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Evaluating Acoustic Comfort in Classrooms equipped with Controlled Mechanical Ventilation: a combined Objective and Subjective Approach

Elisa Di Giuseppe[1], Gianluca Coccia[2], Valter Lori[2], Fabio Serpilli[2], Agnese Ferrini[1*], Marta Maria Sesana[3], Andrea Giovanni Mainini[4]

[1]Department of Civil, Building and Architectural Engineering (DICEA), Università Politecnica delle Marche, Ancona, Italy
[2]Department of Industrial Engineering and Mathematical Sciences (DIISM), Università Politecnica delle Marche, Ancona, Italy
[3]Department of Civil, Architectural, Environmental and Mathematical Engineering (DICATAM), Università degli Studi di Brescia, Brescia, Italy
[4]Department of Architecture, Built Environment and Construction Engineering (DABC), Politecnico di Milano, Milano, Italy

[*]E-mail: a.ferrini@staff.univpm.it

Abstract. In recent years, increasing attention has been devoted to the acoustic quality of learning environments, as room acoustics significantly influence students' concentration, speech intelligibility, and well-being. Concurrently, the growing implementation of Controlled Mechanical Ventilation (CMV) systems in school buildings to ensure proper air exchange and indoor air quality raises concerns about potential noise emissions and their impact on acoustic comfort. Although classroom acoustics are extensively investigated, research addressing the combined assessment of acoustic parameters and perceived comfort in classrooms equipped with CMV systems remain limited. This study presents preliminary results of an in-field acoustic campaign conducted in a Primary School recently retrofitted with a CMV system. The investigation covered two classrooms, representing different spatial configurations and occupancy conditions. Acoustic measurements were performed in accordance with UNI 11532-2:2020. Continuous Equivalent Sound Pressure Level (L_{eq}), Reverberation Time (RT), Speech Clarity (C_{50}), and Speech Transmission Index (STI). Subjective perception of acoustic comfort was assessed through questionnaires distributed in multiple scenarios including different seasons and operativity of the CMV. The integrated analysis enabled direct comparison between measured acoustic performance and users' perceptions, providing insight into the impact of CMV activation on acoustic quality and potential trade-offs between improved air quality and acoustic performance.

1. Introduction

The Indoor Environmental Quality (IEQ) within educational facilities has been globally recognized as a critical determinant of well-being, health, and academic success [1]. Students typically spend a significant portion of their life inside schools buildings, making the assurance of

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a healthy and comfortable internal environment a priority [2]. Poor IEQ, encompassing inadequate thermal, visual, acoustic, or air quality conditions, has been strongly correlated with negative consequences such as reduced attention spans, increased lethargy, fatigue, absenteeism, and a decline in cognitive performance [1,3]. Specifically, issues related to Indoor Air Quality (IAQ) often manifest through elevated concentrations of indoor pollutants in occupied, inadequately ventilated, classrooms, are particularly linked to loss of concentration among students [4,5]. The imperative for robust classroom ventilation has been even amplified in recent years, following the Covid-19 pandemic, which underscored the substantial risk of airborne pathogen transmission in densely occupied indoor settings.

This renewed focus on air exchange, essential for mitigating health risks, simultaneously highlights fundamental and often conflicting constraints inherent in achieving overall optimal IEQ. A critical conflict arises in the trade-off between maximizing IAQ through ventilation and maintaining thermal comfort, especially across seasonal changes. Natural ventilation, commonly employed in older school buildings, typically relies on occupant-controlled window operation. However, during cold periods, occupants often keep windows closed to avoid cold air or drafts, which inevitably results in high indoor pollutant accumulation [6].

In response to these challenges and the growing public demand for reliable IAQ, controlled mechanical ventilation (CMV) systems, and especially decentralized units installed in existing buildings, have emerged as a highly effective intervention [6]. However, these systems present a distinct trade-off: mitigating air quality issues may introduce acoustic discomfort risks [7], related to CMV background noise, which may significantly impair children's concentration, learning performance, and overall cognitive abilities [8]. This noise pollution can offset the cognitive benefits gained from enhanced IAQ, creating a new layer of complexity in IEQ assessments. Consequently, an evaluation focusing solely on IAQ and thermal comfort ignores another critical factor of the learning environment.

