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A simulation-based approach to assess and support optimal acoustic characteristics in classroom environments

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Abstract

This study proposes a simulation-based methodology to investigate the impact of classroom acoustics characteristics on students' listening perception. Using calibrated acoustic simulation, the study explores the extent to which the spatial variability of acoustic conditions across the classroom affects loudness sensation and intelligibility. A numerical model of one classroom was calibrated using on site measurements and the distribution of room acoustic criteria was mapped and related to the acoustic perception rating expressed by the students. Results show that while spatial distribution of room acoustic criteria falls below JND, the distribution of the acoustic sensation are not rated at the same level by all the students.

Key Innovations

- Prediction of sound pressure levels distribution in a classroom: evaluating student acoustic sensation based on their position allows for a more personalized and nuanced understanding of acoustic experience within the classroom, actively contributing to identify strategies to maximize acoustic comfort for all students.
- Exploration of multiple factors through simulation: The study goes beyond basic acoustic analysis by considering factors like multiple listeners' position, which are crucial for understanding the relation between typical factors in a classroom and consequences on the listening experience.
- Integration of field measurements, simulation and subjective questionnaires: This multi-faceted approach combines objective data (field measurements) with simulated data and subjective data (student perception) to provide an effective methodology for evaluating the relation between sound level and subjective perception.

Practical Implications

- The semi-reverberant field theory can be used to provide reliable estimation of SPL distributions in classrooms
- In acoustic simulation of occupied classrooms avoid simulating people as single elements;
- The design of educational spaces and the interpretation of subjective responses should consider that spatial variability below JND might correspond to a relevant dispersion of sensation votes

Introduction

The environmental quality of classrooms has a significant impact on students' comfort and learning performance (Klatte et al. 2010, Minelli et al. 2022, Astolfi and Pellerey, 2008, Shield and Dockrell, 2008). Among the various environmental domains (i.e. thermal, visual, acoustic, indoor air quality), acoustics plays a crucial role in learning activities (Wargocki et al., 2006). Inadequate acoustics can compromise student well-being, negatively affecting their perception and impacting on their stress and fatigue levels (Hygge et al., 2002, Lercher and Guski, R. 2003).

The literature on classroom acoustics is extensive and highlights the growing importance of an optimal acoustic environment for learning (Bradley, 2003). Numerous studies have demonstrated the negative effects of noise and reverberation on speech intelligibility, attention, and consequently, student learning (Astolfi 2009, Recalde J.M. 2021). For example, a negative impact of noise, such as that from trains, on reading ability has been observed. (Bronzaft and McCarthy, 1975). In fact, high background noise levels can interfere with the comprehension of the teacher's speech, forcing students to exert more effort to listen and concentrate (Knecht et al., 2002 and Picard, and Bradley, 2001). This can lead to cognitive fatigue and decreased performance (Mealings, 2022). Excessive reverberation time prolongs the persistence of sound in the environment, creating an echo effect that can mask speech and make it difficult to distinguish between different sounds (Klatte et al., 2010).

Various international and national standards and regulations establish minimum requirements for the acoustics of school buildings, but often the variability of the acoustic parameters in the space is not taken into account. While room acoustic criteria such as reverberation time is defined under diffuse field conditions, and is expected to have limited variability over space, other acoustic descriptors might suffer from a larger spatial variability – that might relate to the distance from the speaker and the vicinity to additional noise source (e.g., open window). In this respect, the position occupied by students exposes them to a unique combination of environmental factors, affecting their perception.

To address these complexities, the present study adopts an approach based on calibrated building simulation. This method allows for virtually extending the measurement network, providing a more comprehensive assessment of both objective and subjective acoustic sensation in a naturally ventilated secondary school located near Rome (Italy). This study aims to utilize simulation to reconstruct a spatial distribution of acoustic descriptors in a classroom located in a high school and explore whether this distribution can explain the variability in subjective data. Additionally, this paper aims to understand whether a spatial variability or uniformity in acoustic parameters is consistent with students' acoustic perception.

