % occupancy), ratio between absorption area and volume in unoccupied conditions (A/V), and clarity C_{50}. The rightmost column indicates the number of students having lesson in the classroom.

School	Classroom	Grade	Volume [m^3]	L_{amb} dB(A)	T_{30} [s] unocc.	A/V [m^{-1}]	T30 [s] occ.	C_{50} (dB)	N students
A	A1	II	164	35.6	1.02	0.16	0.89	0.8	17
	A2	II	121	35.8	1.38	0.12	1.09	−0.7	17
	A3	II	175	35.4	1.37	0.12	1.12	−0.9	20
	A4	III	116	35.7	1.27	0.13	1.01	−0.8	17
	A5	III	116	35.1	1.39	0.12	1.06	0.1	18
	A6	IV	125	35.3	1.38	0.12	1.09	−0.9	18
	A7	IV	120	35.6	1.22	0.13	0.98	0.2	18
	A8	V	175	35.8	1.36	0.12	1.11	−1.0	21
	A9	V	127	35.4	1.14	0.14	0.91	0.3	21
B	B1	IV	110	32.3	0.54	0.30	0.48	7.5	16
	B2	IV	110	32.0	0.52	0.31	0.47	7.3	18
	B3	V	113	29.9	0.49	0.33	0.44	6.7	17
C	C1	III	121	30.2	0.99	0.16	0.87	0.9	15
	C2	IV	121	27.9	0.97	0.17	0.83	0.8	16
D	D1	II	185	44.2	1.02	0.16	0.92	1.3	14
	D2	III	124	47.5	0.77	0.21	0.67	4.2	17
	D3	III	130	44.5	1.04	0.15	0.89	0.0	16
	D4	IV	124	47.7	0.73	0.22	0.62	4.4	16
	D5	V	124	47.9	0.79	0.20	0.69	4.1	19
	D6	V	185	44.6	1.02	0.16	0.89	1.3	19
	D7	V	185	44.3	1.04	0.15	0.85	1.1	20
E	E1	III	140	25.7	1.00	0.16	0.84	1.5	20
	E2	III	137	25.4	1.32	0.12	1.05	−0.3	19
	E3	III	140	25.4	1.31	0.12	1.04	−0.4	20
	E4	V	140	25.2	1.29	0.12	0.99	−0.1	24
	E5	V	140	25.9	1.34	0.12	1.02	−1.3	25

Table 2
Mean values (and standard deviations) of the geometrical, acoustic and occupancy data pooled by grade: background noise in unoccupied conditions (L_{amb}), reverberation time T_{30} (estimated for 80 % occupancy), and clarity C_{50}.

Grade	# of classes	Volume [m^3]	N students	L_{amb} dB (A)	T_{30} [s] occ.	C_{50} (dB)
II	4	161 (28)	18 (2)	37.8 (4.3)	1.01 (0.12)	0.1 (1.1)
III	8	128 (10)	18 (2)	33.6 (8.8)	0.92 (0.14)	0.6 (1.6)
IV	6	118 (7)	16 (1)	35.1 (6.8)	0.76 (0.26)	3.2 (3.6)
V	8	149 (29)	21 (2)	36.1 (8.6)	0.86 (0.22)	1.4 (2.7)
Overall	26	137 (25)	18 (3)	35.3 (7.5)	0.88 (0.20)	1.4 (2.6)

38 dB(A) set by the Italian standard in 19 out of 26 classrooms. In the remaining seven classroom, the exceedance of the limit value was due to the noise generated by a radiator-based heating system, in operation both during the measurement phase and throughout the monitoring activities.

Fig. 1 reports the relationship between reverberation time in unoccupied conditions and speech clarity, compared to the theoretical one [32]. The small offset differences between the theoretical curve and the measured data can be attributed to the source directivity depending on the source position, which is primarily influenced by early reflections rather than late ones.

2.3. Sound level monitoring during lessons

Equivalent sound levels were monitored during one school day in each classroom, during regular lessons (5 to 8 h), using an approach intended to provide reliable results while minimising disruption to teaching.

Sound levels were measured using a sound level meter (DUO, 01 dB) located at one receiver position in the back of the classroom, close to the last row of desks, among the seated occupants of the classroom. The height was set at 1.20 m (height of the ears of a seated child). Data were sampled every 100 ms, to ensure acquisition of the pauses among syllables and words, in 1/3 octave bands [26]. Classroom observations were conducted during monitoring by a researcher, seated in the back of

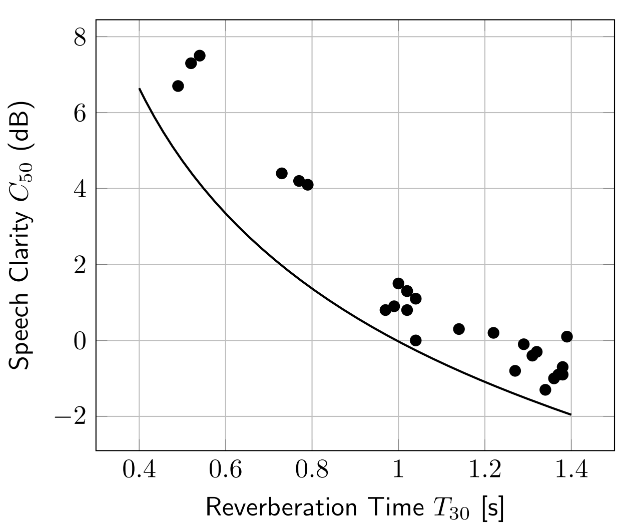

Fig. 1. Scatter plot showing the relationship between reverberation time T_{30} [s] and speech clarity C_{50} (dB). The data points indicate measured values in unoccupied conditions, while the dashed line represents the theoretical relationship [32].

the classroom, to note down the type of activity and unexpected or irrelevant sound events. Based on informal, unsystematic oral reports from the teachers, the presence of the researcher and the sound level meter in the classroom did not influence the behaviour of students or teachers, who acted as they would do during a typical school day.

Moreover, during the first hour of the day, the minutes during which attendance was taken, or lunch orders were requested—periods when the children were very quiet—were annotated. These minutes were used to calculate the 95th percentile of the recorded sound levels, which served as an estimate of the background noise in a moment when the classroom was occupied but the children were quiet and not engaged in any activity. The sound levels during these periods are henceforth referred to as *baseline noises*.

Finally, for comparison purposes with the study by Seitz and Fels [22] the breakfast break was considered as well. It should be noted that, in Italian primary schools, the break is generally spent inside the classroom for at least the first 10 min. During this period, students are allowed to move freely within the classroom and engage in social interactions while having their snack.