From a design perspective, CMV systems in classrooms must comply with strict noise limits to avoid interference with teaching activities. The Italian standard UNI 11532-2 [9] sets a maximum continuous sound pressure level of 35 dB(A) for HVAC systems to ensure speech intelligibility and acoustic comfort. Achieving this threshold while delivering the required airflow rates is technically challenging, particularly in retrofit contexts, where spatial constraints often prevent the installation of large ducts or effective sound attenuators needed to reduce air velocity and aerodynamic noise. The issue is more critical for decentralized CMV units, as the noise source is located within the classroom and does not benefit from the attenuation provided by extended ductwork in centralized systems. Economic considerations further affect equipment selection, frequently favoring standard units that may not adequately balance ventilation performance and acoustic requirements under real operating conditions. Additionally, CMV systems are often sized solely to meet maximum airflow and CO_2 dilution targets, without verifying acoustic performance at the corresponding operating points. These challenges highlight the need for standardized design guidelines to simultaneously optimize indoor air quality and acoustic comfort in educational environments. Despite the clear and urgent need for integrated IAQ and acoustic assessments in CMV-equipped schools, this combined area remains mostly underinvestigated in the literature. Existing IEQ research frequently focus on individual components or prioritizes thermal and air quality over acoustic comfort in composite assessments [10,11]. Furthermore, comprehensive evaluations combining objective noise measurements with subjective student perception surveys within the context of CMV systems are scarce.

This paper addresses this gap by presenting the preliminary findings of an integrated assessment combining objective acoustic measurements and subjective evaluations of perceived comfort in a Primary School recently retrofitted with a CMV system. The study offers novel insights into how different ventilation operating modes and seasonal conditions influence both acoustic performance and users' experience, contributing to the ongoing debate on potential trade-offs between improved indoor air quality and acoustic well-being.

2. Methodology

This work reports on the acoustic characterization activities carried out in September 2025, as well as the acoustic comfort surveys conducted in two classrooms in two distinct conditions: in September 2025, during a very hot day with the CMV system switched off, and in November 2025, on a very cold day with the CMV system operating.

2.1 The school case study

The case study is a Primary School located in Central-Eastern Italy (1789 heating degree days, Italian climate zone D), built between 1976 and 1992. The school complex (**Figure 1**) has a total floor area of 5138 m^2 and accommodates approximately 84 students and 15 staff members between 8:30 and 16:30 from Monday to Friday. The first monitored classroom (E) is facing South, has a volume of about 123 m^3 and typically hosts 21 children and 1 or 2 teachers. The second monitored classroom (B) is facing West, has a volume of about 138 m^3 and hosts 15 children and 1 or 2 teachers. All classrooms are equipped with decentralized CMV units with heat recovery, installed during the COVID-19 pandemic to enhance IAQ. Each unit operates independently and is controlled through a remote control panel allowing teaching staff to adjust activation and operating modes, which include three speed levels: minimum (V1: 165 m^3/h, sound pressure 33 dB(A) at 3 m), medium (V2: 355 m^3/h, sound pressure 36 dB(A) at 3 m) and maximum speed (V3: 620 m^3/h, sound pressure 41 dB(A) at 3 m). For this case study, only the off, V1, and V3 operating modes are considered.

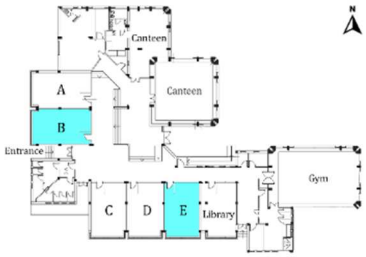


Figure 1. School case study general plan. Monitored classrooms "B" and "E" are indicated in light blue.

2.2 Acoustic measurements

The acoustic characterization was carried out according to the Italian standard for school buildings UNI 11532-2 [9], and to international standards CEI EN 60268-16 [12] and ISO 3382-2 [13]. The primary objective was to assess the existing acoustic quality against recommended performance criteria, essential for optimizing speech intelligibility and overall comfort for students and teaching staff.