Method

The case study analysed in the present work is a High School located in Morlupo (Rome), whose layout is presented in Figure 1. The school is in a rural site, next to a natural park, rather far from the main roads and the west façade overlooks a green area. One classroom west oriented (Figure 2) has been selected, having a floor area of 52 m^2, a volume of 155 m^3, three double glazed windows facing towards the countryside (S/SW). The methodology comprises three steps:

1. **In-field measurements.** Acoustic characterization measurements of the classroom were carried out in unoccupied conditions.
2. **Subjective survey and sound level measurement.** During normal lectures, sound level measurements were carried out in the classroom and right-now-right-here subjective questionnaires were administered to gather students' subjective evaluation regarding acoustic perception.
3. **Model calibration and simulation.** The acoustic model of the classroom was calibrated based on the in situ measurements (Peisheng Z., et al., 2022). After calibration, the model was used to estimate room acoustic criteria, for a fixed sound source, at students' desks. Variability of acoustic descriptors was analysed and compared with students' subjective responses.

In the next subsections, details about these three-steps are presented.

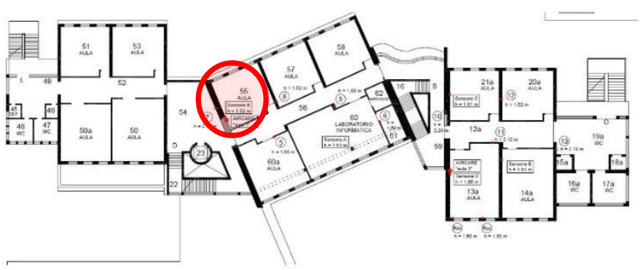

Figure 1: School planimetry: in evidence the considered room.

In-field acoustic measurements

To characterize the classroom, monaural Impulse Response (IR) measurements were carried out in the unoccupied classroom. The measurement apparatus consisted of a B&K 4292-L dodecahedron, a B&K 2734-A amplifier, a B&K ZE0948 audio interface and a B&K 2270-G4 sound level meter. Additionally, for the measurement of Speech Transmission Index (STI), a B&K 4270 echo speech source was used. Data acquisition and processing was performed using the Dirac software, version 6. Five measurement positions were tested with one source position both for ISO 3382 criteria and for STI. The sound source was placed at 1.3 m from the rear wall in the centre of the room at a height of 1.5 m. Five microphone positions were tested, with a height of 1.2 m whose position in the classroom is reported in Figure 2: three points were aligned with the sound source at the center of the room at 1 m, 2.5 m and 4 m from the sound source respectively, and two were shifted towards the window by 1.5 meters, at a distance of 2.5 m and 4 m respectively from the sound source. In the forthcoming analyses, the measurement position at 1 m from the source was discarded. As IR measurements are concerned, ESS test signals were used with a length of 10.9 s, three averages and a sampling rate of 48 kHz. Reverberation time T_{20}, Early Decay Time (EDT) and clarity C_{50} were extracted from the IRs, the energy decay curve being calculated using Schroeder's backward integral method.

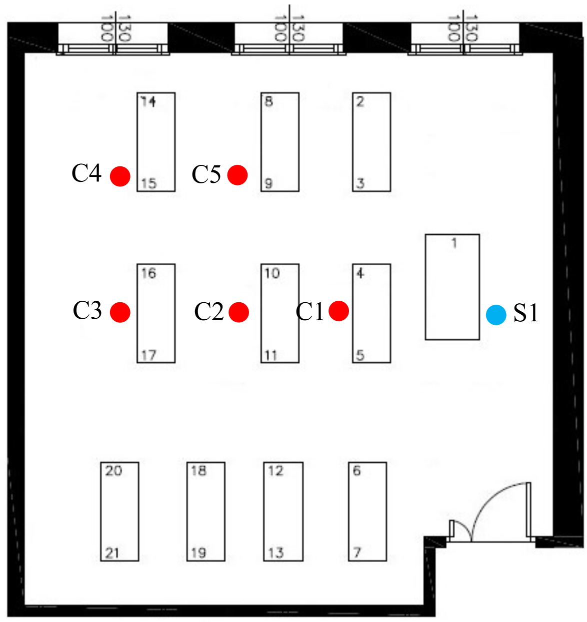

Figure 2: Classroom plan with desk arrangement, numbering and measurement points for the monitoring campaign: C1 to C5 are receivers positions; S1 is source position.

