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**ACOUSTIC QUALITY OF CLASSROOMS FOR PUPILS COMFORT AND
COGNITIVE PERFORMANCE**

Supervisor:

Prof. Piercarlo Romagnoni

Co-Supervisors:

Prof.ssa Francesca Cappelletti

Prof. Antonino Di Bella

PhD student: Lisa Battagliarin

Abstract

The acoustic quality of classrooms plays a crucial role in fostering learning. However, many Italian school buildings do not meet the minimum regulations, turning classrooms into acoustically unfavorable environments. Typically, teaching is conducted with lectures, which is why most studies have focused on the impact of noise on listening. However, noise also interferes with non-auditory cognitive abilities. This research aims to fill the gaps in literature by focusing on the effects of exposure to acute noise on cognitive and learning performance of primary school children in relation to acoustic characteristics of classrooms and environmental parameters. Executive functions such as working memory, attention, and inhibition were assessed by administering neuropsychological tests on tablet devices; learning skills were assessed with comprehension and sentence generation tests distributed on paper media. Through a structured protocol, studies were conducted in real classrooms, comparing silent and noisy conditions, with detailed measurements of acoustic (reverberation time, Speech Transmission Index) and environmental parameters (temperature, air humidity, CO₂ concentrations and illuminance).

This research, with unattended noise monitoring activities, investigated what sound levels children are exposed to during the course of educational activities. Through the calculation of new parameters that allow the assessment of the sound climate in classrooms, such as the Intermittency Ratio, IR, the temporal variability of noise was more accurately described by distinguishing the teaching activities carried out in the classroom.

Innovative interventions were also developed to improve classroom acoustics, including the design and implementation of sound-absorbing panels made of sustainable materials and the participation of students in their decoration, which gave the interventions pedagogical value as well.

These findings significantly contribute to understanding the effects of noise on learning and offer practical solutions to creating more inclusive school environments that are conducive to student well-being and performance. This research proposes an integrated approach which considers subjective human responses, objective measurements and technical applications, thus providing methodological innovation and practical solutions to improve the school environment and reduce the impact of noise on learning.

Riassunto

La qualità acustica delle aule scolastiche riveste un ruolo cruciale nel favorire l'apprendimento e il benessere degli studenti. Tuttavia, molti edifici scolastici in Italia non rispettano i requisiti minimi previsti dalle normative, trasformando le aule in ambienti acusticamente sfavorevoli. Tipicamente, la didattica viene svolta con lezioni frontali, per questo motivo la maggior parte degli studi di sono focalizzati sull'impatto del rumore sull'ascolto. Tuttavia, il rumore interferisce anche sulle abilità cognitive non uditorie. Con questa ricerca si vogliono colmare le lacune presenti in letteratura focalizzandosi sugli effetti dell'esposizione ad un rumore acuto sulle prestazioni cognitive e di apprendimento di bambini di scuole primarie in relazione alle caratteristiche acustiche delle aule scolastiche e ai parametri ambientali. Le funzioni esecutive come memoria di lavoro, attenzione e inibizione sono state valutate somministrando test neuropsicologici su dispositivi tablet; le abilità di apprendimento sono state valutate con test di comprensione e generazione di frasi distribuiti su supporto cartaceo. Attraverso un protocollo strutturato, sono stati condotti studi in aule reali, confrontando condizioni di silenzio e rumore, con misurazioni dettagliate dei parametri acustici (tempo di riverberazione, indice di trasmissione del parlato) e ambientali (temperatura, umidità, livelli di CO₂ e illuminamento).

La ricerca, con attività di monitoraggi acustici non presidiati, ha investigato a quali livelli sonori sono esposti i bambini durante lo svolgimento delle attività didattiche. Attraverso il calcolo di nuovi parametri che permettono la valutazione del clima sonoro nelle aule, come l'Indice di Intermittenza IR, è stata descritta più accuratamente la variabilità temporale del rumore distinguendo la tipologia di didattica svolta in classe. Sono stati inoltre sviluppati interventi innovativi per migliorare l'acustica delle aule, inclusa la progettazione e l'implementazione di pannelli fonoassorbenti realizzati con materiali ecologici e il coinvolgimento degli studenti stessi nella loro decorazione, conferendo agli interventi anche una valenza pedagogica.

I risultati forniscono un contributo significativo alla comprensione degli effetti del rumore sull'apprendimento e offrono soluzioni pratiche per creare ambienti scolastici più inclusivi e favorevoli al benessere e alle prestazioni degli studenti. Questa ricerca propone un approccio integrato che considera le risposte umane soggettive, le misurazioni oggettive e le applicazioni tecniche, fornendo così innovazione metodologica e soluzioni pratiche per migliorare l'ambiente scolastico e ridurre l'impatto del rumore sull'apprendimento.

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Introduction

The Indoor Environmental Quality (IEQ) of an environment, that is, the set of physical quantities describing the visual, thermal, acoustic, and air quality aspects, is essential for ensuring the normal development of a child's communication, language, and cognitive skills [1], [2], [3]. An unfavorable school environment in one or more areas of comfort can lead to excessive cognitive effort, thereby compromising learning and academic performance. Children spend most of their time in classrooms where, often, acoustic standards are not met [4], [5], [6], [7]. This is due to schools frequently being in unsuitable areas or constructed in a way that fails to meet the minimum requirements established by regulations. The issue of the acoustic conditions in classrooms has led many countries in Europe to adopt rules or guidelines on the acoustic design of schools that do not support good Acoustics due to several factors related to their design. Among the main reasons are the size and shape of the classrooms; the rectangular or irregular size and shape of classrooms can cause problems such as standing waves or reverberation; high or vaulted ceilings, although aesthetically pleasing, can contribute to uneven sound propagation and increase reverberation times; and the absence of acoustic treatments. In such environments, the communication process between teachers and students becomes less effective, as the sound signal from the teacher's voice is degraded, reaching the students in a modified form. Typically, teaching in schools is primarily conducted through frontal teaching activity; therefore, the environment must be designed to enable students to clearly understand what the teacher is saying. Poor acoustic design of classrooms creates challenging environments, with a more significant impact on children than on adults [5], [8], [9], [10]. This occurs because speech perception in noise and reverberation improves with age [10], [11] as the maturation of auditory pathways in children is not yet fully complete and their phonological processing abilities have not yet been fully achieved [12]. Children's ability to understand speech in the presence of noise and reverberation does not reach adult levels until late adolescence [13] and children younger than 13 are particularly susceptible as they are more easily distracted by auditory events due to their less developed attention skills [14], [15]. Unfavorable acoustic conditions can impair performance in complex listening tasks even when there is excellent intelligibility [16] due to increased listening effort [17].

One of the factors that degrade the waveform is background noise, which in classrooms refers to any sound stimulus other than the target signal (such as the teacher's voice or a classmate's voice during teamwork). This includes traffic noise from outside the building, the voice of the teacher in the adjacent classroom, noise from teaching aids, and noise from the air conditioning system (if present). All these are stationary noises that reduce intelligibility by creating energetic masking. The situation worsens when the signal is classroom noise, which is the constant noise present within classrooms generated by students moving around, shifting desks or chairs, or talking to each other [4]. This type of noise, having informational content, significantly disrupts speech perception.

The other factor that degrades the waveform is reverberation, which is the reflection of sound waves on the walls of the environment. Reverberation depends on the surface finishes, and the volume of the space, and when it is excessive, it becomes impossible to clearly distinguish words, as each syllable acquires an audible tail that masks the following word. This results in a loss of intelligibility.

Background noise and reverberation are related to each other, so by reducing reverberation, it is also possible to decrease noise coming from students. Often, the effects of poor acoustics are noticeable in the cognitive load required to complete a task, and the purpose of school classrooms is to ensure that students achieve results with the lowest possible cognitive load.

Many studies have focused on the aspect of listening [18], identifying the causes that lead to a decline in speech intelligibility, defined as the number of correctly perceived words. These causes include: (i) acoustically degraded signals due to the presence of noise and reverberation time [19], [20], [21, p. 33]; (ii) defects in the speaker's voice [22] or in the amplification system [23], which result in reduced intelligibility for students and a decrease in the verbal information received; (iii) listener characteristics (such as hearing impairments [24], or non-native listeners [25]).

The effect of noise on auditory performance has been widely studied differently from its impact on cognitive performance [26], [27], [28]. Little attention is given, therefore, to how noise affects children's non-auditory cognitive abilities such as attention, short-term memory [26], sentence comprehension [24], [29], or learning performance, information processing [30], writing or mathematics [31], [32], [33], [34]. The non-auditory effects of noise on children's cognitive and academic performance may differ according to the characteristics of the noise (continuous, intermittent, impulsive, or low-frequency noise) and the type of cognitive tasks performed.

Research on the effect of noise on cognitive performance has grown in recent years, with many reviews focusing on the impact of chronic and acute exposure to noise on children's attention and memory [34], effects on reading skills [35], children's well-being [36] and behaviors [37]. All these studies have highlighted the impact of chronic noise exposure on accuracy, reading comprehension, and mental well-being. Noise can affect executive functions by influencing attentional resources or creating cognitive overload [33] by influencing the development of executive functions themselves [38].

Currently, national regulations on school acoustics are outdated because they define reference values that overlook subjective factors, such as children's sensory perception and their performance when faced with multiple simultaneous stimuli.

Purpose and Research Questions

My doctoral research concerns the evaluation of the effects of noise on cognitive performance of primary school children and the corresponding research questions are:

- a) What are the effects on students's cognitive performance at exposure to acute noise with non-intelligible verbal content compared with the quiet condition?
- b) What are the levels of noise that primary school children are typically exposed and what are the characteristics of variability over time-based on the teaching activities performed?
- c) What are the thermo-hygrometric conditions that students are typically exposed to during lectures?
- d) What acoustic interventions can be used to improve classroom acoustics and have a psycho-pedagogical function for a child?

To achieve these goals, a method was developed, based on literature research, to be applied to have homogeneity and replicability of data. First, measurements to assess the acoustic characteristics of the environments in which neuropsychological data are collected were performed following the directions of ISO 3382 [21] and UNI 11532-2 [39] standards and a measurement protocol was defined to acquire acoustic and environmental data during the execution of trials for the acquisition of neuropsychological data (i); Second, an innovative method of acquiring and analyzing the collected data using innovative indices designed to investigate acoustic and environmental conditions under typically classroom conditions was developed (ii). In addition, possible solutions for the school acoustic environment were developed and studied (iii).

The instruments used to achieve the objectives are:

- assessment of cognitive performance by administering neuropsychological tests as a function of classroom noise and acoustic characteristics of classrooms;
- investigate what levels children are exposed to during everyday classroom activities and the characteristics of the soundscape needed during teaching;
- investigate what environmental conditions children are exposed to during the teaching activities;
- ideate acoustic improvements for classrooms to make the environments acoustically comfortable not only from the auditory but also from the cognitive and psycho-pedagogical sides.

The results of my doctoral research aim to fill the gaps in the literature by attempting to investigate the impact of classroom noise on children's cognitive performance during non-auditory tasks and to validate the use of innovative numerical methods and indices to support the acoustic parameters commonly used for assessing the acoustic landscape in the typical operating situations of complex environments such as classrooms in which the sound signal impairs students' auditory and non-auditory performance. It also offers a cue for acoustic solutions that the students themselves create.

Main Contributions

This research aims to investigate the influence of acute exposure to a signal with non-intelligible verbal content with the addition of sound events on non-listening skills, thus focusing on cognitive and learning skills and the influence of chronic exposure to unfavorable acoustic-architectural conditions on the same non-listening skills.

In detail, the significant contributions of this work that bring novelty compared to studies in the literature are: (i) use of an iOS application with neuropsychological tests for the assessment of cognitive performance in complex environments such as classrooms; (ii) investigate how acute exposure to non-intelligible verbal noise, compared to quiet condition, affects non-auditory cognitive abilities and learning abilities in relation to acoustic characteristics and physical parameters of classrooms (iii) validation in the use of new acoustic parameters as a support to existing ones for the description of the soundscape from the perspective of temporal dynamics under normal operating conditions of school environments; (iv) development of acoustic improvements that also have a pedagogical function on the problem of acoustics in classrooms.

Overview of the Thesis

The dissertation consists of six chapters. It begins by presenting the state of the art, which outlines the bibliographic and normative context required to address the entire work. Then, the developed method proposed in a general description and applied to real contexts. The final considerations summarize all the insights gained from the method's application and the open questions to be addressed through future work.

Chapter 1

Chapter 1 contains an overview of the background in the literature necessary for the development of the work. Studies have investigated the effects on cognitive and learning performance at acute exposure to different types of signals in students of varying age ranges. The types of signals investigated, the method of acquisition and emission of these signals during the trials, and their effects on performance are presented. The Italian regulatory framework in the field of acoustics related to educational buildings is then presented and the parameters and respective reference values to be tested are given. The parameters used to evaluate the sound level to which one is exposed are introduced, and a general background on acoustic improvement techniques for indoor environments is given.

Chapter 2

Chapter 2 describes the method proposed in this work. The detailed descriptions allow reproducibility of the method used to assess students' cognitive performance and the sound power of the signal used to measure acoustic monitoring and environmental parameters.

Chapter 3

Chapter 3 shows the applications of the method used for the assessment of cognitive performance proposed in primary school classrooms. For each case study the descriptions of the analyzed environments, the parameters characterizing the environments from the room's acoustic point of view, and the results obtained in the evaluation of performance in the conditions of the acoustically favorable environment (quiet condition) and unfavorable environment (condition with acute signal input) are given. Considerations of the results obtained were made for each case study.

Chapter 4

Chapter 4 shows the applications of the method used for the proposed cognitive performance assessment in university students. Descriptions of the analyzed environments, the parameters characterizing the environments from the acoustic-architectural point of view, and the results obtained in the evaluation of performance in the conditions of acoustically favorable environment (quiet condition) and unfavorable environment (condition with acute signal input) are reported. Considerations were made on the results obtained.

Chapter 5

Chapter 5 shows the application in the context of primary schools performing long-term and short-term acoustic monitoring and using innovative parameters to describe the acoustic climate. The results obtained and the correlations performed with the acoustic parameters typically used for sound climate assessment are reported to identify the possibility of using the new index with some support to the other acoustic parameters in monitoring. Considerations made on the results obtained are reported. In addition, results obtained from monitoring campaigns of environmental parameters are reported and compared with regulatory limits.

Chapter 6

Chapter 6 shows the development path of the design of improvement interventions to be applied in school settings for improving room acoustics. Its sound-absorbing properties are measured in a reverberation room and the application of the interventions in real-world contexts are reported.

1. State of the Art

This chapter provides an overview of the state of the art in research investigating the effects of acute exposure to a signal on students' non-auditory cognitive abilities. The first section reviews studies from the literature that focus on evaluating the impact of different types of sound signals on cognitive and learning performance. The documents were analyzed with a focus on the non-auditory cognitive domain and the evaluation of performance about acute exposure to the signal by the tested subjects. The second section presents an overview of Italian acoustic regulations applicable to the assessment of school environments, detailing the parameters to be verified and their corresponding limit values. Then, the third and fourth sections outline the types of interventions for improving acoustic conditions in environments and the state of the art in evaluating the acoustic environment under operational conditions in classrooms.

1.1 Effect of Noise on Cognitive Abilities

Attention has been given to the literature analyzing the non-auditory cognitive effects of acute noise in learning contexts. The focus is on academic tasks such as reading and writing, as well as on a range of executive functions. Executive functions are a set of higher-order cognitive abilities (working memory, response inhibition, cognitive flexibility) that enable the control and regulation of thought processes and goal-directed actions [40], [41] and predict academic achievement over the school period [42], [43], [44].

Bibliographical research was performed on databanks like Scopus and Web of Science using the following combination of keywords with the AND Boolean operator: “classroom”; “noise”; “performance”. The query was chosen so that we could be as general as possible about the type of study and test. When the full text of the papers was not available, additional searches were conducted through ResearchGate and Google Scholar. The total database included 888 papers from which, after removing the studies in both databases, a total of 707 papers were analyzed. After an initial selection performed on the title and abstract, 135 papers were selected.

Focusing on studies investigating the effect of noise on cognitive performance, by performing a full-text reading, papers were selected based on the inclusion and exclusion criteria in Table 1.

Table 1: Criteria for inclusion and exclusion of selected studies.

Inclusion	Exclusion
Studies conducted on students in all grades	Participants under 6 years-old
Acute signal exposure	Studies conducted in subjects with hearing impairment or other disabilities
Studies investigating the effects of noise in the domain of cognitive abilities	Studies analyzing chronic noise exposure
Task presentation in visual mode	Studies examining the relationship between intelligibility and performance

(continued)

Table 1: (continued)

Inclusion	Exclusion
Signal administration in headphones/speaker	Studies in which only comfort or annoyance questionnaires are provided
Studies conducted in schools/universities or laboratories or with virtual reality	Studies for which full text was not available
Articles published in English	Literature review

These inclusion (and exclusion) criteria led to the selection of 12 studies. The main reason studies were excluded are: (i) studies that evaluate listening effort and not cognitive effort; (ii) studies that assess the influence of chronic exposure to outdoor noise on academic performance; (iii) studies in which the acoustic performance of school buildings is assessed; and (iv) studies in which an overview of noise levels inside or adjacent to the school is provided.

Table 2 summarizes the key information of each included study. It reports details on the study sample, the administered tests, the acoustic conditions, the type of noise (including emission level, emission source, and signal construction), and the nature of the noise effects.

Table 2: Summary of selected literature studies. PCU: Partial credit unit (mean number of correctly recalled memory items within a list length is calculated, and these proportions are then averaged to obtain the score).

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Bhang et al. [45]	268 children (10-12 years)	Classroom	Korean WISC	N. Correct answer	Background noise	43.1-46.1 dB	-	-	A negative effect of noise.
			Comprehensive Attention Test (CAT)	N. Correct answer, Reaction time	Experimental traffic noise (background + traffic and aircraft noise)	60.8-62.8 dB	-		
			Stroop color-word test	N. Correct answer, Reaction time					
			Children's color trail test	N. Correct answer, Reaction time					
Caviola et al. [46]	162 children (11-13 years)	Classroom	Math skills	Accuracy and response time	Quiet	-	Real environmental noise	Omnidirectional source	The youngest children performed better in the quiet and traffic noise conditions than in the classroom noise conditions, while in the older children, these differences gradually disappeared. The detrimental effect of classroom noise was most evident when the maths task was moderately difficult.
Traffic noise	60 dB(A)	Recordings	Classroom noise	60 dB(A)	Digitally mixed sound				

(continued)

Table 2: (continued)

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Connolly et al. [47]	976 children (11-16 years)	Classroom	Reading comprehension	N. Correct answer	Babble+ sound events	L _{Aeq} of 50 and 70 dB(A) L _{Aeq} of 50 and 64 dB(A)	Recordings	Headphones	High levels of classroom noise can have negative effects. Negative effects were pronounced at levels of L _{Aeq} =70 dB(A) when compared with performance at the lower level of L _{Aeq} =50 dB(A)
Dockrell et al. [48]	158 children (mean age=8.6 years)	Classroom	Academic skills	N. Correct answer	Quiet	-	Real environmental noise	-	Children in the babble and environmental noise conditions performed worse than those in the base and babble conditions on the speed of processing tasks. Performance on verbal tasks was significantly worse only in the babble condition. Children with special educational needs were differentially negatively affected in the babble condition.
			Reading, spelling, speed information, arithmetic	N. Correct answer	Babble+ sound events	L _{Aeq} =65 dB(A) Babble played at L _{Aeq} = 65 dB(A) and the events played with L _{Amax} =58 dB(A)	Recordings		

(continued)

Table 2: (continued)

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Doggett et al. [49]	43 participants (18-29 years. Mean age 20.61)	Virtual classroom	N-back test	Accuracy, Reaction time	Quiet	52–56 dB(A)	Virtual reality	Headphones	Acoustic treatment reduced the negative impact of noise.
					Background chatter in the classroom without acoustic treatment	-	Virtual reality		
					Background chatter in the classroom with acoustic treatment	-	Virtual reality		
Fernandes et al. [31]	162 children (8-12 years)	Classroom	Reading	Reading time	Quiet	-	Real environmental noise	Stereo sound equipment	The higher the noise intensity, the greater its interference on the tests.
			Writing	N. Errors	Child conversation	20 dB	-		
					Interference noise	40 dB	-		
Ljung et al. [32]	187 children (12-13 years)	Classroom	Reading speed and comprehension	Reading time and N. correct answer	Traffic noise	$L_{Aeq} = 66$ dB(A) at 2m in front of loudspeaker (peaks 78 dB(A))	Recordings	Loudspeaker	Traffic noise impairs reading. Speed and basic mathematics. No effect on reading comprehension or mathematical reasoning. Irrelevant speech did not disrupt performance on any task.
			Mathematics	Mean scores	Irrelevant speech	62 dB(A)	Recordings		
			Mathematics reasoning	Mean scores	Quiet	-	Real environmental noise		

(continued)

Table 2: (continued)

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Guerra et al. [50]	63 children (8-10 years)	Quiet room at school	Reading speed and comprehension	Reading time and N. correct answer	Intelligible speech	45-50 dB(A) 65-72 dB(A)	-	Headphones	Reading speed decreased with louder background speech. Reading comprehension was disrupted by the intelligibility of the distraction. The larger intelligibility effect in children with poorer interference control suggests that these children may be more vulnerable in environments where background speech is present.
			Stroop test	Accuracy and reaction time	Unintelligible speech	45-50 dB(A) 65-72 dB(A)	-		
Massonniè et al. [51]	44 children (5-11 years)	Room	Backward digit span and Corsi block test	N. Correct answer	Quiet	-	-	-	Younger children with low selective attention skills were especially at risk of noise: they gave fewer ideas in the presence of noise, and these ideas were rated as less original. Children with good selective attention skills were globally protected against the effects of noise, performing, similarly, in quiet and noise.
			Stroop test and Flanker test	Accuracy and reaction time					
			Idea generation (Alternative Uses task or Just Suppose Task)	Fluency and original scores	Classroom noise	$L_{Aeq,5min}=63.1$ [52.8– 76.1 dB(A)]	-		

(continued)

Table 2: (continued)

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Massonnié et al. [52]	65 children (mean age=10.23)	Quiet room at school	Text recall	N. Correct answer	Intelligible noise	$L_{Aeq,7min30}=65$ dB [50-81 dB(A)]	Recordings	Headphones	Noise does not impair overall performance. Children might use compensatory strategies (e.g., re-reading) to reach the same level of performance in silence and noise. Children with lower working memory were more impaired by noise when doing mathematics.
			Reading comprehension	N. Correct answer	Classroom noise (babble+sound events)	$L_{Aeq,7min30}=65$ dB [50-80 dB(A)]	Recordings		
			Mathematics	N. Correct answer					
			Backward digit span	N. Correct answer	Quiet	35-45 dB	Real environmental noise		
			Flanker test	Reaction time					
Sorqvist [53]	108 children (17 years old)	Classroom	Operation span	N. Correct answer	Aircraft noise	55-60 dB(A)	Recordings	Headphones	Speech is more detrimental to prose memory than aircraft noise, and individual differences in working memory capacity contribute more to individual differences in susceptibility to the effects of aircraft noise on prose memory than to the effects of speech.
					Speech noise	-	Recordings		
			Prose memory	N. Correct answer	Quiet	-	Real environmental noise		

(continued)

Table 2: (continued)

Author	Sample characteristics (age range or mean age)	Environment	Task	Outcome	Signal	Levels of the signal	Signal construction	Source of the signal	Effect of noise on performance
Zhang et al. [54]	248 children (7-12 years)	Semi-anechoic chamber	Attention	Error rate	Traffic noise	35 - 65 dB(A) every 5 dB	Recordings	Headphones	Low-frequency noise had a greater effect on younger children than road traffic noise in reading and calculation processes. Performance in attention and short-term memory was not affected by noise level and type of noise.
			Short-term memory	Error rate	Low-frequency noise of air conditioners	35 - 65 dB(A) every 5 dB	Recordings		
			Calculation	Error rate	White noise	35 - 65 dB(A) every 5 dB	MATLAB		
Reading comprehension	Error rate								

1.1.1 Sample

In the selected studies, participants belonged to different age ranges: children in the age range of 11-16 years [32], [46], [47], [51]; children in the age range of 7-12 years [31], [45], [48], [50], [52], [54], [55]; and young adults [49]. The study in which the highest number of participants were involved is the study by Connolly et al. with a total of 976 participants from 7 schools [47].

1.1.2 Noise Signal

The selected studies examined the effects of exposure to acute noise. The auditory stimuli used can be classified into intelligible verbal content signals [31], [50], [51], [53], [55], non-intelligible/irrelevant verbal content signals, or non-intelligible verbal content signals with added sound events (classroom noise) [31], [32], [46], [48], [49], [50], [51], [52], [55], environmental signals (traffic, airplanes) and broadband noise [32], [45], [46], [53], [54]. In most studies (n=6), the signal was delivered through headphones. When signal were emitted through a source, omnidirectional sources [46], loudspeaker [32] or stereo sound equipment [31] were used. Emitted signals are typically recordings; only in the case of white noise used by Zhang et al. was a signal recreated using MATLAB [54] and classroom noise used by Caviola et al. resulted from a base recording of babble noise with digitally mixed events [46].

1.1.3 Effect of Noise on Cognitive Performance and Learning Abilities

The effects of noise have been evaluated on working memory [49], [51], [52], [53], [54], [55], several studies investigated attention and inhibition skills [45], [50], [51], [52], [54], arithmetic skills [32], [46], [52], [54], [55] and one evaluated the effects of noise on children's performance in creative tasks (Alternative Uses tasks and Just suppose test [51]). For learning skills, reading comprehension and writing skills were assessed [31], [32], [47], [48], [50], [52], [54], [55].

Massonié et al. (2019) examining the impact of classroom noise at a level of 64 dB on school-age children's creativity, assessed by idea generation tests called Alternative Uses task and Just Suppose task, found differences related to age and selective attention skills. Younger children (5-8 years old) with lower selective attention skills showed a reduction in the amount and originality of ideas generated in the presence of noise. In contrast, children with better selective attention skills who performed similarly in both quiet and noise conditions [51].

Regarding exposure to a non-speech signal, such as traffic or airplane noise, due to its unexpected and unfamiliar nature, results obtained from assessments of reading speed, comprehension, and computation of 12-13 year-old students, also tested under irrelevant noise conditions, showed a negative influence in reading speed and calculation, but no effect on mathematical reasoning and comprehension. However, the same tests conducted with irrelevant signals showed no significant differences in 11- to 12-year-old students tested in calculation and reading, the presence of a signal composed of road traffic noise does not affect performance, however, it increases the error rate in younger children (7-8 years old) when the noise is emitted with an intensity greater than 55 dB(A) [54]. The same students were tested under low-frequency noise and white noise conditions. Compared to

traffic noise, low-frequency noise had a more pronounced negative effect in 7 to 8-year-old children by leading to increased errors in calculation and reading tasks. In white noise situations, the effects are more mitigated in calculation tasks than in memory and reading tasks [54]. Results obtained by Sorqvist et al. (2010) testing the performance obtained in memory tests in airborne noise, verbal noise, and quiet condition of groups of adolescents (17 years old), show that airborne noise impairs memory but affects it to a lower extent than the performance obtained in the verbal noise condition. The same results were obtained in memory and attention test conditions with children exposed to traffic noise. Lower scores and increased processing speed were observed in children aged 10-12 years having a greater negative impact on children at risk of learning difficulties [45].

An intelligible speech signal, compared to an unintelligible speech signal in 8- to 10-year-old children, had an impact on comprehension, the intensity of signal emission, at levels of 65-72 dB also resulted in a reduction in reading speed compared with exposure to the same sound signal at a lower intensity (45-50 dB). In addition, the intelligibility effect was more significant in children with lower interference control, assessed using the Stroop test [50]. Even in text comprehension, a verbal content signal that directly competes with the processing of the read text has a negative impact on memory. This type of noise causes more interference in children with lower working memory abilities because it requires simultaneous processing of semantic information that distracts from comprehension. This type of signal impairs memory abilities more in comparison with the airborne noise signal [53].

In the evaluation of arithmetic performance with intelligible verbal content signal ($L_{Aeq,7min}=65$ dB), a negative impact on performance was observed only in children with low working memory, while performance in comprehension tasks was not significantly affected. Children could use compensatory strategies, such as rereading, to achieve the same performance in quiet and noisy conditions [52]. The same tests in the presence of babble noise with sound events had no negative effects; in some cases of reading tasks, the presence of the signal was associated with slight facilitation for the reading task suggesting that the variety of sound sources might help refocus attention. However, again, the results depend on the individual abilities of the subjects tested [52].

Dockrell et al. (2007), testing children with an average age of 8.6 years, showed that noise in the classroom, both pupil-generated noise (babble) and environmental noise, impairs pupils' performance on processing speed and verbalization tasks. Babble noise has a negative impact on verbal tasks, while babble noise with events affects processing speed tasks more. Children with special educational needs were more negatively affected by noise, suggesting that noise in the classroom may exacerbate learning difficulties and reduce cognitive performance [48].

In subjects aged 18 to 29 years (mean age 20.6), the impact of ambient noise on performance in the n-back test in the case of ambient noise using virtual reality was evaluated. The subjects were tested in the condition of a reverberant environment and in an acoustically corrected environment with the presence of ambient noise. It was observed that in the condition of virtual reality with an acoustic intervention environment for reverberation, the negative effect of noise on performance was eliminated. It follows that improving room acoustics can improve the impact of noise on students [49]. In children aged 11-13 years, an adverse effect of the listening condition on mathematics performance was found to result in decreased accuracy and increased response time in mathematical tasks. This effect is also a function of task complexity; the greater the complexity, the more the effect was

attenuated as more concentration was required, which may reduce noise interference. Younger children performed better in the traffic noise condition than in the classroom noise condition, while in older children the differences disappeared. The results support the idea that younger children are more sensitive to the detrimental effects of classroom noise than older children [46].

The effects of classroom noise were also noted in comprehension tests. In 11-16-years-old students with noise levels at 70 dB, students answered less accurately and completed fewer questions. The noise increased reading time and reduced the ability to comprehend the text. At a level of 64 dB, negative effects were observed only in older students, suggesting that age affects the ability to tolerate noise [47]. Fernandes et al. examined the effect of different noise levels (20 dB and 40 dB) on children in 3rd, 4th, and 5th grades (8-12 years old) by evaluating performance on reading, writing, and attention tasks. Noise emitted at 20 dB showed no significant effects on attention, writing, or reading performance, in contrast to the effects of noise at 40 dB, which negatively impacted all tasks by leading to a reduction in the number of correct responses in the attention and writing test and an increase in reading time. The effects of 40 dB noise were most pronounced in 3rd and 5th graders. The 4th-grade students showed greater resilience to the adverse effects of noise than the other school levels.

1.1.4 Discussion

The analysis of the selected studies suggests that both speech and non-speech signals generally have a negative impact on cognitive performance, with a more pronounced effect in the case of intelligible speech signals. It is also evident that age is a predominant factor influencing noise susceptibility. Younger children perform worse in noise conditions than older children or adults. As children get older, their cognitive skills develop, enabling them to handle distractions in the classroom. However, some research indicates mixed results, suggesting a greater impact of noise on older children than on younger children. However, studies in which younger children showed greater susceptibility to noise focused on assessing the effects of noise on cognitive performance. In contrast, studies that showed a more substantial impact of noise on older children focused on reading and writing tasks.

These conflicting results could arise from the stage of cognitive development: younger children may be more susceptible to noise because of their early cognitive development, affecting their ability to concentrate. In contrast, older children engaged in academic tasks that require more complex cognitive skills, the need for more processing, make them more vulnerable to noise interference.

These findings emphasize the need to explore the relationship between children's age and their cognitive performance in noisy environments. In addition to age, individual differences in cognitive abilities may also influence the impact of noise on performance. Children with more robust selective attention are less affected by noise, while younger children are more sensitive to its detrimental impact. Aircraft or traffic noise, for example, can disrupt memory and computation tasks more than comprehension tasks. In contrast, intelligible verbal noise is particularly detrimental to tasks that require attention and semantic processing. Therefore, the nature of noise in the classroom should not be overlooked.

Further exploration of how individual differences, age, and types of noise affect children's reaction to noise in cognitive skills, with particular attention to how compensatory strategies develop.

1.2 Italian National Legislation and Technical Standards

Recent research on acoustics in educational environments has led to the development and revision of numerous recommendations, guidelines, technical standards, directives, and laws. The primary legislative references at the Italian national level for the design and construction of public school buildings are: the D.P.C.M. of 5.12.1997 “Determination of passive acoustic requirements of buildings” [56]; Law n. 221 of 28.12.2015 “Provisions on environmental matters to promote green economy measures and to limit the excessive use of natural resources” [57]; D. M. 11.10.2017 on “Minimum Environmental Criteria” [58] and the D.M. of 23.06.2022 “Minimum Environmental Criteria for the contracting of design services for building interventions, for the contracting of works for building interventions and for the joint contracting of design and works for building interventions” [59].

The identification of reference values and criteria for the design and verification of acoustic requirements for educational buildings is based on a series of recently updated technical standards such as UNI 11367 “Acoustics in buildings - Acoustic classification of building units - Procedure for evaluation and verification in place” [60] and UNI 15532 “Indoor acoustic characteristics of confined spaces” [61].

1.2.1 Italian National Legislation: D.P.C.M. 5.12.1997

The D.P.C.M. 5.12.1997 [56] executes Law n. 447 of 26.10.1995 [62] on noise pollution and applies in the case of private educational buildings. The Decree defines the performance that buildings must possess an insulation from airborne noise between different building units, insulation from external noise, insulation from footstep noise, insulation from noise from continuous and discontinuous operation systems, and reverberation time for classrooms and school gyms. Performance must be verified on-site when the building is completed.

The Decree is not applicable to sound insulation between adjacent rooms in the case of two adjacent classrooms because they do not constitute two distinct building units [63]. The Decree gives no indication of partitions between a classroom and corridor. For reverberation time, the Decree provides reference values that refer to the Ministry of Public Works Circular n. 3150 of 22.05.1967 [64].