The following indicators were then considered for the two classrooms in unoccupied conditions: Continuous Equivalent Sound Pressure Level (L_{eq}), Reverberation Time (RT), Speech Clarity (C_{50}), and Speech Transmission Index (STI). Measurements of RT, C_{50} and STI were carried

out using a dodecahedron and a half-inch microphone. Impulse responses were acquired with the ESS technique by Dirac V6. The dodecahedron was placed 1.5 m above the floor, while the receiver was positioned 1.2 m above the floor in 4 different positions, according to standard UNI 11532-2. *RT* and C_{50} were determined with the CMV off, while *STI* was also evaluated with the CMV on (V1 and V3). Measurement of L_{eq} were done using a B&K 2250 sound level meter. The L_{eq} was evaluated in terms of corrected noise level emitted by continuously operating systems (L_{iC}), which is a fundamental acoustic parameter for assessing the impact of the noise of technological systems (such as ventilation, air conditioning, pumps, elevators, etc.) within an environment. The methodology for its assessment, adapted in the context of the UNI 11532-2, aims to normalize the measured noise level with respect to the existing background noise and the acoustic conditions (reverberation) of the receiving environment. The L_{iC} was therefore calculated on-site (with the CMV system active, at V1 and V3 conditions) considering two corrections (K_1 and K_2). The first correction K_1 allows to subtract the contribution of pre-existing background noise from the total measurement. Without this correction, L_{iC} would be overestimated if the background noise is significant. The second correction K_2 normalizes the measured noise level with respect to a reference reverberation time, eliminating the influence of the acoustic characteristics of the receiving room.

2.3 IAQ measurements

The school building is equipped with an IEQ continuous monitoring system based on wall-mounted sensors, detecting CO_2 concentration (measurement range: 400 – 10000 ppm; resolution: 1 ppm; accuracy: ±30 ppm/±3 % of reading), indoor air temperature (measurement range: 0 - 50 °C; resolution: 0.1 °C; accuracy: ±0.2 °C), relative humidity (measurement range: 0 – 85 %; resolution: 0.1%; accuracy: ± 2 %), and illuminance (measurement range: 0 – 2000 lx; resolution: 1 lx; accuracy: ± 10 lx). Occupants' operations on windows and doors are measured by magnetic sensors mounted on frames. All the sensors register data with a 10-minute sample interval. To determine the on/off status of CMV units, smart meters are installed at the power outlet of each device, registering data with a 1-hour sample interval. The outdoor weather conditions are recorded with a 1-hour sample interval by a public weather station located on the school street.

2.4 Comfort Surveys

Perceived acoustic comfort in the classrooms was assessed through structured questionnaires specifically designed for pupils aged 9–11 years, considering their cognitive and linguistic abilities [14,15]. The 36 students completed the questionnaire several times on the same day to capture morning and afternoon scenarios. The acoustic comfort questionnaire consisted of four items addressing sound perception, noise-related discomfort, sound preference and sound acceptance.

3. Results

3.1 Acoustic Measurements

According to the standard UNI 11532-2 [9], the optimal value of *RT* for the two classrooms, evaluated as mean value of the octave band range 125-4000 Hz on the 30 dB decay of the sound decay curve, should be equal to approximately 0.5 s. The acceptance range and the measured values, for each octave band, are provided in **Table 1** It can be noted that the measured *RT* is always above the upper limit of acceptance, indicating that the two rooms are too much reverberant. **Table 1** also reports the values determined for C_{50}. Based on the UNI 11532-2 [9], for volumes smaller than 250 m^3 its value should be greater than or equal to 2 dB.

According to the CEI EN 60268-16 [12], the *STI* can be considered "good" if higher than 0.60. The UNI 11532-2 [9] specifies that, in absence of an amplification system and for volumes smaller than 250 m³, the *STI* should be higher than 0.55. **Table 2** provides the results of measured *STI* with different CMV activation conditions, which are always lower than the suggested ones, indicating that the global evaluation can be considered "fair" (and "poor" for Room B with the CMV system operating at maximum velocity V3, as *STI* is even lower than 0.45). The L_{iC} for the two classrooms is provided in **Table 3**. Based on current Italian legislation [16,17], in classrooms with a volume smaller than or equal to 250 m³, the L_{iC} should be smaller than or equal to 34 dB(A). This means that the noise level of the actual CMV system in the school can be considered acceptable at the minimum velocity (V1), while it is not acceptable at the maximum velocity (V3).