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Subjective survey and sound pressure level measurement

A right-here-right-now questionnaire was administered to students during regular classes. The questionnaire is presented and validated in Morandi et al. (2022). Students were asked to rate the acoustic sensation during the lecture, the loudness and the clarity of the teacher's voice. Evaluation scales are listed in Table 2, while Figure 2 reports the position of the desks inside the classroom During the filling of the questionnaire and the corresponding lecture, A-weighted sound pressure level was measured in the center of the classroom, at a height of 1.2 m, using the B&K 2270 sound level meter.

Table 2: Listening features and evaluation scales.

Attribute	Evaluation scale
Sensation (overall loudness)	0 (quiet) to +3 (very noisy)
Loudness of the teacher's voice	-3 (very loud) to +3 (very soft)
Intelligibility of the teacher's voice	0 (clear) to +3 (very unclear)

Classroom acoustic model calibration and simulation

The acoustic simulations were carried out using the software ODEON Room Acoustics 13 (Christensen 2011). The classroom model was created in 3DSketchUp *(Figure 3)* following best practices (Vorländer, 2007) and maintaining a suitable level of detail; model surface sizes were consistently above 0.30 m, as per Christensen (2011). Sound absorption and scattering coefficients for the various materials were initially sourced from established databases in scientific literature (Fratoni et al., 2019, Fratoni et al., 2024, Astolfi et al., 2008), the simulation software itself (Odeon Room Acoustics Material Library), and relevant standards (UNI, 2020). These coefficients were then refined through an iterative calibration process, following the methodology outlined by Astolfi et al. (2008b) and with the help of the Genetic Material Optimizer by Odeon Room Acoustic Software. The average frequency standard variation of the discrepancies from the initial absorption coefficients was considered acceptable between 0.01 and 0.03.

Calibration was performed based on three room acoustic criteria, namely T_{20}, EDT and C_{50} over an appropriate frequency range. Calibration was deemed successful when the difference between measured and simulated values of EDT, T_{20} and C_{50} fell within the Just Noticeable Difference (JND) as defined by ISO 3382-1 (EN ISO 2009), i.e. 5 % for EDT, 1 dB for C_{50}.

The calibrated model was used to run further simulations to estimate the acoustic scenario in which Sound Pressure Level (SPL) measurements were carried out. In detail, in the calibrated empty classroom model, the equivalent absorption area of the 17 students attending the lecture during the acoustic monitoring was accounted for by adjusting the absorption coefficient of the desks considering the equivalent absorption of desks and students, as reported in Table 3. Students' surface was calculated through Du Bois equation and absorption coefficient was derived from Lazzarin and Strada (2007). The scattering coefficient of occupied desks was set to 0.7 while the unoccupied desk was set to 0.5.

The occupied model was used to simulate the room acoustic criteria in occupied conditions. Subsequently, speech simulation was performed with students' background noise by a source located at the teacher's desk, adjusting the sound power level until the sound pressure level simulated at the centre of the classroom was equal to the sound level measured during the lecture. The calibrated model with the sound source represented by the teacher voice was then used to investigate the distribution of sound pressure levels across the classroom.