1.2.2 Italian National Legislation: Law 28.12.2015, n. 221

Law 28.12.2015, n. 221 [57] “Provisions on environmental matters to promote green economy measures and to limit the excessive use of natural resources” introduces significant changes to the current public contracts code aimed at facilitating the use of green procurement and the application of Minimum Environmental Criteria (CAM). CAMs are “environmental and ecological requirements defined by the Ministry of the Environment aimed at directing Public Administrations toward a rationalization of consumption and purchasing by providing indications for the identification of design solutions, products or services that are better from an environmental point of view.” Regarding educational buildings, it provides for the use of materials and design solutions suitable for achieving the values indicated for acoustic descriptors by UNI 11367 [60] and UNI 15532 [61] standards.

1.2.3 Italian National Legislation: D.M. 11.10.2017 on “Minimum Environmental Criteria”

The D.M. 11.10.2017 “Minimum Environmental Criteria for the awarding of design services and works for the new construction, renovation, and maintenance of public buildings” [58]; stipulates in the acoustic field that professionals provide evidence of compliance with the requirements, both at the design stage and at the final verification of compliance through an acoustic design and a test Report prepared through acoustic measurements in-situ, by UNI 11367 [60], UNI 11444 [65] and UNI 11532 [61] standards or equivalent standards attesting to the achievement of the required acoustic class.

In schools, the Decree indicates that the building's passive acoustic requirement values must meet the “superior performance” level given in UNI 11367 Appendix A Schedule A.1 [60]. The “good performance” values in UNI 11367 Appendix B prospectus B.1 [60] must also be met. Indoor rooms must be suitable for achieving the values indicated for the acoustic descriptors given in the UNI 11532 [61] standard.

1.2.4 Italian National Legislation: D.M. 22.06.2022

The D.M. 22.06.2022 [59] updates the Minimum Environmental Criteria requirements previously defined in Decree 11.10.2017 for public buildings subject to new construction, renovation, and maintenance tenders.

A novelty introduced by the Decree concerns the requirement to prepare a Technical Report, accompanied by the relevant documents, in which the designer describes in detail, for each criterion, the design choices made. This document must specify how the requirements have been applied, the integration of materials, components, and technologies adopted, as well as a list of graphical drawings, diagrams, calculation tables, and others, highlighting (i) the ante operam state; (ii) the planned interventions; (iii) the achievable results; and (iv) the post opera state. In addition, compliance with the criteria defined in the CAM document must be demonstrated.

The theme of acoustic comfort is addressed in Chapter 2.4.11, which includes requirements in line with UNI 11367[60] and UNI 11532 [61] standards. In particular:

- the passive acoustic requirements of technical elements must comply with at least Class II of UNI 11367 standard [60];
- schools must meet the passive acoustic and indoor acoustic comfort requirements of UNI 11532-2 standard [39];
- hospitals and nursing homes must meet the “superior performance” level given in Appendix A of the UNI 11367 standard [60];
- Sound insulation between common areas and living spaces must meet at least the “good performance” values given in Appendix B of UNI 11367 standard [60];
- indoor environments, except for schools, must comply with the reference values given in Appendix C of the UNI 11367 standard [60] for parameters such as reverberation time and STI (Speech Transmission Index).

1.2.5 Technical Standard: UNI 11367

Technical standard UNI 11367 [60] guides the acoustic quality of buildings through the method of acoustic classification of building units based on the measurement of the passive acoustic requirements of buildings. This classification does not apply to school buildings, but reference values are provided in the standard on requirements covering sound insulation, system noise, and speech intelligibility.

1.2.6 Technical Standard: UNI 11532

UNI11532 standard [61] identifies which descriptors best represent the acoustic quality, techniques for predictive calculation and in-place measurement, and reference values according to the environment's intended use. The standard is developed in several parts: Part 1, "General Requirements", which defines the descriptors to be used and the procedures for calculations and measurements. Part 2 is specific to the educational environment.

Focusing on UNI 15532-2 standard [39], which provides guidelines for the design of acoustically suitable environments for both teaching staff and pupils and defining acoustic descriptors and their reference values that represent acoustic quality for the school sector. The standard classifies rooms into different categories, depending on their intended use by reporting their description (Table 3). An innovative element is the introduction of a new category related to the design of environments intended for occupants who learn a second language or who have auditory disadvantages, reflecting a focus on the need for inclusiveness.

Table 3: Room categories about activities in the environment and detailed description for categories A1 to A6. From UNI 11532-2.

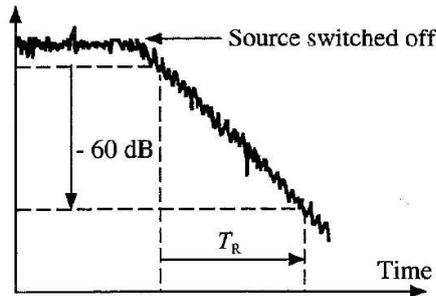
Category	Activities in the environment	Purpose description
A1	Music	Music. Musical performances.
A2	Speaking/conference	Speaking/conference. Presentations with frontal speaker.
A3	A3.1	Lecture/communication as speech/conference (large classrooms) teacher-student interaction
	A3.2	Speech. Communication with the simultaneous presence of multiple speakers in the classroom.
A4	Lecture/communication, including special classrooms	Multiple speaking people in the room (as category A3.2) and designated for people with special needs (special classrooms). Excluding special classrooms with volume over 500 m ³ , or for musical use.
A5	Sport	Sports: swimming pools and gyms.
A6	Non-learning areas and spaces and libraries	

The standard defines reference values for the descriptors of the acoustic performance of building elements, referring to the UNI 11367 standard [60]. Other parameters considered are the optimal

reverberation time, the maximum noise level in the environment, and other essential parameters to ensure good communication and comfort in educational spaces.

Reverberation time is an acoustic parameter of environments determined by the decay curve of the sound pressure level over time, at a point in space, after a sound source is turned off. The UNI 3382-2 standard [66] defines it as the time, in seconds, required for the sound pressure level generated by a source within the room to decrease by 60 dB after the source has been turned off [67].

Figure 1: Representation of the decay curve of sound pressure level for the definition of reverberation time.



To relate reverberation time to room characteristics such as volume and equivalent sound absorption area, Wallace C. Sabine determined a law known as “Sabine's formula” (1):

$$T = 0.16 \frac{V}{A_{tot}} \text{ [s]} \quad (1)$$

With:

V is the volume of the environment [m^3];

A_{tot} is the equivalent sound absorption area [m^2].

The Equivalent Sound Absorption Area of a room is calculated by the following formula:

$$A_{tot} = \sum_{i=1}^k \alpha_i S_i + \sum_{j=1}^g n_j A_j + 4mV \text{ [m}^2\text{]} \quad (2)$$

With:

α_i and S_i are the sound absorption coefficient and the area of the i -th surface in the room, respectively [m^2];

k is the number of surfaces;

n_j and A_j are the number of absorbing units of the j -th type and the equivalent absorption in m^2 in a unit of the j -th type, respectively;

g is the number of types of absorbing units;

m is the power attenuation coefficient calculated according to ISO 9613-1 standard [m^{-1}] [68];

V is the volume of the environment [m^3].

UNI 11532-2 standard [39] introduces the definition of optimal reverberation time T_{ott} , calculated considering a conventional room occupancy of 80%. This value is determined by the use of the room considered and its volume. Figure 2 shows the dependence of the optimal reverberation time T_{ott} on volume for different uses. Around this value, which varies with volume, there is a compliance window in the frequency range of 125-4000 Hz. This means that for each frequency band, in both validation and testing, the reverberation time must fall within the gray area depicted in Figure 3.

Regarding ambient noise, which is crucial for ensuring clear speech intelligibility, it is essential to assess the overall noise, L_{amb} , that will occur in the furnished but unoccupied environment. L_{amb} represents the overall noise determined by noise from sources outside the school and noise from continuously operating facilities serving the environment relative to a midweek morning representative of the noise climate present with the facilities operating at regular operation. Table 4 shows the reference values.

Table 4: Reference value of L_{amb} . From UNI 11532-2.

Purpose description	L_{amb} [dB(A)]
Classrooms and libraries < 250 m ³	≤38
Classrooms and libraries ≥ 250 m ³	≤41
Office	≤38
Exhibition rooms, study spaces	≤48
Gyms, swimming pools, administration offices, laboratories, open areas to the public, cafeterias, hallways, reception/desk area	≤48

Figure 2: Dependency of optimal reverberation time T_{ott} on the volume of the activity in the environment. On the x-axis, the volume in m³ is shown, on the y-axis the optimal reverberation time T_{ott} in s. From UNI 11532-2

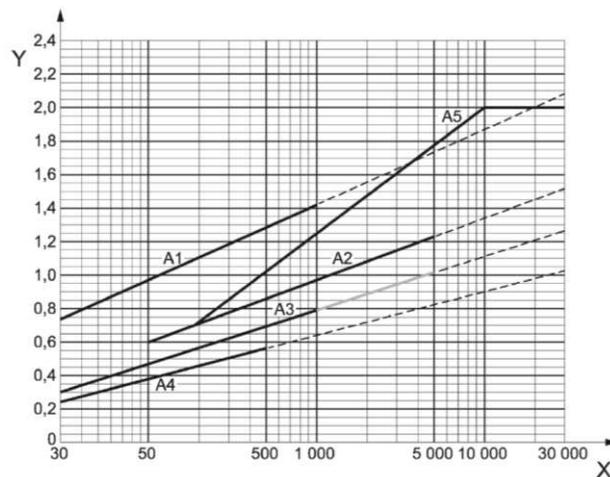
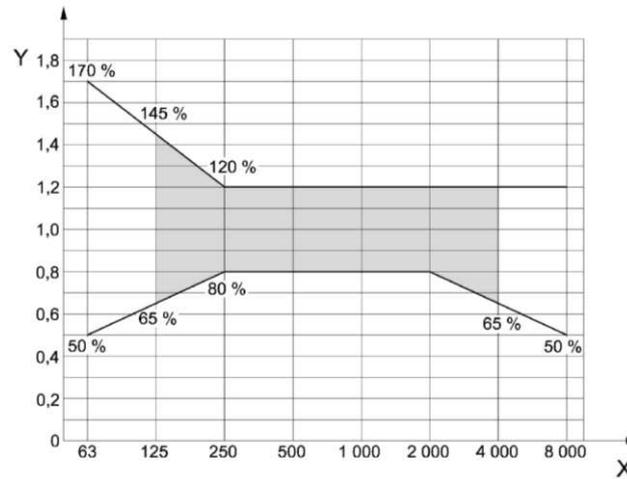


Figure 3: Trend and compliance interval of frequency-dependent reverberation time T for categories A1 to A4. The x-axis shows the frequency in Hz, and the y-axis shows the T/T_{ott}. From UNI 11532-2



The standard introduces Speech Transmission Index (STI) and Speech Clarity Index C_{50} .

STI, defined in IEC 60268-16 standard [69], was introduced and developed by Houtgast and Steeneken as an objective method for assessing the quality of a communication channel, which can be affected by various acoustic and electroacoustic distortions. Speech is a signal that fluctuates over time in the sound intensity envelope. Slower fluctuations in the envelope represent boundaries between words and phrases, while faster fluctuations correspond to individual phonemes within words. Phonemes are considered the fundamental units of speech and connected discourse. Preserving the intensity envelope ensures high intelligibility.

STI index evaluates the extent to which intelligibility is maintained, providing a value between 0 and 1. The calculation is based on weighted contributions from seven-octave frequency bands where speech energy is significant. Specifically, a modulation transfer function determines the degradation of the intensity envelope and signal fluctuations caused by the transmission channel [70], [71], [72]. STI model describes an ideal situation in which a speaker with a standardized male vocal spectrum speaks with good articulation, at a nominal rate of about 3–4 syllables per second, assuming that listeners have normal hearing. However, people adapt their speaking and listening styles based on many factors, such as age, gender, native language, and the social relationship between the speaker and listener. Speech intelligibility may also be influenced by conditions such as speech and hearing disorders. For non-native speakers/listeners and listeners with hearing loss, corrections can be applied according to IEC standards. Figure 4 illustrates the effect of the acoustic properties of the environment on the speech signal. The top part of the image shows the speaker's position in the room marked with a cross and the receiver's position with a circle. In the lower part, the modulation transfer function is evaluated for each modulation frequency within each octave band.

The reference values of STI indicated in UNI 11532-2 standard [39] are reported in Table 5. Table 6 provides the speech quality classification based on STI index ranges as described by the IEC 60268-16 standard [69].

Figure 4: Modulation transfer function - input/output comparison. Parameters m_1 and m_2 are the modulation depths of respectively input and output signals; \bar{I}_1 and \bar{I}_0 are the input and output intensities. From IEC 60268-16. Sound System Equipment-part 16: Objective rating of speech intelligibility by speech transmission index

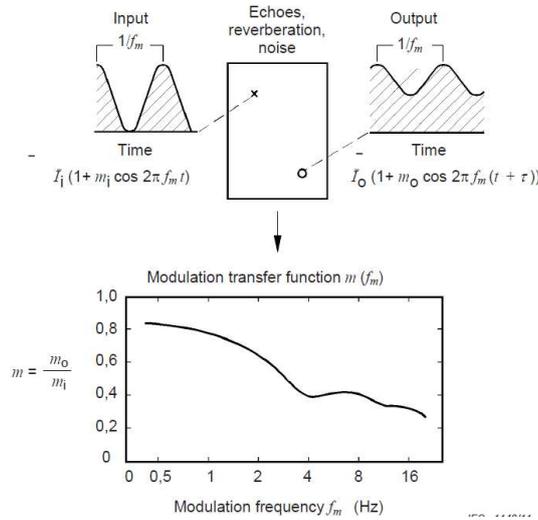


Table 5: Reference value of STI. From UNI 11532-2.

	< 250 m ³	≥250 m ³
Without an amplification system or with the system turned off	≥0.55 With the emission signal at 1m on the axis to the source equal to 60 dB(A)	≥0.50 With the emission signal at 1m on the axis to the source equal to 70 dB(A)
With amplification system	≥0.60 With emission signal under normal conditions of use of the amplification system	

Table 6: Description of speech quality according to IEC 60268-16 based on the STI index intervals.

STI value	STI label categories according to IEC 60268-16
0 < STI ≤ 0.30	Bad
0.30 < STI ≤ 0.45	Poor
0.45 < STI ≤ 0.60	Fair
0.60 < STI ≤ 0.75	Good
0.75 < STI ≤ 1.00	Excellent

For environments in categories A1, A2, A3, and A4 with volumes less than 250 m³, Speech Clarity Index, C₅₀, can be used as an alternative to STI. This index was defined by Cremer and Muller [73] and is defined as the ratio of sound energy reaching the listener in the first 50 ms at the end of signal decay [74]. The index is determined by the equation:

$$C_{50} = 10 \log \frac{\int_0^{50 \text{ ms}} p^2(\tau) d\tau}{\int_{50 \text{ ms}}^{\infty} p^2(\tau) d\tau} \quad (3)$$

Where:

$p(\tau)$ is the sound pressure, defined as the response to the impulse emitted by a source with $\tau=0$ corresponding to the instant when the direct sound reaches the receiving point

The numerator is the useful energy that reaches the listener within the first 50 ms; the denominator is the harmful energy that reaches the listener in subsequent instants. The perception of clarity depends on the human brain's ability to integrate direct sound with early reflections, allowing clear and distinct syllables or notes. The reference values in UNI 11532-2 standard [39] are given in Table 7.

Table 7: Reference value of C_{50} . From UNI 11532-2.

	$< 250 \text{ m}^3$
Without amplification system	$\geq 2 \text{ dB}$

The standard identifies the user positions where to perform measurements during the testing phase about the size and dimensions of the environment and the possible presence of amplification systems (Figure 5). It also indicates the required and optional positions in Table 8.

Figure 5: Measurement positions about the source of the speech signal. From UNI 11532-2.

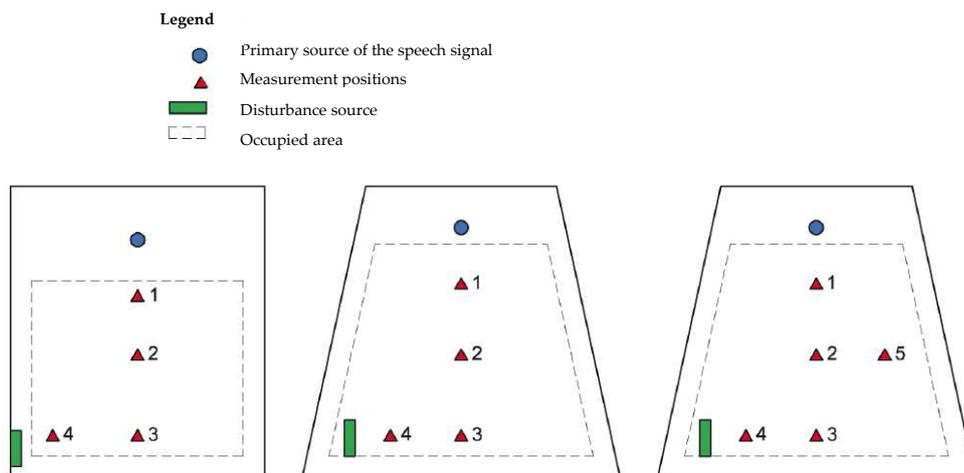


Table 8: Required and optional measurement positions. From UNI 11532-2.

Position	$< 250 \text{ m}^3$		$\geq 250 \text{ m}^3$	
	STI - C_{50}		STI	
	Without amplification system		Without amplification system	With amplification system
	Required	Optional	Required	Optional
1		☒	☒	☒
2	☒		☒	☒
3		☒	☒	☒
4	☒		☒	☒
5				☒

1.3 New Parameters for Evaluation of the Sound Levels Variability in Educational Spaces

To characterize the noise level of a room, the indicator that is commonly used is the equivalent sound level, $L_{Aeq,T}$. This is the value of the sound pressure level, weighted according to the "A" curve, of a constant sound that, over a specified period T has the same root mean square pressure as the sound being considered, whose level varies over time (calculated using equation (4)). Alternatively, its statistical value, L_{A95} , may be used. This represents the sound pressure level that is exceeded by 95% of the measured values during the measurement period.

$$L_{Aeq,T} = 10 \log \left[\frac{1}{T} \int_0^T \frac{p_A^2(t)}{p_0^2} dt \right] [dB(A)] \quad (4)$$

Where:

$p_A(t)$ is the instantaneous value of the "A" weighted sound pressure of the acoustic signal in Pascal;

$p_0=2 \cdot 10^{-5}$ Pa is the reference sound pressure;

T Is the time that is considered for the evaluation of the equivalent continuous sound level.

However, sound pressure level alone may not be sufficient to characterize the variability of the measured noise. Studies have shown that variations in sound levels over time, their frequency, and their magnitude relative to background noise can have a significant impact on well-being and health. One of the most common non-auditory effects in populations exposed to environmental noise is annoyance. This can result from interference with daily activities, rest, or sleep and may be accompanied by negative emotional and behavioral responses such as anger, distress, and stress [75], [76]. Recent studies aimed at analyzing the variability of the soundscape about anthropogenic activities [77], [78] and at identifying the relationship between sound events and body movements during sleep [79], have employed a metric called the IR index. This metric expresses the percentage of sound energy, out of the total energy received by an environment, that is determined by noise events exceeding a certain threshold during a given period [80]. Such metrics could prove to be useful and supportive of acoustic parameters commonly used in the school setting as well. This is because students are subject to variations in sound levels that depend on contextual factors such as the acoustic characteristics of the environment, the number of people in the environment, and the activities performed, and that can influence students' behaviors and development.

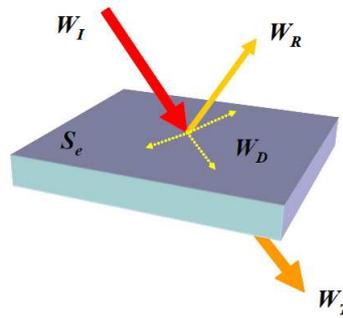
1.4 Sound Absorption Materials for Educational Buildings

The primary acoustic requirement of a classroom is to provide a good level of speech intelligibility while a teacher is speaking. During self-learning activities, the classroom should primarily offer a quiet environment to aid concentration on individual tasks; therefore, the noise level caused by the speech of other children must be as low as possible, ensuring it is not intelligible [81].

The use of sound-absorbing materials helps to reduce sound reverberation, absorb energy from late and unwanted reflections, and attenuate background noise. The selection of these materials must aim to achieve the optimal reverberation time across different frequency bands, depending on the intended use of the space.

Each material is characterized by a specific sound absorption coefficient, α , which is the ratio of sound energy not reflected (absorbed and transmitted) to the energy incident on the material. Its value ranges from 0 (when all energy is reflected) to 1 (when all energy is absorbed) and depends on the angle of incidence of the sound wave.

Figure 6: Distribution of the sound wave incident on the surface of a material. Where: W_I is the incident sound energy; W_R is the sound energy reflected; W_T is the transmitted sound energy; W_D is the sound energy absorbed.



$$\alpha = \frac{W_I - W_R}{W_I} = \frac{W_D + W_T}{W_I} \quad (5)$$

Where:

W_I is incident sound energy;

W_R is sound energy reflected;

W_D is sound energy absorbed by the material;

W_T is transmitted sound energy.

Each material, depending on its working principle, can be divided into three categories:

- Porous or fibrous materials: materials that rely on viscous dissipation;
- Cavity or Helmholtz resonator: materials that exploit cavity resonance;
- Panel or membrane resonators: materials that utilize panel resonance.

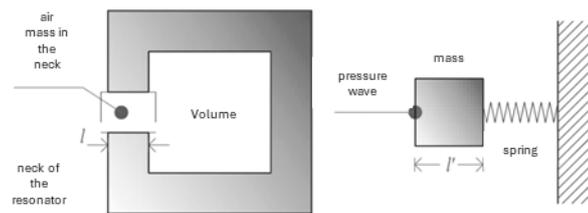
Absorption in porous materials occurs through the conversion of mechanical energy carried by the incident wave into heat, facilitated by friction phenomena within the micro-cavities open to the air. The incident acoustic wave oscillates the air inside the pores, which dissipates energy by viscous friction. Absorption increases with the material's porosity [82].

Cavity resonators, known as Helmholtz resonators, provide selective absorption at their resonance frequency, typically in the mid-to-low frequency range. They consist of a volume of air enclosed in a cavity with rigid walls, connected to the external environment through a relatively narrow opening,

called the "neck" of the resonator. When a sound wave strikes the neck, the air within the cavity undergoes periodic compressions and rarefactions.

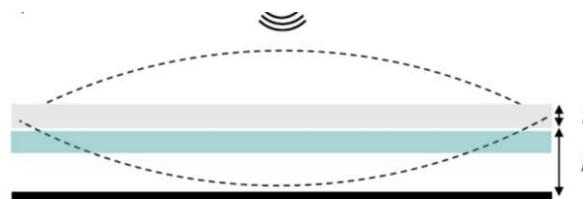
Analogous to mechanical systems, the air in the neck behaves like a vibrating mass, while the air in the cavity acts as an acoustic spring, forming a mass-spring system. This type of resonator dissipates acoustic energy by converting it into heat due to viscous friction caused by air oscillations in the neck. Dissipation primarily occurs at the system's fundamental resonance frequency, triggered by the sound wave incident on the mouth of the resonator [83].

Figure 7: Scheme and working principle of a cavity resonator.



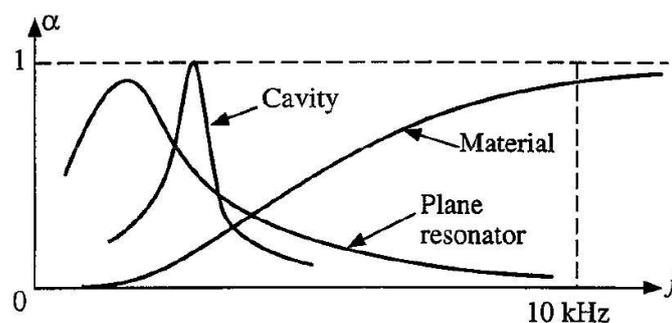
Panel resonator, in response to the sound wave, vibrates on a cushion of air and absorbs acoustic energy at low frequencies through viscous dissipation caused by the flexural vibrations of the panel.

Figure 8: Schematic operation of a panel resonator



Each of these mechanisms is effective within a specific frequency range. By combining multiple mechanisms, it is possible to create a material that absorbs sound across the entire audible frequency spectrum. Figure 9 illustrates the absorption curves of porous sound-absorbing materials, cavity resonators, and vibrating panels, along with the frequency ranges in which they are most efficient.

Figure 9: Sound absorption curve corresponding to porous materials, cavity resonator, and plane resonator [84].

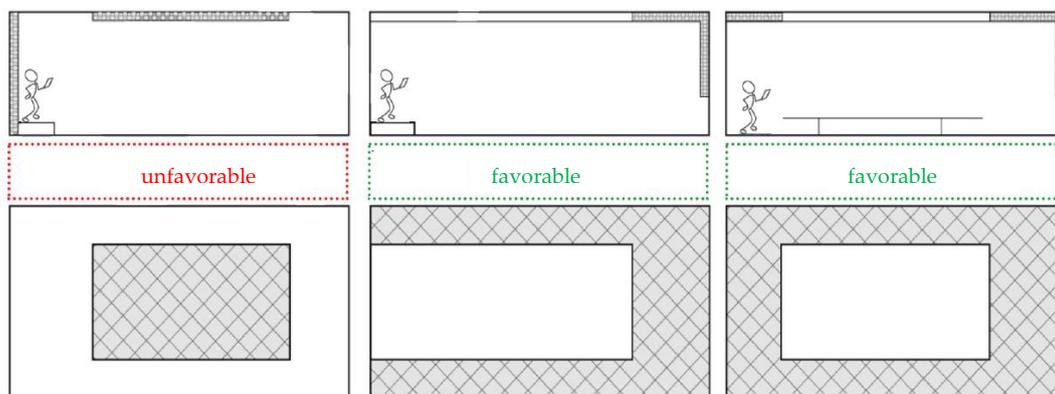


The acoustic comfort of educational spaces is generally ensured by achieving specific target reverberation values. To meet these objectives, common practice involves using acoustical ceiling tiles with uniformly absorbing surfaces [85]. However, this approach may compromise compliance with the conditions required by the classical diffuse field theory due to the uneven distribution of the room's total absorbing materials.

In contrast, using heterogeneous surfaces ensures an appropriate balance between the sound absorption provided by the presence of people and that offered by the classroom itself, thereby improving speech intelligibility conditions [86]. The first surfaces to be treated should be the back wall and the rear portion of the ceiling, followed by the upper areas of the side walls, starting from the back of the classroom. To avoid reducing the sound level at listening positions, it is advisable not to place sound-absorbing materials near the sound source.

The best practice is to maintain a central acoustically reflective area on the ceiling to provide an effective early reflection of the speaker's sound (Figure 10).

Figure 10: Section and plan distribution of sound-absorbing surfaces in small and medium-sized school environments. From Guidelines AIA [87]



However, a challenge in treating walls in school classrooms is the presence of educational materials, posters, and drawings affixed to the walls, which reduces the free surfaces available for acoustic interventions.

Porous materials are often covered with woven fabrics, considered acoustically transparent coverings. [88], but these may not always integrate aesthetically with the environment. Applying a layer of paint to these fabrics could represent an aesthetic solution, making the materials more visually suitable for the context while maintaining their original sound-absorbing function and adding an artistic element. Studies have shown that a layer of spray paint could preserve the acoustic properties of the material [89] [90] and that the sound absorption of paintings supported by an absorber depends on factors such as whether the fabric is made permeable or impermeable by the paint, the thickness of the paint, the dimensions of the painting, and other factors that could be used to vary the sound absorption coefficient across frequencies [91] [92].

Another crucial point concerns the variation in material absorption depending on their placement in the environment. ISO 354 standard [93] specifies that the average reverberation time of the reverberation chamber must be measured with and without the test specimens installed. From this

measurement, the equivalent sound absorption area of the sample is calculated using the Sabine equation.

For a sample that uniformly covers a surface (a plane absorber or a specified array of test objects), the sound absorption coefficient is obtained by dividing the difference in absorption area between the empty and full chamber by the projection of the surface area affected by the setup [94]. For samples consisting of discrete objects, the sound absorption area of each object is calculated by dividing the total area by the number of objects used.

For the three possible configurations of samples in a reverberation chamber (plane absorber, array of objects, and discrete objects), the standard provides installation specifications for only six setup conditions—five for plane absorbers and one for “baffles” (arrays of objects arranged at regular intervals, orthogonal to a reflective plane).

When a sample can be used in a way that is interchangeable in any of the three possible configurations, the issue arises of which reference condition should be assumed for its acoustic characterization. The setup of samples within the reverberation chamber thus becomes a critical aspect, as it can influence the resulting sound absorption measurement.

2. Methods

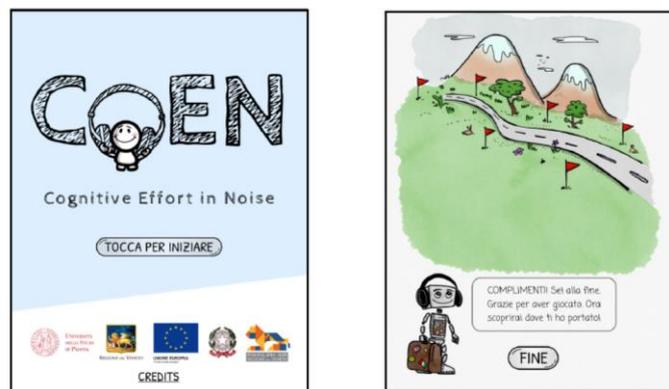
This chapter describes the methodology developed during the doctoral program to evaluate the effects of acoustic conditions on primary school students' cognitive and learning performance and in a group of university students.

In the first part, the tests used and the scoring methods for performance assessment are presented. The acoustic conditions to which the students were subjected during the performance of the tests are also presented, and the characteristics of the sound signals emitted are given. In the second part, a description of the instruments used for conducting acoustic monitoring in the exercise conditions of school environments is provided.

2.1 Evaluation of Cognitive Performance and Learning Abilities of Primary School Children

Children's cognitive abilities are assessed with neuropsychological tests administered in the form of a tablet game using the iOS application "CoEN-Cognitive Effort in Noise" [95]. CoEN was developed by researchers at the University of Padova and the University of Venice.

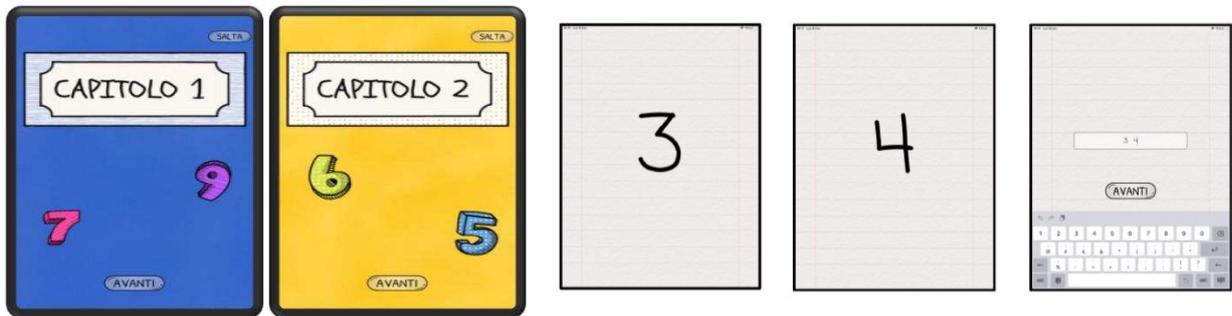
Figure 11: The user interface of the CoEN App.



CoEN includes five tasks, among which there are adaptations of standardized neuropsychological tests such as Digit Span Test (Forward and Backward), a visual attention test from WISC-IV (cancellation subtest) [96], a visual attention test from NEPSY-II (visual search for faces) [97], a Reading span [98] and Cognitive Inhibition Task adapted from Diamond et al.[99].

In the Digit Span Test, verbal working memory is assessed. Children are asked to remember a series of digits in the same order (or in reverse order for the backward subtest) as they are visually presented on the screen. Children shall type the set of digits on a keyboard in direct (forward span) or reverse (backward span) order. The scoring criteria are: a score of 2 is given when children remember both items in a set, while a score of 1 is given if they remember only one of the two items correctly. The task ends when children fail to remember two consecutive sets of digits of the same length.

Figure 12: The user interface of CoEN App: Digit Span Test



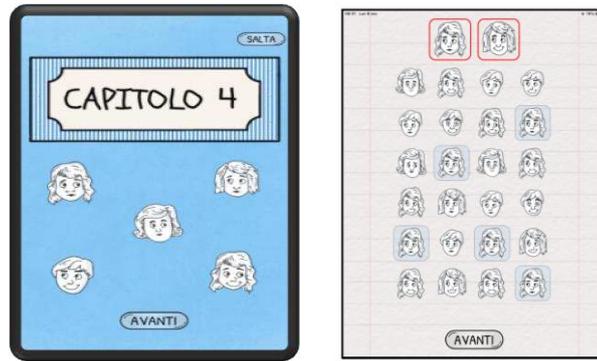
The Reading span [98] is an Italian reading test adapted from Daneman and Carpenter's original task [100]. Children are asked to read a series of sentences. The task involves two activities: understanding each sentence by answering a true/false question and memorizing the final word of each sentence to be written down later. The sentences are presented in progressively increasing groups of two to five sentences per group for a total of 28 syntactically and semantically simple sentences. At the end of each set, participants must remember and write down all the final words. The task ends if the participant cannot remember the final words of two consecutive series. The item is considered complete if the child remembers the words, even if not in the correct serial order. Scoring is assigned as follows: a word is scored 2 if it is remembered in the correct serial order, and a score of 1 for words that are remembered correctly but out of the original sequence. All answers are considered correct regardless of grammatical errors or mispronunciation, ensuring that minor errors do not affect the overall grade.

Figure 13: The user interface of the CoEN App: Reading Span Test



The visual attention test (NEPSY-II) [97] consists of identifying target faces from a page displayed on the tablet screen in CoEN, which also contains distractors. The test consists of identifying two faces with certain features amidst other similar faces but with different features (e.g., different gaze direction, haircut, etc.). The test is timed; the child has only three minutes to identify as many target stimuli as possible among several pages of distractor stimuli. The final score is given by the number of correctly identified faces subtracted by those incorrectly identified.