Table 1. *RT* and C_{50} of the two classrooms (CMV system off).

	Room E				Room B			
f (hz)	Acceptance range (s)	Mean absorption area (m²)	Measured *RT* (s)	C_{50} (dB)	Acceptance range (s)	Mean absorption area (m²)	Measured *RT* (s)	C_{50} (dB)
125	0.32 – 0.72	16.3	1.21	0.77	0.33 – 0.75	13.2	1.68	-4.41
250	0.40 – 0.60	19.4	1.01	-1.09	0.41 – 0.62	16.6	1.33	-1.03
500	0.40 – 0.60	23.3	0.85	0.31	0.41 – 0.62	18.7	1.18	-2.07
1000	0.40 – 0.60	24.9	0.79	-0.12	0.41 – 0.62	19.8	1.12	-1.16
2000	0.40 – 0.60	26.9	0.73	-0.14	0.41 – 0.62	22.4	0.98	-1.30
4000	0.32 – 0.60	28.0	0.70	-0.03	0.33 – 0.62	24.1	0.91	-0.34
Mean (500-1000-2000 Hz)				-1.0				-2.5

The underlined values do not comply with the current regulation.

Table 2. Speech transmission index *STI* of the two classrooms.

CMV system	Room E - *STI*	Room B - *STI*
Off	0.51	0.47
V1 min (165 m³/h)	0.51	0.46
V3 max (620 m³/h)	0.49	0.43

The underlined values do not comply with the current regulation.

Table 3. Corrected noise level emitted by continuously operating systems (L_{iC}) and background noise (L_{eq}) for the two classrooms.

	Room E			Room B		
f (hz)	L_{eq} (CMV off, dB)	L_{eq} (V1 min, dB)	L_{eq} (V3 max, dB)	L_{eq} (CMV off, dB)	L_{eq} (V1 min, dB)	L_{eq} (V3 max, dB)
125	30.86	38.7	49.5	32.19	38.9	49.1
250	20.97	31.3	46.7	22.28	32.0	43.1
500	16.41	31.4	44.0	17.62	31.1	46.4
1000	18.16	25.6	39.9	18.85	25.8	36.8
2000	14.59	20.4	38.6	15.76	21.8	31.6
4000	14.33	18.8	38.9	17.62	19.3	24.6
L_{iC} (dB(A))		29.3	39.6		28.4	41.8

The underlined values do not comply with the current regulation.

3.2 IAQ measurements and comfort surveys

Figure 2 presents the CO_2 concentrations and the occupants' operations on doors and windows, recorded during the two selected days representing a typical summer (CMV off) and a typical autumn (CMV on) scenario. The CO_2 profiles clearly show how quickly indoor air quality responds to changes in the opening conditions of the classrooms. On the summer day, classroom E experienced a consistently high level of natural ventilation, as both door windows remained open throughout the day. Under these conditions, CO_2 concentrations were stable, with average values close to 645 ppm. Conversely, in classroom B, although the window was kept open for the entire period, the door was repeatedly closed, and each closure led to a noticeable increase in CO_2 levels, which often reached peaks between 1200 and 1700 ppm. In the autumn monitoring campaign, CO_2 concentrations were significantly higher overall, averaging around 1700 ppm, even with the CMV system in operation. The measured values were again strongly influenced by occupants' behaviour, reflecting the more variable patterns of door and window use observed during this period. These findings underline the critical role of user-driven ventilation practices in shaping indoor air quality. In total, 114 and 105 responses to the questionnaires were pooled during warm and autumn mid-season, respectively. The histograms in **Figure 3** show the aggregated responses from all questionnaires administered on the same day in the two classrooms, distinguishing between the CMV off and the CMV on scenario. When the CMV system is operating, students report higher perceived noise levels, with the combined share of responses indicating "noisy" and "very noisy" increasing by 14% compared to the condition with the CMV switched off. Correspondingly, the proportion of students experiencing acoustic discomfort ranging from mild to severe rises by 7%. Students also express a stronger preference for a quieter classroom environment, with an increase of 8%, and consequently judge the acoustic conditions of the classroom to be unacceptable more frequently, showing an increase of 17%.