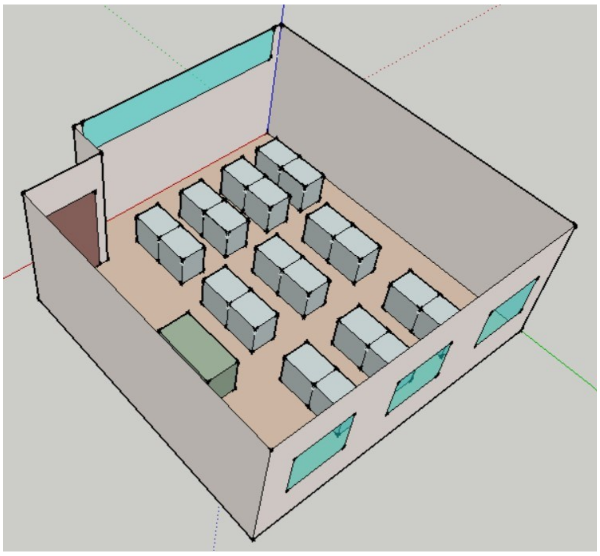

Figure 3: Classroom model

Table 3: Absorption coefficients applied to desks and students

	Area	Absorption coefficient (α)				
	[m²]	250	500	1000	2000	4000
Desk	2.2	0.06	0.07	0.07	0.04	0.06
Student	1.7	0.3	0.5	0.55	0.6	0.5

Results

Model calibration

The Schroeder frequency of the room is about 238 Hz, therefore the following analysis is presented on results ranging from 250 to 4000 Hz. Table 4 reports the absorption and scattering coefficients that minimize the difference between measured and calculated indicators, i.e. EDT, T_{20} and C_{50}. A preliminary estimate of the critical radius r_c based on the equivalent absorption area computed from the measured reverberation time shows r_c to be below 1 m, indicating thus that no relevant variability of sound pressure level across space is expected. Figures 4 to 6 show a comparison of the frequency distribution of each indicator (measured vs simulated). As it can be seen, the difference between measured and simulated spectral values is lower than the JND for each indicator. Moreover, measured STI vs calculated STI in unoccupied conditions are compared in Figure 7, showing that the simulated value is lower than the measured one with a difference between 8 % and 6 % near the source (C2 and C3) and a better agreement for the furthest positions.

Table 4: Absorption (α) and scattering (s) coefficients in frequency for all room materials resulting from the model calibration.

	Area [m²]	Absorption coefficient (α)					Scattering
		250	500	1000	2000	4000	
Wall	75.32	0.03	0.04	0.04	0.05	0.45	0.1
Ceiling	49.60	0.03	0.04	0.04	0.04	0.03	0.1
Floor	49.60	0.02	0.03	0.04	0.04	0.02	0.1
Desks & seats	74.80	0.06	0.07	0.07	0.04	0.06	0.5
Window	3.90	0.25	0.11	0.06	0.04	0.01	0.1
Door	2.52	0.10	0.06	0.08	0.10	0.08	0.1

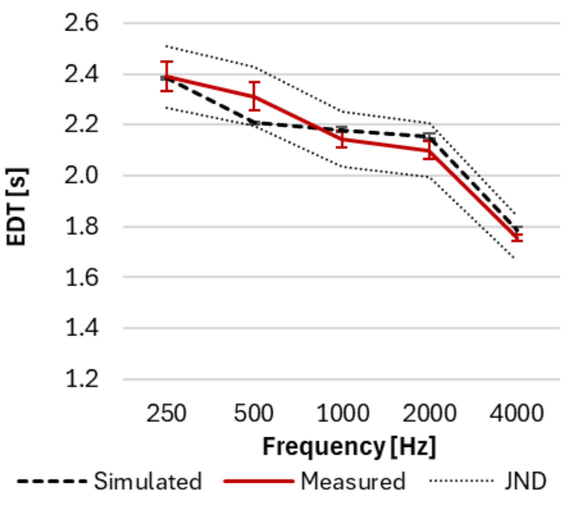

Figure 4: Comparison between measured and simulated frequency distribution of the average EDT values in empty room. Error bars represent the standard deviation while dotted lines represent the JND.