Figure 14: The user interface of CoEN App: Attention Test



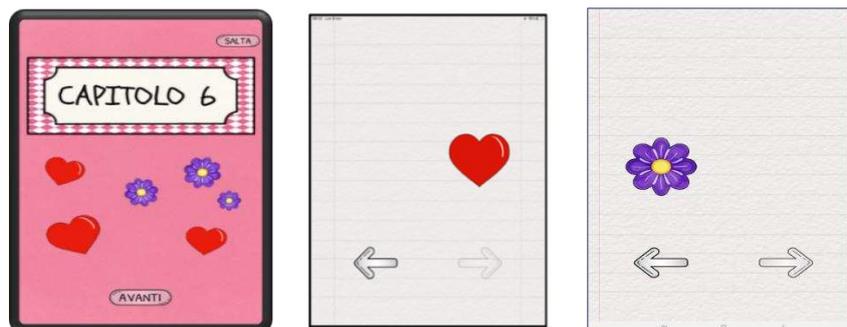
The Cancellation Test (WISC-IV) [96] is similar to the NEPSY-II test but has a shorter duration. The test consists of recognizing and identifying which drawings represent animals amid other stimuli (e.g., trees, musical instruments, cars, etc.). It gives just 90 seconds to identify as many target stimuli as possible among the different pages of distractor stimuli. The final score is the number of correctly identified animals subtracted from the number of incorrectly identified animals.

Figure 15: The user interface of CoEN App: Cancellation Test



The Inhibition task [99] assesses inhibitory control by displaying a red heart or a flower on either side of the tablet screen. The child must tap the arrow corresponding to the side of the heart (congruent condition) or the opposite side when a flower appears (non-congruent condition). The final score on the test is given by the number of arrows clicked correctly (e.g., heart to the right, arrow to the right; flower to the right, arrow to the left).

Figure 16: The user interface of CoEN App: Inhibition Test



Learning abilities are assessed with a comprehension task and a writing task to be carried out on paper. In the comprehension task, children are asked to read age-appropriate passages, and they are asked to answer a series of multiple-choice questions. Each question has four answers of which only one is correct. The final score is obtained by awarding one point for each correct answer, and the maximum that can be obtained is 14. The Appendix A – Learning Ability Tests for Quiet and Noisy Conditions in Figure 64 and Figure 65 shows the texts used for the tests and the corresponding questions to assess text comprehension.

In the writing task, the Sentence Generation Test [101], children are instructed to write as many sentences as possible within a 5-minute time frame, each containing two given word pairs. The final score is obtained by assigning two points to each sentence that is correct both grammatically and semantically, one point for each sentence that is correct either grammatically or only semantically, and half a point for each sentence with minimal variation (e.g., *la tigre sta nell'acqua – la tigre é nell'acqua*). As the sentence generation task is intended to measure only text generation skills, punctuation, capitalization, or spelling errors were not considered in assessing sentence accuracy.

Appendix A – Learning Ability Tests for Quiet and Noisy Conditions in Figure 66 and Figure 67 shows the extracts of the sheets used with the word combinations used in sentence generation.

Table 9 describes details of the executive functions assessed in the tests administered through CoEN and their description. Table 10 describes the learning tests.

Table 9: List of cognitive tests administered to primary school children and description of executive function (EFs) investigated.

Test	Subtest	Code	Cognitive function (EFs)	Description of EFs	Type of check
Digit Span Test (forward or backward)	Forward	#A1	Verbal working memory	Ability to hold verbal information in mind for short periods and utilize it effectively.	Number of correct responses
	Backward	#A2			
Reading Span	-	#A3	Working memory	Ability to maintain and manipulate information in working memory simultaneously.	Number of correct responses
Visual Attention Test da NEPSY-II e WISC-IV	Attention	#A4	Selective attention	Ability to filter incoming information and focus attention solely on what is relevant to the task or goal.	Ratio of right/wrong responses (accuracy)
	Cancellation	#A5			
Inhibition	Congruent	#A6	Inhibition	Ability to control one's impulses, behaviors, or thoughts to adapt to demands.	Number of correct responses
	Incongruent	#A7			
	Mixed	#A8			

Table 10: List of learning abilities test administered to primary school children.

Test	Code	Description	Type of check
Comprehension	#A9	Evaluate children's abilities in understanding passages	Number of correct responses
Sentence Generation Test	#A10	Children's fluency in generating ideas in written sentences.	Total score

After the testing session, children are asked to fill out a self-report questionnaire to assess cognitive effort. It is taken from the Bess et al. fatigue scale [102] and consists of six items rated on a 5-point Likert scale from “not at all” to “very much” (Appendix B – Self-Report Cognitive Effort Figure 68). The tests are administered during school hours in two sessions, once in quiet conditions and once in noisy conditions. To minimize potential learning effects, all tasks were administered with a minimum interval of two weeks between the two sessions. The quiet condition simulates the usual classroom noise environment that may occur during individual tasks. Children are then asked to be as quiet as possible. The noisy condition reproduces the background noise condition often encountered in classrooms. This condition is recreated by emitting some signals through a Talkbox placed at the teacher's position.

The acoustic signals emitted are a multi-talker babble noise and a multi-talker babble noise with the addition of intermittent transient sounds (e.g. door slamming, door knocking, the sound of ambulance sirens, etc.).

2.2 Evaluation of Sound Power Level of the Signal Emitted

To characterize the signals emitted during cognitive and learning test sessions, the sound power of Talkbox was evaluated in a reverberant room by comparison with a reference sound source (RSS), following the protocol of ISO 3747 standard [103]. The RSS emits a constant broadband noise with a sound power level conforming to the requirements of ISO 6926 standard [104].

The method described in ISO 3747 standard [103] is comparative, as the sound power emitted by Talkbox is compared with the known sound power of a reference sound source.

The procedure involves taking 30-second sound pressure level measurements of the background noise, the source under test, and the RSS at each microphone position (in our case, 6 positions arranged in a circular configuration at 50 cm from the source under test). The number and arrangement of the microphone positions were chosen to ensure full coverage of every signal emitted by the source under test, the reference sound source, and the background noise.

Following the measurements, it is possible to calculate the sound power for each octave band using the formula:

$$L_W = L_{W(RSS)} + 10 \lg \left[\frac{1}{n} \sum_{i=1}^n 10^{0.1 \Delta L_{pi}} \right] [dB] \quad (6)$$

Where:

n is the number of microphones positions;

$L_{w(RSS)}$ is the sound power level of the RSS derived from its calibration;

$$\Delta L_{pi} = L_{pi(ST)} - L_{pi(RSS)}$$

$\Delta L_{pi(ST)}$ and $\Delta L_{pi(RSS)}$ is the sound pressure level of the source under test in microphone position i , corrected for background noise, and the sound pressure level of the RSS in microphone position i , corrected for background noise

Figure 18 and Figure 19 show the frequency spectrum in octave bands of the signals emitted by the tested source. The obtained L_w values are shown in Table 11.

Figure 17: Pictures of sound power evaluation according to ISO 3747 standard of the RSS and signals emitted by the source under test. The signals emitted by the source under test are the signals emitted during the administration of cognitive tests.



Figure 18: Frequency spectrum of the sound power of the Talkbox emitting the babble noise signal measured according to ISO 3747 standard.

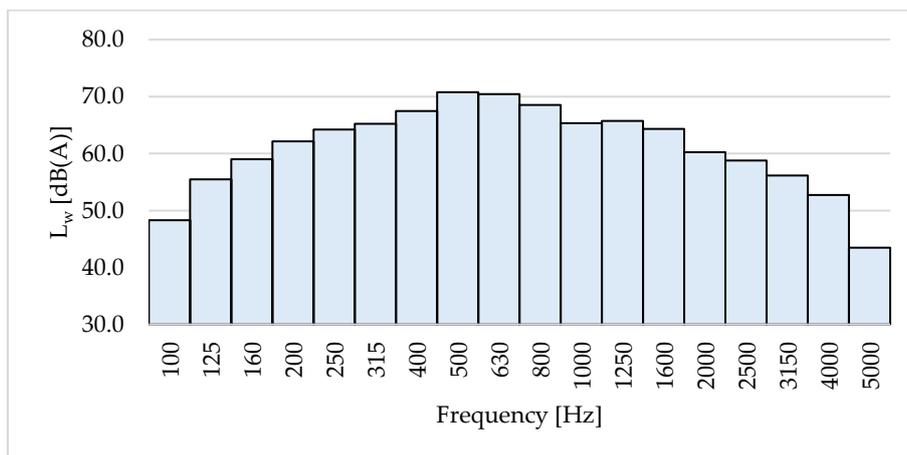


Figure 19: Frequency spectrum of the sound power of the Talkbox emitting the babble noise with transient events signal measured according to ISO 3747 standard.

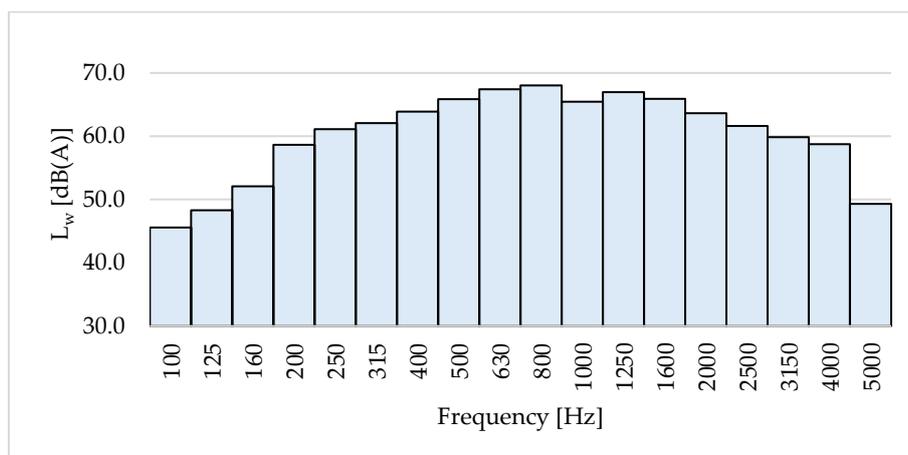


Table 11: Sound power level L_w of the signals emitted by the Talkbox calculated according to the ISO 3747 standard.

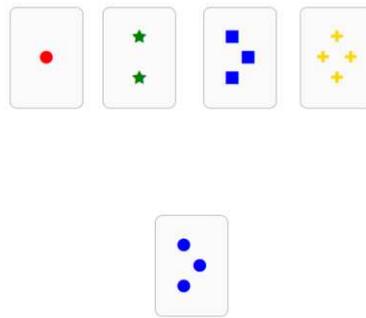
Signal	L_w [dB(A)]
Babble noise	77.5
Babble noise with events	76.0

2.3 Evaluation of the Cognitive Performance of University Students

The cognitive abilities of university students were assessed with neuropsychological tests found on the online platform Neurotask [105]. Before the test is run, there are instruction for the proper execution. Five tasks are administered with Neurotask: the Card Sorting test [106], Digit Span Test Forward, Go-No Go task [107], Flanker Test [108], and Stroop Test [109].

The Card Sorting Test [106] is used to assess the ability for cognitive flexibility. It is used to measure a person's ability to adapt to new rules and change strategy when necessary, as well as the ability to solve problems and make decisions. During the test, four cards are presented at the top of the screen and one at the bottom to be matched to one of them according to a secret rule that must be guessed. The cards can differ in color (e.g. red, green, blue, yellow), shape (e.g. circle, triangle, cross, star), and number (e.g. one star, two stars, three stars). The task is to match the cards in the deck to one of these four cards, following a categorization rule (by color, shape, or number). The rule to be followed is not made explicit, and the participant must infer it through the feedback ("correct" or "incorrect") he or she receives after each choice.

Figure 20: User interface of Neurotask: Card Sorting Test



During the test, the rule guiding the matching is changed without warning. For example, a participant might start by matching cards by color, but later the rule changes and now he or she must match them by shape or number. One must then guess the new rule.

With this test, it is assessed:

- Cognitive flexibility: the ability to adapt to new rules or strategies when previous ones are no longer valid;
- Executive control: The test measures how well a person can handle executive cognitive processes, such as planning, handling multiple rules at once, and the ability to inhibit automatic or inappropriate responses.
- Abstract reasoning: The ability to understand rules and reason abstractly is tested as participants must interpret categories (color, shape, number) without them being explicitly stated.
- Problem-solving skills: The test measures how a person deals with ambiguous or novel situations, trying to deduce the matching rule through trial and error.
- Inhibition of Perseverance: Perseverance means continuing to apply a rule or strategy even when it is evident that it no longer works. People who struggle to change strategies may show perseverance by continuing to rank cards according to an old rule even when feedback says it is wrong.

It is possible to have a maximum of 64 correct answers. The number of times in which a correct answer is given according to the previously valid matching criterion but is incorrect at the time of the new matching criterion (perseverance) and the number of matching rules given correctly is then returned.

The Digit span Test assesses verbal working memory. The participant is asked to remember a series of digits in the same order as they are visually presented on the screen. The participant is then asked to type the series of digits on a keyboard in direct order (forward span). A maximum of 9 digits of string length is expected. Scoring is based on the length of the correctly remembered string.

Figure 21: The user interface of Neurotask: Digit Span Test



The Go-No Go task [107] assesses the inhibitory control. Two letters are displayed on the screen, P and R, with P being the target signal. The candidate must press the spacebar every time they see the letter P. The length of the trial is 20 (presentations of the letters P and R). To evaluate the score, the Signal Detection Theory (SDT) is applied through the calculation of d' prime [110].

SDT is a theory that focuses on an individual's ability to distinguish between two different types of stimuli. This parameter is used to quantify an observer's discrimination ability. According to the theory, when a person must decide on a signal (such as recognizing a sound or image), they are faced with two possibilities:

1. The signal is present (actual stimulus)
2. The signal is absent (only noise)

Depending on what the observer perceives and their decision, there are four possible outcomes:

- Hit: The signal is present, and the person correctly detects it.
- Miss: The signal is present, but the person does not detect it.
- False Alarm: The signal is absent, but the person believes they detected it.
- Correct Rejection: The signal is absent, and the person correctly rejects it.

In summary:

- High d' : means the person has excellent discrimination ability between signals and noise (Hits are much more frequent than False Alarms).
- Low or near 0 d' : indicates the person is unable to distinguish between signal and noise, showing poor discrimination ability.
- Negative d' : may indicate that the person is making more errors (False Alarms) than correct detections.

Figure 22: The user interface of Neurotask: Go-No Go Test



The Stroop Test [109] assesses attention by measuring how well a person can ignore irrelevant information to focus on a task. A series of words written in different colors are presented on the screen. Each word represents the name of a color (e.g., “red,” “green,” “blue”), but can be written in a different ink color than the one it describes. The participant should press the first letter of the ink with which the word is written, ignoring the meaning of the word: r, g, or b. The average reaction time given in the correct answers is returned.

Figure 23: The user interface of Neurotask: Stroop Test

RED

In the Flanker Test [108], a series of visual stimuli consisting of the character set “<” are presented on the screen. The participant is asked to focus on the central stimulus and ignore the other stimuli surrounding it, called flankers. Stimuli can be presented in two main conditions:

- congruent condition: flankers point or are oriented in the same direction as the central stimulus;
- incongruent condition: flankers point in the opposite direction from the central stimulus.

The test assesses how quickly a person can respond to the central cue while ignoring the distraction of the flankers. Incongruent conditions require more cognitive control because the brain must ignore irrelevant information (flankers) and focus only on the central stimulus. The mean time to congruent stimulus responses and the mean time to incongruent responses are returned.

Figure 24: The user interface of Neurotask: Flanker Test

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Table 12 shows in detail the executive functions assessed in the tests administered through Neurotask and their description.

Table 12: List of cognitive tests administered to university students and description of executive function (EFs) investigated.

Test	code	Cognitive function	Description of EFs	Type of check
Card sorting test – correct response	#B1	Problem-solving	Ability for cognitive flexibility.	Number of total correct responses
Card sorting test – matching rules	#B2			Number of correct matching rules
Card sorting test – preservation	#B3			Number of preservations
Digit Span test – forward	#B4	Working memory	Ability to hold verbal information in mind for short periods and utilize it effectively.	Number of correct responses
Go-No Go task	#B5	Inhibition	Ability to control one's impulses, behaviors, or thoughts to adapt to demands.	d-prime score
Flanker test – congruent	#B6			Response Time [ms]
Flanker test – incongruent	#B7			Response Time [ms]
Stroop test	#B8	Attention and Inhibition	Ability to filter incoming information and focus attention solely on what is relevant to the task or goal.	Response Time [ms]

Tests are conducted during class hours in two sessions, one in quiet conditions and one in noisy conditions. The quiet and noisy sessions were counterbalanced between the groups of students participating in the study and took place on the same day, following a short break of a few minutes between the two sessions. After completing the cognitive tasks, participants were asked to fill out a self-report questionnaire to assess cognitive effort. It is derived from the fatigue scale of Bess et al. [102] and consists of six items evaluated on a 5-point Likert scale, ranging from "not at all" to "very much."

Participants were then asked to complete a questionnaire evaluating the IEQ, with the questions and rating scales listed in Appendix C – IEQ Survey Table 39.

The questionnaire investigates the preference and satisfaction with the thermal environment, air quality, visual environment, and acoustic environment at the time of the test. Satisfaction is expressed on a 4-point scale (from satisfied to very dissatisfied), and for the thermal environment, it is influenced by factors such as adequate temperature, humidity, and air speed. For air quality, dissatisfaction may be caused by a feeling of stale air or the presence of unpleasant odors. Visual satisfaction is influenced by factors such as proper lighting and the absence of glare. Acoustic dissatisfaction may arise when

there are difficulties in distinguishing the teacher's words, communicating, or performing a task due to noise.

The preference for the thermal environment reveals the source of discomfort by specifying the direction of change concerning the overall perception of the thermal condition at the time the participant responds. The visual environment helps identify the source of discomfort and evaluates the situation more specifically at the moment the participant responds. In the air quality and acoustic domains, the preference indicates the extent of discomfort relative to the condition at the time the participant responds.

2.4 Acoustic and Environmental Long-Term Measurement

The sound pressure levels to which the students are exposed during regular school activities were measured by placing an iOS tablet connected to an omnidirectional condenser microphone near the teacher's desk.

The sound pressure levels were recorded using the OpeNoise app [111], [112], an open-source application developed by Arpa Piemonte. The app can be downloaded for free from the Play Store. It allows the acquisition and saving of L_{Aeq} with a 1-second sampling rate in a .txt file. Figure 25 shows the application's main screen.

Figure 25: OpeNoise application user interface: the interface shows the date, time, and duration of the measurement. Minimum and maximum A-weighted equivalent level (L_{Amax} , L_{Amin}) and equivalent level of the measurement ($L_{Aeq(t)}$). The graph shows the time history per second of the measured sound levels ($L_{Aeq,1s}$) and the time-integrated level value ($L_{Aeq(t)}$).



In the settings, it is possible to calibrate the microphone to ensure the reliability of the sound levels measured with the application. The calibration is performed by comparing it with a Class 1 sound level meter while measuring an RSS that complies with the requirements of ISO 6926 standard [113], in the reverberation room of the "LabAcus" acoustics laboratory at the Department of Industrial Engineering, University of Padova. The calibration involves comparing the $L_{Aeq,30s}$ of the noise emitted in the reverberation room by the RSS, measured with the Class 1 sound level meter and the low-cost instrumentation. The difference between the $L_{Aeq,30s}$ measured with the two instruments determines the gain to be set in the OpeNoise application installed on the low-cost device. Figure 27 shows the sound

pressure levels acquired by the sound level meter and the OpeNoise application installed on the four devices, before and after calibration. Table 13 shows the gain added to the screen related to the calibration of the application in each instrument used.

Another type of comparison is performed to assess the dynamic range of Class 2 instrumentation. It compares the $L_{Aeq,1s}$ of pink noise emitted from a dodecahedron in a reverberation chamber at levels ranging from 45 to 95 dB with 5 dB increments (7 noise levels), measured by Class 1 and Class 2 instrumentation. The measurement range was selected to reflect most of the typical noise exposures in today's workplaces [114], [115].

Figure 26: Calibration of OpeNoise application by comparison with RSS.



Figure 27: $L_{Aeq,1s}$ of the instruments before (a) and after (b) the calibration performed by comparison with RSS.

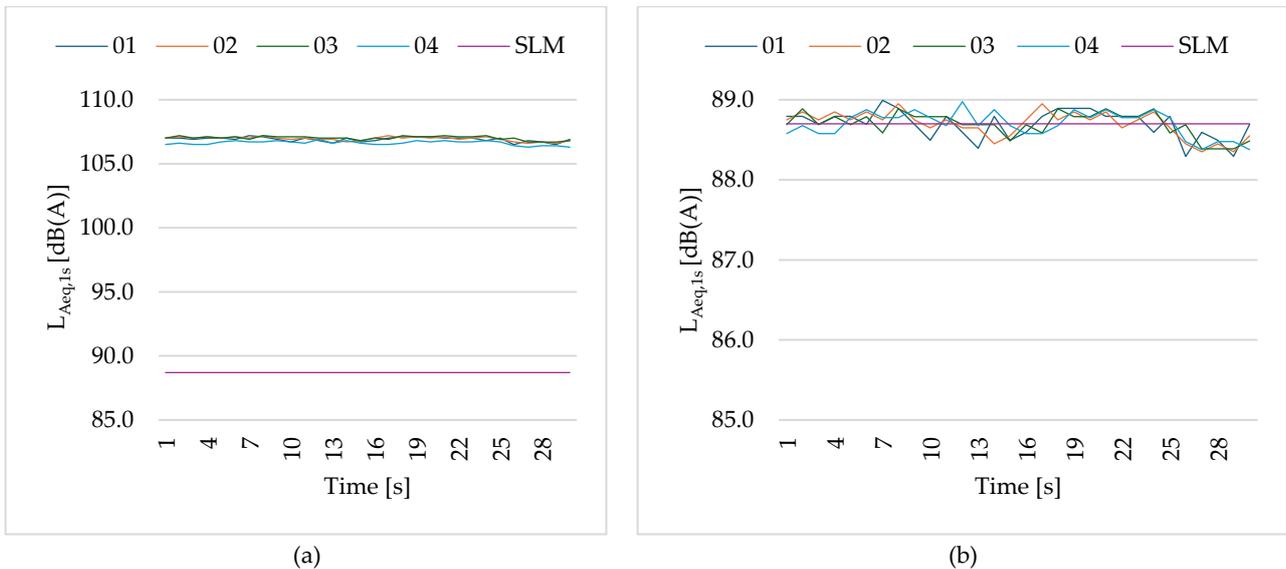


Table 13: Gain value set in the OpeNoise app in each tablet used for acoustic monitoring conducted.

Instrument	Correction from calibration
01	-1.4
02	-1.4
03	-1.5
04	-1.1

At the same time as the acquisitions of sound pressure levels, HOBO connect MX1102 and HOBO connect MX1104 sensors whose instrumental characteristics are given in Appendix D – Instruments

Characteristics Table 40, the parameters necessary for the assessment of thermal environment, which represents the set of environmental conditions that affect the thermohygrometric balance of the body and affect the sensation and comfort of the occupants, and of the air quality, which represents what the occupants breathe, are acquired.

2.5 Sound-Absorbing Materials for Primary School

Providing suitable environmental conditions for indoor spaces is a need that is becoming increasingly important, especially in places where acoustics affect learning and listening skills, such as classrooms. It is well known that primary school classrooms are decorated with numerous drawings on the walls and paper-based teaching materials, which create a lively and colorful environment. Considering the design of acoustic improvement interventions that also serve as educational aids, a solution was explored that combines acoustic enhancement with the use of materials that also function as educational and artistic supports. In this context, the suitability of polyester fiber panels was assessed by examining their sound-absorbing properties before and after the application of a painted layer. For this purpose, teachers were asked to use sound-absorbing panels as painting support for art education exercises.

To evaluate the suitability of the supports and the change in their sound-absorbing characteristics after the application of a paint layer, comparative tests were conducted in a reverberation room using the methods outlined in ISO 354 standard [93]. Panels were tested first in their original condition and then after decoration by primary school students, and the Equivalent Absorption Area was calculated. Additional measurements following the ISO 354 standard [93] were carried out to study the effect of distributing the sound-absorbing material in a configuration other than a plane absorber, arranging the material to alternate reflective and absorbing elements on a surface.

Figure 28: Activities of using sound-absorbing panels as painting support by primary school students.



3. Application in Classrooms – Evaluation of Cognitive Performance and Learning Abilities of Primary School Children

Primary school represents the first context in which assessments of cognitive and learning performance have been carried out. The reason lies in the need to assess these aspects in the early stages of students' growth since the maturation of knowledge occurs precisely at these stages.

The chapter shows the application of the described method in three primary schools located in the province of Padova.

Figure 29: Localization of case studies.



Students tested belong to fourth-grade classes (ages 9-10). The three schools, one of which is divided into two campuses, are located in an urban context with low traffic intensity and are surrounded by a green area near the school, making them comparable. In fact, in the absence of school activities and under normal external traffic conditions, an $L_{Aeq} < 30$ dB(A) was measured. Schools, referred to as schools A, B, and C, are located in buildings dating back to the 1970s. Schools A and C are developed on two floors (the ground floor and the first floor). School B is on the ground floor, and the classrooms have large windows on one side of the room. Only one classroom in school C has windows on two sides. Only school A has acoustic improvement interventions, which consist of a suspended ceiling. Schools A and B are equipped with radiator heating systems, while school C, on the Villatora campus, has a floor heating system. The three schools are not equipped with mechanical ventilation systems.

The number of participants and the number of classes tested in each school are:

- School A, located in Torreglia, Padova: children from two classes with a total of 31 children (18 females) were tested, mean age $9,2 \pm 0.4$ years;
- School B, located in Albignese, Padova: children from four classes with a total of 92 children (52 girls) were tested, mean age 9.08 ± 0.38 years;

- School C, classrooms are located in two school buildings, the first located in Villatora, the second in Saonara, both in Padova, Italy: children in four and one classrooms, respectively, were tested, for a total of 82 children (36 girls), mean age 9.28 ± 0.54 years.

No child was diagnosed with cognitive, learning, or sensory disabilities. All parents provided informed consent for their children's participation in the study. This research was approved by the Ethics Committee of the Human-Inspired Technologies Research Center at the University of Padova (protocol number 2020_92R1).

3.1 School A

The following section provides descriptions of the environments, the measurements taken, and the results obtained from the assessments performed in the two classrooms of School A, located in Torreglia (PD). Cognitive performance assessments were performed: (i) 13.01.2022 in quiet condition in class A1 and in noise condition in class A2; (ii) 25.02.2022 noise condition in class A1 and quiet condition in class A2.

3.1.1 Description of the Classrooms

Classrooms are located on the second floor of the building. They have plastered walls and are equipped with arrangements for acoustic improvement, achieved by placing a false ceiling of sound-absorbing material. In both classrooms, there are strip windows along one entire wall.

A preliminary measurement campaign aimed at quantifying acoustic properties in unoccupied classroom conditions was carried out. Measurements were performed according to the procedures and equipment prescribed by ISO 3382-2 standard [21], [66]. Reverberation time was acquired by the interrupted source method using the bursting of a balloon as a signal. For the evaluation of the STI, measurements were performed according to the positions indicated in §1.2.6 Figure 5 from UNI 11532-2 standard [39].

To consider students' influence, reverberation times in the occupied condition were evaluated using the equation (7).

$$T_{occ} = \frac{T_{inocc}}{1 + \frac{T_{inocc} C N \Delta A_{1p}}{0.16V}} [s] \quad (7)$$

Where:

N is the maximum occupancy of the classroom;

C is the percentage of occupancy (C=1 means a fully occupied classroom, C=0.8 means an occupancy of 80%);

ΔA_{1p} is the increase of the equivalent absorption area due to one person in m^2 Sabine. Values are taken from Appendix C of the Italian acoustic regulation for classroom UNI 11532-2 standard.

Figure 31 shows pictures and plans of the measured classrooms with the locations of the source-receiver pairs for reverberation time assessment. Table 14 shows a general overview of the properties of the classrooms. It shows geometric data, i.e., volume, maximum occupancy, reverberation in different occupancy configurations: unoccupied, 80%, and 100% of maximum occupancy, and the average value of the STI index. Appendix E – School A in Table 41 and Table 42 show, respectively, the frequency reverberation time values measured and calculated according to formula (7) and STI values at measurement positions required by UNI 11532-2 standard [39] (§1.2.6 Figure 5).

Figure 30 graphically shows the frequency values of reverberation time in unoccupied, 80% occupied, and 100% occupied room conditions, the optimum reverberation time, and the compliance interval of the optimum reverberation time of Classroom A1.

Table 14: Data overview of the classroom and ISO 3382-2 measurements results: where: “V” is the volume, “S” is the area of the classroom, “N” the maximum occupancy, “STI” is the Speech Transmission Index, “ $RT_{m,unocc}$ ” is the reverberation time in unoccupied, “ $RT_{m,occ80\%}$ ” is the reverberation time in occupied condition at 80%, “ $RT_{m,occ100\%}$ ” is the reverberation time in occupied condition at 100%. The subscript “m” means a value averaged over all the receivers in the octave bands of 125-4000 Hz.

School	Classroom	Volume [m ³]	S [m ²]	N	STI	$RT_{m,unocc}$ [s]	$RT_{m,occ 80\%}$ [s]	$RT_{m,occ 100\%}$ [s]
A	A1	149	47	15	0.74	0.49	0.47	0.46
	A2	155	47	16	0.70	0.51	0.48	0.47

Figure 30: An example of a graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80%, $RT_{occ,80\%}$ reverberation time in occupied condition at 100% $RT_{occ,100\%}$ of A1.

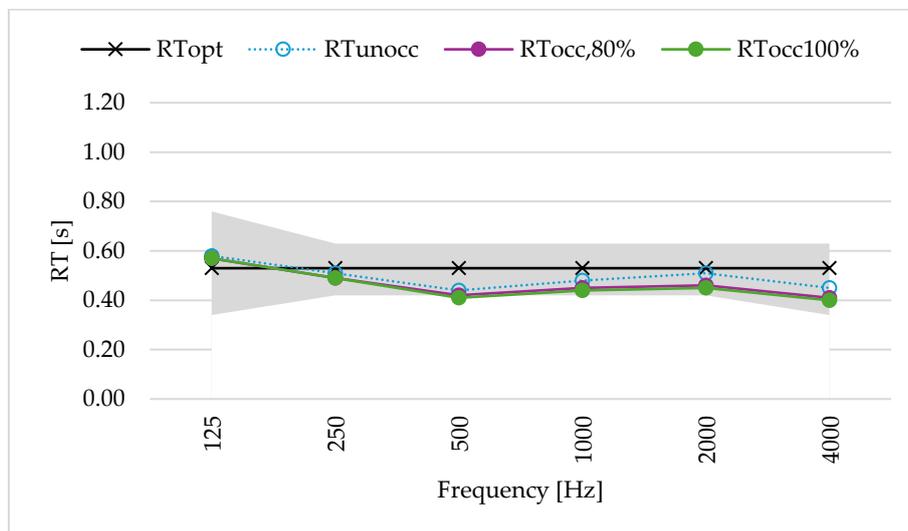
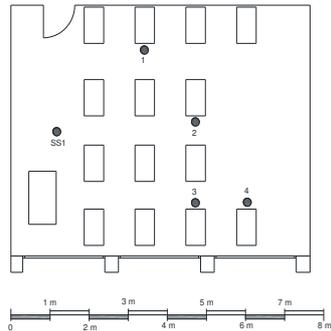


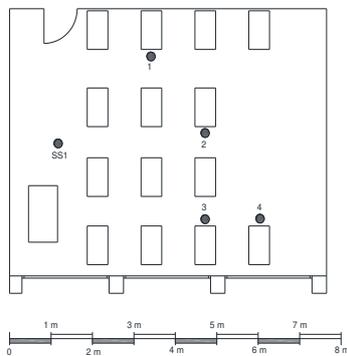
Figure 31: Pictures and floor plans of two classrooms of School A under study: class A1 (a and b), class A2 (c and 3d). Plans show sources and receivers' positions.



(a) Class A1 - plan



(b) Class A1



(c) Class A2 - plan



(d) Class A2

3.1.2 Acoustic Measurements Methods

To evaluate the effect of noise on students' cognitive and learning abilities, the multi-talker babble noise signal was introduced throughout the administered tests. This signal was emitted by a Talkbox NTi Audio signal generator positioned at the teacher's station at a height of 1.50 m.

During the cognitive tests conducted in the classroom, both in quiet and noisy conditions, the equivalent continuous sound level per second ($L_{Aeq,1s}$) was recorded using an omnidirectional microphone (model XL2 by NTi Audio) placed at a height of 1.2 m in the center of the area occupied by the students' desks. The recordings were carried out throughout the entire test session, starting with the distribution of materials required for the tests, for a total duration of approximately 1 hour and 30 minutes. The specifications of the measurement instruments used are given in Appendix D – Instruments Characteristics Table 40. Acquired data were processed by selecting only samples corresponding to the actual execution of the tests, calculated from the moment that children started the first test (either on tablets or paper) until the last child completed the tests. The total time required to complete the tests can vary from child to child and, consequently, from class to class. The actual test durations, and therefore the length of the analyzed $L_{Aeq,1s}$ acquisition sample, are reported in Appendix E – School A Table 43.

Since acoustic data processing refers to acquisition lengths that differ between cognitive and learning test sessions and between classes, the equivalent sound level, SEL, is calculated to make the acquired data comparable.

SEL is the sound level of a single event and is defined as the continuous noise level over 1 second that contains the same energy content as the considered event. In other words, it represents the sound level the single event would have if its sound energy were concentrated into a duration of 1 second. SEL is calculated using equation (8).

$$SEL = 10 \log \left(\frac{1}{t_0} \int_{t_1}^{t_2} 10^{\left(\frac{L_p(t)}{10}\right)} dt \right) [dB] \quad (8)$$

Where $L_{p(t)}$ represents the pressure level at instant t .

3.1.3 Evaluation of Cognitive Performance and Learning Abilities

Due to the limited availability of tablets for administering the cognitive tests, while half of the class completed tests using the app, the other half completed the tasks on paper, and then they switched roles (A1_1 – A2_1 respectively for the two classes, and A1_2 – A2_2 respectively for the two classes). Following the test session, children were provided with a self-report questionnaire to assess cognitive effort during the tasks.

Acoustic conditions during the tasks were counterbalanced between the two classes. Additionally, to avoid increased familiarity with tasks, the second test session was conducted several weeks apart from the first.