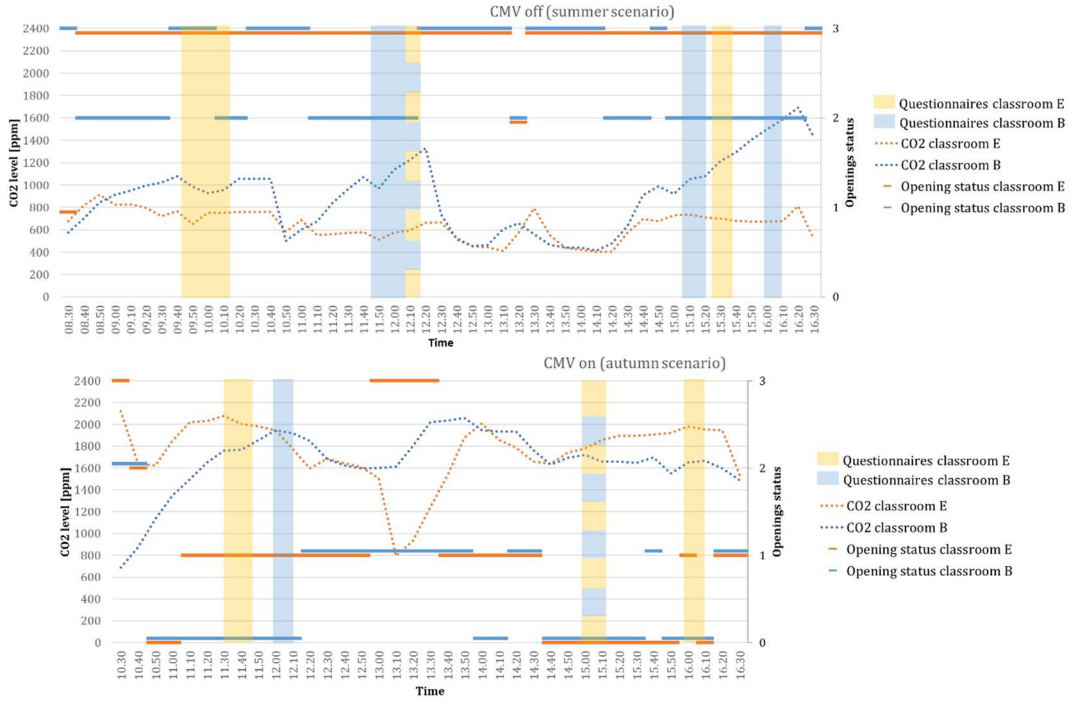


Figure 2. CO2 levels and windows/doors opening activities during the selected days with CMV off (summer scenario) and on (autumn scenario). The time intervals of questionnaire administration are highlighted by coloured bands (yellow for classroom E and light blue for classroom B). The values on the secondary y-axis

indicate the four possible scenarios: both door and window are closed (0); the door is open and the window is closed (1); the door is closed and the window is open (2); both door and window are open (3).