The recordings of each class were analysed and segmented according to the period and the teacher conducting the lesson. For each period, 20-min slots each characterized by the same activity were extracted for the subsequent analyses. The duration of the analysis slots was determined by two considerations. First, it was not possible to identify periods of homogeneous classroom activity longer than 20 min for second-grade classes, which constrained the maximum slot length. Second, based on pilot analyses, the distribution of sound levels for a given homogeneous activity stabilizes after at least 20 min, ensuring reliable results from the analysis algorithm. The selected slot duration thus balanced the practical limitations of classroom schedules with the need for stable acoustic measurements. It was often the case that the same type of activity was monitored in a class during the day, but with different teachers. In such instances, the results were kept separate. Indeed, the observations made during the monitoring sessions showed that the behaviour of a class could vary significantly depending on the teacher conducting the lesson.

Classroom activities were categorized based on the experimenter's in-class observations. Three types of activity were defined:

- L1: quiet work (children doing individual activities)
- L2: one person talking (teacher-led teaching, with interactions with the children, but always with one speaker at the time)
- L3: group work (children working in groups of two or three, with multiple talkers at the same time)

Table 3 reports the number of lessons monitored, by grade and type of activity. Notably, all teachers involved in the study were females.

2.4. Data analysis

Data for each lesson were analysed via Gaussian Mixture Modelling [33], a probabilistic algorithm that models a dataset as a combination of

Table 3
Number of monitored lessons (i.e., 20-minute slot of homogeneous activity) and number of classes, by grade and type of activity (L1: individual work, L2: teacher-led lesson, L3: group work).

Grade		Activity L1	Activity L2	Activity L3	Break
II	# lessons	5	4	10	4
	# classes	3	3	4	4
III	# lessons	3	21	5	8
	# classes	3	8	3	8
IV	# lessons	5	12	6	6
	# classes	4	6	3	6
V	# lessons	6	9	7	8
	# classes	5	6	4	8
Overall	# lessons	19	46	28	26

multiple Gaussian distributions, each of them identified by mean, variance and weight. In the context of classroom acoustics, the algorithm can be applied to the statistical distribution of measured A-weighted sound levels. The estimated underlying components can be interpreted as representing distinct sound sources, such as background noise, lecturer's speech and ventilation noise [10], or speech and non-speech sounds [19]. In this study the algorithm for the analysis of the logged sound levels was implemented in Matlab (v. 2024b), defining *a priori* two output distributions, corresponding to the contributions of speech and activity noise.

The analysis was conducted on the 93 monitored lessons, resulting in the construction of a dataset that, for each class and lesson, included equivalent A-weighted levels, speech and activity noise levels, their respective standard deviations, and component proportions (i.e., the prior probabilities associated with each Gaussian component in the mixture model, reflecting their relative contribution to the overall distribution).

Statistical analyses were conducted using R (version 4.4.2) and RStudio (version 2025.5.0.496). The *lme4* package (version 1.1.36) was used to fit linear mixed-effect effects models (LMMs), with a by-class random intercept included to account for potential differences across classes. Fixed factors included in the models were C_{50}, number of children in the classroom, grade, type of activity, and their two-way interaction. To understand which measure of reverberation better relate to the dependent variable, the base model was compared with three additional models, each incorporating one of the following variables: reverberation time under unoccupied conditions, reverberation time under occupied conditions, and the A/V ratio. The final model was identified as the one, among the three, minimizing the AIC metric. Post-hoc comparisons were carried out using the *emmeans* package (v1.10.7). For multiple comparisons, p-values were adjusted using the Bonferroni correction. To facilitate interpretation of continuous predictors, model coefficients were standardized (mean of 0 and standard deviation of 1) using the *parameters* package (v0.26.0).

3. Results

To investigate the sound environment in active classrooms, the monitored data were analysed in several steps. First, the relationship between sound levels in unoccupied conditions (as typically defined in standards) and those under quiet occupancy (baseline levels) was examined. Next, overall sound levels were analysed for comparison with published data. Finally, speech and activity noise levels were disentangled and analysed to evaluate the effects of grade, activity type, and classroom acoustics, as well as their relationship.

3.1. Baseline noise levels

A multi-linear regression model was set up, with baseline level as the dependent variable and including as independent factors: noise levels in unoccupied conditions (L_{amb}), reverberation (see Section 2.4), grade and number of children in the classroom. The analysis revealed that A/V had a significant positive effect on baseline noise levels ($F(1,19) = 138.3$, $p < 0.001$, $\beta = 0.79$, $SE = 0.16$), while none of the other predictors reached statistical significance (all $ps > 0.13$). The model explained a substantial portion of the variance, with an adjusted R^2 of 0.67.

On average, baseline noise levels were 44.6 dB(A) (SD = 3.7), compared to 35.3 dB(A) (SD = 7.6) under unoccupied conditions. When data from School E—where HVAC malfunctioning was identified—were excluded, the difference between baseline and ambient noise increased to 14.6 dB, with baseline noise averaging 44.6 dB(A) (SD = 4.2) and unoccupied levels dropping to 30.9 dB(A) (SD = 3.8).

3.2. Overall sound levels

Fig. 2 shows the equivalent, A-weighted sound levels measured in the active classrooms, by grade and type of activity. For comparison purposes, the baseline noise level (see Section 3.1) is displayed as well.

The results of the statistical analysis indicated that the type of activity had a significant main effect on the overall sound level ($\chi^2(3) = 104.2$, $p < 0.001$). Pairwise comparisons indicated that the sound level during breaks (M = 76.3 dB(A)) was significantly higher than during regular lessons. Moreover, the sound levels during quiet work (M = 65.6 dB(A)) were significantly lower than during teacher-led teaching (M = 68.9 dB(A), $t = -2.30$, $p = 0.028$), and group work (M = 67.9 dB(A), $t = -2.44$, $p = 0.025$). A/V also significantly affected sound level ($\chi^2(1) =$