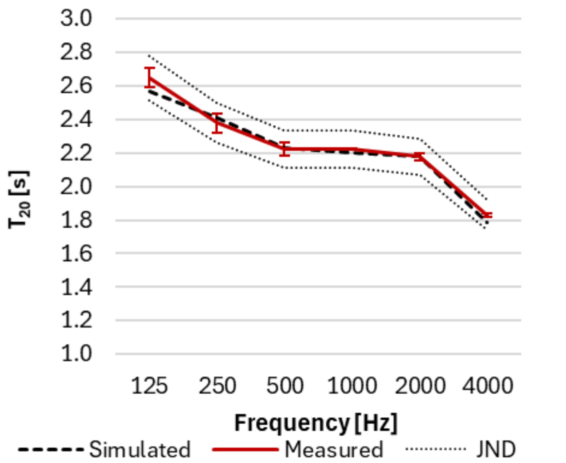

Figure 5: Comparison between measured and simulated frequency distribution of the average T_{20} values in empty room. Error bars represent the standard deviation while dotted lines represent the JND.

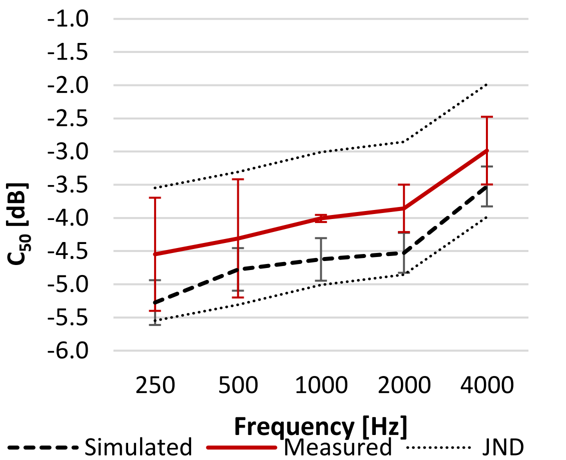

Figure 6: Comparison between measured and simulated frequency distribution of the average C_{50} values in empty room. Error bars represent the standard deviation while dotted lines represent the JND.

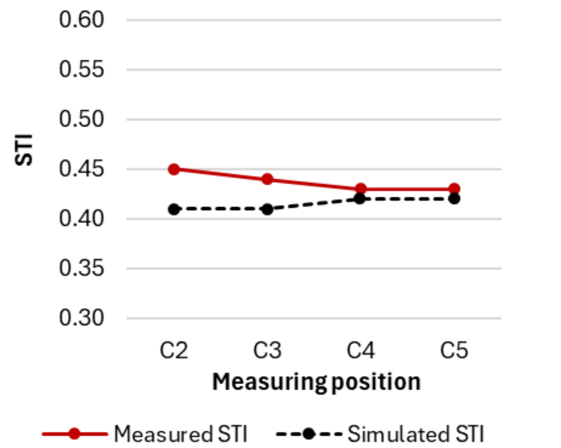

Figure 7: Comparison of measured and calculates Speech Transmission Index (STI) in 4 positions for unoccupied classroom.

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Acoustic simulation during the lecture

The simulated distribution of the acoustic indicators SPL(A), STI and C_{50} in the occupied classroom is represented in Figure 8 and in Table 5, where also the average values and the standard deviation are reported. Regarding T_{20}, the spatial mean value is 1.00 s with a standard deviation of 0.03 s, thus showing a very high uniformity of the value in the space. Similarly, a very low variability in the space of all the other acoustic parameters can be noted. While the SPL is quite above 65 dB(A) at each desk, its variability is well below the JND (Florentine, 1983). The STI never exceeds 0.57 at each position thus showing a poor speech listening experience in all the space. The worst indicator is C_{50}, whose values are very low and below the recommended threshold of 2 dB (UNI, 2020).

Table 5: Sound Pressure Level, Speech Transmission Index and Clarity at each desk.