3.1.4 Results

SEL values calculated from acquired $L_{Aeq,1s}$ in the two different conditions, are presented in Table 15. In Table 16 the students' cognitive performance in quiet and in noise is reported in terms of a correct number of answers (from #A1 to #A3 and from #A6 to #A9), an accuracy that is the ratio of right/wrong responses (#A4 and #A5), total score (#A10). Table 16 also reports the mean value, the standard deviation (SD), and the t-test coefficient of the children's cognitive performance in quiet and noisy conditions. A P-value lower than 5% has been considered to evaluate the statistical significance level of noise on cognitive performance.

The groups of students tested are referred to for classes A1 and A2 respectively: A1_1/A2_1 for the students who first completed the test using the app, and A1_2/A2_2 for the students who first completed the test on paper.

Table 15: SEL values across acoustic conditions during performing CoEN tasks and learning abilities.

	A1_1	A1_2	A1_1	A1_2	A2_1	A2_1	A2_2	A2_2
Test	"Quiet"	"Quiet"	"Noise"	"Noise"	"Quiet"	"Quiet"	"Noise"	"Noise"
#A1-#A8	88.0	77.6	92.0	93.4	91.8	83.3	93.4	92.9
#A9	77.6	88.0	93.4	92.0	83.3	91.8	92.9	93.4
#A10	77.6	88.0	93.4	92.0	83.3	91.8	92.9	93.4

Table 16: Children's performance on the CoEN tasks and learning abilities across acoustic conditions – Classes A1 and A2

(n=31; 18 girls)						
		"Quiet"		"Noise"		
Test	Mean	SD	Mean	SD	t	
#A1	6.04	1.40	6.15	1.89	-0.259	
#A2	5.27	2.05	5.85	1.29	-1.364	
#A3	2.00	1.697	2.23	1.966	-0.507	
#A4	14.69	9.752	11.65	17.410	1.194	
#A5	26.42	10.708	22.69	10.743	1.704*	
#A9	9.36	2.97	9.96	2.80	-0.742	
#A10	13.40	4.89	12.36	5.65	0.783	
Cognitive Effort Self-Report	1.73	0.572	2.10	0.696	-2.408*	

*p<.05; **p<.01; ***p<.001

The results of the paired-sample t-test indicate that in noisy conditions children showed significantly worse performance on the Cancellation Test (#A5, $t=1.704$, $p<0.05$) and reported higher levels of cognitive effort ($t=-2.408$, $p<0.05$) than in quiet conditions.

3.1.5 Discussion

As can be seen from the average STI values in Table 14, both classes in School A meet the speech intelligibility requirements specified in UNI 11532-2 standard [39] reported in §1.2.6 Table 5. The same is true for reverberation time as well, as seen in Figure 30 the RT_{unocc} , $RT_{occ,80\%}$ and $RT_{occ,100\%}$ fall within the range of optimal reverberation time defined according to UNI 11532-2 standard.

From the perspective of cognitive performance, in the Cancellation Test (#A5) a deterioration of performance under noisy conditions was observed. Results are in line with the hypotheses that babble noise negatively impacts students' cognitive performance. The impaired performance in the test can be attributed to the noise component in that part of the attention needed to process relevant visual information is diverted to the auditory signal, disrupting task performance. This result is consistent with previous studies suggesting that babble noise more negatively affects attention in children [31].

However, another consideration is essential. The worsening of performance in noisy conditions with increased cognitive effort could be caused by students not being accustomed to performing tasks in unfavorable acoustic conditions. This is because of the Covid-19 pandemic that took place in the years preceding the study. In fact, in Italy, until April 2021, teaching took place at a distance. Only since the 2021-2022 school year have classes returned to taking place almost entirely in person.

3.2 School B

The following section gives descriptions of the environment, measurements, and results obtained from the assessments performed in the four classrooms of School B, located in Albignasego. Cognitive performance evaluations were carried out: (i) 30.01.2023 in quiet condition and 13.02.2023 in noise condition in class B1; (ii) 03.02.2022 quiet condition and on 17.02.2023 in noise condition in class B2; (iii) 26.02.2024 in noise condition in classes B3 and B4 11.03.2024; (iv) in quiet condition in classes B3 and B4.

3.2.1 Description of the Classrooms

School B is organized on a single floor, with all classrooms located on the ground floor. One side of each classroom (facing southeast), characterized by large windows, overlooks the school garden. No room acoustic improvement measures are present.

Measurements to assess room acoustic characteristics were performed by the guidelines of ISO 3382-2 [66] and UNI 11532-2 [39] standards. Reverberation time was acquired by the interrupted source method using the bursting of a balloon as a signal. For the evaluation of STI, measurements were performed according to the procedures and equipment provided in UNI 11532-2 standard [39].

Table 17 shows a general overview of the properties of the classrooms, and Figure 33 shows images and floor plans of the classrooms under investigation with the locations of the source-receiver pairs for reverberation time assessment. Appendix F – School B Table 44 and Table 45 show, respectively, the measured and calculated frequency reverberation time values according to formula (7) and STI values at the measurement positions required by UNI 11532-2 [39] (§1.2.6 Figure 5 shows the figure of the UNI 11532-2 standard with the measurement positions).

As an example, the frequency values of reverberation time in unoccupied, 80% occupied, and 100% occupied room conditions, the optimal reverberation time, and the compliance interval of the optimal reverberation time of classroom B2 are shown graphically in Figure 32.

Table 17: Data overview of the classroom and ISO 3382-2 measurements results: where: “V” is the volume, “S” is the area of the classroom, “N” the maximum occupancy, “STI” is the Speech Transmission Index, “ $RT_{m,unocc}$ ” is the reverberation time in unoccupied, “ $RT_{m,occ80\%}$ ” is the reverberation time in occupied condition at 80%, “ $RT_{m,occ100\%}$ ” is the reverberation time in occupied condition at 100%. The subscript “m” means a value averaged over all the receivers in the octave bands of 125-4000.

School	Classroom	Volume [m ³]	S [m ²]	N	STI	$RT_{m,unocc}$ [s]	$RT_{m,occ 80\%}$ [s]	$RT_{m,occ 100\%}$ [s]
B	B1	140	47	23	0.56	1.55	1.25	1.20
	B2	139	47	24	0.54	1.36	1.10	1.05
	B3	142	47	26	0.55	1.55	1.26	1.21
	B4	140	47	24	0.54	1.54	1.24	1.18

Figure 32: An example of a graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80%, $RT_{occ,80\%}$ reverberation time in occupied condition at 100% $RT_{occ,100\%}$ of B1.

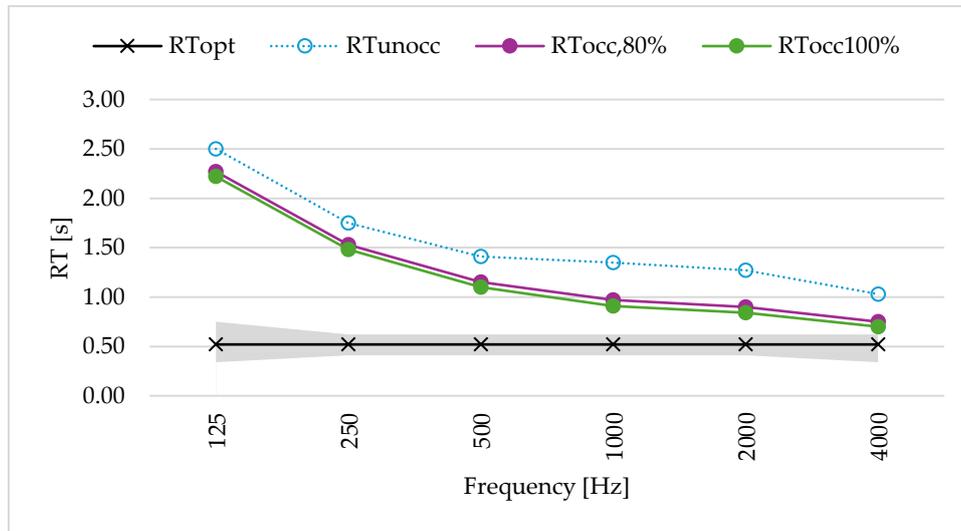
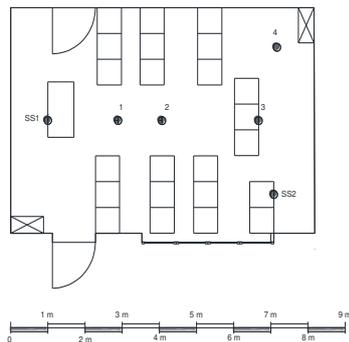


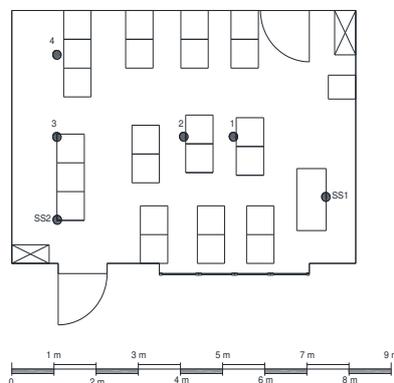
Figure 33: Pictures and floor plans of four classrooms of School B under study: class B1 (a and b), class B2 (c and d), class B3 (e and f), and class B4 (g and h). Plans show sources and receivers' positions.



(a) Class B1 - plan



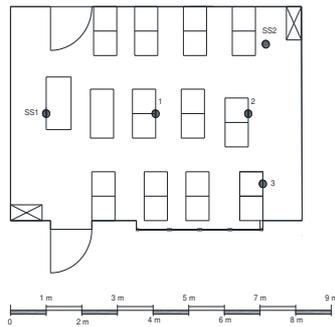
(b) Class B1



(c) Class B2 - plan



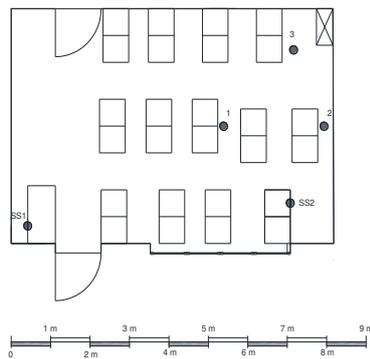
(d) Class B2



(e) Class B3 - plan



(f) Class B3



(g) Class B4 - plan



(h) Class B4

3.2.2 Acoustic and Environmental Measurements Methods

To assess the effect on cognitive and learning abilities of noise on students, the multi-talker babble noise signal with the addition of transient events (such as door slamming, knocking, ambulance sirens, etc.) emitted through the NTi Audio Talkbox signal generator positioned at the teacher's desk at a height of 1.50 m was introduced for the duration of the administered tests. Throughout the cognitive tests in quiet and noisy conditions, the continuous sound level equivalent per second ($L_{Aeq,1s}$) was acquired with an omnidirectional microphone (model XL2 from NTi Audio) at a height of 1.2 m in a central position of the area occupied by the classroom desks. The actual duration of the tests, and thus the length of the $L_{Aeq,1s}$ acquisition sample analyzed, is given in Appendix F – School B Table 46.

In the same way as the acquisition of noise levels, values of environmental conditions were acquired throughout the tests. In detail, temperature, air humidity, and CO₂ concentration were acquired every 5 minutes with a HOBO MX1102 data logger sensor placed near the teacher's desk. Illumination values, in classrooms B1 and B2, were collected with a Konica Minolta Luxmeter several times during children's performance of tests at 10 points in the classroom. Differently in classrooms B3 and B4, where illuminance levels were acquired, every minute, with five HOBO MX1104 data Logger sensors placed on the students' desks.

The specifications of the measurement instruments used are given in Appendix D – Instruments Characteristics Table 40.

Figure 34: Picture captured while performing cognitive and learning tests under noise conditions in a classroom at School B.



3.2.3 Evaluation of Cognitive Performance and Learning Abilities

The four classes of school B were analyzed over two distinct school years. In the 2022–2023 school year, classes B1 and B2, for organizational reasons, completed the first test in quiet and the second test in noisy conditions. The following year, classes B3 and B4 completed the first session in noisy and the second in quiet conditions. This approach was designed to counterbalance the tests conducted in classes B1 and B2.

Children in all four classes began with the tablet-based tests and once completed, moved on to the paper-and-pencil learning tests. Following the test session, a self-report questionnaire was provided to assess cognitive effort during the tasks. To avoid increased familiarity with the tasks, the second test session was conducted several weeks apart from the first.

3.2.4 Results

The mean physical parameters measured during the tests under the two different acoustic conditions, together with the corresponding SEL values calculated from acquired L_{Aeq1s} , are presented in Table 18 and Table 20. Appendix F – School B Table 47 shows the measurement locations and the mean and standard deviation values of the illuminance levels measured at each measurement location. Figure 35 shows the comparisons of the mean values of performance obtained in cognitive and learning tests in classes B1-B2 and B3-B4. For organizational reasons, classes B1 and B2 conducted the first session in quiet conditions, and classes B3 and B4 in noisy conditions. In Table 21 the students’ cognitive performance in quiet and in noise is reported in terms of a correct number of answers (from #A1 to #A3 and from #A6 to #A9), an accuracy that is the ratio of right/wrong responses (#A4 and #A5), total score (#A10). Table 21 also reports the mean values, standard deviations, and t-test results of the performance of children in all classes (B1, B2, B3, B4) in quiet and noisy conditions. A P-value lower than 5% has been considered to evaluate the statistical significance level of noise on cognitive performance.

Table 18: SEL values across acoustic conditions during performing CoEN tasks and learning abilities.

Test	B1	B1	B2	B2	B3	B3	B4	B4
	“Quiet”	“Noise”	“Quiet”	“Noise”	“Quiet”	“Noise”	“Quiet”	“Noise”
#A1-#A8	92.4	105.0	88.5	101.5	88.6	102.5	92.8	104.8
#A9	94.4	99.3	86.0	97.7	90.1	98.2	88.2	98.1
#A10	85.4	96.8	88.0	99.0	90.4	96.8	88.3	96.2

Table 19: Difference between SEL measured in noise condition and quiet condition when performing cognitive and learning tests in classes of school B.

Test	B1	B2	B3	B4
	Δ SEL [dB(A)]	Δ SEL [dB(A)]	Δ SEL [dB(A)]	Δ SEL [dB(A)]
#A1-#A8	12.6	13.0	13.9	12.0
#A9	4.9	11.7	8.1	9.9
#A10	11.4	11.0	6.4	7.9

Table 20: Mean values and standard deviation of Temperature, Air humidity, CO₂ concentrations, and Illuminance levels across acoustic conditions.

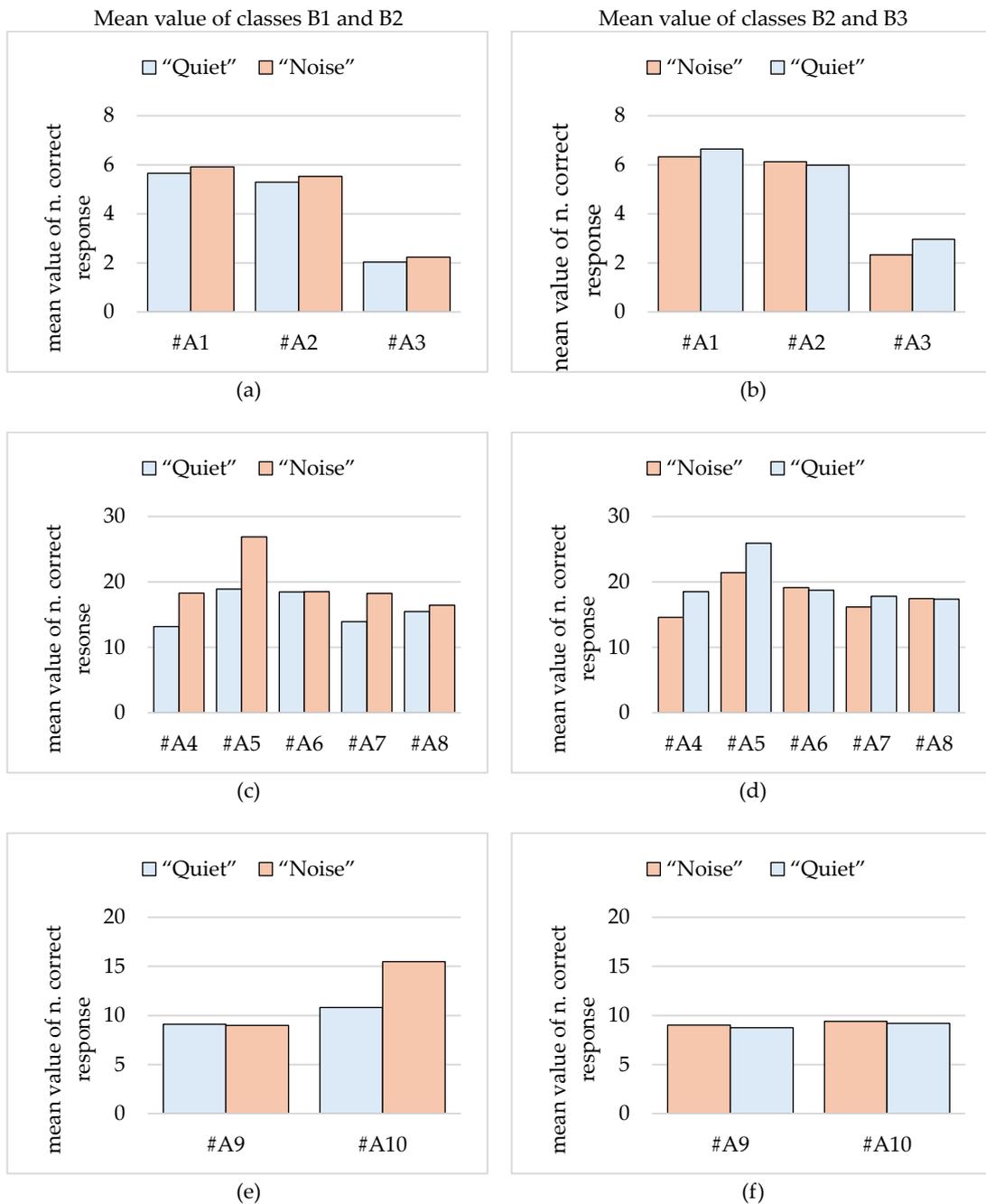
Class	Temperature [°C]		Air Humidity [%]		CO ₂ concentrations [ppm]		Illuminance [lux]	
	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"
B1	18.9	20.0	43.3	36.9	1865	1714	85	251
	±0.03	±0.12	±1.00	±0.45	±197	±122	±47	±177
B2	20.0	20.0	56.2	52.1	2479	1895	548	455
	±0.06	±0.05	±0.83	±0.40	±239	±64	±1088	±191
B3	16.1	20.9	69.3	67.0	1939	3480	193	268
	±0.67	±0.63	±2.04	±2.13	±430	±229	±40	±138
B4	18.6	19.6	71.3	67.6	4634	1498	402	213
	±0.67	±0.66	±2.00	±2.00	±412	±71	±285	±46

Regarding environmental conditions, the EN 16798 standard [116] prescribes that, during the winter period for school classrooms, considering sedentary activities and an average level of expectation, the temperature values should be between 20°C and 24°C. The acceptable range for air humidity is between 25% and 60%. Regarding CO₂ concentration, a reference maximum value of around 900 ppm (500 ppm above the CO₂ concentration measured outdoors) is suggested. Regarding luminance level, the UNI 12464-1 standard [117] requires a minimum illuminance value on the desk set at 500 lux.

As Table 20 shows, the values measured during the administration of the cognitive tests under quiet and noisy conditions do not meet the regulations' requirements. In particular, the CO₂ concentration is always above 900 ppm, and for illuminance values, the measured values are always below 500 lux. Only in the quiet condition in B2 the levels of 548 lux were reached.

From Figure 35 it is possible to observe better average performance at the second test administration session. In particular in Attention and Cancellation test (#A4, #A5), Inhibition test in incongruent subtest (#A7) and Sentence generation test (#A10).

Figure 35: Children's performance on the CoEN tasks across acoustic conditions – classes B1 and B2 (a), (c), (e); and B3 and B4 (b), (d), (f). B1 and B2 perform first in quiet and then in noisy conditions. B3 and B4 perform both first in noisy conditions and then in quiet conditions. Graphs are divided by executive function investigated by the tests: #A1, #A2, #A3 working memory; #A4, #A5, #A6, #A7, #A8 Attention and Inhibition; #A9, #A10 learning abilities.



As Table 21 shows, the results of the paired sample t-test show the absence of significant differences between the performance of the tests performed in the quiet condition and those obtained with the tests performed in the noise condition.

Table 21: Children's performance on the CoEN tasks across acoustic conditions – all classes

(n=92; 52 girls)					
Test	"Quiet"		"Noise"		<i>t</i>
	Mean	SD	Mean	SD	
#A1	6.16	1.83	6.11	1.55	0.230
#A2	5.66	1.99	5.82	1.97	-0.735
#A3	2.00	1.41	2.47	2.09	-1.676
#A4	15.84	12.93	16.42	9.01	-0.447
#A5	22.25	13.09	23.45	9.41	-0.817
#A6	18.55	3.48	18.82	3.32	-0.537
#A7	16.46	6.50	17.07	6.18	-0.813
#A8	16.66	3.79	17.14	3.49	-1.504
#A9	8.94	2.98	9.01	3.13	0.741
#A10	10.01	3.21	12.43	3.66	-0.421
Cognitive Effort Self-Report	2.10	0.41	2.14	0.48	0.488

*p<.05; **p<.01; ***p<.001

3.2.5 Discussion

As can be seen in Table 17, the average STI values of classes B1 and B3 meet the requirements (unlike B2 and B4) about speech intelligibility specified in UNI 11532-2 standard [39] reported in §1.2.6 Table 5 but with values very close to the required. Regarding reverberation time, as seen in Figure 32, in unoccupied and occupied conditions at 80% and 100%, it is above the range of optimal reverberation time defined according to the UNI 11532-2 standard. This means that the environment is too reverberant. The conditions of temperature, air humidity, CO₂ concentration, and luminance measured in the classes are similar in the two acoustic conditions considered in all four classes. Other than the sound pressure level of noise, the influence of physical aspects could be neglected, although not within the comfort limits.

The results show that the classes performed better, in terms of mean value, in the second test session, regardless of the acoustic conditions. This is clearly attributable to students' familiarity with the tests. Despite the initial expectation that noise, including transient noise, would be more disturbing to the children, the results showed otherwise. In fact, counterbalancing the acoustic conditions, no significant differences were observed between tasks performed in quiet and in noise.

Considering what was obtained in §3.1 using noise considered less disturbing, they hint that contextual factor play an essential role in the impact of noise on cognitive performance. In fact, in contrast to School A, School B does not have interventions to improve the acoustics of the environment. The RT and STI, shown in Table 17 and Figure 32, are not within regulatory limits.

Prolonged exposure to unfavorable acoustic environments may have prompted the development of compensatory strategies to perform best even under adverse acoustic conditions. However, even the unintelligible nature of the administered signal might not be so disturbing as to induce a change in performance.

3.3 School C

The following section provides descriptions of the environment, the measurements taken, and the results obtained from the assessments performed in the five classrooms of School C. The classrooms are in two buildings, the first in Villatora (classrooms C1-C4) and the second in Saonara (classrooms C5). Cognitive performance assessments were conducted: (i) 12.03.2024 under quiet conditions in classroom C1 and noisy conditions in C4; (ii) 13.04.2024 under quiet conditions in classroom C2 and noise conditions in classroom C3; (iii) 14. 03.2024 in quiet condition in class C5; (iv) 09.04.2024 in quiet condition in classes C3 and C4 and in noise condition in class C2; (v) 10.04.2024 in noise condition in classes C1 and C5.

3.3.1 Description of the classrooms

School C classrooms are distributed in two buildings. Four of them are in the Villatora school complex, located on the two wings on the second floor of the building. The fifth classroom is in the Saonara school building situated on the ground floor of a two-story building. None of the five classrooms have acoustic improvement interventions. All classrooms have large windows on one side of the room; classrooms C1, C4, and C5 have the windowed wall facing Southeast, and classrooms C2 and C3 facing Northwest.

Room acoustic characterization measurements were performed in the classrooms by the guidelines of ISO 3382-2 [66] and UNI 11532-2 [39] standards. Reverberation time was acquired by the interrupted source method using the bursting of a balloon as a signal. For the evaluation of the STI values, measurements were performed according to the procedures and equipment provided in the UNI 11532-2 standard [39]. Table 22 shows a general overview of classroom properties. Figure 33 shows pictures and plans of the classrooms under investigation with the locations of the source-receiver pairs for reverberation time assessment. Appendix G – School C Table 48 and Table 49 show, respectively, the measured and calculated frequency reverberation time values according to formula (7) and STI values at the measurement positions required by UNI 11532-2 standard [39] (§1.2.6 Figure 5 shows the figure of the UNI 11532-2 standard with the measurement positions).

As an example, the frequency values of reverberation time in unoccupied, 80% occupied, and 100% occupied room conditions, the optimal reverberation time, and the compliance interval of the optimal reverberation time of classrooms C1 and C5 are shown graphically in Figure 36 and Figure 37.

Table 22: Data overview of the classroom and ISO 3382-2 measurements results: where: “V” is the volume, “S” is the area of the classroom, “N” the maximum occupancy, “STI” is the Speech Transmission Index, “ $TR_{m,unocc}$ ” is the reverberation time in unoccupied, “ $TR_{m,occ80\%}$ ” is the reverberation time in occupied condition at 80%, “ $TR_{m,occ100\%}$ ” is the reverberation time in occupied condition at 100%. The subscript “m” means a value averaged over all the receivers in the octave bands of 125-4000.

School	Classroom	Volume [m ³]	S [m ²]	N	STI	$RT_{m,unocc}$ [s]	$RT_{m,occ 80\%}$ [s]	$RT_{m,occ 100\%}$ [s]
C	C1	129	43	16	0.50	1.62	1.34	1.29
	C2	148	46	18	0.49	1.78	1.45	1.39
	C3	138	49	17	0.54	1.42	1.19	1.14
	C4	132	44	20	0.56	1.36	1.11	1.07
	C5	149	46	16	0.54	1.43	1.19	1.16

Figure 36: An example of a graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80%, $RT_{occ,80\%}$ reverberation time in occupied condition at 100% $RT_{occ,100\%}$ of C1.

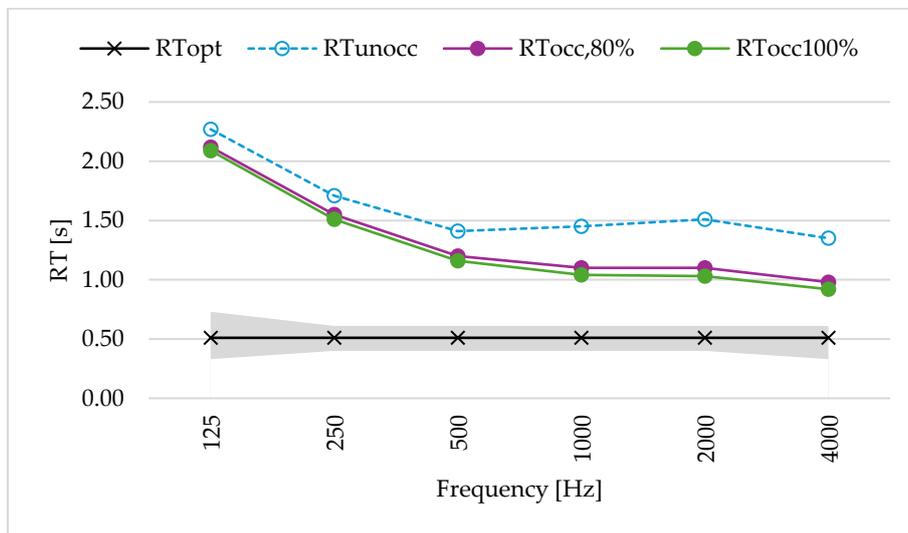


Figure 37: An example of a graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80%, $RT_{occ,80\%}$ reverberation time in occupied condition at 100% $RT_{occ,100\%}$ of C5.

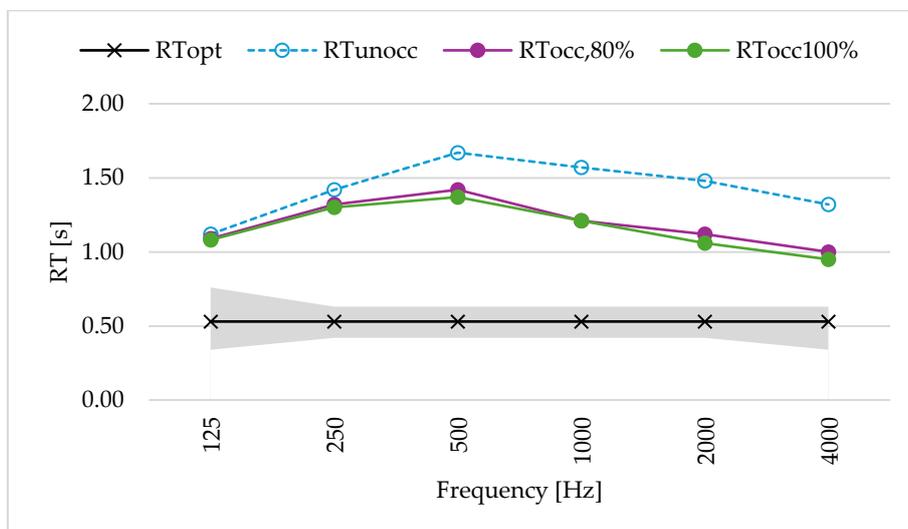
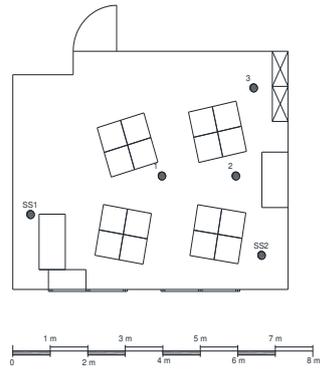


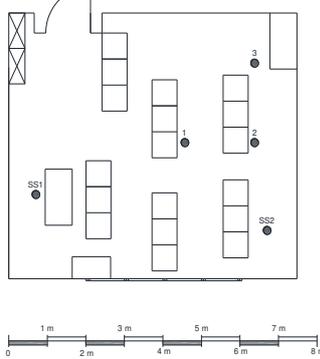
Figure 38: Pictures and plans of five classrooms of School C under study: class C1 (a and b), class C2 (c and d), class C3 (e and f), class C4 (g and h), and class C5 (i and j). Plans show sources and receivers' positions.



(a) Class C1 - plan



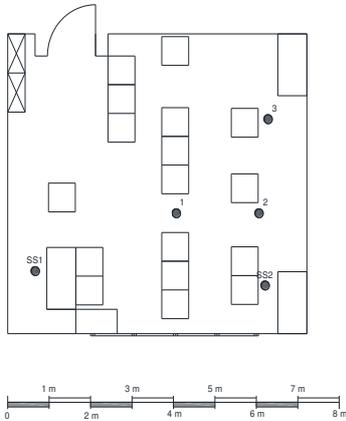
(b) Class C1



(c) Class C2 - plan



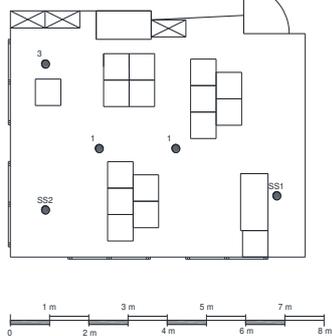
(d) Class C2



(e) Class C3 - plan



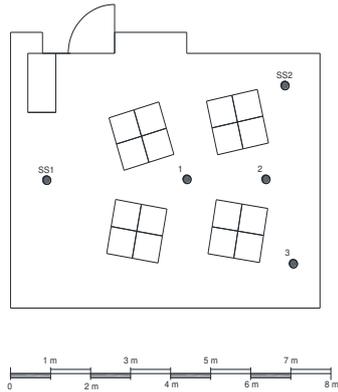
(f) Class C3



(g) Class C4 - plan



(h) Class C4



(h) Class C5 - plan



(i) Class C5

3.3.2 Acoustic and Environmental Measurement Methods

To assess the effect of noise on the cognitive and learning abilities of students, the multi-talker babble noise signal with the addition of transient events (such as door slamming, knocking, ambulance sirens, etc.) emitted through the Talkbox NTi Audio signal generator at the teacher's station at a height of 1.50 m was introduced for the duration of the administered tests. During the cognitive tests in the classroom under both quiet and noisy conditions, the continuous sound level equivalent per second ($L_{Aeq,1s}$) was recorded through an omnidirectional microphone (NTi Audio's XL2 model) at a height of 1.2 m at the central location of the area occupied by the classroom desks. The actual test durations, and thus the length of the $L_{Aeq,1s}$ acquisition sample analyzed, are shown in Appendix G – School C Table 50. Similarly to the acquisition of noise levels, values of environmental conditions were acquired throughout the tests. Values of temperature, air humidity, and CO₂ concentration were acquired every minute with a HOBO MX1102 Data Logger sensor placed near the teacher's desk. In addition, with the placement of five other HOBO MX1104 Data Logger sensors in the area occupied by the desks where the children were arranged, lighting levels were also acquired. The specifications of the measurement instruments used are given in Appendix D – Instruments Characteristics Table 40.

Figure 39: Picture captured while performing cognitive and learning tests in quiet and noisy conditions in two classrooms at School C.



3.3.3 Evaluation of Cognitive Performance and Learning Abilities

Children in the five classes started with tablet tests and once completed, took paper-pencil learning tests. Following the testing session, a self-report questionnaire was provided to assess cognitive effort during the tasks performed. To avoid more familiarity with the tasks provided, the second testing

session was performed a few weeks apart between tests. The acoustic conditions of test performance were counterbalanced among the five classes.

3.3.4 Results

The mean physical parameters measured during the tests under the two different acoustic conditions, together with the corresponding SEL values calculated from acquired L_{Aeq1s} , are presented in Table 23 and Table 25. Appendix G – School C in Table 51 shows the measurement locations and the mean and standard deviation values of the illuminance levels measured at each measurement location.

In Table 26 the students' cognitive performance in quiet and in noise is reported in terms of a correct number of answers (from #A1 to #A3 and from #A6 to #A9), an accuracy that is the ratio of right/wrong responses (#A4 and #A5), total score (#A10). Table 26 also reports the mean values, standard deviations, and t-test results of the performance of children in all classes (C1, C2, C3, C4 and C5) in quiet and noisy conditions. A P-value lower than 5% has been considered to evaluate the statistical significance level of noise on cognitive performance. The results of 5 children were excluded from the analyses as they were foreign speakers.