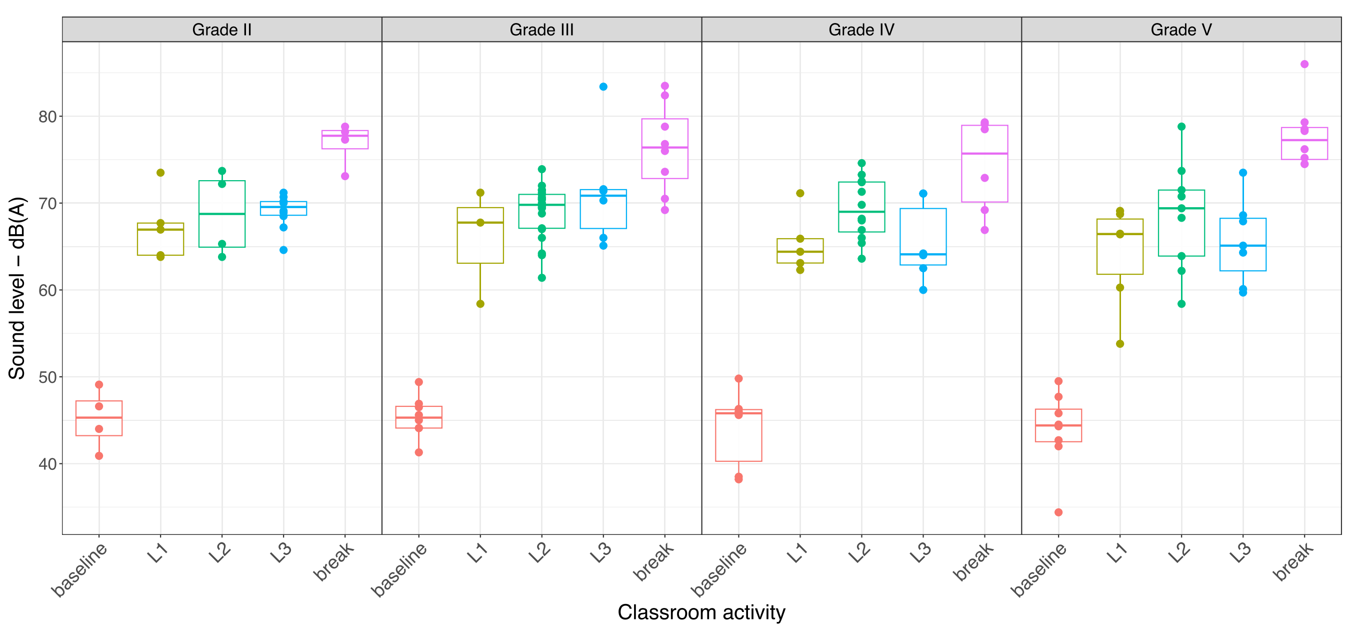

Fig. 2. Boxplots of the sound pressure levels measured in active classrooms, by grade and activity. Each point in the figure correspond to a 20-minute slot of activity in each class. The activity included in the graph are baseline (L_{95} in the occupied classroom, but when children were quiet and not engaged in any activity), L1 (quiet work), L2 (teacher-led lesson), L3 (group work), morning break.

6.6, $p = 0.01$, $\beta = -1.14$, SE = 0.44), with higher levels in classrooms with less absorption. None of the other predictors reached statistical significance (all *ps* > 0.07). The conditional R^2 of the model was 0.63.

3.3. Speech and activity noise levels

Fig. 3 displays three examples of the distribution of A-weighted equivalent sound levels, as identified through GMM analysis, monitored in the same classroom during distinct classroom activities. In all cases the calculated density function is skewed, suggesting that the sound level distribution can be split into two separate distributions, with the higher-level curve associated to the speech levels and the lower level associated to activity noise. The weight and relative location of the two sound sources appears to be modulated by the nature of the ongoing activity. As depicted in the three panels of Fig. 3, teacher-led activities yield a left-skewed distribution, with most occurrences corresponding to the teacher's speech (Fig. 3b). Conversely, during individual work, the distribution becomes right skewed, reflecting a predominance of events associated with student activity (Fig. 3a). It should be noted that, even during quiet individual work, the teacher continued speaking to monitor progress and to provide individual assistance to the students. For the third type of activity considered (group work, Fig. 3c), based on the observations conducted in class, the highest-level distribution was deemed to correspond to the students' speech (sometimes mixed with teacher's voice), while the lowest level was associated to the background noise in the classroom. The distribution of sound levels during this activity is generally left skewed, with a predominance of high-level sound events.

Fig. 4 summarizes the distribution of speech and activity noise levels in active classes across grades and type of activities, output by the GMM process.

3.3.1. Changes in activity noise levels

Activity noise level data from the GMM were analysed using a linear mixed-effects model (LMM), which included, in addition to the fixed factors described in Section 2.4, the baseline noise level as a covariate.

The results showed that baseline noise levels had a moderate positive effect on activity noise levels in occupied classrooms ($\chi^2(1) = 5.59$, $p = 0.019$, $\beta = 0.38$, SE = 0.16). In contrast, speech clarity showed a stronger negative effect, indicating that classrooms with higher C_{50} values experienced significantly lower activity noise levels ($\chi^2(1) = 6.15$, $p = 0.013$, $\beta = -1.01$, SE = 0.41). These relationships are displayed in Fig. 5. No other predictors or interaction terms showed significant effects (all *ps* > 0.052). The model's conditional R^2 was 0.47, indicating that it accounted for a moderate proportion of the variance in activity noise levels.

A linear mixed-effects model was then used to analyse the component proportion of the noise level distribution derived from the GMM. The results showed that the proportion of occurrences classified as activity noise was significantly influenced only by the type of activity ($\chi^2(2) = 11.17$, $p = 0.004$). Pairwise comparisons revealed that this proportion was significantly higher during activity L1 ($M = 0.40$) compared to L2 ($M = 0.25$, $t = 3.33$, $p = 0.004$) and L3 ($M = 0.30$, $t = 2.41$, $p = 0.027$). The model's conditional R^2 was 0.22, indicating a modest proportion of variance explained by the fixed and random effects.

3.3.2. Changes in speech levels

Statistical analysis revealed significant effects of grade level ($\chi^2(3) = 18.22$, $p < 0.001$), type of activity ($\chi^2(2) = 18.22$, $p = 0.03$), number of