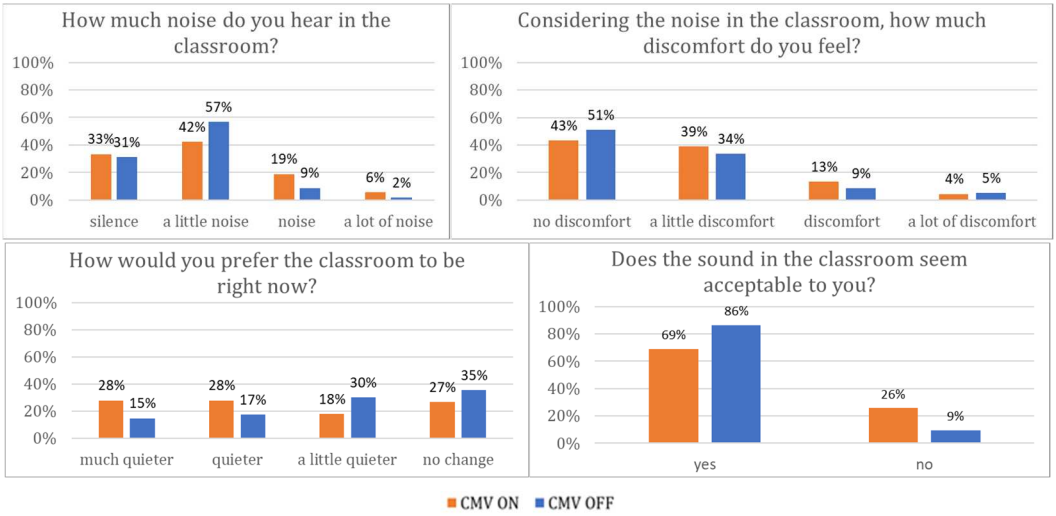


Figure 3. Results of the acoustic comfort survey during the selected days with CMV off and on.

4. Discussion and conclusion

The acoustic characterization of the two classrooms indicates a clear deviation from the indoor acoustic quality requirements established by the UNI 11532-2 standard [9]. Specifically, the measured values for the RT exceed the limits defined for educational spaces, suggesting insufficient sound absorption and potential issues with speech overlapping. This is also confirmed by the values of the Speech Clarity, which can negatively impact the definition and crispness of speech sounds. The influence of the CMV systems on the background noise levels (L_{iC}) varies significantly depending on the operational mode: when the CMV operates at its minimum velocity (V1), the internal noise levels remain within acceptable limits, while at maximum velocity (V3) the L_{iC} values exceed the current regulatory limits, introducing excessive broadband noise that can compromise the signal-to-noise ratio. This aspect is supported by the recorded values of the Speech Transmission Index *STI*: globally, the listening conditions can be categorized as "fair", meaning that the overall intelligibility of the environment is not entirely unsatisfactory, but if falls short of the high-quality acoustic standards necessary to prevent vocal strain for teachers and cognitive fatigue for pupils.

The findings from the student questionnaires closely align with the acoustic measurements conducted within the two classrooms. Data collected during the autumn season indicate that CO_2 concentration levels remain suboptimal even when the CMV units are operational. Consequently, supplementary natural ventilation (achieved by opening doors and windows) is required to maintain an acceptable level of IAQ. This hybrid approach, while necessary to mitigate pollutant buildup, creates a clear conflict between air exchange efficiency and thermal comfort. Empirical data suggests that occupants mitigate this discomfort by limiting the duration of window openings, resulting in inconsistent ventilation patterns.

The evident gap between regulatory requirements and measured acoustic performance suggests that the CMV systems, as currently implemented in this retrofit, are inadequate for the specific needs of the studied classrooms. This reflects a lack of integration of the CMV systems in the retrofit process, which is particularly challenging in existing educational buildings. The

implementation of a rigorous, site-specific approach is therefore essential, balancing IAQ and acoustic performance within structural constraints from the design phase through construction and commissioning. The latter is especially crucial to verify, under real "as-built" conditions, that required airflow rates are achieved without exceeding prescribed noise limits.

The study also highlighted that teachers occasionally neglected to activate the CMV units or maintained them at low-velocity settings. While these settings enhance acoustic comfort, they are often insufficient to meet IAQ requirements. Furthermore, regular maintenance protocols should be established to inspect filters and ductwork, as their degradation can significantly impair airflow rates and increase noise emissions. The current reliance on a mix of mechanical and natural ventilation suggests that the existing CMV systems may be insufficient for the occupant density of these classrooms, at least at the lowest velocities that guarantee a good degree of acoustic comfort. To further investigate these discrepancies, future research should focus on direct measurement of the effective ventilation flow rates provided by the CMV units to identify potential mechanical underperformance and a comprehensive performance evaluation of IAQ.

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