Table 23: SEL values across acoustic conditions during performing CoEN tasks and learning abilities.

Test	C1	C1	C2	C2	C3	C3	C4	C4	C5	C5
	"Quiet"	"Noise"								
#A1- #A8	87.4	99.5	87.6	101.2	94.2	100.9	93.8	100.9	86.6	100.8
#A9	86.1	97.4	82.6	96.7	86.7	99.7	84.4	96.9	97.0	97.8
#A1 0	84.8	96.0	86.2	97.9	87.2	97.8	86.4	95.1	82.6	96.3

Table 24: Difference between SEL measured in noise condition and quiet condition when performing cognitive and learning tests in classes of school C.

Test	C1	C2	C3	C4	C5
	Δ SEL [dB(A)]				
#A1-#A8	12.1	13.6	6.7	7.1	14.2
#A9	11.3	14.1	13.0	12.5	0.8
#A10	11.2	11.7	10.6	8.7	13.7

Table 25: Mean values and standard deviation of Temperature, Air Humidity, CO₂ concentrations, and Illuminance levels across acoustic conditions.

Class	Temperature [°C]		Air Humidity [%]		CO ₂ concentrations [ppm]		Illuminance [lux]	
	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"
C1	23.9 ±0.27	23.4 ±0.35	59.8 ±2.42	61.7 ±1.51	2345 ±608	978 ±65	616 ±135	903 ±2944
C2	22.9 ±0.41	23.2 ±0.31	56.8 ±2.65	64.0 ±2.34	2051 ±372	1371 ±60	542 ±153	861 ±743
C3	22.2 ±0.21	22.0 ±0.34	67.2 ±1.93	54.7 ±1.08	1524 ±26	1553 ±158	649 ±748	591 ±479
C4	24.4 ±0.30	23.2 ±0.68	56.5 ±2.34	56.4 ±2.75	876 ±33	2270 ±599	322 ±118	697 ±174
C5	21.4 ±0.56	22.5 ±0.34	56.6 ±1.02	65.9 ±3.11	1889 ±354	1176 ±247	269 ±11	252 ±18

Regarding environmental conditions, the EN 16798 standard [116] prescribes that, during the winter period for school classrooms, considering sedentary activities and an average level of expectation, the temperature values should be between 20°C and 24°C. The acceptable range for air humidity is between 25% and 60%. Regarding CO₂ concentration, a reference maximum value of around 900 ppm (500 ppm above the CO₂ concentration measured outdoors) is suggested. Regarding luminance level, the UNI 12464-1 standard [117] requires a minimum illuminance value on the desk set at 500 lux.

As Table 25 shows, temperature, air humidity, and illumination, with the exception of class C4 (with a luminance level in quiet conditions of 322 lux) and C5 (with a luminance level in quiet conditions of 269 lux and 252 in noisy conditions), the values required by the standards are met. However, the CO₂ concentration is always above 900 ppm.

Table 26: Children's performance on the CoEN tasks and learning abilities across acoustic conditions – School C.

(n=82; 36 girls)						
Test	"Quiet"		"Noise"		<i>t</i>	
	Mean	SD	Mean	SD		
#A1	6.75	1.54	6.33	1.77	1.742	
#A2	6.17	2.12	5.81	2.16	1.169	
#A3	2.34	1.55	2.87	1.66	-2.531	
#A4	14.28	8.76	16.31	9.38	-1.781	
#A5	23.30	12.30	25.03	12.47	-0.826	
#A6	19.56	0.78	19.51	1.07	0.299	
#A7	14.36	8.14	15.13	7.96	-0.649	
#A8	16.59	3.97	17.20	3.25	-1.289	
#A9	8.46	2.97	8.72	3.36	-0.826	
#A10	6.47	4.27	7.14	4.34	-1.316	
Cognitive Effort self-report	2.43	0.43	2.56	0.52	-1.651	

*p<.05; **p<.01; ***p<.001

The results of the paired-sample t-test indicate that there is no significant difference between the performance of tests performed in quiet and noise.

3.3.5 Discussion

As can be seen in Table 22, the average STI values of classes C1-C5 do not meet the requirements of speech intelligibility specified in UNI 11532-2 standard [39] reported in §1.2.6 Table 5. The same is true for reverberation time. As seen in Figure 36 and Figure 37, the reverberation time in unoccupied conditions and occupied conditions at 80% and 100% is above the range of optimal reverberation time defined according to UNI 11532-2 standard. This means that the environment is too reverberant.

The conditions of temperature, air humidity, CO₂ concentration, and luminance measured in the classes are similar in the two acoustic conditions considered in all four classes. Other than the sound pressure level of noise, the influence of physical aspects could be neglected, although not within the comfort limits.

From the perspective of cognitive performance, no significant differences were observed between performance in cognitive and learning tests performed under quiet and noisy conditions. Considering what was obtained in §3.1 using a noise considered less disturbing, they hint that contextual factors play an essential role in the impact of noise on cognitive performance. In fact, in contrast to School A, School C does not have interventions to improve the acoustics of the environment. The RT and STI, shown in Table 22, Figure 36 and Figure 37, are not within regulatory limits.

Prolonged exposure to unfavorable acoustic environments may have prompted the development of compensatory strategies to perform best even under adverse acoustic conditions.

However, even the unintelligible nature of the administered signal might not be so disturbing as to induce a change in performance.

4. Application in a University Classroom – Evaluation of the Cognitive Performance of University Students

The second context in which tests were administered to assess cognitive performance is the university setting. The chapter shows the application of the described method to two groups of university students (age range 25-32 years; mean age of 27.35 years). The classroom chosen for administration was a lecture hall located on the second floor of the Department of Energy Engineering at KTH University in Stockholm. Participants were recruited by e-mail invitation.

All participants provided informed consent for participation in the study. This research has received approval from the Research Ethics Committee of the IUAV University of Venice.

4.1.1 Description of the Classrooms

The classroom chosen for conducting cognitive tests on university students has large windows on one side of the room, which face a connecting space between two wings of the building. Natural lighting, therefore, comes from the connecting space, which also has large windows. The desks are joined and arranged centrally to the space to create a single table. This is due to the teaching activity that is typically carried out in the classroom.

Figure 40: Picture of the classroom of School D under study.



4.1.2 Acoustic and Environmental Measurement Methods

To assess the effect of noise on the cognitive abilities of university students, a signal composed of multi-talker babble noise with the addition of transient events (such as door slamming, knocking, ambulance sirens, etc.) emitted through external computer speakers placed at the teacher's station at a height of 0.80 m was introduced for the duration of the tests. Throughout the tests, $L_{Aeq,1s}$ was recorded by low-cost instrumentation consisting of iPads equipped with the calibrated OpeNoise application to which an omnidirectional condenser microphone was connected at a height of 0.80 m at the central location of the area occupied by the desks. Similarly, the values of environmental parameters were acquired. Temperature, air humidity, and CO₂ concentration were acquired every minute with a Chauvin Arnoux 1510 sensor positioned near the teacher's station. In addition, lighting levels were acquired with a

HOBO onset sensor. The specifications of the measurement instruments used are provide in Appendix D – Instruments Characteristics Table 40.

4.1.3 Evaluation of Cognitive Performance and Comfort

Students involved in the study were divided into two groups (D1, D2) to counterbalance the acoustic conditions of test performance. Tests in the two sessions were administered to each group on the same morning, with a break between the two acoustic conditions. At the beginning of the session, after explaining in detail the procedure and objective of the study, participants were forwarded a Google Forms sheet to fill out with their biographical data and references to the Neurotask tests to be performed. Following the testing session, a self-report questionnaire was provided to assess cognitive effort during the tasks performed, and a dedicated questionnaire was used to assess IEQ (Appendix C – IEQ Survey). Upon completion, participants were asked to take a break following which the second test session was conducted. The total duration of each test session with questionnaire completion was 30 minutes.

4.1.4 Results

The mean physical parameters measured during the tests under the two different acoustic conditions, together with the corresponding SEL values calculated from acquired L_{Aeq1s} , are presented in Table 27 and

Table 29.

In Table 30 the university students' cognitive performance in quiet and in noise is reported in terms of a correct number of answers (from #B1 to #B4), a d-prime score that is a measure of an individual's ability to detect signals so fewer misses or false alarms (#B5), response time (#B6 to #B8). Table 30 also reports the mean value, the standard deviation (SD), and the t-test coefficient. A P-value lower than 5% has been considered to evaluate the statistical significance level of noise on cognitive performance.

Table 31 compares the performance in quiet conditions of students in groups D1 and D2 and noise condition with t-test, while Table 32 compares the performance in quiet and noisy conditions of all tested students.

Table 27: SEL values across acoustic conditions during performing Neurotask tasks.

Test	D1		D2	
	"Quiet"	"Noise"	"Quiet"	"Noise"
Neurotask	86.9	109.3	86.3	111.7

Table 28: Difference between SEL measured in noise condition and quiet condition when performing cognitive test.

Test	D1	D2
	Δ SEL [dB(A)]	Δ SEL [dB(A)]
Neurotask	22,4	25,4

Table 29: Mean values and standard deviation of Temperature, Air Humidity, CO₂ concentrations, and Illuminance levels across acoustic conditions.

Class	Temperature [°C]		Air Humidity [%]		CO ₂ concentrations [ppm]		Illuminance [lux]	
	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"
D1	20.3 ±0.2	20.8 ±0.1	35.3 ±0.1	35.0 ±0.4	730 ±13	751 ±5	200 ±2	201 ±1
D2	21.6 ±0.1	21.2 ±0.2	32.8 ±0.2	33.3 ±3.4	786 ±9	785 ±12	185 ±0	186 ±3

Table 30: University student's performance on Neurotasks tasks across acoustic conditions. Performance in noisy and quiet conditions of group D1 and performance in noisy and quiet conditions of group D2.

Test	D1 (n=7)					D2 (n=10)				
	"Quiet"		"Noise"		t	"Quiet"		"Noise"		t
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
#B1	48.25	9.73	54.37	3.37	-2.461*	54.0	2.72	50.87	6.72	1.195
#B2	3.50	1.60	10.87	18.24	-1.181	4.25	0.70	3.12	1.12	2.825*
#B3	7.12	3.87	6.62	1.99	0.423	7.37	2.32	6.25	3.84	1.229
#B4	6.28	1.60	6.71	1.11	-0.527	6.5	1.30	6.37	1.06	0.551
#B5	2.26	0.63	2.69	0.65	-1.20	2.63	0.74	2.60	0.68	0.041
#B6	612	257	585	239	1.133	758	352	868	454	-2.124
#B7	759	299	679	239	2.366*	858	378	966	427	-1.641
#B8	1056	283	879	198	0.863	871	230	2009	1478	-2.366*
Cognitive Effort Self-Report	2.55	1.13	2.50	1.14	0.308	2.33	1.32	2.50	1.15	-1.033

*p<.05; **p<.01; ***p<.001

Table 31: University student's performance on Neurotasks tasks across acoustic conditions. Comparison from group D1 and D2 in noisy and quiet condition.

Test	D1-D2					D1-D2				
	"Quiet"		"Quiet"		t	"Noise"		"Noise"		t
	Mean	SD	Mean	SD		Mean	SD	Mean	SD	
#B1	54	2.72	48.25	9.73	1.748	54.37	3.37	50.87	6.72	1.4
#B2	4.25	0.70	3.5	1.603	1.111	10.87	18.24	3.12	1.12	1.195
#B3	7.37	2.32	7.12	3.87	0.163	6.62	1.99	6.25	3.84	0.209
#B4	6.28	1.60	6.42	1.39	-0.172	6.71	1.11	6.28	1.11	0.596
#B5	2.42	0.80	3.06	-	-1.115	3.06	0	2.44	0.88	1
#B6	612.27	257.84	675.82	282.91	-0.482	585.83	239.21	787.64	423.92	-1.161
#B7	759.04	299.28	760.36	278.23	-0.009	679.31	239.09	908.58	426.8	-1.375
#B8	1152.07	298.88	871.13	230.13	2.16	879.82	198.23	1810.89	1551.30	-1.319
Cognitive Effort Self-Report	2.64	1.12	2.33	1.32	1.13	2.62	1.14	2.5	1.14	0.590

*p<.05; **p<.01; ***p<.001

Table 32: University student's performance on Neurotasks tasks across acoustic conditions. All the students in the two groups together.

Test	"Quiet"		"Noise"		t
	Mean	SD	Mean	SD	
#B1	51.12	7.51	52.62	5.45	-0.7097
#B2	3.87	1.25	7	13.11	-0.9721
#B3	7.25	3.08	6.43	2.96	1.1194
#B4	6.4	1.40	6.53	1.06	-0.343
#B5	2.34	0.68	2.56	0.62	-0.5326
#B6	690.5	310.1	736.6	386.1	-1.3616
#B7	812.1	335.9	832.3	371.2	-0.4515
#B8	1011.6	294.8	1490.4	1202.9	-1.7172
Cognitive Effort Self-Report	2.4	1.2	2.5	1.1	-0.3763

*p<.05; **p<.01; ***p<.001

Regarding the preference of environmental conditions, students' responses to the question on the preference of the four macro areas of the IEQ are presented in Figure 41. Regarding satisfaction, the responses are presented in Figure 42.

Figure 41: Responses to the question “How would you prefer to be now?” of groups D1 and D2 in quiet and noise sessions of cognitive test performance.

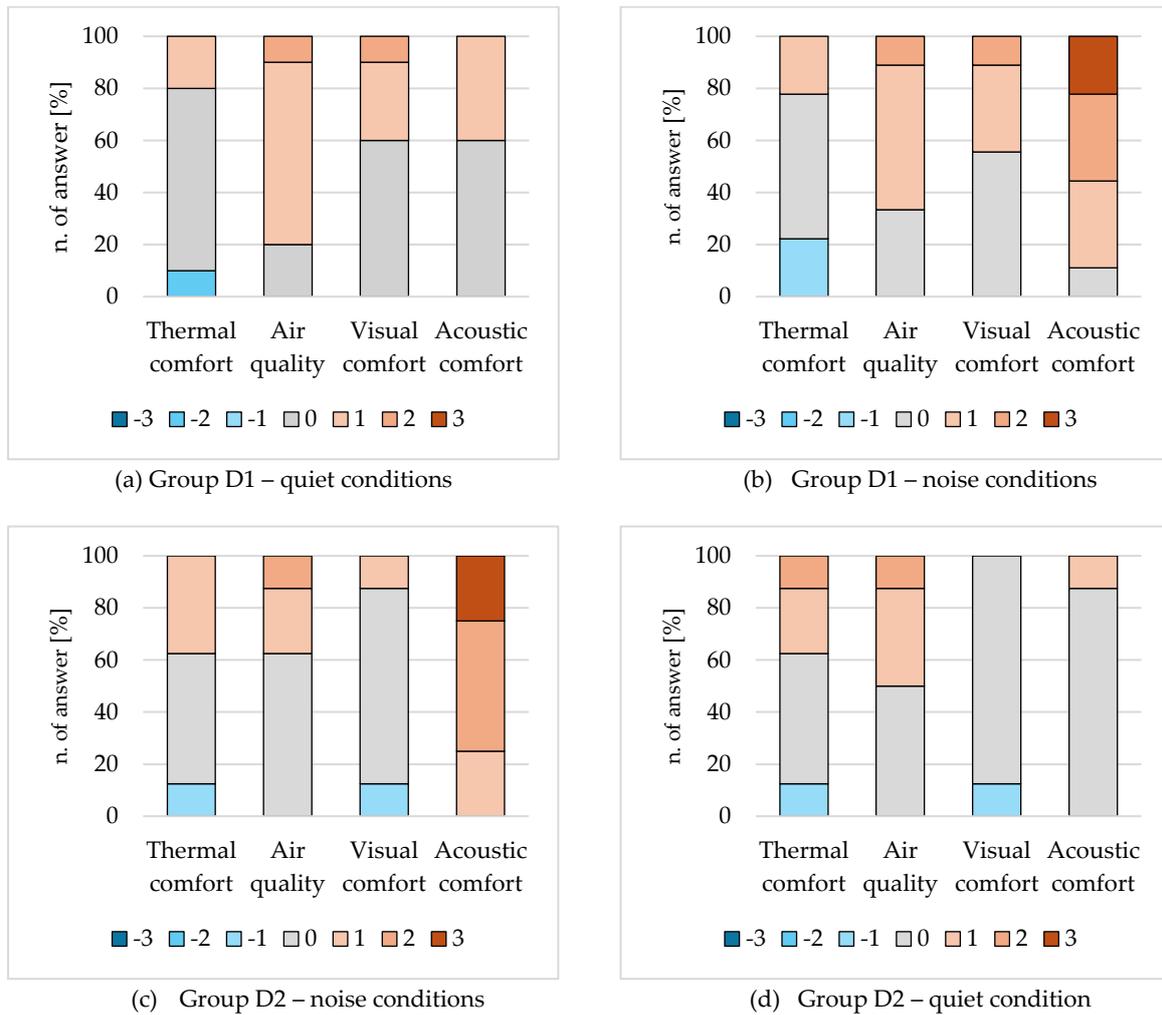
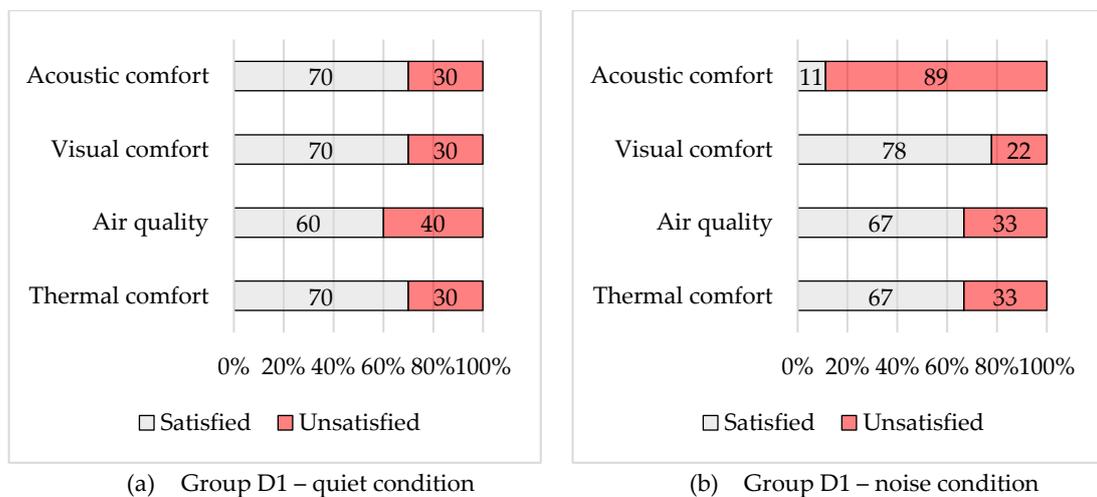
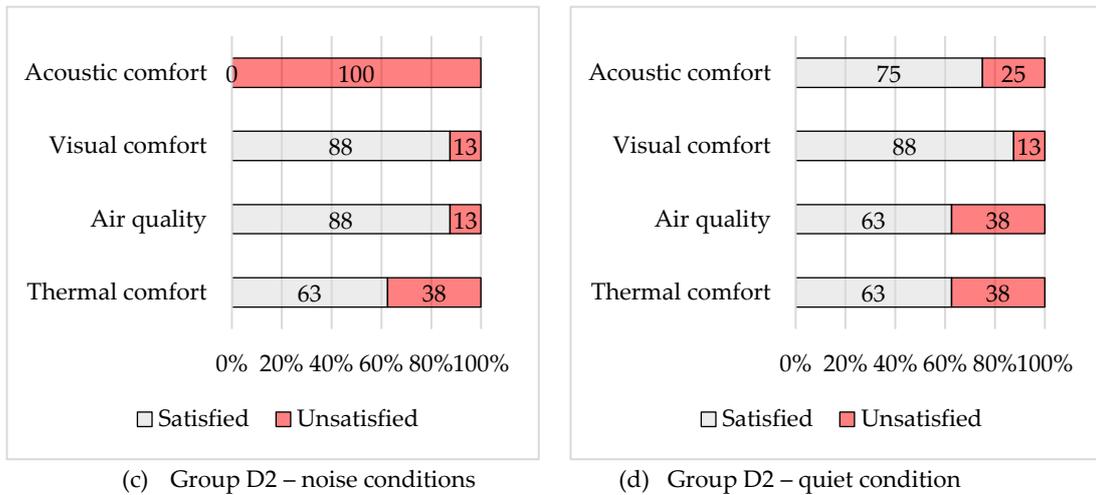


Figure 42: Responses to the question “Are you satisfied with the thermal/air/visual/acoustic environment?” of groups D1 and D2 in quiet and noise sessions of cognitive test performance.



(continued)

Figure 42: (continued)



4.1.5 Discussion

Temperature and air humidity conditions were similar during tests both in quiet and noisy conditions. Results obtained from the monitoring of physical parameters are in line with the responses given by students in the IEQ evaluation questionnaire regarding the perception and satisfaction of the classroom while performing the tests during the trials. The influence of physical aspects could be neglected other than the sound pressure level of noise.

The improvement in performance in noisy conditions in group D1 and quiet conditions in group D2 can be attributed to students' familiarity with the tests performed in the second session.

Working memory was unaffected by noise, but significant effects were observed in inhibition tests for both groups. The first group responded faster in noise, while the second performed better in quiet.

Counterbalancing the acoustic conditions, no significant differences were observed between tasks performed in quiet and in noise. Comparing performance in quiet and noisy conditions between the two groups, no significant differences in performance were observed. Regarding perceived cognitive effort, although statistical analysis does not show significant effects, the second group reported a higher average effort rating during the noise condition. Results are in line with the responses given to the IEQ evaluation questionnaire on perception and satisfaction with the acoustic environment during test performance. In fact, under test conditions performed in noise, there is a high percentage of dissatisfaction with the environment.

5. Acoustics and Environmental Monitoring Parameters During Teaching Activities

The chapter shows the application of the described method for performing acoustic and environmental monitoring of Temperature, Air humidity, and CO₂ concentration during typical classroom situations. The monitoring took place in two schools, School B (classes B1 and B2) and School C (classes C1-C4). The two schools, similar in terms of room acoustics and landscape context, differed in the number of students belonging in each classroom. The paragraphs, divided into acoustic monitoring and environmental monitoring, report the results obtained and discussions.

5.1 Evaluation of the Sound Variability

The variability of the acoustic environment was analyzed through continuous monitoring of the sound pressure level during school activities. For each monitoring day, without the student's knowledge, the equipment was placed near the teacher's desk. The tablet, equipped with the OpeNoise app [112], was concealed inside a bag to mask its presence (Figure 43). At the end of the school day, the recordings were stopped, and the equipment was collected. The duration of each lesson was 60 minutes. Break times, lunch periods, and hours during which students engaged in activities outside the monitored classroom were excluded from the analysis during the processing stage. This was made possible by the teachers filling out a log in which they recorded the subject being taught and the teaching activity made according to the following definitions:

- Oral teaching: teacher speaks while students sit quietly at their desks;
- Individual activities: students perform individual tasks such as exams, reading, writing, or drawing, each sitting quietly at their desk;
- Interactive education: a dialogue between the teacher and students;
- Team activities: the simultaneous presence of multiple people speaking and moving, including music.

The data collection took place at two schools over two different school years but within the same period of the year. Monitoring occurred in classes B1 and B2 during the 2022-2023 school year, and in classes C1, C2, C3, and C4 during the 2023-2024 school year. In classes B1 and B2, recordings were conducted over a total of four weeks (from January 23rd, 2023, to February 17th, 2023), during which it emerged that the collected parameters and the teaching methods tended to repeat. For this reason, at school C, the monitoring was reduced to one week (from March 4th, 2024, to March 8th, 2024).

Figure 43: Example of arrangement of low-cost instrumentation in monitored classrooms.



After removing the samples in which no lecture was present in the classroom, the collected data were analyzed by proceeding to calculate the acoustic parameters listed in Table 33 from $L_{Aeq,1s}$.

Table 33: Acoustic descriptors calculated.

Equivalent sound pressure level L_{Aeq} [dB(A)]
Standard deviation of $L_{Aeq,1s}$ S [dB(A)]
Percentile levels L_{A10} , L_{A90} e L_{A95} [dB(A)]
Noise climate L_{A10} - L_{A90} [dB(A)]
Intermittency Ratio IR [%]

In addition to the common acoustic parameters L_{Aeq} and percentile levels, the Intermittency Ratio (IR) was calculated. This parameter makes it possible to describe the variability of sound levels over time [80]. Formula for calculating IR is:

$$IR = \frac{10^{0.1L_{Aeq,T,events}}}{10^{0.1L_{Aeq,T}}} \cdot 100 \text{ [%]} \quad (9)$$

Where:

$L_{Aeq,T,events}$ [dB(A)] is the total equivalent level of sound events identified above threshold K and related to total time T.

$L_{Aeq,T}$ [dB(A)] is the total equivalent level related to the total time T.

A single events contributes to $L_{Aeq,T,events}$ only if its level exceeds a given threshold K determined by:

$$K = L_{Aeq,T} + C \text{ [dB]} \quad (10)$$

Where $C=3$ dB.

In this research, the value of C for the definition of K was assumed to be 3. However these are never events associated with vehicular pass-by but events related to the school's sound climate.

The value of IR is between 0 and 100. High values highlight the presence of clearly distinguishable and very pronounced events concerning the level $L_{Aeq,T}$.

Another descriptor considered for describing noise fluctuation over time is the noise climate $L_{A10-L_{A90}}$ [dB(A)] and the standard deviation of the levels $L_{Aeq,1s}$, s .

5.1.1 Results

Table 35 shows the total number of monitoring hours performed in each class. Excluding the hours of non-classroom activities, the recess and lunch periods, the acquisitions were divided based on the teaching activity performed (Table 35).

Table 34: Total hourly surveys carried out in school B and C classes.

School	Classrooms	Monitoring duration [hours]
B	B1	114
	B2	114
C	C1	31
	C2	40
	C3	40
	C4	31

Table 35: Hourly surveys among the teaching activities conducted with the exclusion of hours of teaching undertaken not in the classroom.

School	Hours taken into account	Hours of oral teaching	Hours of interactive education	Hours of team activities	Hours of individual activities
B	173	121	13	30	9
C	84	15	36	26	7

The consistent set of acoustic data acquired and results obtained for the various acoustic descriptors can be analyzed according to multiple aspects. By way of description, the box plots diversified by teaching activities of the $L_{Aeq,h}$ levels (Figure 44), and IR (Figure 45) for the surveys conducted are shown. Figure 46 shows the comparisons of the mean values of $L_{Aeq,h}$, and IR of schools B and C differed by teaching activity.

Figure 44: Box plots of variation of $L_{Aeq,h}$ divided by teaching activities for school B (a) and school C (b). The dots represent the outlier with their values.

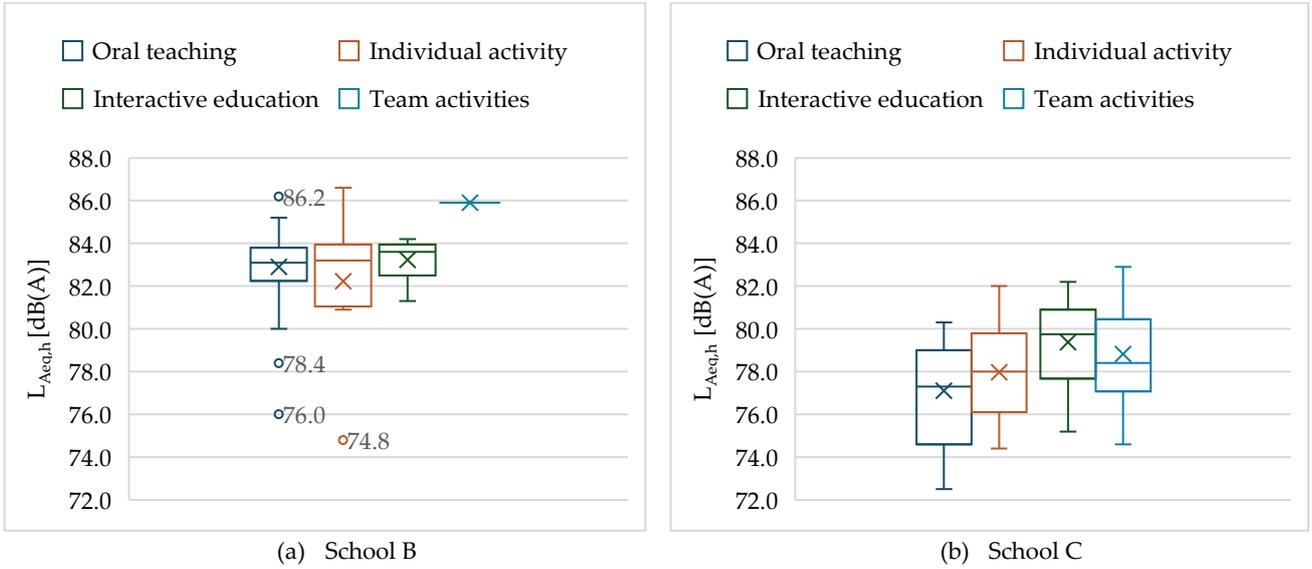


Figure 45: Box plots of the variation of IR divided by teaching activities in school B (a) and school C (b). The dots represent the outliers with their values.

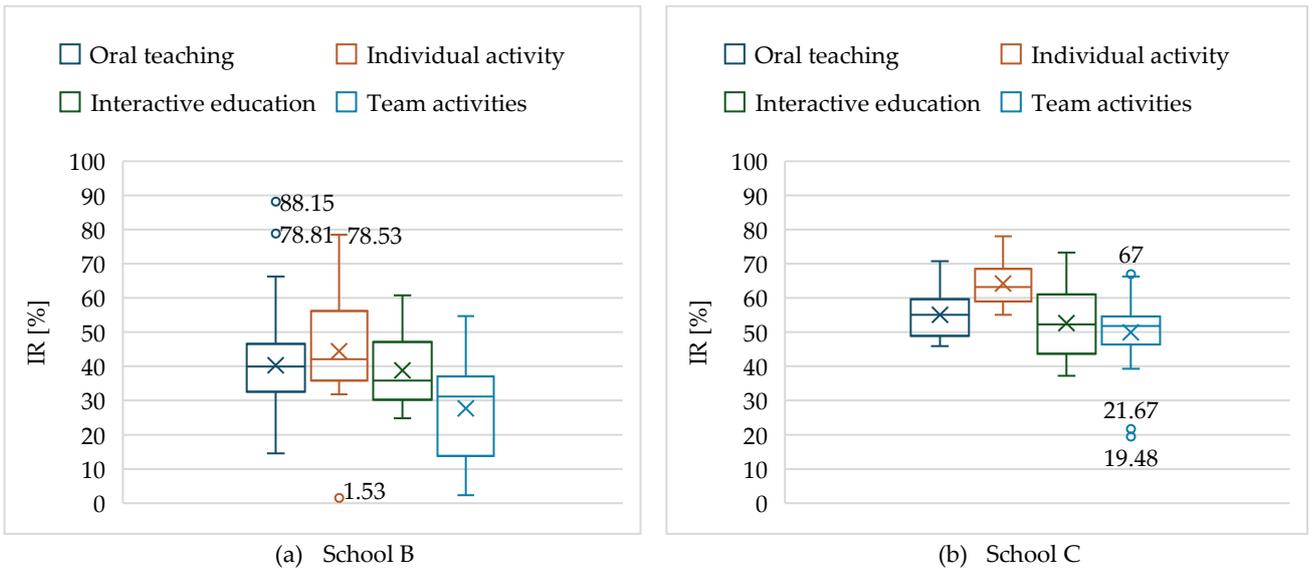


Figure 46: Comparison of average $L_{Aeq,h}$ between the teaching activities measured in schools B and C (a) and comparison of average IR between the teaching activities carried out in schools B and C (b)

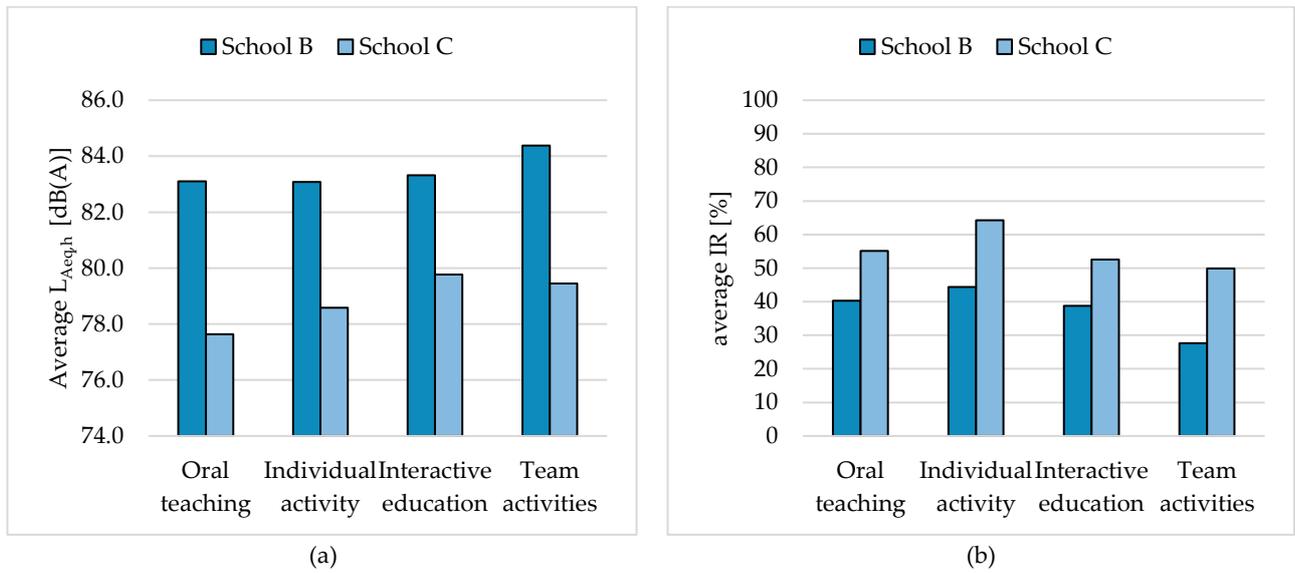
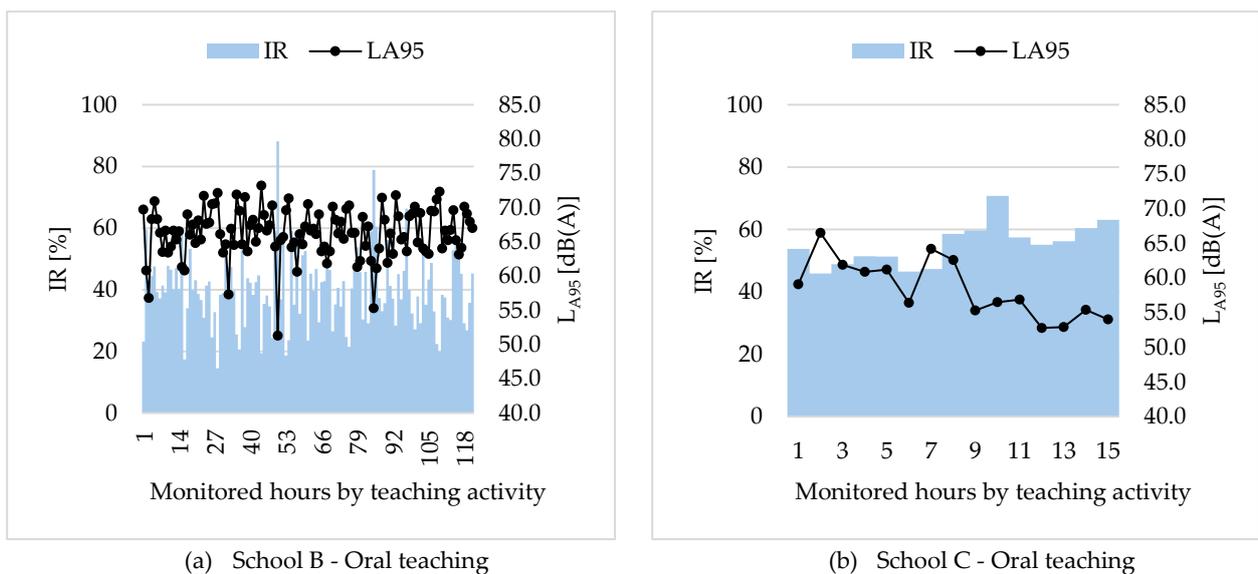
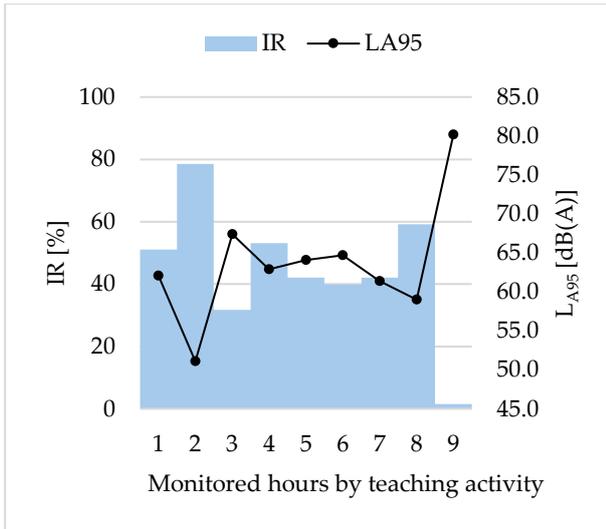


Figure 47 shows a comparison for each teaching activity in B and C schools, the change over time of IR with the corresponding L_{A95} value. The numbers on the x-axes indicate the progressive number of hours surveyed, indicating the sample size of the surveys by teaching activity.