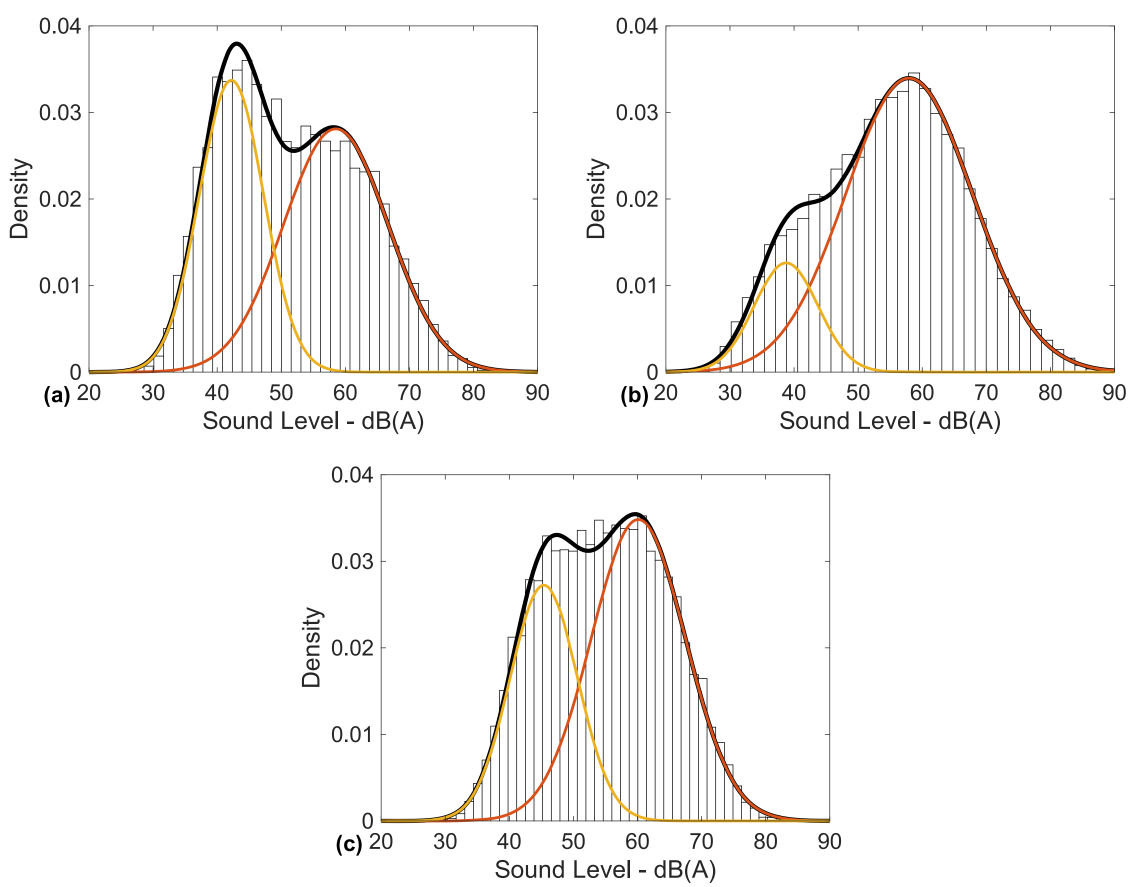

Fig. 3. Fitting of the two Gaussian curves to match the frequency distribution of sound levels at the microphone position in a grade IV class: (a) quiet work, (b) teacher-led lesson, (c) group work.

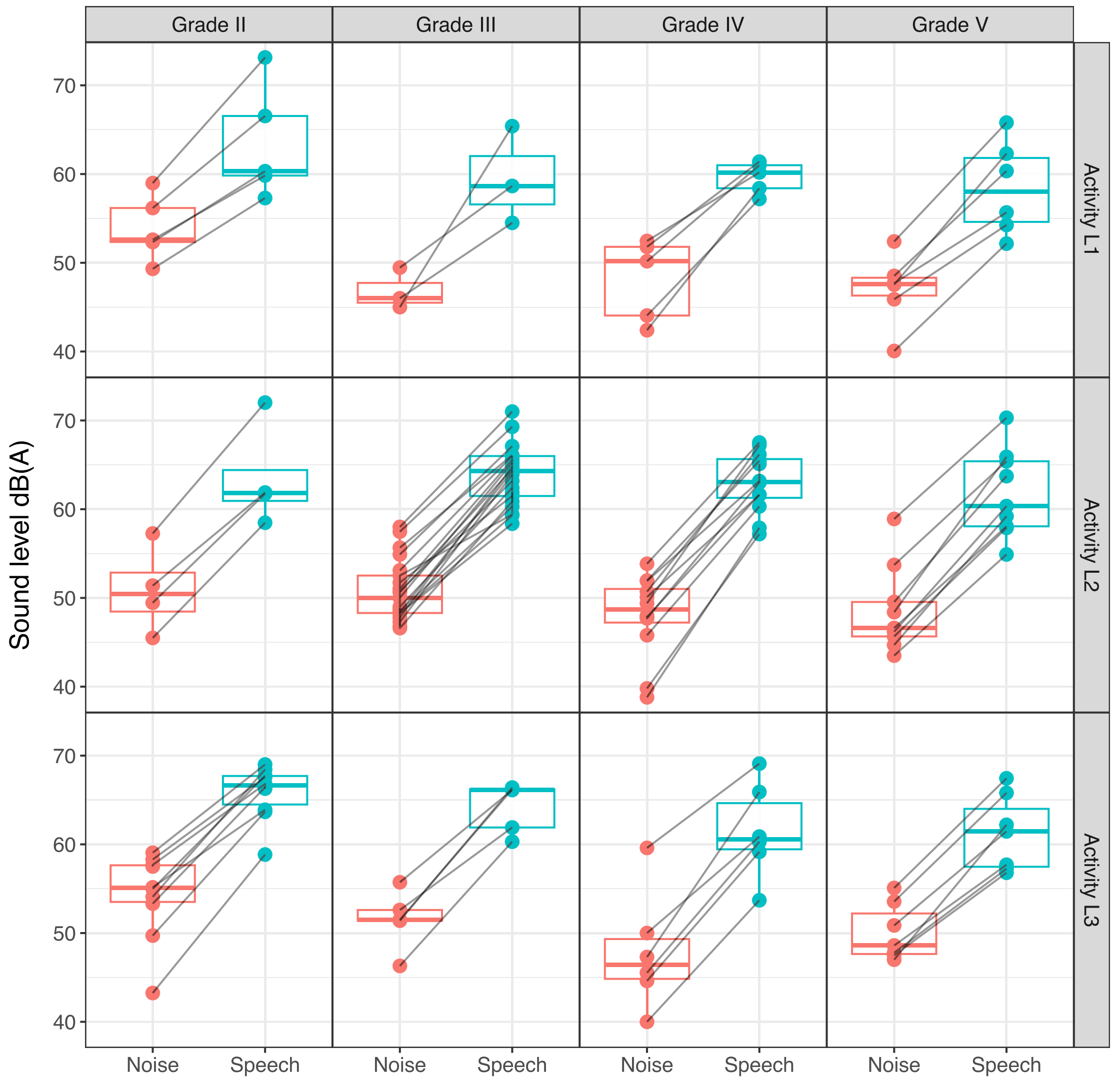

Fig. 4. Boxplots of speech and activity noise levels estimated using GMM analysis, stratified by grade level and activity type (L1: quiet work, L2: teacher-led lesson, L3: group work). Each data point represents a 20-minute activity slot within a classroom. Gray lines connect speech and activity noise levels measured within the same class.

children in the classroom ($\chi^2(1) = 8.6$, $p = 0.003$; $\beta = 0.37$, SE = 0.13), and C_{50} ($\chi^2(1) = 3.86$, $p = 0.049$; $\beta = -0.76$, SE = 0.38) on the speech levels measured in active classrooms. The conditional R^2 of the model was 0.44.

Pairwise comparisons showed that speech levels during quiet work (M = 60.2, SD = 5.0 dB(A)) were significantly lower than during teacher-led lessons (M = 63.2, SD = 3.9 dB(A); $t = -2.3$, $p = 0.048$) and group work (M = 63.5, SD = 4.3 dB(A); $t = -2.2$, $p = 0.048$). Additionally, speech levels were significantly higher in grades II (M = 64.7, SD = 4.6 dB(A)), III (M = 63.5, SD = 3.6 dB(A)), and IV (M = 61.9, SD = 3.9 dB(A)) compared to grade V (M = 60.7, SD = 4.8 dB(A)).