	SPL [dBA]	STI [-]	C_{50} [dB]
B2	67.0	0.57	0.1
B3	67.1	0.56	-0.2
B4	67.0	0.54	-0.9
B5	67.1	0.55	-0.7
B6	66.7	0.55	-0.5
B7	66.6	0.55	-0.4
B8	66.2	0.56	-0.2
B9	66.4	0.56	-1.2
B10	66.3	0.55	-0.9
B11	66.3	0.55	-0.9
B12	66.3	0.55	-0.7
B13	66.2	0.55	-0.8
B14	65.8	0.57	-0.2
B15	66.1	0.57	-0.4
B16	66.0	0.56	-0.7
B17	66.1	0.56	-0.7
B18	66.0	0.55	-0.6
B19	66.0	0.56	-0.6
B20	66.2	0.55	-0.8
B21	66.2	0.56	-0.6
average	**66.4**	**0.56**	**-0.6**
st.dev.	**0.40**	**0.01**	**0.31**

Subjective votes vs calculated indicators

Subjective votes expressed by students regarding acoustic sensation, teacher's voice loudness and intelligibility are reported in table 6.

In detail, sensation and loudness distributions were compared with SPL distribution and clarity was compared with C_{50}. Despite all the students rate the loudness good, and about the 80 % of them declare to listen clearly the teacher's voice, however the comprehensive acoustic sensation is rated from 1 (slightly noisy) to 3 (very noisy). The interquartile range of acoustic sensation is 1, indicating that even under uniform conditions, subjective evaluations are still scattered.

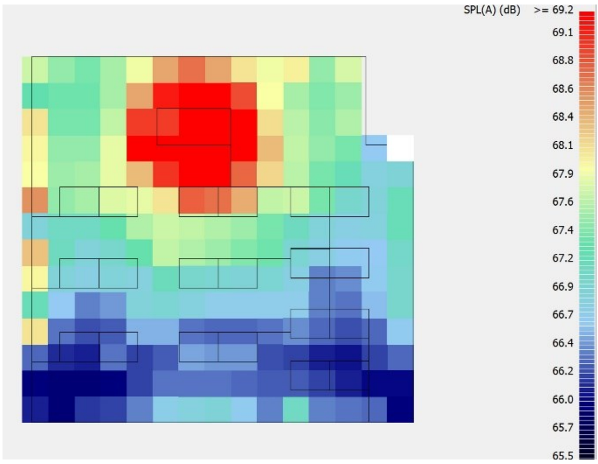

Figure 8: SPL(A) distribution at 1 m above the floor.

Table 6: Subjective ratings at each desk.

Desk number	Acoustic sensation vote	Loudness of the teacher's voice	Intelligibility of the teacher's voice
B2			
B3	1	0	0
B4			
B5			
B6	1	0	0
B7	2	0	0
B8	1	0	0
B9	3	0	1
B10	1	0	0
B11	1	0	0
B12	1	0	0
B13	2	0	2
B14	1	0	0
B15	1	0	0
B16	1	0	0
B17	1	0	0
B18	2	0	0
B19	2	0	1
B20	2	0	0
B21	2	0	1
median	**1**	**0**	0
IQR	**1**	**0**	0

Conclusion

This study aims to explore the possibility to use simulation to extend acoustic measurements acquired at

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one point in the centre of the room to all the students' desks, thus avoiding interference with the class activities.

- The acoustic model calibration carried out in this study enabled the estimation of the materials' acoustic properties.
- The calibrated model was used to estimate acoustic conditions that could not be monitored on site, allowing a virtual extension of the measurement network.
- The simulations of the occupied classroom with the sound sources revealed a low Speech Transmission Index (STI) for all receivers at the desks in the simulated classroom, indicating "fair" speech intelligibility.
- The calibrated acoustics model, developed through a simplified yet meticulous procedure, effectively implement speech intelligibility predictions via spatial sound pressure level distribution. The spatial variability of C_{50}, T_{20} and SPL is below the respective JND, confirming the initial guesses.
- The subjective evaluation provided by the students with respect to teacher's voice loudness and the intelligibility match the low spatial variability of objective criteria, the distribution of votes concerning overall noise shows a larger scatter.
- The applied methodology and its effectiveness should be tested on other types of classrooms thus broadening its applicability.

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