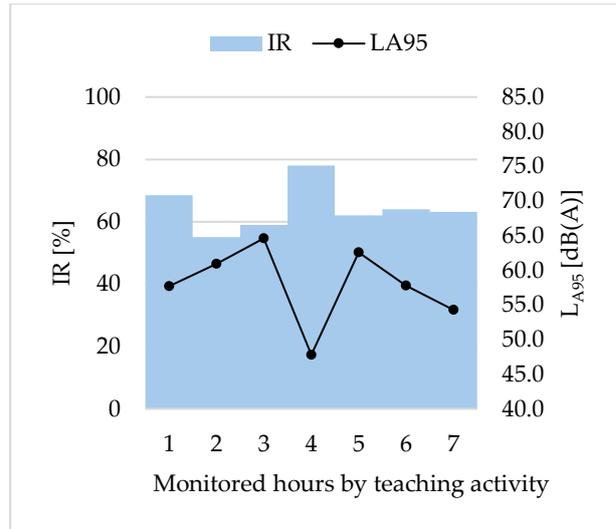
Figure 48 shows the minimum and maximum values of the IR index and the minimum and maximum values of L_{A95} calculated, by teaching activity, in the two schools.

Figure 47: Variation of IR and the corresponding value of L_{A95} monitored in B and C schools by teaching activities. Oral teaching in school B (a) and C (b); Individual activity in school B (c) and C (d); Interactive education in school B (e) and C (f); Team activities in school B (g) and C (h).

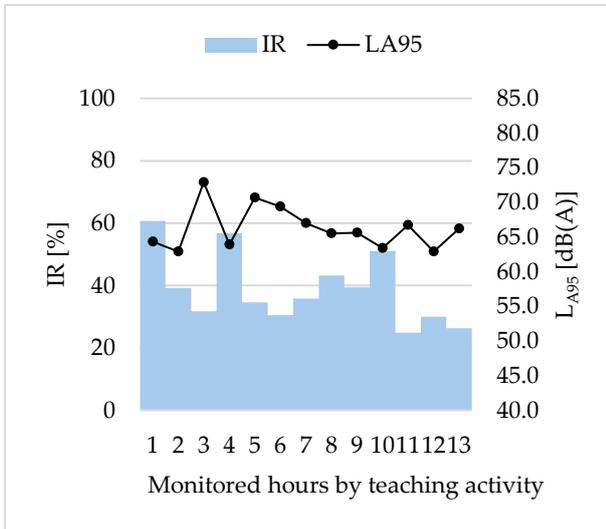




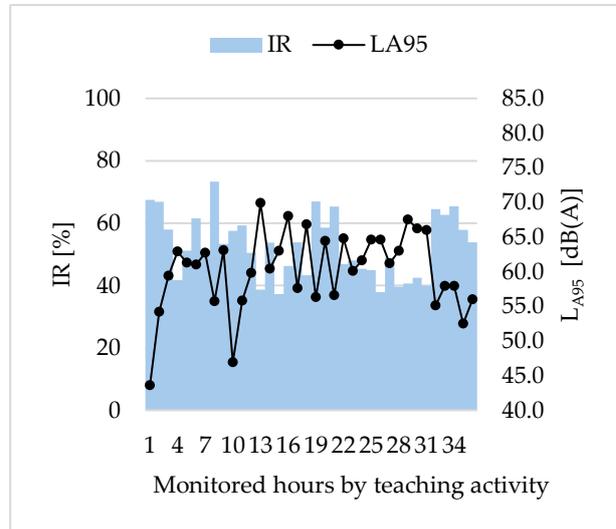
(c) School B – Individual activity



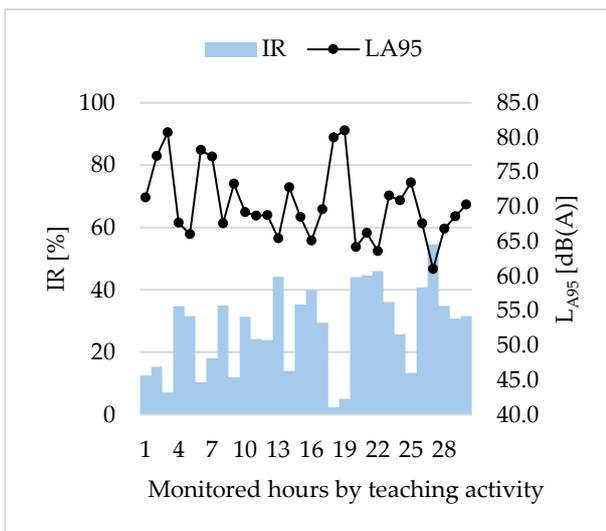
(d) School C – Individual activity



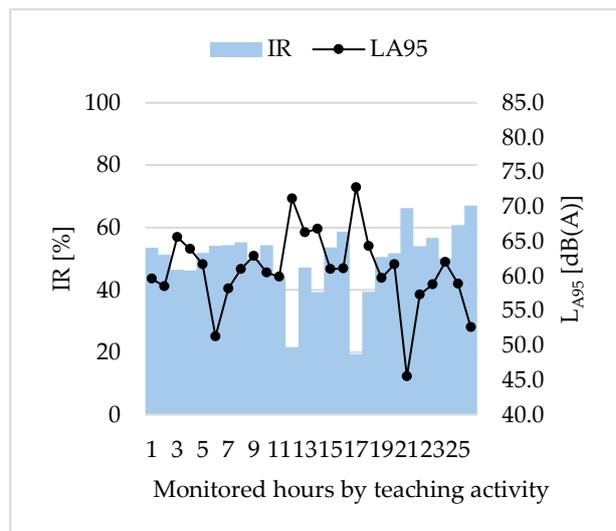
(e) School B – Interactive education



(f) School C - Interactive education



(g) School B – Team activities



(h) School C – Team activities

Figure 48: Min and max IR and LA95 values by teaching activity in School B, classes B1 and B2.

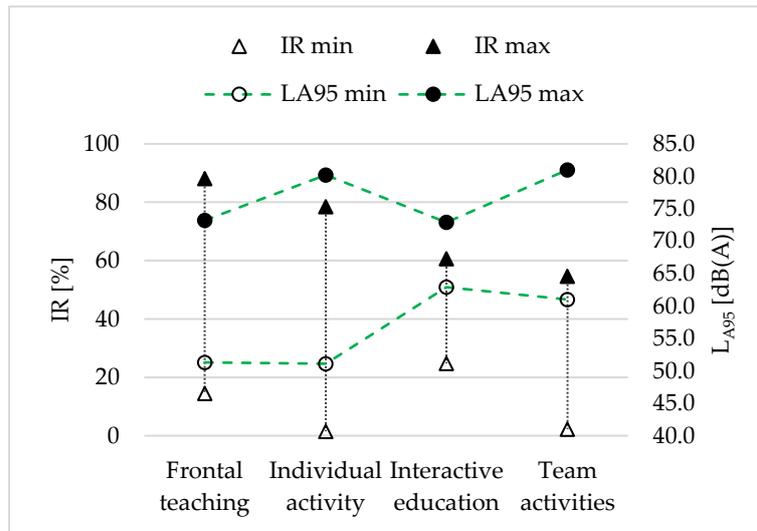
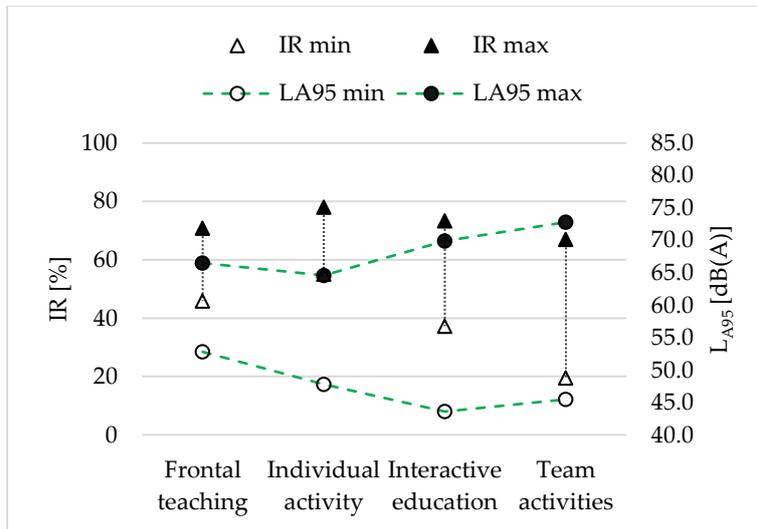


Figure 49: Min and max IR and LA95 values by teaching activity in School C, classes C1, C2, C3, and C4.



Oral teaching and individual activities represent standardized teaching activities, making it possible to compare IR values directly. The difference between the medians of IR of school B and school C is observed to be more intermittent in school C due to the different number of pupils in school C classes than in school B classes (3.2.1 Table 17 and 3.3.1 Table 22).

Table 36: Difference between medians measured in oral teaching and individual activities (quiet condition) in schools B and C.

	Oral teaching	Individual activity
Δ IR median (School C – School B) [%]	15.2	21.1

The presence of sound events distinguishable from background noise can initially be assessed based on the IR. Table 37 shows the percentage of observations with IR values $\geq 50\%$, indicating events contributing more than 50% to the LAeq, differentiated by teaching activities.

Table 37: Percentage of times IR \geq 50%.

School	Oral teaching	Individual activity	Interactive education	Team activities
B	18%	44%	23%	3%
C	73%	100%	58%	65%

Further analysis with Pearson's matrix, examined the correlation between the main calculated acoustic descriptors connected with fluctuations in sound level over time, such as those produced by the presence of sound events distinguishable from background noise. The Pearson matrix is a statistical tool used to display the correlations between multiple variables. Each element in the matrix represents the Pearson correlation coefficient between two specific variables. This coefficient measures the strength and direction of the linear relationship between the variables, with values ranging from -1 to 1. Pearson's matrix was calculated on the results of the acoustic descriptors for School B, grouping them by teaching activity and grouping them all together Figure 50. The same was done for the parameters of School C Figure 51. Figure 52 shows the Pearson matrix for the acoustic parameter values of schools B and C together.

Figure 50: Pearson correlation matrix between the main acoustic descriptors of school B.

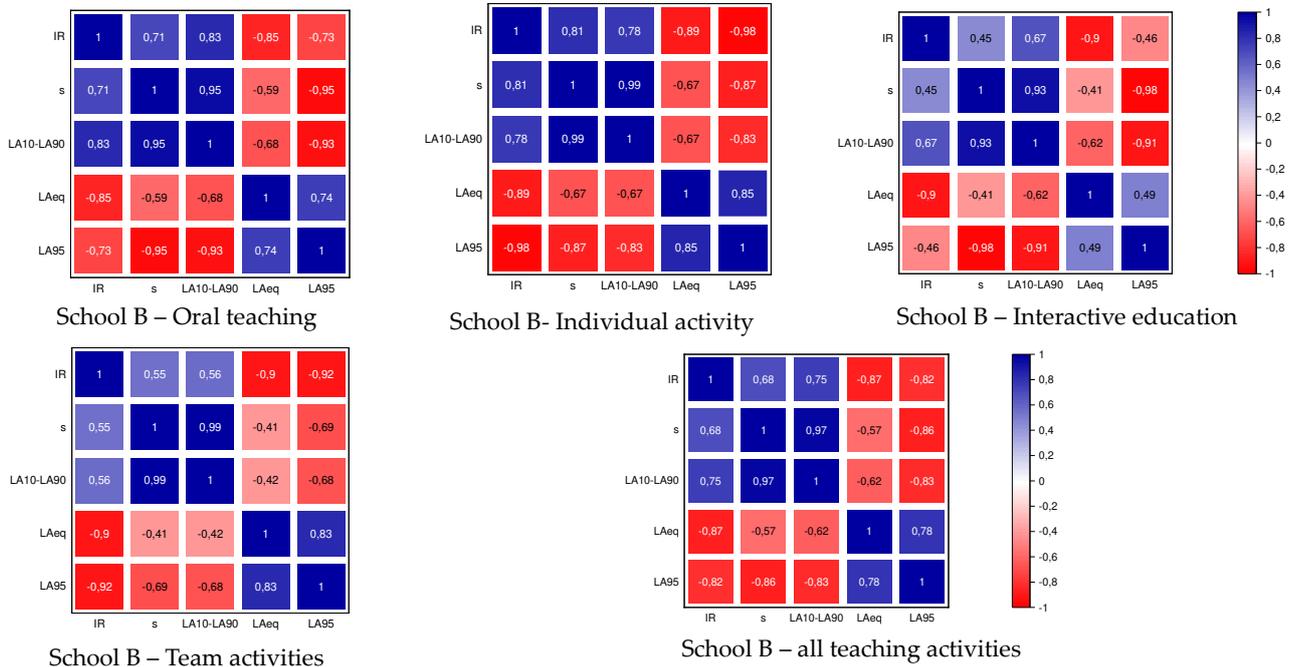


Figure 51: Pearson correlation matrix between the main acoustic descriptors of school C.

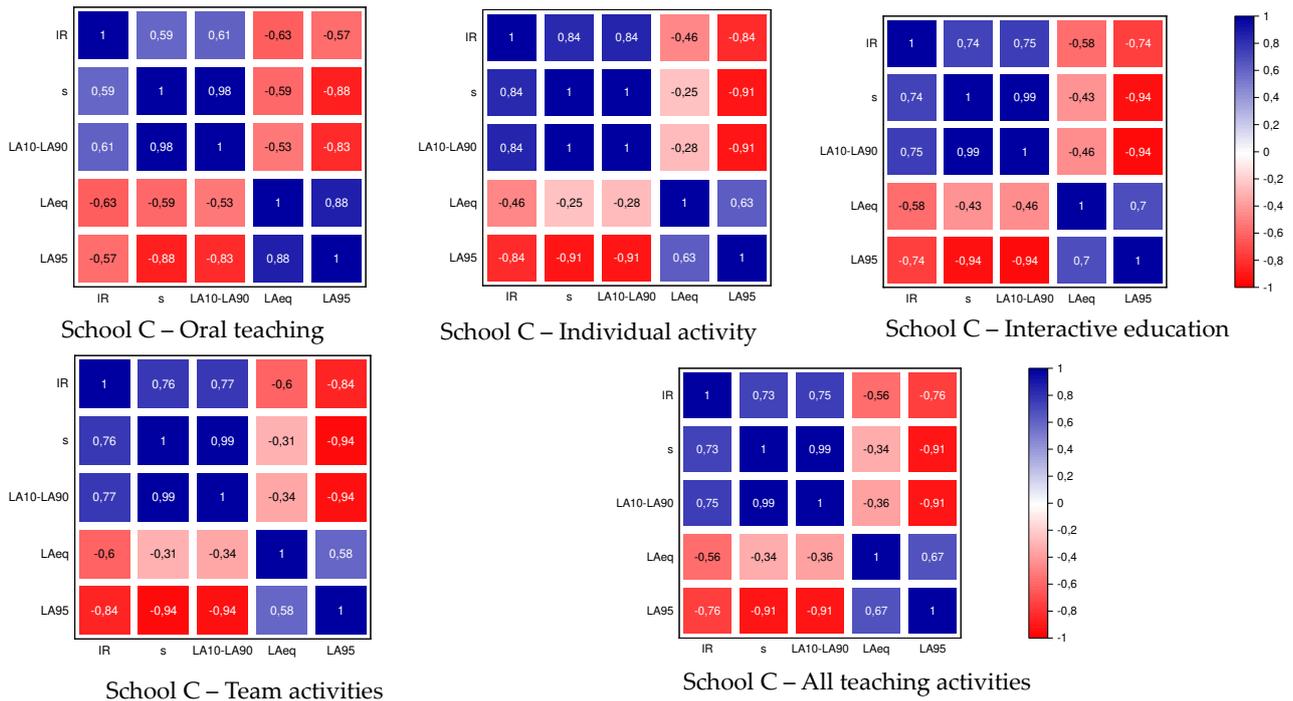
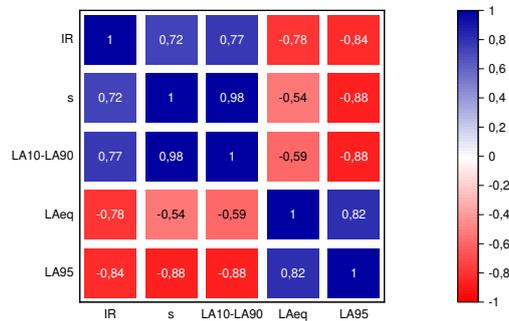


Figure 52: Pearson correlation matrix between the main acoustic descriptors of schools B and C.



5.1.2 Discussion

Analysis of the temporal dynamics of noise using innovative indices provided interesting insights. It emerged that the temporal dynamics of noise are influenced by the teaching activity adopted and the number of students present in the classroom. These observations were made possible due to the significant differences between the monitored schools B and C. As identified in Chapter 3, although both schools have room acoustic properties that do not meet regulatory limits, they differ in the number of students in the classes.

A smaller number of students, as in school C, results in a lower background noise level. Still, it is characterized by more significant intermittency due to the lack of masking by the background noise of occasional events.

The same considerations apply to the teaching activity adopted in the class. Group activities generate higher background noise due to the movement of the occupants or other noise sources, which results

in lower intermittency of occasional events. On the other hand, individual activities, characterized by lower background noise levels, lead to the occurrence of events that are not masked, increasing intermittency in the temporal dynamics.

It was observed that School C, due to the smaller number of students in the classroom, can adopt the strategy of changing the furniture arrangement layout according to the teaching activity being done. The same approach cannot be applied to school B due to the considerably significant number of students in the classrooms. As a result, despite the long reverberation times, proper management of school spaces compensates for the acoustic deficits in the classrooms.

Thanks to the Pearson matrices, it was possible to observe that the use of the IR index can be a good compromise for describing the soundscape. A clear distinction is evident between the groups of indicators related to the description of the temporal fluctuation of the sound level, such as IR, the standard deviation of sound levels (s), and the variation in the sound environment $L_{A10-LA90}$, and those related to the amount of sound energy, such as L_{Aeq} and L_{A95} .

The exclusive use of the L_{Aeq} , considering the potential disturbance effects, proves to be insufficient. Therefore, additional parameters that help describe the temporal dynamics of sound levels resulting from activities in an environment need to be considered. Based on the findings, the IR index can be used in conjunction with the L_{Aeq} .

5.2 Evaluation of Environmental Parameters Variability

To provide an overview of the environmental conditions to which students are exposed during the normal course of educational activities, the values of Temperature, Air Humidity, and CO₂ concentration were acquired. HOBO Connect MX1102 sensors, whose technical characteristics are provided in Appendix D – Instruments Characteristics Table 40 were placed daily, without the student's knowledge, in the monitored classroom near the teacher's desk.

The acquired data were analyzed by excluding, as with the acoustic monitoring, break times, lunch periods, and hours during which students engaged in educational activities outside the monitored classroom. The results were compared with the ranges specified in the EN 16798 standard [116].

The monitoring, according to teachers, took place at school B from 23rd January 2023 to 17th February, and at school C from 4th March 2024 to 8th March 2024. The EN 16798 standard [116] prescribes that, during the winter period for school classrooms, considering sedentary activities and an average level of expectation, the temperature values should be between 20°C and 24°C. The acceptable range for air humidity is between 25% and 60%. Regarding CO₂ concentration, a reference maximum value of around 900 ppm (500 ppm above the CO₂ concentration measured outdoors) is suggested.

5.2.1 Results

Boxplots (Figure 53) summarize the distribution of Temperature, Air Umidity, and CO₂ concentration measurements to which students were exposed during the weeks of continuous monitoring. The histograms (Figure 54) show the percentage of time that classrooms fall (light blue) or do not fall (red) within the ranges specified in EN 16798 standard [116].

Figure 53: Distribution of measured temperature (a), Air humidity (b), and CO₂ concentration (c) in the monitored classes of schools B and C. The dots represent the outlier.

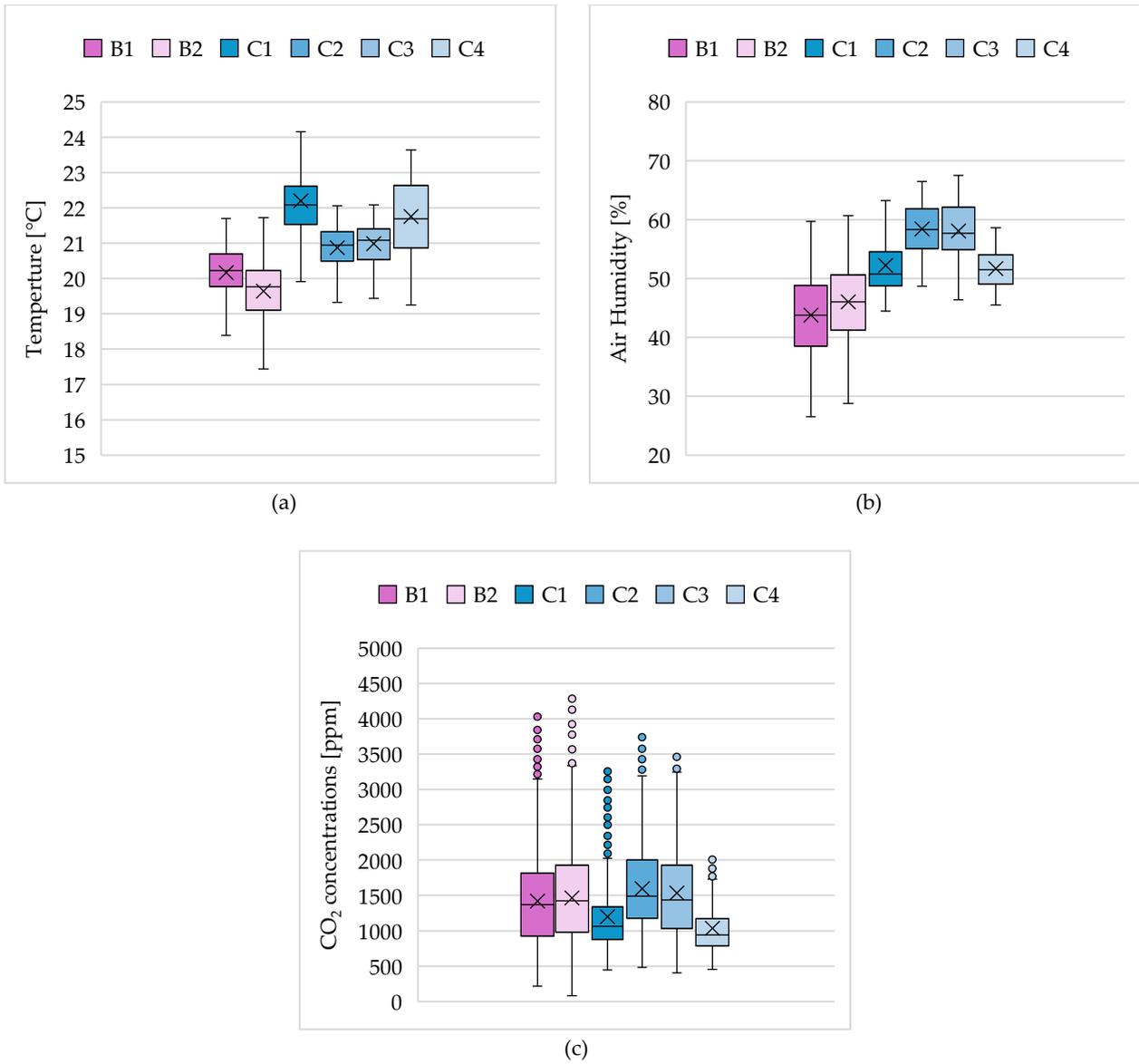


Figure 54: Histograms show the percentages of time that classrooms in schools B and C fall (light blue) or do not fall (red) within the ranges given in EN 16798. Class B1 in histogram a, Class B2 in histogram b, Class C1 in histogram c, Class C2 in histogram d, Class C3 in histogram e, and Class C4 in histogram f.



5.2.2 Discussion

Regarding temperature, the interquartiles are relatively close and straddle the temperatures indicated for comfort in all classes. Conditions meet environmental requirements with a minimum of 38% (B2) and a maximum of 96% (C4).

The interquartiles of air humidity are between 40% and 60%. The conditions meet environmental requirements more than 58% of the time with a minimum of 58% in class C2 and a maximum of 100% in class B1 and C4.

Regarding CO₂ concentration, conditions are verified 11% of the time in class C2 and a maximum of 41% in the case of class C4.

Regarding students' exposure to the values identified by the reference standard EN 16798 [116], regarding thermo-hygrometric aspects, the characteristics of the heating system allow for maintaining values in line with the ranges suggested by the standard. Regarding CO₂ concentration, the survey showed that the required air quality values were not obtained for almost the entire exposure time.

6. Design of Sound-Absorbing Panels for Educational Buildings

The chapter shows the application of the method described for evaluating the suitability of sound-absorbing panels with a layer made of paint applied by students as improvements to be affixed in classrooms. The sound-absorbing characteristics of the materials are evaluated in a reverberation room, and it is assessed whether a more thinned material configuration than the plane absorber arrangement affects their sound-absorbing characteristics. The panels were then applied in the real context of classrooms to measure the change in reverberation time under the assumption of material arrangement in classrooms.

6.1 Use of Polyester Fiber Soundproofing Panels as a Painting Support

The materials analyzed are white panels made of 100% polyester fiber in staple form (recycled PET fiber with added thermobonding fiber), measuring 50x50 cm with a thickness of 5 cm and a nominal density of 40 kg/m³. Two sets of materials were used for the evaluations: the first set (P1), unlike the second set (P2), has a stiffer surface layer due to repeated external thermosmoothing operations on the sound-absorbing panels.

The evaluation of sound-absorbing acoustic behavior involved measuring the Equivalent sound absorption area per object, A_{obj} , in the reverberation room of the "LabAcus" laboratory at the Department of Industrial Engineering, University of Padova. Measurements were taken both in the production state and after the application of a paint layer by primary school children. The material was arranged in the reverberation room in a plane absorber configuration (type "A", Appendix B of ISO 354 standard [93]). For P1, the painted layer was applied to the surface with the thermosmoothing effect. The calculation of the materials' sound absorption properties was based on the measurement of the average reverberation time in the reverberation room, both with and without the sample. From the reverberation time, the Equivalent sound absorption area of the sample, A_T , was calculated using Sabine's equation. When the sample uniformly covers the surface (plane absorber), the sound absorption coefficient is obtained by dividing A_T by the treated surface area S . If the sample consists of multiple identical objects, the equivalent sound absorption area, A_{obj} , of a single object is calculated by dividing A_T by the number of objects N .

The equivalent sound absorption area of the empty reverberation room, A_1 , and that of the chamber containing the test specimen, A_2 , were calculated using the equations (11)(12).

$$A_1 = \frac{55.3V}{cT_1} - 4Vm_1 \quad (11)$$

$$A_2 = \frac{55.3V}{cT_2} - 4Vm_2 \quad (12)$$

Where:

V is the volume of the empty reverberation room [m³];

c is the propagation speed of sound in air [m/s];

T₁ and T₂ are respectively the reverberation time of the empty reverberation room and the reverberation time of the reverberation room after the test specimen has been introduced;

m₁ and m₂ are the power attenuation coefficients calculated according to ISO 9613-1 [68] using the climatic conditions that have been present in an empty reverberation room during the measurement [m⁻¹]

The equivalent sound absorption area of the test specimen, A_T, shall be calculated using the formula (13).

$$A_T = A_2 - A_1 = 55.3V \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4V(m_2 - m_1) \quad (13)$$

Where:

c₁ e c₂ is the propagation speed of sound in air respectively at the temperature t₁ e t₂

The equivalent sound absorption area of a single object is obtained by dividing A_T by the number of objects n.

$$A_{obj} = \frac{A_T}{n} \quad (14)$$

The sound absorption coefficient of the test specimen, α_s shall be calculated using the formula (15).

$$\alpha_s = \frac{A_T}{S} \quad (15)$$

Where:

A_T is the equivalent sound absorption area of the test specimen;

S is the area covered by the test specimen.

The P1 material set (composed of 10 panels) was tested by arranging the material both on the side with the thermosmoothing effect (P1_1) and on the opposite side (P1_2). Since the quantity of material was

insufficient to cover the 12 m² surface area required by ISO 354 standard [93] to calculate the sound absorption coefficient, α , the equivalent sound absorption area per panel, A_{P1} was determined. For the P2 material set, which was available in larger quantities, both A_{P2} and the coefficient α_{P2} were calculated. The measurements were conducted with the materials in their original state (P1 and P2) and after the application of the painted layer (P1_1p, P2_p). The values were calculated as an average of 18 measurements for each material arrangement, derived from a combination of 3 source positions and 4 receiver positions (two measurements per receiver point).

Figure 55: Picture of P1_1p (a) and P2_p (b) materials



6.1.1 Results

Figure 56 shows a comparison of the A_{obj} of material P1 measured from both sides of the material (side with and without effect due to the repeated thermosmoothing operation P1_1 and P1_2, respectively) and material P2 in the original state according to a reverberation room arrangement “Type A” of ISO 354 standard [93]. Figure 57 compares the equivalent sound absorption area A_{obj} of P1_1 and P2 in the original state and after the application of the painting layer by primary school children P1_1p and P2_p. Having enough P2 material to cover the reverberation room area of 12 m², formula (15) was applied to calculate α_{P2} e α_{P2_p} (Figure 58).

Figure 56: A_{obj} of test specimen P1_1, P1_2, and P2_p with the configuration of plane absorber “Type A” ISO 354.