3.3.3. *Correlation between speech and activity noise levels*

The relationship between speech and activity noise levels, pooled across grades and types of activity (Fig. 6) was then examined, aiming to quantify the Lombard effect (i.e., the tendency for a speaker to raise his/her voice in the presence of background noise) with reference to the measurement position at the back of the classroom. A linear model was fit to the response variable, speech level, and the predictor, activity noise level. All measures were included in the linear model, despite the well-known effect typically emerging only above 45 dB(A) [34]. The slope of the relationship was 0.75, with an R^2 of 0.64, meaning that a 0.75 dB(A) increase in speech level was expected for every 1 dB increase in the activity noise.

Then, a linear mixed-effects model (LMM) was used to assess the influence of grade and activity type on the Lombard effect, with speech level as the dependent variable. Fixed effects included activity noise level, grade, activity type, and their two- and three-way interactions. Class was modelled as a random effect. The model indicated significant effects of activity noise levels ($\chi^2(1) = 185.9$, $p < 0.001$), type of activity ($\chi^2(2) = 15.52$, $p < 0.001$), and the three-way interaction between noise level, activity type, and grade ($\chi^2(6) = 27.2$, $p < 0.001$). The conditional R^2 of the model was 0.84.

We analysed the three-way interaction by fitting first four separate LMMs, one for each grade. Each model included active noise level, type of activity, and their interaction as explanatory variables. Then, three LMMs - one for each type of activity - were fitted with activity noise level, grade, and their interaction as explanatory variables. Model estimates with associated standard errors and p values are reported in Tables 4 and 5. For significant two-way interactions, differences in the slopes of the regression lines were examined using the function *lstrends* from the *emmeans* package. The results indicated that for activity L3,

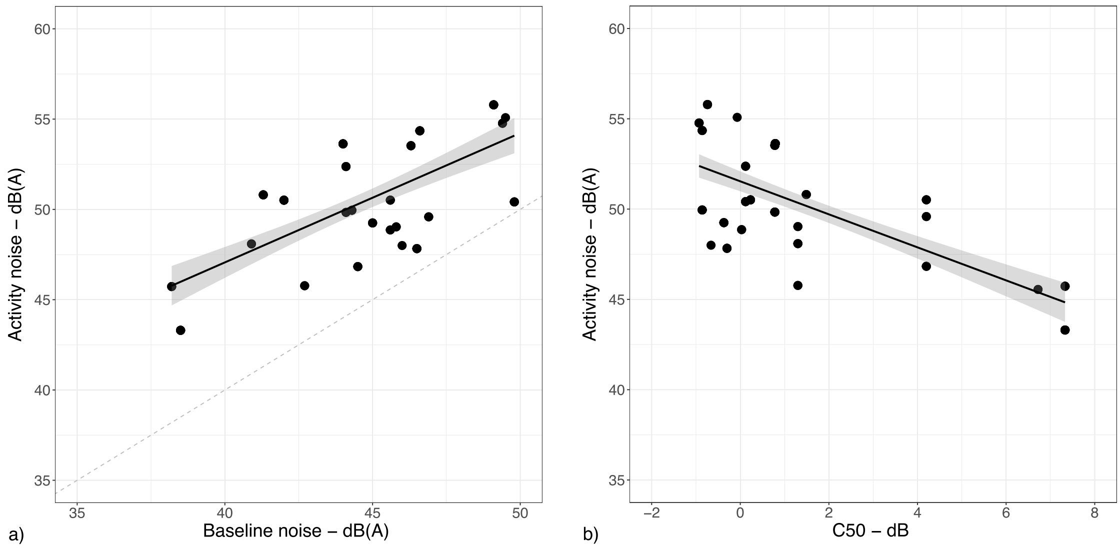

Fig. 5. Relationships between activity noise levels and (a) baseline noise, (b) speech clarity C_{50}. Each point represents the mean value of the activity noise levels monitored in a class during different activities.

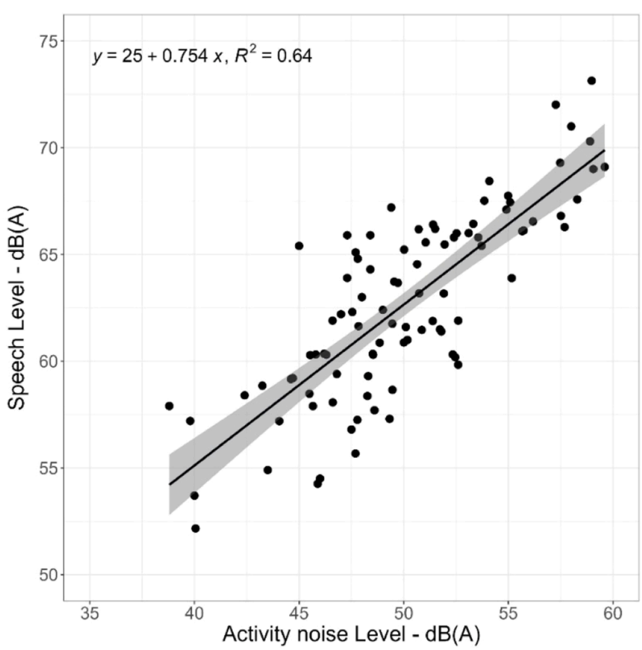

Fig. 6. Relationship between activity noise and speech levels [dB(A)] measured in classrooms. Each point represents an activity for a specific class. The solid line indicates the fitted linear regression, and the shaded area denotes the 95 % confidence interval.

there were no significant differences in the slope across grades (all *ps* > 0.11). In contrast, for activities L1 and L2, the slope was significantly higher for grade II compared to the other grades, which did not differ significantly from each other. Specifically, in L1, the estimated slopes were: grade II = 1.90 (SE = 0.03), grade IV = 0.62 (SE = 0.03), and grade *V* = 0.72 (SE = 0.04); and in L2: grade II = 1.30 (SE = 0.20), grade III = 0.72 (SE = 0.12), grade IV = 0.54 (SE = 0.14), and grade *V* = 0.81 (SE = 0.12).

Additionally, as showed in Fig. 7, within grade II the slope was significantly higher in L1 and L2 compared to L3 (L1 = 1.84, SE = 0.20; L2 = 1.40, SE = 0.19; L3 = 0.48, SE = 0.09). For grades III, IV, and V, the difference in slope between L1, L2 and L3 was not statistically significant.

Table 4
Output of the linear mixed-effects models for the four models with response variable Speech level, as a function of activity noise level (Lnoise) and type of activity (reference level: L1). For Grade III, the reference level was set to L2, as data from activity L1 were removed from the analysis.

Predictor	Estimate	St. error	t-value	*p* value
		Grade II		
(int.)	−35.28	9.93	−3.55	0.003**
Lnoise	1.84	0.18	10.04	< 0.001 ***
Activity [L2]	27.58	11.53	2.39	0.036 *
Activity [L3]	75.14	11.20	6.71	< 0.001 ***
Lnoise : Activity L2	−0.44	0.22	−2.00	0.07
Lnoise : Activity L3	−1.37	0.20	−6.70	< 0.001 ***
		Grade III		
(int.)	−2.0	10.89	−0.18	0.86
Lnoise	1.29	0.21	6.06	< 0.001***
Activity [L3]	41.95	12.13	3.46	0.007 **
Lnoise : Activity L3	−0.81	0.23	−3.47	0.007 **
		Grade IV		
(int.)	39.53	10.14	3.9	0.002 **
Lnoise	0.43	0.21	2.05	0.045 *
Activity [L2]	−5.69	10.67	−0.53	0.60
Activity [L3]	−15.44	10.75	−1.44	0.17
Lnoise : Activity L2	0.17	0.22	0.70	0.44
Lnoise : Activity L3	0.36	0.22	1.6	0.13
		Grade V		
(int.)	9.22	12.22	0.75	0.46
Lnoise	1.05	0.26	4.05	0.001 **
Activity [L2]	13.03	14.01	0.93	0.37
Activity [L3]	−3.98	19.54	−0.20	0.84
Lnoise : Activity L2	−0.24	0.30	−0.82	0.42
Lnoise : Activity L3	0.06	0.40	0.15	0.88

4. Discussion

4.1. *Effects of classroom activity type on sound levels*

4.1.1. *Changes in overall sound levels*

In line with previous research, we found that overall L_{Aeq} levels varied significantly depending on the type of classroom activity, with the highest values observed during group work and teacher-led instruction. These findings generally align with those reported in earlier studies, except for the "quiet work" activity, showing a wide range of measured sound levels across studies. This variability likely reflects differences in how "quiet work" was defined and interpreted. In some

Table 5
Output of the linear mixed-effects models for the three models with response variable Speech level as a function of activity noise level (Lnoise) and grade (reference level: grade II).

Predictor	Estimate	St. error	t-value	*p* value
		Activity L1		
(int.)	−39.51	2.22	7.45	< 0.001***
Lnoise	1.92	0.02	1.01	0.007 **
Grade [III]	136.93	45.96	10.00	0.014 *
Grade [IV]	69.27	3.06	6.20	< 0.001***
Grade [V]	63.28	3.11	4.80	< 0.001***
Lnoise : Grade III	−2.73	0.98	10.00	0.019 *
Lnoise : Grade IV	−1.30	0.04	1.01	0.017 *
Lnoise : Grade V	−1.20	0.04	1.02	0.021 *
		Activity L2		
(int.)	−1.40	11.59	−0.12	0.904
Lnoise	1.28	0.23	5.63	< 0.001***
Grade [III]	28.94	13.07	2.21	0.033 *
Grade [IV]	38.28	13.18	2.91	0.006 **
Grade [V]	23.71	12.97	1.83	0.076
Lnoise : Grade III	−0.56	0.26	−2.18	0.036 *
Lnoise : Grade IV	−0.74	0.26	−2.82	0.008 **
Lnoise : Grade V	−0.47	0.26	−1.84	0.074
		Activity L3		
(int.)	40.02	6.92	5.79	< 0.001***
Lnoise	0.48	0.12	3.83	0.003 **
Grade [III]	−21.23	18.66	−1.14	0.269
Grade [IV]	−19.31	10.83	−1.78	0.090
Grade [V]	−25.19	15.31	−1.65	0.116
Lnoise : Grade III	0.39	0.35	1.11	0.282
Lnoise : Grade IV	0.37	0.21	1.77	0.092
Lnoise : Grade V	0.45	0.30	1.53	0.144

cases, it may involve near-silence—such as during tests or brief periods of individual concentration—while in others, it may include considerable speech, primarily from teachers checking students' progress. Additional variability across studies could be attributed to differences in measurement methodologies, including the number and placement of microphones in the classroom, the duration of the monitoring period, and variations in teaching styles across countries [35]. Data from previous literature and the present findings are reported in Table 6 for direct comparison.

Unlike earlier studies [11,20], we found no significant difference in overall sound levels between teacher-led lessons and group work. This may be due to the way group work was organized—typically in pairs or small groups under close teacher supervision—to minimize noise and maintain acoustic control. However, while overall levels are similar, the interplay between sound sources differ markedly between the two activities. In teacher-led lessons, a single speaker—usually the teacher or a responding student—serves as the main signal for the entire class. In contrast, during group work, students attend to peers within their group amid multiple, simultaneous conversations [37]. A given voice may function as signal within one group and as background noise for others. Similarly, the teacher's voice, when addressing a single group, may act as a signal for that group but a source of noise for others. As such, it becomes challenging interpreting SNR values during group activities, as the same sound can be both signal and noise, depending on the listener's perspective. It can be speculated that the overall level represents a source of disturbance for students engaged in group work.

During breakfast break, classroom sound levels averaged 76.3 dB(A), higher than the 69.3 dB(A) observed in similar German classrooms [22]. While some increase in noise during break compared to regular teaching

Table 6
- Comparison of overall A-weighted sound levels [dB(A)] recorded in various primary school classrooms during different activities.

Study	Type of activity			Measurement time	Country
	Quiet work	Teacher-led lesson	Group work		
Present study	65.6	68.9	67.9	20 min	Italy
Ref [36]	50.1		67.7	3 min	Italy
Ref [20] (Enclosed classrooms)*	63.8		66.7	10 to 95 min	Finland
Ref [21] (Reference classroom)	52.7	52.5	58.8	30 min	Finland
Ref [22]	55.5	65.1	67.4	15 min	Germany
Ref [11]**	64.7	61.2	72.9	2 min	UK

* Activities were coded as "Calm" or "Lively.".
** Correspond respectively to "Activity 3 – Individual work", "Activity 2 – 1 person speaking", and "Activity 5 – Group work.".