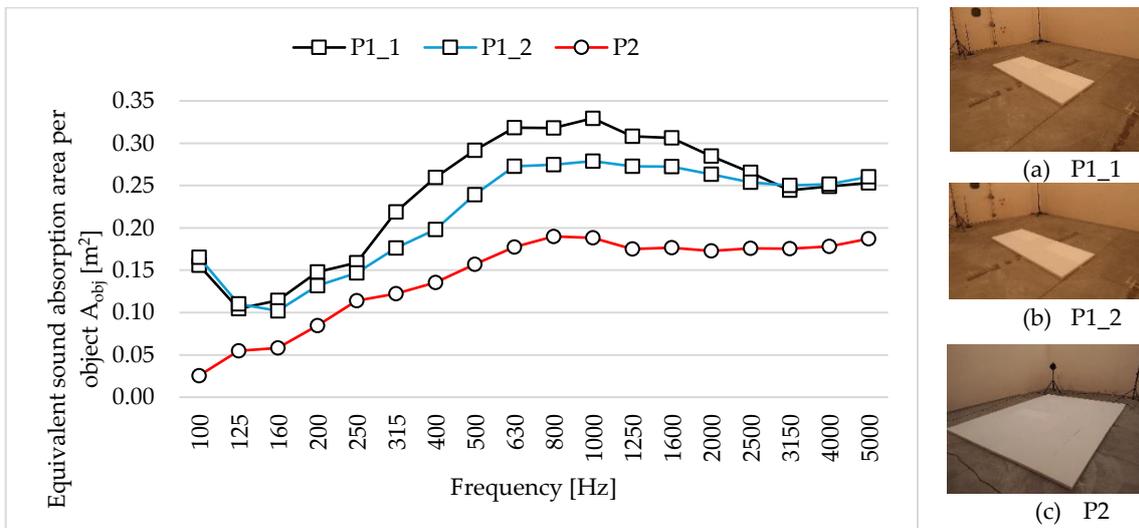
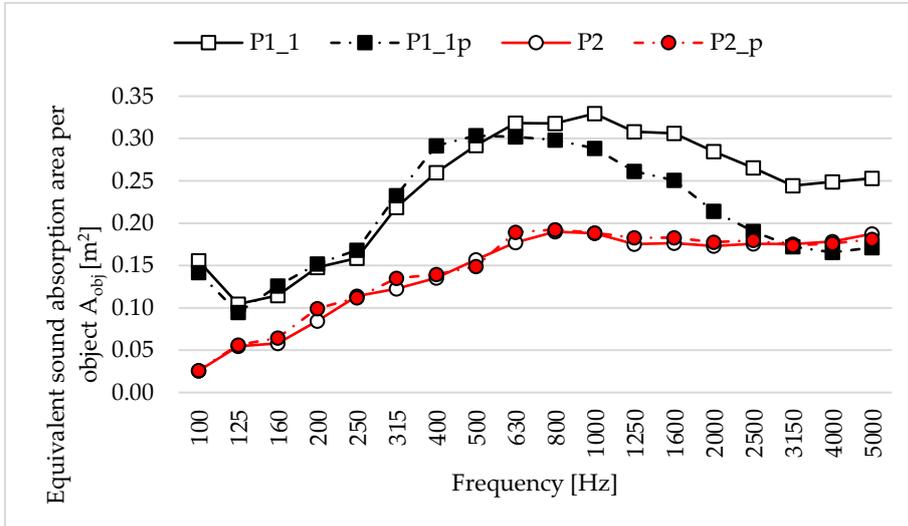


Figure 57: A_{obj} of test specimen P1_1p and P2_p with configuration of plane absorber "Type A" ISO 354.



(a) P1_1



(c) P1_p

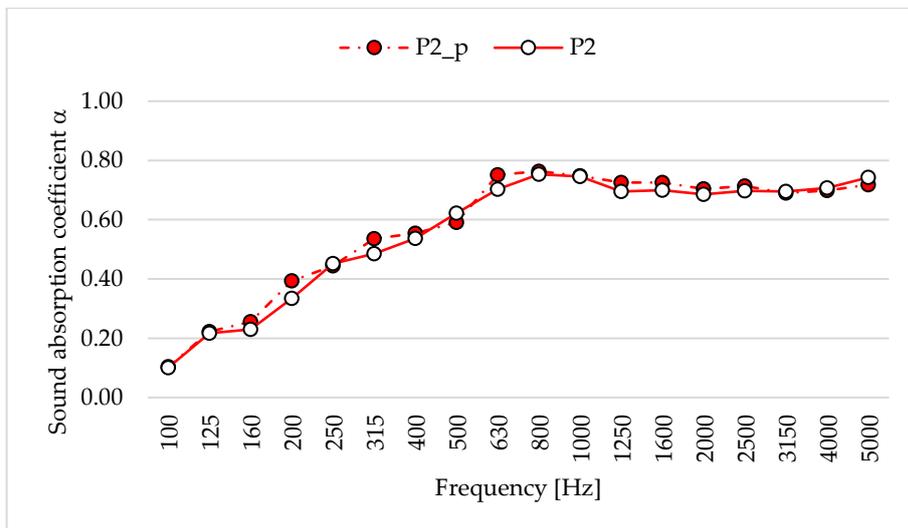


(d) P2



(e) P2_p

Figure 58: Sound absorption coefficient of P2 and P2_p with the configuration of plane absorber "Type A" ISO 354



(a) P2



(b) P2_p

Appendix H – Sound Absorption Characteristics Table 52 shows the measured frequency values of the equivalent absorption area of the panels in the production state and following the application of the paint layer. Appendix H – Sound Absorption Characteristics Table 53 shows the sound absorption coefficient of the panels in the production state and following the application of the paint layer.

6.1.2 Discussion

Regarding the first set of material used, P1, tested on both faces (P1_1 and P1_2), where face P1_1 featured a layer resulting from the thermosmoothing operations on the material, it behaves in the same way on both faces. Comparing it to the second set of materials, P2, both exhibit characteristics of fibrous materials.

When primary school students applied a paint layer to the samples (P1_1p and P2_p), laboratory tests on the calculation of the equivalent sound absorption area showed that, despite being made of the same material, the two samples displayed distinct behaviors.

In P1, following the application of the paint layer (P1_p), a change in the energy dissipation mechanism was observed, due to the formation of a membrane created by the paint layer combined with the layer resulting from the thermosmoothing operation. This hybridization leads to a tendency for the absorption peak to shift toward lower frequencies, a typical effect of vibrating panels.

In P2, the addition of the paint layer (P2_p) does not alter the energy dissipation mechanism. Therefore, the material continues to behave as a fibrous material. The added paint layer does not affect the fibers of the material.

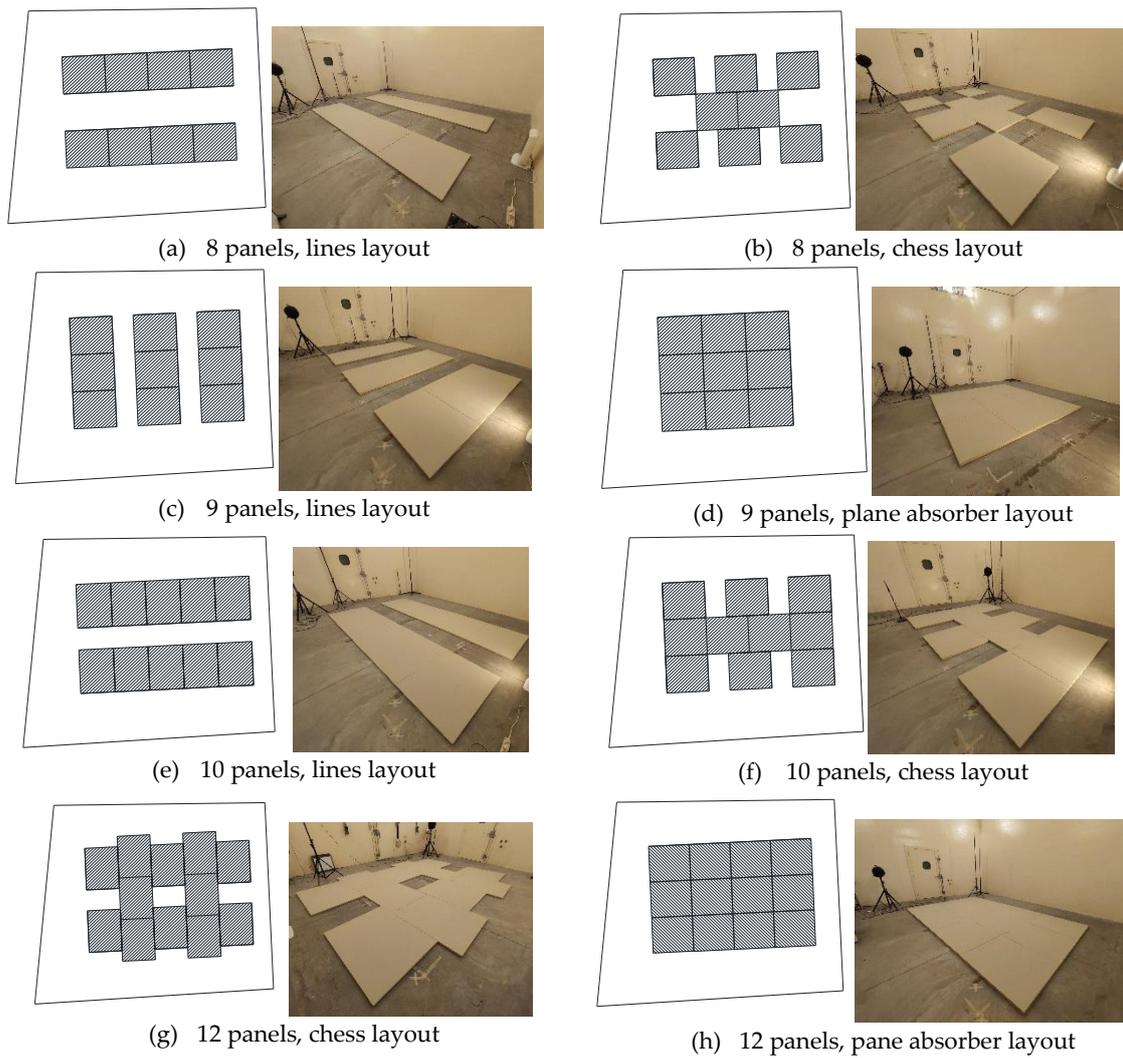
6.2 The Influence of Different Configurations of the Panels on Sound-Absorbing Properties

The effect of the different arrangements of sound-absorbing materials on sound absorption was evaluated using white sound-absorbing panels made of 100% polyester fiber in staple form (recycled PET fiber with the addition of thermobonding fiber). The panels measured 120x100 cm, had a thickness of 5 cm, and a nominal density of 40 kg/m³.

The measurements were carried out by the ISO 354 standard [93] in the reverberation room of the Acoustics Laboratory (LabAcus) at the University of Padova. These measurements included determining the reverberation time of the empty room and the reverberation time of the chamber with the test specimens arranged according to various spatial distributions. Specifically, the materials were arranged in lines, in a checkerboard pattern, and as plane absorbers Figure 59. This approach created areas with reflective and absorbing elements by combining filled and empty spaces. The number of panels used varied, corresponding to 8, 9, 10, and 12 panels, arranged in different configurations.

The evaluation of the material's influence on absorption included calculating the A_{obj} value using the formula (14).

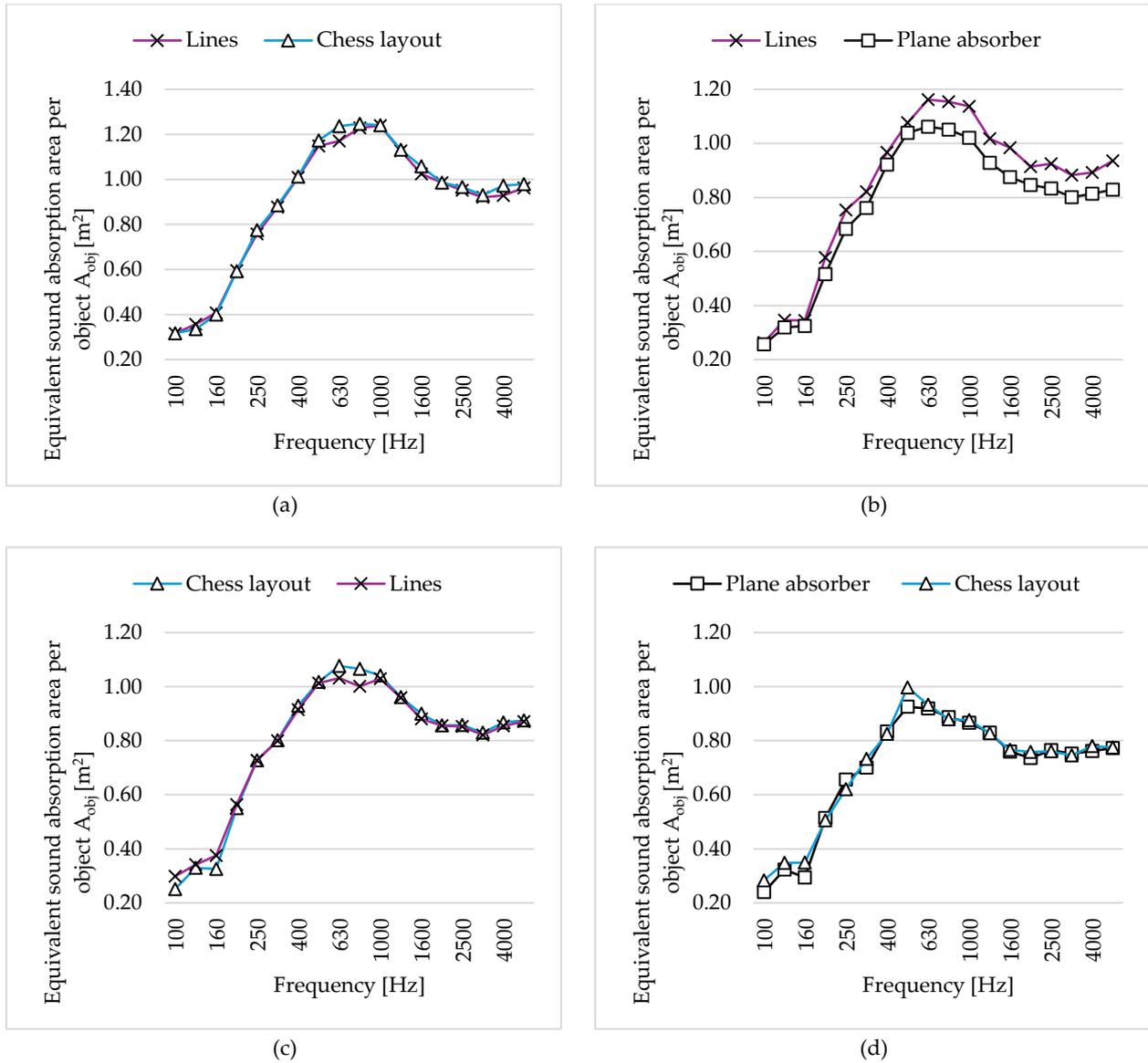
Figure 59: Pictures and plans of the arrangement of samples in the reverberation room for comparison of A_{obj}



6.2.1 Results

Figure 60 shows the comparisons of A_{obj} of the panels in the reverberation room in different quantities, arranged according to in-line, checkerboard, and flat absorber configurations. Appendix H – Sound Absorption Characteristics Table 54 shows frequency values of A_{obj} , of the panels within the reverberation room in a line, checkerboard, and plane absorber arrangement (type “A” ISO 354 [93]).

Figure 60: Comparisons of A_{obj} according to different arrangements within the reverberation room. Comparison between line and checkerboard arrangement of 8 panels (a), comparison between line and plane absorber arrangement of 9 panels (b), Comparison between line and checkerboard arrangement of 10 panels (c), and comparison between checkerboard and plane absorber arrangement of 12 panels (d)



6.2.2 Discussion

Based on the tests with sound-absorbing panels of the same type according to more compact or more thinned arrangements of the material on the surface of the reverberation room, comparisons were made between the A_{obj} obtained. The arrangements on the surface consist of plane absorber arrangement, thus a compact arrangement of the material; checkerboard arrangement, therefore alternating full and empty spaces creating reflective elements; and thinned line arrangement of the material.

Comparisons of A_{obj} were made for the different surface configurations, keeping the number of panels constant. The results provided interesting insights. The use of a smaller amount of material arranged more sparsely on the surface demonstrated greater absorption when compared to a more compact arrangement of the panels.

6.3 Application in Case Study

To observe the effect of distributing sound-absorbing panels in a space as discrete objects, the P2_p samples were placed in the real context of school classrooms to evaluate their impact on variations in reverberation time.

Each class of School C was provided with several panels equal to the number of students in each class participating in the project. Each child was then able to paint their panel during school hours dedicated to art activities. Thus, each decoration is the result of an educational activity carried out in collaboration with the teachers

Reverberation time was calculated from measurements taken in unoccupied classrooms without the addition of sound-absorbing panels and with the panels installed. The influence of students was also considered, assuming classroom occupancy of 80% and 100%, using the equation (7).

6.3.1 Acoustic Measurement Methods

To evaluate the influence of sound-absorbing panels on the acoustics of school classrooms, measurements of the reverberation time were carried out in unoccupied, normally furnished classrooms. The same measurements were repeated with the addition of sound-absorbing panels painted by the children. The placement of the panels was chosen to consider them as elements that could be arranged within classrooms according to the activities and needs during lessons.

Each teaching activity conducted in the classroom requires a different acoustic environment. For traditional frontal teaching, the primary requirement of the classroom is to provide a good level of speech intelligibility. During activities where children are required to carry out self-learning tasks, the environment should be quiet to encourage concentration on their work [81]. Focusing on a scenario where the materials are arranged randomly to improve the room's acoustics for non-listening-oriented teaching activities, the materials were placed in the corners of the classrooms, on the back wall, and the desks.

The measurements were conducted by the procedures and equipment specified in the ISO 3382-2 standard [66]. Reverberation time was measured using the decay of a pink noise signal emitted by a dodecahedron loudspeaker, and the source-receiver positions are shown in Figure 38.

Figure 61: Picture with an example of the distribution of sound absorbing panels in classrooms.



6.3.2 Results

Table 38 provides an overview of the acoustic properties of the classrooms, showing the number of panels placed in each room and the reverberation times under different occupancy configurations: unoccupied, 80%, and 100% of maximum occupancy; unoccupied but with the addition of sound-absorbing panels; and 80% and 100% of maximum occupancy with the presence of the sound-absorbing panels. Appendix G – School C Table 48 presents the reverberation time values by frequency, measured and calculated according to formula (7). For illustrative purposes, Figure 62 and Figure 63 graphically show the frequency values of the reverberation time in an unoccupied environment, the reverberation time with the addition of decorated panels considering 80% and 100% occupancy, the optimal reverberation time, and the compliance range for the optimal reverberation time in Classroom C1.

Table 38: Data overview of the classroom and ISO 3382-2 “N” is the number of sound absorbing materials positioned in classroom, “ $TR_{m,unocc}$ ” is the reverberation time in unoccupied, “ $RT_{m,occ80\%}$ ” is the reverberation time in occupied condition at 80%, “ $TR_{m,occ100\%}$ ” is the reverberation time in occupied condition at 100%, “ $RT_{m,p}$ ” is the reverberation time in unoccupied conditions with the sound absorbing material, “ $RT_{m,p+,occ80\%}$ ” is the reverberation time in occupied condition at 80% with the sound absorbing material, “ $RT_{m,p+,occ100\%}$ ” is the reverberation time in occupied condition at 100% with the sound absorbing material. The subscript “m” means a value averaged over all the receivers in the octave bands of 125-4000.

School	Classroom	N_p	$RT_{m,unocc}$ [s]	$RT_{m,occ80\%}$ [s]	$RT_{m,occ100\%}$ [s]	$RT_{m,p}$ [s]	$RT_{m,p+,occ80\%}$ [s]	$RT_{m,p+,occ100\%}$ [s]
C	C1	16	1.62	1.34	1.29	1.20	1.04	1.01
	C2	18	1.78	1.45	1.39	1.20	1.03	1.00
	C3	17	1.42	1.19	1.14	1.17	1.01	0.98
	C4	20	1.36	1.11	1.07	1.07	0.93	0.81
	C5	16	1.43	1.19	1.16	1.08	0.94	0.92

Figure 62: An example of graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , reverberation time measured under unoccupied room conditions with sound absorbing materials, RT_p , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80% with sound absorbing materials, $RT_{p+,80\%}$ reverberation time in occupied condition at 100% with sound absorbing materials $RT_{p+,100\%}$ of C1.

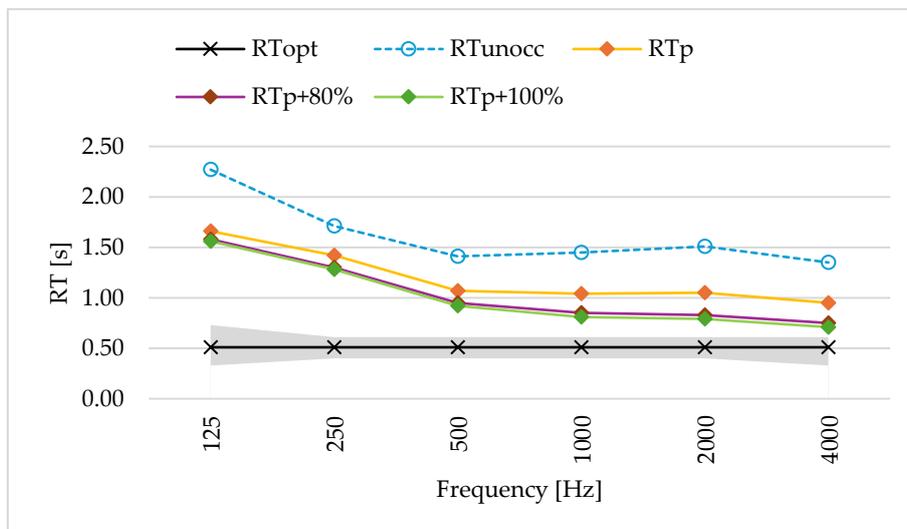
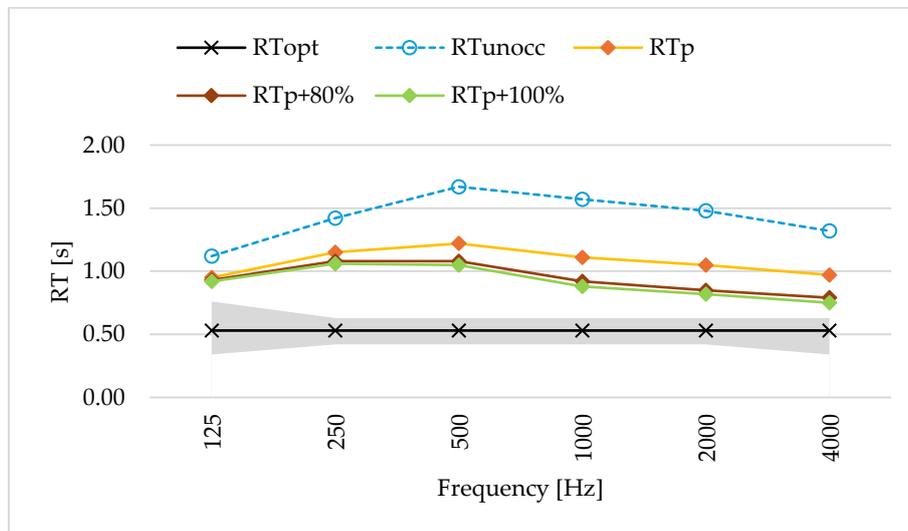


Figure 63: An example of graphical representation of reverberation time measured under unoccupied room conditions RT_{unocc} , reverberation time measured under unoccupied room conditions with sound absorbing materials, RT_p , Optimal reverberation time RT_{opt} , range of optimal reverberation time represented by the gray range, reverberation time in occupied condition at 80% with sound absorbing materials, $RT_{p+occ,80\%}$ reverberation time in occupied condition at 100% with sound absorbing materials $RT_{p+occ,100\%}$ of C5.



6.3.3 Discussion

Previous studies indicate that acoustic improvements at the classroom level, such as using ceiling panels, do not work well in solving noise problems in classrooms. In addition, the use of sound-absorbing materials to be affixed to the ceiling, floor or walls are classroom-level solution; not much has been done regarding the preferences and needs of the individual child. Only for children with special needs, some individually controlled devices are available [118], [119], [120]. In addition, according to a previous study, the use of an individually controllable soundproofing device in classrooms is the most popular device among primary school pupils in the Netherlands. This study introduces a new way to improve classroom acoustics by analyzing the effect of arranging sound-absorbing material as discrete objects.

The study evaluates the acoustic quality of classrooms by arranging the sound-absorbing panels painted by students according to considering them as discrete objects. The results show a decrease in room reverberation time. The solution can be easily applied in classrooms and modified by students and teachers. The panels, being lightweight, can be easily moved and arranged or used according to different configurations in the classroom. Thus, the solution can be an improvement not only for room acoustics when there is a need to improve reverberation time for frontal teaching, but it can also help in situations where there is a need to isolate or separate areas of the classroom in aid of conducting mixed teaching.

Conclusion

Children spend most of their time in classrooms where, often, acoustic standards are not met, and an unfavorable school environment in one or more areas of comfort can lead to excessive cognitive effort, thereby compromising learning and academic performance. Typically, teaching in schools is primarily conducted through frontal instruction, and for that reason, many studies have focused on the aspect of listening [18]. However, noise also interferes with non-auditory cognitive skills such as attention, memory [26], comprehension [24], [29], learning, writing, and mathematics [31], [32], [33], [34]. Little attention has been given to how noise interferes with non-auditory cognitive skills in children. The impact of noise on well-being and cognition is well documented [27], [28], but its specific effects on cognitive functioning and learning remain largely unexplored. Therefore, in this dissertation, an attempt has been made to fill the gaps in the literature by attempting to discuss the effects of noise on cognitive performance. From the Literature, studies agree that acute exposure, from moderate to severe levels, affects cognitive and learning performance. They also point out that the effects of noise vary according to the individual characteristics of students in a classroom. Non-verbal and verbal noises may impact some children differently. Children with attention problems potentially benefit from specific types and levels of noise [121], [122], [123]. In addition, the type of noise itself, whether verbal or not, may also impact executive functions differently.

The dissertation is based on investigations of the impact of acute exposure to a signal in 11 fourth-grade classes (205 children) of 3 primary schools in the province of Padova.

The tests administered were neuropsychological tests contained in the "CoEN" application developed by the University of Padova and paper-based comprehension and sentence generation tests. The sessions took place quietly and in noisily. The signal used in the noise session consisted of a non-intelligible speech signal in two classes (school A) and a non-intelligible speech signal with the addition of sound events (classroom noise) in the remaining classes (school B and school C).

Preliminary to the test sessions, investigations were carried out into the acoustic characteristics in an unoccupied environment in schools' classrooms. Only two classrooms of one school (school A) meet the regulatory requirements in terms of reverberation time and STI.

Sound pressure levels, Temperature, Air humidity, CO₂ concentrations and Illumination values were acquired during the test sessions. From the results obtained, the influence of physical aspects could be neglected other than the sound pressure level of noise although not within the comfort limits.

In terms of cognitive and learning performance, significant differences were observed between performance achieved in quiet and noise in School A classrooms. The noise condition (babble noise) led to worse performance by leading children to perceive greater cognitive effort. It is important to consider, however, that the result of School A may have been influenced by the teaching conditions conducted in the years prior to the test sessions due to the COVID-19 health emergency and the initial methodological errors in the research.

Children in schools B and C were exposed to classroom noise (babble+events) during a noise session. The analysis performed do not show a detrimental effect of noise on performance. In fact, no significant differences were observed between performance achieved in quiet and noise. Also, no cognitive effort was observed in the analysis of the cognitive effort self-report.

The explanation may lie in the effect of chronic exposure to unfavorable classroom noise conditions. Chronic exposure may have induced the development of noise compensation strategies in order to perform best even under acoustically unfavorable conditions. In fact, classrooms in Schools B and C do not meet the acoustic standards required by regulations. However, it is also essential to consider the classroom occupancy index of Schools B and C. School C has significantly fewer students in each classroom. This aspect results in a substantial change in the teaching methodology and behavior of the students themselves. Classes with a small number of students turn out to be more behaviorally manageable for teachers.

In addition, the type of signal and its mode of emission also influence the results. Non-intelligible verbal content may not have activated sufficient disturbance, and signal emission from a source in a diffuse field may not have had the same effect on all students.

In addition, conducting acoustic monitoring during lessons made it possible to investigate what sound levels children are normally exposed to.

Conventionally used noise descriptors are the equivalent sound level L_{Aeq} and statistical levels, i.e., percentiles. The latter indicates sound pressure levels exceeded for a certain percentage of time indicated by their subscripts. The most used are L_{10} , L_{50} , and L_{90}/L_{95} . The sound pressure level L_{Aeq} is defined in energy. The physical meaning of statistical levels is not always precise, except for L_{90} or L_{95} , which usually refers to background noise. These parameters, however, allow general considerations about the sound environment while missing details. The use of a parameter expressed in percentage terms would make it possible to have more detailed descriptions of the data describing the phenomena that have been obtained through monitoring. In this regard, monitoring took place in 6 classrooms of two schools (B and C) with similar room acoustic characteristics and located in similar spatial settings. All 6 classes do not meet the acoustic requirements of the regulations. However, they differ in the number of components belonging to each class with the same volume. The two classes in School B have an average number of students in each class of 24 children. In the classes of School C there were 18 children in average.

The monitoring was conducted, without the students' knowledge, with the OpeNoise application installed on a tablet equipped with a hidden external microphone for the duration of the monitoring. From the acquired data, the hours of actual teaching in the classroom were analyzed by dividing the activities based on the type of teaching performed. In addition to the conventionally used noise descriptors, an additional parameter was also used to describe in percent, the fluctuation of noise during monitoring.

The results showed that the number of students in the classroom and the type of teaching conducted affect the temporal dynamics of noise. Fewer students in the classroom results in less background noise resulting in more intermittence of individual sound events not masked by background noise. The same considerations apply to teaching conducted in the classroom. Group activities generate more background noise, resulting in fewer individual events being identified. In contrast to activities conducted individually. Adopting strategies to compensate for room acoustic deficits can also influence the variability of the sound climate. However, such strategies, such as changing the layout of the desk arrangement according to the teaching performed, are applicable in classrooms with a small number of pupils.

The parameter, Intermittency Ratio, IR, was then correlated with conventional parameters observing a good correlation with the parameters describing the sound climate. This allows us to say that L_{Aeq} and percentiles turn out to be useful in representing a general overview of the sound environment. However, the support of another parameter such as the IR index describing noise fluctuation can be useful.

Reducing the impact of noise is not easy, and solutions to counteract room noise require structural changes. However, improving room acoustics without interventions in classroom noise management strategies is not enough. It is essential to combine the improvement of classroom acoustics with behavioral programs that teach noise management. Finally, it was intended to propose room acoustic improvement solutions to schools that were not only a structural improvement but also teaching noise management and understanding. They were asked to decorate sound-absorbing panels with tempera paint during art activities and recreational times, explaining that the activities were useful for improving the environment acoustically and aesthetically. The children thus helped improve the environment in which they spend most of their time.

The materials used are polyester fiber panels of which, the first set analyzed, was equipped with a surface effect due to the thermosetting operations. Such a surface made the material appear to have a fabric on which the pictorial layer was required to be applied. From the point of view of sound absorption, the effect of the thermosmoothing operation, at which the pictorial layer was applied, causes the peak sound absorption of the material to be shifted toward low frequencies, thus changing the dissipation principle of the material. The application of the pictorial layer in the panels without the thermosmoothing effect does not change the characteristics of the material, causing it to continue to behave as a fibrous material. The panels, therefore, turned out to be an excellent acoustic solution with a twofold function: from the physical point of view, the addition of the pictorial layer alters the sound-absorbing characteristics of the material by making it dissipate sound energy according to a different mechanism, only in the case where the material has a "firmer" surface layer; from the educational and aesthetic point of view, it allows children to understand the function of the material and they can make sure to decorate it to their liking.

Moreover, the material, being inexpensive and lightweight, can be easily distributed to schools and moved and applied at one's leisure and according to the needs of the reaching carried out in the classroom.

Outlook and Future Work

At the end of this dissertation, many open issues remain to be debated and investigated. Further research is needed to fully understand the interactions and implications of noise, especially considering that children spend most of their time in noisy environments.

One of the future prospects of this study will be to perform further analysis on the interindividual variability of the subjects and on the influence of the contextual factors in the environment. Additionally, it will try to analyze the effects of different types of noise.

It will be essential to perform auditory screenings and add acquisitions of physiological parameters (i.e., heart rate, pupillary reaction) that can give important information about students' actual reactions

to test administration conditions. Additional measurements could be carried out on a small sample of children in a controlled setting such as climate chambers.

In addition, the effects of chronic noise could be an area of particular interest for future research because of the potential long-term consequences of associating it with parameters that characterize noise variability. To evaluate the effect of the proposed acoustic improvements on cognitive and learning performance, it will be critical to allow students a period of adaptation to the new acoustic conditions and then see the effects on performance.

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Appendix A – Learning Ability Tests for Quiet and Noisy Conditions

Figure 64: Text and questions for Comprehension test to evaluate learning abilities.



PROVA DI COMPRENSIONE

Classe 4^a Primaria – Indagine approfondita 1

Voglia di giocare

Era un giorno bellissimo di fine luglio, azzurri cielo e mare. Nuotavo da circa mezz'ora, quando mi scordai delle bandierine rosse e presi il largo. Bracciate lente, a "rana"; di tanto in tanto mi lasciavo trasportare inerte dalle onde. Il mare mi accarezzava e cantava: un canto lieve, tenue, come una nenia da bambini.

D'un tratto vidi lontano un sommovimento di acque e un triangolo nero avanzare. Mi ricordai di colpo dei pescicani. E mi dissi: "Se è un pescecane, è inutile affannarsi, tanto fra poco sarò fra le sue zanne. Se non lo è, tanto meglio".

Dedisi di tornare indietro e, come nulla fosse, mi diressi verso la lontanissima riva. Poco dopo, fra un ribollire d'acque, lo vidi vicino: non era un pescecane, era un grosso delfino.

E aveva voglia di giocare, il pazzereccio.

Si mise a fare, intorno a me, giri vorticosi, poi saltò fuori dalle onde, così che ne vedevo tutto il grande e bellissimo corpo; poi scomparve. Passò un po' di tempo, non saprei dire quanto...

All'improvviso il delfino venne di nuovo a galla buttandomi in aria, poiché si era posto con la schiena proprio sotto di me: sembrava io fossi diventato il suo giocattolo preferito.

Il gioco durò una buona mezz'ora, fra uno schiumare dell'acqua, un luccicare del grande animale, un diramarsi di rivoli come se fossero percossi da remi.

Alfine, stanco di saltare e di giocare, il delfino scomparve, e il mare ritornò tranquillo, azzurro, uniforme.

E io lentamente tornai a riva: ero veramente stanchissimo. Toccando terra non riuscivo neppure a stare in piedi.

(di E. Franceschini)

Rispondi alle seguenti domande facendo una croce sulla risposta giusta.