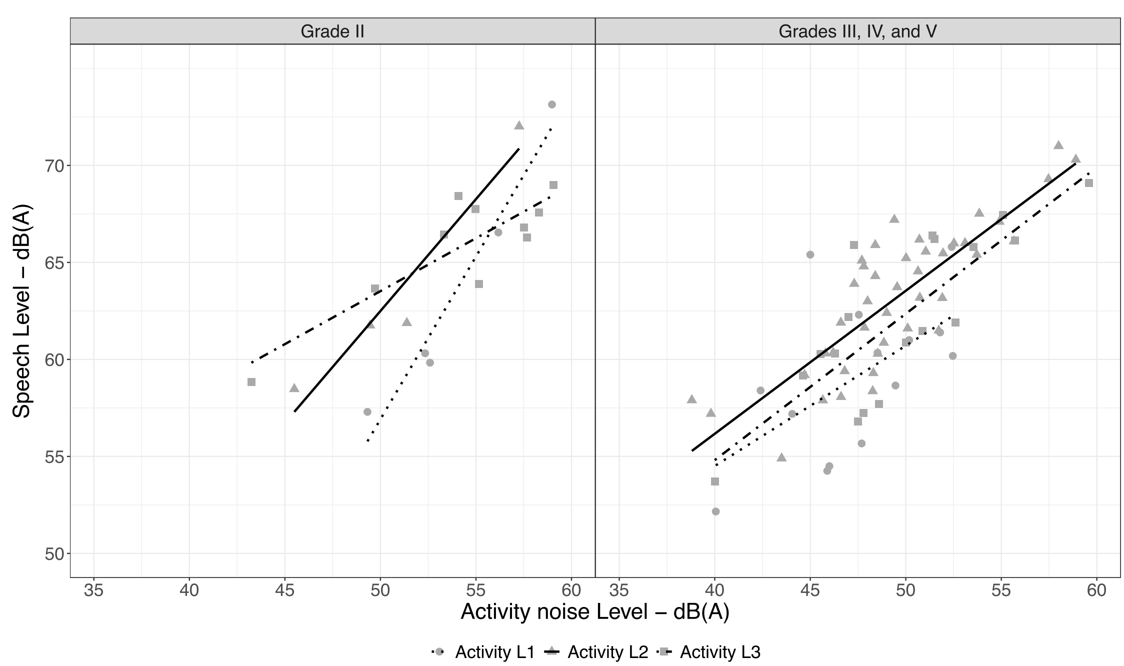

Fig. 7. Relationship between activity noise and speech levels [dB(A)] measured in classrooms, stratified by type of activity and grade.

periods is expected due to the unstructured and socially interactive nature of the former—which promote and support communication and cooperative behaviour—excessive levels may compromise its restorative purpose [38]. Indeed, the breakfast break is intended to facilitate cognitive, social, and emotional recovery, all of which are essential for effective learning and readiness for subsequent instruction [39]. Excessive noise can hinder meaningful conversation, leave some students isolated, and reduce opportunities for self-regulation [40]. The elevated noise levels observed during breakfast breaks reflect similar issues reported during lunch breaks, where high background noise is also common [41].

4.1.2. Patterns of activity noise and influencing factors

When disentangling overall sound levels into their components, average activity noise was estimated at 50 dB(A) (SD = 4.6 dB), which is consistent with the results of Sato and Bradley (49.1 dB(A); [17]), lower than values reported by Choi (55.5 dB(A); [25]) and slightly higher than the values of non-speech sounds reported by Wang and Brill (47 dB(A); [19]).

We found that activity noise was positively associated with the baseline noise level (see Section 4.2) but not significantly affected by the number of students in the classroom. The latter result contrasts with findings from other studies [11,42] though the lack of association may stem from the limited range in class size in our sample, which varied only between 14 and 25 students.

Moreover, we found no significant differences in activity noise levels across activity types, which may be partly explained by the large variability observed within each activity type (Fig. 4). This variability likely stems from a combination of classroom acoustics and class-specific behavioural dynamics [43]. For example, even within the same class and activity, noise levels can vary depending on the lesson topic [24], the teacher's classroom management style [44], and student engagement [45].

Finally, it is worth noticing that the average noise level of 50 dB(A) monitored in Italian (un-refurbished) primary schools is close to the critical threshold identified by Shield and Dockrell [5] above which students show reduced academic performance in literacy and numeracy tasks.

4.1.3. Speech levels and implications for teachers

Unlike activity noise, speech levels were significantly affected by class size, supporting existing evidence that speakers raise their vocal effort in larger groups and larger spaces [46]. We also found a significant effect of the activity type, with speech levels that were lower during quiet work and higher during more collaborative activities. Speech levels ranged from 60 to 63.5 dB(A), consistently with the finding of Sato and Bradley (60.1 dB(A); [17]). However, the speech levels were lower than those found by Wang and Brill (66 dB(A); [19]) and Choi (69.3 dB (A); [25]).

For activity type L2 (one person speaking)—the only one suitable for a meaningful SNR analysis—SNR values ranged from 10 to 19 dB, with an overall mean of +13.6 dB. Mean SNRs by grade were: 12.6 dB (SD 1.8) in Grade II, 13.1 dB (SD 2.1) in Grade III, 15.0 dB (SD 2.5) in Grade IV, and 13.2 dB (SD 2.1) in Grade V. The proportion of measurements exceeding the recommended SNR threshold of +15 dB [47] was 0 % (Grade II), 24 % (Grade III), 42 % (Grade IV), and 11 % (Grade V), indicating that in at least one-third of classrooms, the optimal SNR for normal-hearing students was not met. It is noteworthy that in Grade II classrooms—where students are more vulnerable to the negative effects of noise due to their young age—the optimal SNR was never reached.

Evidence of the Lombard effect was also observed in this study (Fig. 6), with a slope of $c = 0.7\ \mathrm{dB_{voice\ level}/dB_{noise}}$, consistent with findings from other research in primary school settings [17,48]. The influence of classroom noise on voice production is reknown and it is also identified as a major occupational risk factor for voice disorders among teachers [44]. Another critical, though under-researched aspect is the relationship between noise in the classroom and teacher performance, particularly regarding classroom management [49]. The L3 framework [23] highlights classroom management as essential for maximizing learning time, minimizing disruptions, and improving student outcomes. However, activity noise can hinder a teacher's ability to monitor the classroom effectively. It may cause teachers to make quicker, less informed judgments, overlook individual student cues, or interpret the noise as a sign of off-task behaviour—leading to more frequent interventions or overly critical evaluations of student work. These findings underscore the need for an integrated approach that considers the interplay between activity noise, teacher vocal load, and classroom management—factors that are deeply interconnected and collectively impact both teaching effectiveness and student learning outcomes.

4.2. Effects of acoustic parameters on sound levels

Four of the five Italian schools included in this study do not meet current acoustic standards, which were not mandatory at the time of their construction nearly 50 years ago. Moreover, although some classrooms were acoustically treated to improve acoustic comfort, no interventions were made to improve the sound insulation of horizontal or vertical partitions, including those adjoining corridors. As such, they are representative not only of the existing Italian school building stock but also of typical international scenarios, which often consist of outdated school facilities designed without specific acoustic regulations. Despite this, these buildings remain in active use, hosting increasingly diverse, multiethnic, and inclusive student populations.

Most classrooms met normative limits for background noise in unoccupied conditions, largely due to their location in quiet urban areas and the presence of surrounding green courtyards. However, during school hours, the presence of occupants alone—regardless of ongoing activities—increased noise levels by approximately 9 dB. The lack of significant association between ambient and baseline noise suggests that baseline levels were primarily influenced by sounds originating from adjacent indoor spaces rather than from outdoors or from mechanical/electronic equipment. This is consistent with previous findings indicating that indoor noise in active classrooms is mainly affected by external sources only during silent activities [11], and that in buildings with poor sound insulation, noise from corridors significantly contributes to classroom sound levels [25]. Further, in active conditions levels raised of an additional 5 dB due to student activity, bringing typical noise levels to around 50 dB(A), with a significant positive association between baseline levels and in-class activity [17]. Overall, our results suggest that beside controlling ambient noise levels and façade insulation, for good acoustics in active conditions it is crucial to ensure an adequate sound insulation of internal partitions. Although regulations often emphasize insulation between learning spaces, attention should be paid also to transitional zones (e.g., corridors, hallways), reflecting the fact that – in the design of increasingly flexible learning spaces [50] - these spaces are frequently used not only as transit zones, but also as informal learning spaces for small groups.

Speech levels and activity noise exhibited a positive correlation with the clarity index (C_{50}) but showed no significant association with reverberation time (T_{30}), which was instead related to overall levels. These results partially align with previous studies, which have reported weak correlations between speech or noise levels and both T_{30} and C_{50} [17,36], as well as relationships between occupied reverberation time, noise levels, and SNR [25]. In contrast, Wang and Brill [19] did not observe such associations in their large-scale survey of primary school classrooms. The relationship observed between student activity noise and C_{50} is of particular significance, as it suggests that such noise is primarily governed by direct sound and early reflections rather than by late reverberant energy. This reflects the typical spatial arrangement of classrooms, in which students—the principal source of activity noise—are located in close proximity to one another, thereby increasing the relative contribution of early sound components. As a result, conventional acoustic treatments that focus predominantly on reducing late reflections may be insufficient for mitigating activity noise. These findings underscore the importance of addressing early reflections alongside late ones, for example through the targeted placement of absorptive materials, to enhance speech clarity even when T_{30} values are similar across classrooms. Such measures could contribute to reducing activity noise and improving the acoustic environment for both teaching and learning.

4.3. Effects of students' age on sound levels

Concerning the effect of children's age on the sound environment in active classrooms, our findings indicate that age-related differences were observed only in speech levels, which decreased steadily from Grade II to Grade V (64.7 to 60.7 dB(A)), while overall levels and activity noise remained unaffected.

Picard and Bradley [16], in their review of published data on school noise levels, reported a general decline in overall classroom noise as student age increased, from kindergarten through university. However, within the primary school age range (6–12 years), findings are inconsistent, with some studies reporting decreases in background noise with increasing grade [19,24], while others finding unchanged levels across grades [11,17,22]

The decrease in speech level with increasing age of the students is also reflected by the significant relationship between speech levels and activity noise. The modulation of the speech levels happens partly automatically, through the Lombard effect [51], and partly through deliberate adjustments aimed at maintaining effective and fluent communication [52]. Notably, we found age-related variations in the slope of the relationship, with Grade II students exhibiting a significantly steeper relationship during more structured activities, such as quiet work and teacher-led lessons. In contrast, no grade-related differences were detected in the slope during group work, suggesting that short-distance peer communication patterns are already well-established by Grade II. These findings imply that managing structured tasks still demands more vocal effort and adaptive strategies from teachers of younger students, who are more susceptible to noise-related distractions.

4.4. Monitoring the sound environment in active classrooms: an open challenge

Disentangling the two sources of speech and activity noise in primary school classrooms is particularly challenging due to the dynamic nature of sounds arising from speech, movement, and student interaction, which often overlap with the teacher's voice. Interactive and participatory teaching methods further increase this overlap. Among source segregation approaches, blind segmentation methods—such as Gaussian Mixture Models (GMM) and K-means (KM)—have shown promise, even though some limitations were identified already in the initial applications [10]. Similar challenges were encountered in our study and of 120 recorded teaching periods, only 93 (77 %) were retained for analysis. The remaining 23 % were excluded due to two main reasons.

Firstly, the lack of a continuous, homogeneous activity lasting at least 20 min. This is a common feature of primary education, where teaching formats often change multiple times within a single lesson. These frequent shifts—particularly prevalent in lower grades—make supervised monitoring essential for accurately identifying activity types in the classroom. Although this approach is time-consuming, it allows for precise classification of activities, which cannot be achieved using teacher logbooks alone. Unsupervised methods such as KM can detect broad patterns (e.g., speech vs. non-speech, occupancy) but, without contextual information, cannot reliably differentiate between specific instructional formats.

Secondly, the presence of highly interactive lessons (e.g., school play rehearsals, music lessons) that often yield a unimodal sound level distribution—confirmed via visual inspection and the Shapiro–Wilk test—and prevent meaningful component separation. This highlights a limitation of GMM under low SNR conditions, as the method performs poorly when SNR falls below approximately 5–6 dB. Consequently, such highly participatory, low-SNR lessons may be systematically excluded from analysis, potentially biasing estimates of classroom acoustic conditions.

Finally, it is acknowledged that the present study did not employ a statistically designed experimental framework, limiting the possibility of identifying potential interaction effects among the many acoustic and contextual factors influencing classroom sound environments. However, given the in-situ nature of the research and the dynamic, variable conditions of real teaching activities, it was not feasible to control all parameters simultaneously. Future studies should adopt controlled or multivariate experimental designs to further investigate such interaction effects under more controlled conditions.

5. Conclusions

This study examined the acoustic environment of 26 primary school classrooms during lessons, disentangling speech and activity noise contributions using Gaussian Mixture Models (GMM). Ninety-three periods of homogeneous activities were analysed across grades II–V, investigating the influence of activity type, student age, and classroom acoustic characteristics.

Results confirmed that activity type is a primary factor of acoustic variability, with the highest overall levels observed during teacher-led lessons and group work, and the lowest during quiet work. Activity noise averaged 50 dB(A) regardless of activity type, with a large variability likely stemming from class-specific behavioural dynamics, whereas speech levels were higher in more interactive settings.

Student age affected speech levels in active classrooms, with a nearly 5 dB reduction from Grade II to Grade V, and, together with activity type, shaped the speech–noise relationship. Younger students showed a steeper slope in structured activities, suggesting that lower grades place greater vocal demands and noise-control needs on teachers.

Regarding classroom noise levels, we found that moving from unoccupied to baseline conditions—defined as occupied classrooms without any ongoing activity—resulted in an average increase of 10 dB. A significant correlation was also observed between activity noise and baseline noise, with classroom activities producing an additional rise of more than 5 dB above the baseline. Additionally, classrooms with better speech clarity exhibited lower activity noise, underscoring the role of early reflections management in reducing noise from student movement and interaction.

Overall, our findings indicate that classroom acoustics remain an undervalued aspect of school design, with current conditions often inadequate for speech communication, particularly for younger children. Greater emphasis should be placed on acoustic ergonomics in both new construction and refurbishment projects, ideally through multiprofessional collaboration that incorporates expertise from acoustics and pedagogy to meet the evolving needs of modern classrooms.

CRediT authorship contribution statement

Chiara Visentin: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicola Prodi:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nicola Prodi reports financial support was provided by Italian Ministry

of University and Research (MUR). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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