1. (PLT) In che periodo dell'anno siamo?
 - A. Verso la metà di agosto
 - B. All'inizio dell'estate
 - C. Nel pieno dell'estate
 - D. In primavera inoltrata

2. (IL) Il rumore del mare sembra:
 - A. Quello di una canzone per bambini
 - B. Un gioco che fanno i bambini
 - C. I capricci dei bambini
 - D. Una cosa noiosa da bambini

3. (IS) Il mare era:
 - A. Rumoroso
 - B. Sporco
 - C. Mosso
 - D. Calmo

4. (SL) Il protagonista si accorge che sta arrivando un grosso pesce:
 - A. Perché sente un rumore strano
 - B. Perché vede dei pesci scappare
 - C. Perché ha superato le bandierine rosse
 - D. Perché nota uno strano movimento di onde nel mare

5. (FLESS) Quando pensa di aver visto il pescecane, il protagonista ha paura di essere preso:
 - A. Tra i suoi denti
 - B. Dalle sue zampe
 - C. Dalla sua coda
 - D. Tra le sue pinne

6. (EI) Quando vede il triangolo nero il protagonista decide:
 - A. Di chiamare aiuto
 - B. Di aspettare per vedere che animale è
 - C. Di uccidere quel grosso pesce
 - D. Di andare con calma verso riva

7. (FS) Come mai il protagonista quando vede il triangolo nero non scappa?
 - A. Perché la riva è troppo lontana e sarebbe quindi inutile
 - B. Perché sa già che è un delfino
 - C. Perché è bloccato dalla paura

- D. Perché non ha paura del pescecane
8. (IS) Il triangolo nero è:
- A. Una macchia nera sulla schiena del pesce
 - B. La caratteristica pinna dei delfini
 - C. Una boa in mezzo al mare
 - D. La testa del delfino
9. (FLESS) Il delfino, dopo aver girato intorno al protagonista:
- A. Nuota con lui
 - B. Va incontro al pescecane
 - C. Fa le bolle sotto acqua
 - D. Sparisce per un po' di tempo
10. (SS) Il delfino, per buttare in aria il protagonista:
- A. Si mette con la schiena sotto il corpo del protagonista
 - B. Dà un colpo con la coda
 - C. Lo afferra per le gambe
 - D. Si mette sopra la schiena del protagonista
11. (FS) Alla fine il delfino scompare perché:
- A. Erano ormai arrivati a riva
 - B. È stato spaventato da qualcuno o qualcosa
 - C. Era stanco di giocare
 - D. Il mare era diventato calmo
12. (FS) Alla fine, quando il delfino scomparve, il protagonista:
- A. Sviene
 - B. Resta in acqua
 - C. È dispiaciuto che il delfino se ne sia andato
 - D. Torna sulla riva
13. (IS) Il protagonista è stato imprudente a non osservare le bandierine rosse:
- A. Perché poteva disturbare i pesci
 - B. Perché poteva farsi male contro gli scogli
 - C. Perché poteva perdersi
 - D. Perché poteva trovarsi in pericolo
14. (GT) Se dovessi cambiare titolo a questa storia, quale metteresti?
- A. Una avventura in mezzo al mare
 - B. I pericoli del mare

- C. La lotta del delfino
- D. Una gara di nuoto

Figure 65: Text and questions for Comprehension test to evaluate learning abilities.



PROVA DI COMPrensIONE

Classe 4^a Primaria – Indagine approfondita 2

Il panda

Il panda è un buffo, timido, simpatico “orsacchiottone” di abitudini ritirate e abitatore delle foreste di bambù di alta montagna del Tibet orientale e della Cina meridionale. Gli piace giocare, scivolare sull'erba, fare le capriole.

È molto bravo ad arrampicarsi sugli alberi grazie alle sue dimensioni ridotte.

Un po' per la sua rarità, un po' per il suo aspetto grazioso, quasi da animale di pezza, il panda è stato scelto come simbolo della più grande organizzazione internazionale per la conservazione degli animali, il Fondo Mondiale per la Natura (WWF).

Tranne che allo zoo di Pechino non si è mai riusciti a far riprodurre in cattività questo graziosissimo animale bianco e nero, che tutti chiamano orso ma che con gli orsi ha solo una lontana parentela, poiché appartiene alla stessa famiglia dei procioni.

Il panda si nutre esclusivamente di germogli di bambù che mangia in grossa quantità dato che si tratta di un alimento poco nutriente. Infatti ne mangia all'incirca 12 chilogrammi al giorno.

Raccoglie delicatamente le foglie e i germogli con le zampe anteriori: una specie di sesto dito gli permette di afferrare anche i pezzetti più piccoli.

Inoltre la sua abitudine a star seduto o sdraiato sul dorso, mentre strappa a morsi il cibo che tiene stretto tra le zampe anteriori, lo rende irresistibile.

(da Pfeffer, Baschieri - Salvadori - Florio,
A. Zoi e D.B. Zoi)

Rispondi alle seguenti domande facendo una croce sulla risposta giusta.

1. (IL) Il panda:

- A. Non ha voglia di farsi vedere e di mettersi in mostra
- B. È contento se tutti lo guardano
- C. Gira sempre in cerca di novità
- D. Ama vivere in compagnia con orsi e procioni

2. (EI-FLESS) Il panda è bravo a salire sugli alberi perché:

- A. Si allena ogni giorno
- B. In Cina gli alberi sono piccoli e bassi
- C. È un animale molto forte
- D. È piccolo e agile

3. (SS) Il Fondo Mondiale per la Natura (WWF) è:

- A. Una organizzazione internazionale
- B. Un parco nazionale del Tibet
- C. Una associazione che protegge i panda
- D. Il simbolo del panda

4. (FLESS) In che posto si è riusciti a far riprodurre i panda?

- A. A Roma
- B. In alcuni circhi di Pechino
- C. In uno zoo della Cina
- D. In un parco del WWF

5. (IL) È molto difficile che il panda si riproduca:

- A. Quando non è in libertà
- B. Nelle foreste del Tibet
- C. Perché è cattivo e antisociale
- D. Durante l'inverno

6. (E) Perché si cerca di far riprodurre il panda in cattività?

- A. Per la sua pelliccia pregiata
- B. Per regalarne uno a tutti i bambini
- C. Perché è molto richiesto negli zoo
- D. Perché ce ne sono pochi

7. (PLT) Possiamo dire che il panda:

- A. In realtà è proprio un orso di piccole dimensioni
- B. È un animale amico dell'uomo e può vivere nelle nostre case
- C. Appartiene alla stessa categoria di animali cui appartiene il procione

D. Appartiene a una specie rara ed è unico nel suo genere

8. (FLESS) Cosa mangia il panda?

A. Di solito si nutre di germogli e di foglie

B. È capace di divorare un albero intero, tronco e rami

C. Solo pezzi molto piccoli di una pianta

D. Solo alimenti molto nutrienti

9. (FLESS) Quanto bambù mangia ogni giorno il panda?

A. Diversi chilogrammi

B. Tutto un albero

C. Due chilogrammi

D. Dipende da quanto ha fame

10. (EI) Il panda mangia molto bambù perché:

A. Ha molta fame

B. Non c'è altro da mangiare

C. Il bambù è un alimento poco nutriente

D. Deve accumulare grasso per l'inverno

11. (IS) Il panda vive soprattutto in Cina perché:

A. Lì è vicino allo zoo di Pechino

B. Lì trova il suo cibo preferito

C. In Cina ci sono molti alberi dove si può arrampicare

D. E il simbolo scelto dal WWF

12. (IS) Il sesto dito permette al panda di:

A. Prendere anche i pezzi molto piccoli di bambù

B. Prendere il bambù con le zampe anteriori

C. Cercare i pezzi piccoli di bambù

D. Tagliare il bambù in piccoli pezzi

13. (GT) In questo brano l'argomento principale è:

A. A cosa serve il bambù

B. La vita e le abitudini del panda

C. Che cosa fa il WWF

D. Come vivono gli orsi in Cina

14. (SENS) Questo brano è:

A. Una descrizione

B. Una favola

- C. Un racconto di un bambino
- D. Un'avventura

Figure 66: Word pair for Sentence generation Test to evaluate learning abilities.

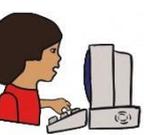
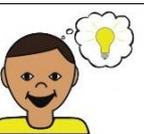
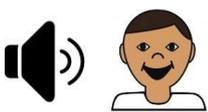
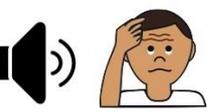
1. Tazza - Latte
NON GIRARE IL FOGLIO FINCHÈ NON DICO VIA!
2. Pecora - Gabbia
NON GIRARE IL FOGLIO FINCHÈ NON DICO VIA!

Figure 67: Word pair for Sentence generation Test to evaluate learning abilities.

1. Cani - Gatti
NON GIRARE IL FOGLIO FINCHÈ NON DICO VIA!
2. Tigre - Acqua
NON GIRARE IL FOGLIO FINCHÈ NON DICO VIA!

Appendix B – Self-Report Cognitive Effort

Figure 68: Self-report cognitive effort from Bess et al. [102]

ID		CLASSE			DATA	
SELF-REPORT COGNITIVE EFFORT (Bess et al., 2014)						
		Mi sento stanco/a				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		
		Gli esercizi erano facili				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		
		Mi fa male la testa				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		
		È stato facile rimanere attento/a				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		
		Ho fatto fatica a ricordare				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		
		Ero distratto/a dal rumore				
Per niente	Un po'	Abbastanza	Molto	Moltissimo		
I	II	III	IIII	IIIIII		

Appendix C – IEQ Survey

Table 39: Overview of items and perception scales related to the perceived indoor environmental quality.

Assessed environment	Type of judgment	Wording	Wording of the degree
Thermal Environment	Thermal sensation	How do you feel now?	-3 cold -2 cool -1 slightly cool 0 neither cool nor warm +1 slightly warm +2 warm +3 hot
	Thermal Preference	How do you prefer to be now?	-3 much colder -2 colder -1 slightly colder 0 no change +1 slightly warmer +2 warmer +3 much warmer
	Thermal Comfort	Considering all the above-mentioned thermal aspects, how do you feel now?	0 comfortable +1 slightly comfortable +2 uncomfortable +3 very uncomfortable
	Thermal satisfaction	Referring to the last hour, are you satisfied with the thermal environment?	0 satisfied +1 slightly unsatisfied +2 unsatisfied +3 very unsatisfied
Indoor Air Quality	IAQ sensation (air)	How do you perceive the indoor air now?	0 fresh +1 slightly stuffy +2 stuffy +3 very stuffy
	IAQ sensation (odour)	How do you perceive the odour now?	0 odourless +1 slightly odour +2 odours +3 very odours
	IAQ Preference	How would you prefer the indoor air to be now?	0 no change +1 slightly fresher +2 fresher +3 much fresher
	IAQ Comfort	Considering all the above-mentioned aspects related to the IAQ, how do you feel now?	0 comfortable +1 slightly comfortable +2 uncomfortable +3 very uncomfortable
	IAQ satisfaction	Referring to the last hour, are you satisfied with the indoor air quality?	0 satisfied +1 slightly unsatisfied +2 unsatisfied +3 very unsatisfied

(continued)

Table 39: (continued)

Assessed environment	Type of judgment	Wording	Wording of the degree
Visual environment	Visual Sensation	How do you perceive the room now?	-3 very dark -2 dark 0 neither dark nor bright +1 slightly bright +2 bright +3 very bright
		How do you perceive your desk now?	-3 very dark -2 dark -1 slightly darker 0 neither dark nor bright +1 slightly bright +2 bright +3 very bright
	Visual Preference	How would you prefer the visual environment to be now?	-3 much darker -2 darker -1 slightly darker 0 no change +1 slightly brighter +2 brighter +3 much brighter
		How can you see your notes on your desk?	0 clear +1 slightly unclear +2 unclear +3 very unclear
	Visual Comfort	Considering all the above-mentioned visual aspects, how do you feel now?	0 comfortable +1 slightly comfortable +2 uncomfortable +3 very uncomfortable
	Visual satisfaction	Referring to the last hour, are you satisfied with the visual environment?	0 satisfied +1 slightly unsatisfied +2 unsatisfied +3 very unsatisfied
	Acoustic environment	Acoustic Sensation	How did you perceive the room during the last hour?
Acoustic Preference		How would you prefer the room?	0 no change +1 slightly quieter +2 quieter +3 much quieter
Acoustic Comfort		Considering all the above-mentioned acoustic aspects, how do you feel now?	0 comfortable +1 slightly comfortable +2 uncomfortable +3 very uncomfortable
Acoustic satisfaction		Referring to the last hour, are you satisfied with the acoustic environment?	0 satisfied +1 slightly unsatisfied +2 unsatisfied +3 very unsatisfied

Appendix D – Instruments Characteristics

Table 40: Instrument, measured indoor environmental parameters, and description of the measuring device.

Instrument	Parameters	Range	Accuracy
Nti Audio XL2	LA _{eq,1s}	10-110 dB	Class 1, Mic Sensitivity: 20,5 mV/Pa
HOBO connect MX1102	T	0°C-50°C	±0.21°C from 0° to 50°C; Resolution: <1% per year typical
	RH	1%-90% RH	±2% from 20% to 80% typical to a maximum of ±4.5% including hysteresis at 25°C; Resolution: 0,01%
	CO ₂	0 to 5000 ppm	±50 ppm ±5% of reading at 25°C
KONICA MINOLTA	Illumination	1 to 200000 lux	Linearity: ± 2% ± 1 digit of displayed value
HOBO connect MX1104	T	0°C-50°C	±0.21°C from 0° to 50°C; Resolution: <1% per year typical
	RH	1%-90% RH	±2% from 20% to 80% typical to a maximum of ±4.5% including hysteresis at 25°C; Resolution: 0,01%
	Illumination	0 to 167,731 lux	±10% typical for direct sunlight
Chauvin Arnoux 1510	T	-10°C-60°C	±0,5°C at 50% RH; Resolution: 0,1°C
	RH	5%-95% RH	± 2 %RH ± R from 10 to 90 % RH
	CO ₂	0 to 5000 ppm	±3% ±50 ppm at 25°C and 1013 mbar; Resolution: 1ppm
HOBO onset	T	-20°C-70°C	±0,35°C in the interval from 0°C to 50°C; Resolution (12 bit): 0,03°C at 25°C
	Illumination	1 to 3000 footcandles	External input channel: ± 2 mV ± 2.5% of absolute reading

Appendix E – School A

Table 41: Results of ISO 3382-2 measurements and UNI 11532-2 calculations on octave bands from 125-4000 Hz for classrooms in School A, where: “RT_{opt}” is the optimal value of reverberation time; “RT_{lim sup}” is the upper limit of the optimal reverberation time range, “RT_{lim inf}” is the lower limit of the optimal reverberation time range “RT_{m,unocc}” is the reverberation time in unoccupied, “RT_{m,occ80%}” is the reverberation time in occupied condition at 80%, “RT_{m,occ100%}” is the reverberation time in occupied condition at 100%.

School	Classroom	RT	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
A	A1	RT _{opt}	0.53	0.53	0.53	0.53	0.53	0.53
		RT _{lim sup}	0.76	0.63	0.63	0.63	0.63	0.63
		RT _{lim inf}	0.34	0.42	0.42	0.42	0.42	0.34
		RT _{unocc}	0.58	0.51	0.44	0.48	0.51	0.45
		RT _{occ,80%}	0.57	0.49	0.42	0.45	0.46	0.41
	RT _{occ100%}	0.57	0.49	0.41	0.44	0.45	0.40	
	A2	RT _{opt}	0.53	0.53	0.53	0.53	0.53	0.53
		RT _{lim sup}	0.77	0.64	0.64	0.64	0.64	0.64
		RT _{lim inf}	0.35	0.42	0.42	0.42	0.42	0.35
		RT _{unocc}	0.58	0.50	0.46	0.55	0.52	0.47
RT _{occ,80%}		0.57	0.48	0.44	0.50	0.47	0.42	
RT _{occ100%}	0.57	0.48	0.44	0.49	0.46	0.41		

Table 42 STI values at the positions given in UNI 11532-2 [39] and classification of STI according to the intervals of IEC 60268-16 [69]

School	Classroom	Measurement position	STI	IEC 60268-16
A	A1	1	0.65	Good
		2	0.79	Excellent
		3	0.69	Good
		4	0.65	Good
	A2	1	0.83	Excellent
		2	0.76	Excellent
		3	0.69	Good
		4	0.67	Good

Table 43: Duration in minutes of cognitive and learning tests in school A.

Test	A1_1 “Quiet”	A1_2 “Quiet”	A1_1 “Noise”	A1_2 “Noise”	A2_1 “Quiet”	A2_1 “Quiet”	A2_2 “Noise”	A2_2 “Noise”
CoEN	00:28	00:18	00:18	00:21	00:19	00:17	00:21	00:23
#A9+#A10	00:18	00:28	00:21	00:18	00:17	00:19	00:23	00:21

Appendix F – School B

Table 44: Results of ISO 3382-2 measurements and UNI 11532-2 calculations on octave bands from 125-4000 Hz for classrooms in School B, where: “RT_{opt}” is the optimal value of reverberation time; “RT_{lim sup}” is the upper limit of the optimal reverberation time range, “RT_{lim inf}” is the lower limit of the optimal reverberation time range “RT_{m,unocc}” is the reverberation time in unoccupied, “RT_{m,occ80%}” is the reverberation time in occupied condition at 80%, “RT_{m,occ100%}” is the reverberation time in occupied condition at 100%.

School	Classroom	RT	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
B	B1	RT _{opt}	0.52	0.52	0.52	0.52	0.52	0.52
		RT _{lim sup}	0.75	0.62	0.62	0.62	0.62	0.62
		RT _{lim inf}	0.34	0.41	0.41	0.41	0.41	0.34
		RT _{unocc}	2.50	1.75	1.41	1.35	1.27	1.03
		RT _{occ,80%}	2.27	1.53	1.15	0.97	0.90	0.75
		RT _{occ100%}	2.22	1.48	1.10	0.91	0.84	0.70
	B2	RT _{opt}	0.52	0.52	0.52	0.52	0.52	0.52
		RT _{lim sup}	0.75	0.62	0.62	0.62	0.62	0.62
		RT _{lim inf}	0.34	0.41	0.41	0.41	0.41	0.34
		RT _{unocc}	2.38	1.76	1.43	1.35	1.29	1.07
		RT _{occ,80%}	2.16	1.53	1.14	0.96	0.89	0.75
		RT _{occ100%}	2.11	1.48	1.09	0.89	0.83	0.70
	B3	RT _{opt}	0.52	0.52	0.52	0.52	0.52	0.52
		RT _{lim sup}	0.75	0.62	0.62	0.62	0.62	0.62
		RT _{lim inf}	0.34	0.42	0.42	0.42	0.42	0.34
		RT _{unocc}	2.25	1.80	1.48	1.37	1.30	1.07
		RT _{occ,80%}	2.07	1.57	1.19	0.99	0.92	0.77
		RT _{occ100%}	2.02	1.53	1.14	0.92	0.85	0.72
	B4	RT _{opt}	0.52	0.52	0.52	0.52	0.52	0.52
		RT _{lim sup}	0.75	0.62	0.62	0.62	0.62	0.62
		RT _{lim inf}	0.34	0.41	0.41	0.41	0.41	0.34
		RT _{unocc}	1.75	1.41	1.39	1.35	1.23	1.05
		RT _{occ,80%}	1.63	1.26	1.12	0.96	0.87	0.75
		RT _{occ100%}	1.60	1.22	1.07	0.90	0.81	0.70

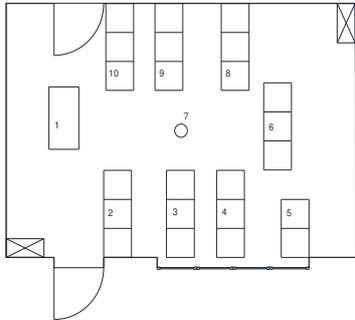
Table 45: STI values at the positions given in UNI 11532-2 [39] and classification of STI according to the intervals of IEC 60268-16 [69]. School B.

School	Classroom	Measurement position	STI	IEC 60268-16
B	B1	1	0.61	Good
		2	0.56	Fair
		3	0.52	Fair
		4	0.54	Fair
	B2	1	0.55	Fair
		2	0.54	Fair
		3	0.56	Fair
		4	0.52	Fair
	B3	1	0.57	Fair
		2	0.52	Fair
		3	0.57	Fair
		4	0.53	Fair
	B4	1	0.59	Fair
		2	0.52	Fair
		3	0.51	Fair
		4	0.55	Fair

Table 46: Duration of cognitive and learning tests in school B.

Test	B1	B1	B2	B2	B3	B3	B4	B4
	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"	"Quiet"	"Noise"
CoEN	00:36	00:30	00:26	00:23	00:23	00:30	00:28	00:35
#A9	00:10	00:13	00:10	00:10	00:10	00:12	00:10	00:10
#A10	00:12	00:10	00:25	00:10	00:11	00:10	00:10	00:10

Table 47: Mean values and standard deviation of illuminance at the measurement points indicated in the plans corresponding to each classroom during the performance of cognitive and learning tests under quiet and noise conditions. School B.

School	Classroom	Measurement position	Illumination	Illumination	Plan
			"Quiet" [lux]	"Noise" [lux]	
B	B1	01	318±202	224±176	
		02	251±143	210±214	
		03	495±407	146±38	
		04	170±110	292±171	
		05	320±173	282±160	
		06	190±146	251±239	
		07	210±163	190±54	
		08	192±115	187±47	
		09	201±161	154±47	
		10	203±176	96±48	

(continued)

Table 47: (continued)

School	Classroom	Measurement position	Illumination	Illumination	Plan
			["Quiet"]	["Noise"]	
	B2	01	144±23	431±38	
		02	207±53	415±59	
		03	193±39	452±50	
		04	140±40	445±49	
		05	161±53	334±24	
		06	414±270	340±29	
		07	240±46	601±59	
		08	1845±2171	751±45	
		09	1464±1827	1334±305	
		10	356±74	455±70	
	B3	01	163±16	152±10	
		02	190±12	237±40	
		03	256±36	534±65	
		04	159±5	197±26	
		05	196±11	300±17	
	B4	01	226±36	165±5	
		02	418±115	197±10	
		03	862±315	285±24	
		04	252±52	202±13	
		05	253±43	174±4	
		06	-	259±11	

Appendix G – School C

Table 48: Results of ISO 3382-2 measurements and UNI 11532-2 calculations on octave bands from 125-4000 Hz for classrooms in School C, where: “RT_{opt}” is the optimal value of reverberation time; “RT_{lim sup}” is the upper limit of the optimal reverberation time range, “RT_{lim inf}” is the lower limit of the optimal reverberation time range “RT_{m,unocc}” is the reverberation time in unoccupied, “RT_{m,occ80%}” is the reverberation time in occupied condition at 80%, “RT_{m,occ100%}” is the reverberation time in occupied condition at 100%, “RT_{m,p}” is the reverberation time in unoccupied conditions with the sound absorbing material, “RT_{m,p,occ80%}” is the reverberation time in occupied condition at 80% with the sound absorbing material, “RT_{m,p,occ100%}” is the reverberation time in occupied condition at 100% with the sound absorbing material.

School	Classroom	RT	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
C	C1	RT _{opt}	0.51	0.51	0.51	0.51	0.51	0.51
		RT _{lim sup}	0.73	0.61	0.61	0.61	0.61	0.61
		RT _{lim inf}	0.33	0.40	0.40	0.40	0.40	0.33
		RT _{unocc}	2.27	1.71	1.41	1.45	1.51	1.35
		RT _{occ,80%}	2.12	1.55	1.20	1.10	1.10	0.98
		RT _{occ100%}	2.09	1.51	1.16	1.04	1.03	0.92
		RT _p	1.66	1.42	1.07	1.04	1.05	0.95
		RT _{p+80%}	1.58	1.30	0.95	0.85	0.83	0.75
		RT _{p+100%}	1.56	1.28	0.92	0.81	0.79	0.71
	C2	RT _{opt}	0.52	0.52	0.52	0.52	0.52	0.52
		RT _{lim sup}	0.76	0.63	0.63	0.63	0.63	0.63
		RT _{lim inf}	0.34	0.42	0.42	0.42	0.42	0.34
		RT _{unocc}	2.37	1.83	1.72	1.74	1.64	1.41
		RT _{occ,80%}	2.21	1.64	1.42	1.27	1.17	1.02
		RT _{occ100%}	2.17	1.60	1.36	1.19	1.09	0.95
		RT _p	1.60	1.40	1.14	1.12	1.04	0.93
		RT _{p+80%}	1.52	1.28	0.99	0.88	0.81	0.73
		RT _{p+100%}	1.50	1.25	0.95	0.84	0.77	0.69
	C3	RT _{opt}	0.51	0.51	0.51	0.51	0.51	0.51
		RT _{lim sup}	0.75	0.62	0.62	0.62	0.62	0.62
		RT _{lim inf}	0.33	0.41	0.41	0.41	0.41	0.33
		RT _{unocc}	1.62	1.49	1.36	1.40	1.41	1.26
		RT _{occ,80%}	1.54	1.37	1.16	1.08	1.04	0.93
		RT _{occ100%}	1.52	1.34	1.12	1.02	0.98	0.88
		RT _p	1.50	1.24	1.12	1.13	1.07	0.97
		RT _{p+80%}	1.43	1.15	0.98	0.90	0.84	0.76
		RT _{p+100%}	1.41	1.13	0.95	0.86	0.79	0.72
	C4	RT _{opt}	0.51	0.51	0.51	0.51	0.51	0.51
RT _{lim sup}		0.74	0.61	0.61	0.61	0.61	0.61	
RT _{lim inf}		0.33	0.41	0.41	0.41	0.41	0.33	
RT _{unocc}		1.71	1.39	1.19	1.23	1.37	1.25	
RT _{occ,80%}		1.60	1.26	1.01	0.93	0.97	0.88	
RT _{occ100%}		1.58	1.23	0.97	0.93	0.90	0.82	

(continued)

Table 48: continued

School	Classroom	RT	125 [Hz]	250 [Hz]	500 [Hz]	1000 [Hz]	2000 [Hz]	4000 [Hz]
C4		RT _p	1.42	1.16	1.00	0.93	0.97	0.92
		RT _{p+80%}	1.36	1.08	0.89	0.77	0.78	0.73
		RT _{p+100%}	1.29	0.99	0.77	0.63	0.62	0.58
		RT _{opt}	0.53	0.53	0.53	0.53	0.53	0.53
		RT _{lim sup}	0.76	0.63	0.63	0.63	0.63	0.63
		RT _{lim inf}	0.34	0.42	0.42	0.42	0.42	0.34
C5		RT _{unocc}	1.12	1.42	1.67	1.57	1.48	1.32
		RT _{occ,80%}	1.09	1.32	1.42	1.21	1.12	1.00
		RT _{occ100%}	1.08	1.30	1.37	1.21	1.06	0.95
		RT _p	0.95	1.15	1.22	1.11	1.05	0.97
		RT _{p+80%}	0.93	1.08	1.08	0.92	0.85	0.79
		RT _{p+100%}	0.92	1.06	1.05	0.88	0.82	0.75

Table 49: STI values at the positions given in UNI 11532-2 [39] and classification of STI according to the intervals of IEC 60268-16 [69]. School C.

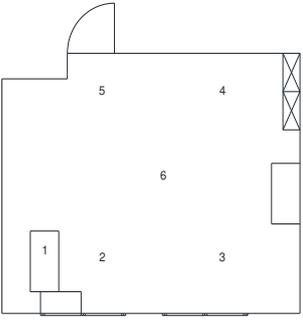
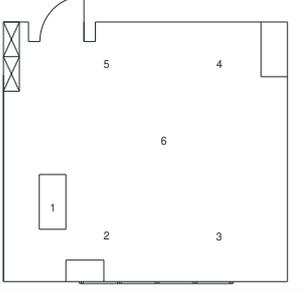
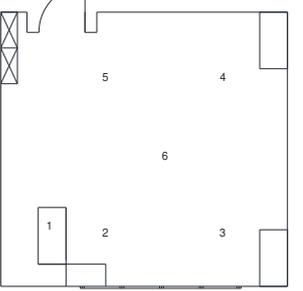
School	Classroom	Measurement position	STI	IEC 60268-16
C	C1	1	0.52	Fair
		2	0.53	Fair
		3	0.47	Fair
		4	0.47	Fair
	C2	1	0.49	Fair
		2	0.48	Fair
		3	0.50	Fair
		4	0.48	Fair
	C3	1	0.58	Fair
		2	0.53	Fair
		3	0.55	Fair
		4	0.51	Fair
	C4	1	0.56	Fair
		2	0.54	Fair
		3	0.57	Fair
		4	0.55	Fair
C5	1	0.57	Fair	
	2	0.51	Fair	
	3	0.56	Fair	
	4	0.53	Fair	

Table 50: Duration in minutes of cognitive and learning tests in school C.

Test	C1	C1	C2	C2	C3	C3	C4	C4	C5	C5
	"Quiet"	"Noise"								
CoE	00:34	00:26	00:34	00:21	00:27	00:26	00:27	00:34	00:26	00:28
N	00:16	00:15	00:11	00:13	00:14	00:25	00:14	00:15	00:17	00:15
#A9	00:11	00:10	00:11	00:11	00:11	00:10	00:10	00:10	00:10	00:11
#A10										

Table 51: Mean values and standard deviation of illuminance at the measurement points indicated in the plans corresponding to each classroom during the performance of cognitive and learning tests under quiet and noisy conditions.

Due to the different layouts of the classroom layout at each trial, student desks are not represented. School C.

School	Classroom	Measurement position	Illumination	Illumination	Plan	
			[lux]	[lux]		
			"Quiet"	"Noise"		
C	C1	01	677±93	396±354		
		02	665±120	790±639		
		03	756±69	3705±6510		
		04	463±55	168±135		
		05	517±40	218±177		
		06	-	144±117		
	C2	01	802±127	1243±76		
		02	-	2158±170		
		03	404±80	1143±218		
		04	549±35	115±6		
		05	544±11	149±12		
		06	459±24	366±21		
	C3	01	324±35	257±8		
		02	-	-		
		03	2103±267	359±12		
		04	112±10	400±44		
		05	478±9	1516±242		
		06	230±15	425±30		

(continued)

Table 51: (continued)

School	Classroom	Measurement position	Illumination	Illumination	Plan
			["Quiet"]	["Noise"]	
	C4	01	300±12	538±21	
		02	174±9	627±145	
		03	480±38	752±31	
		04	474±22	997±83	
		05	285±13	680±25	
		06	224±13	-	
	C5	01	272±4	223±16	
		02	269±5	268±5	
		03	285±3	253±5	
		04	265±3	267±3	
		05	255±9	251±4	

Appendix H – Sound Absorption Characteristics

Table 52: Frequency values of A_{obj} , of P1_1; P1_2; P2; P1_1p and P2_p. Panels arranged according to a “Type A” plane absorber ISO 354. Where N.p is the number of panels.

	N.p	100 [Hz]	125 [Hz]	160 [Hz]	200 [Hz]	250 [Hz]	315 [Hz]	400 [Hz]	500 [Hz]	630 [Hz]	800 [Hz]	1000 [Hz]	1250 [Hz]	1600 [Hz]	2000 [Hz]	2500 [Hz]	3150 [Hz]	4000 [Hz]	5000 [Hz]
AP1_1	10	0.16	0.10	0.11	0.15	0.16	0.22	0.26	0.29	0.32	0.32	0.33	0.31	0.31	0.28	0.27	0.24	0.25	0.25
AP1_2	10	0.17	0.11	0.10	0.13	0.15	0.18	0.20	0.24	0.27	0.27	0.28	0.27	0.27	0.26	0.25	0.25	0.25	0.26
AP1_1p	10	0.14	0.09	0.13	0.15	0.17	0.23	0.29	0.30	0.30	0.30	0.29	0.26	0.25	0.21	0.19	0.17	0.17	0.17
AP2	48	0.03	0.05	0.06	0.08	0.11	0.12	0.14	0.16	0.18	0.19	0.19	0.18	0.18	0.17	0.18	0.18	0.18	0.19
AP2_p	48	0.03	0.06	0.06	0.10	0.11	0.14	0.14	0.15	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.17	0.18	0.18

Table 53: Sound absorption coefficient α calculated according to ISO 354 of the sound-absorbing panel P2 and P2_p.

	100 [Hz]	125 [Hz]	160 [Hz]	200 [Hz]	250 [Hz]	315 [Hz]	400 [Hz]	500 [Hz]	630 [Hz]	800 [Hz]	1000 [Hz]	1250 [Hz]	1600 [Hz]	2000 [Hz]	2500 [Hz]	3150 [Hz]	4000 [Hz]	5000 [Hz]
α_{P2}	0.10	0.22	0.26	0.39	0.44	0.54	0.55	0.59	0.75	0.76	0.75	0.72	0.73	0.70	0.71	0.69	0.70	0.72
α_{P2_p}	0.10	0.22	0.23	0.33	0.45	0.49	0.54	0.62	0.70	0.75	0.75	0.70	0.70	0.69	0.70	0.70	0.71	0.74

Table 54: Frequency values of A_{obj} , of panels in a line, checkerboard and plane absorber (type “A” ISO 354) arrangement. Where N.p. is the number of panels.

	N.p	100 [Hz]	125 [Hz]	160 [Hz]	200 [Hz]	250 [Hz]	315 [Hz]	400 [Hz]	500 [Hz]	630 [Hz]	800 [Hz]	1000 [Hz]	1250 [Hz]	1600 [Hz]	2000 [Hz]	2500 [Hz]	3150 [Hz]	4000 [Hz]	5000 [Hz]
Lines	8	0.32	0.36	0.41	0.60	0.76	0.88	1.01	1.15	1.17	1.23	1.24	1.13	1.02	0.99	0.95	0.92	0.93	0.96
Chess	8	0.32	0.34	0.40	0.59	0.77	0.89	1.01	1.17	1.24	1.25	1.24	1.13	1.06	0.99	0.97	0.93	0.97	0.98
Lines	9	0.26	0.35	0.34	0.58	0.75	0.82	0.97	1.08	1.16	1.15	1.14	1.02	0.98	0.91	0.92	0.88	0.89	0.94
Plane absorber	9	0.26	0.32	0.32	0.52	0.68	0.76	0.92	1.04	1.06	1.05	1.02	0.93	0.87	0.85	0.83	0.80	0.81	0.83
Chess	10	0.25	0.33	0.33	0.55	0.73	0.80	0.93	1.02	1.08	1.07	1.04	0.96	0.90	0.86	0.86	0.83	0.87	0.87
Lines	10	0.30	0.34	0.37	0.56	0.73	0.80	0.91	1.01	1.03	1.00	1.03	0.96	0.88	0.86	0.85	0.82	0.85	0.87
Plane absorber	12	0.24	0.32	0.29	0.51	0.66	0.70	0.83	0.93	0.92	0.89	0.87	0.83	0.76	0.74	0.76	0.75	0.76	0.77
Chess	12	0.28	0.35	0.35	0.50	0.62	0.73	0.82	1.00	0.93	0.88	0.88	0.83	0.77	0.76	0.76	0.75	0.78	0.77



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