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Classroom acoustics for learning and well-being: in-field measurements, questionnaires and binaural speech intelligibility model

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* * * * * *

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Greta Minelli

Turin, 30th January 2022

To my family

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Abstract

The acoustic characteristics of a school classroom may have an influence on the cognitive developmental processes in children, as well as on the voicing demand in teachers. High reverberation times and excessive background noise levels negatively affect speech communication and can be the causes of psychophysical diseases in both students and teachers. Recent studies highlighted the effects of classroom acoustics on students' performances, in terms of learning, speech intelligibility and subjective perceptions, however there is still a lack of agreement on preferred acoustical criteria for unconstrained speech communication in classrooms.

The objective of my research is to contribute to the identification of tools, procedures and requirements to address the design of an adequate sound environment for educational facilities, that maximize the acoustic comfort for the listeners and support students to perform at their best, in order to improve the working conditions of students and teachers and as a step toward to support the learning process of students.

The first part of the research activity within these three years was oriented to the collection of data through an extensive campaign of objective acoustical measurements in-field. In particular, measurements took place in 29 primary school classrooms located in Torino. Within this framework, questionnaires on noise annoyance and well-being were administrated to about 330 pupils aged from 6 to 7 years.

The second part of the research was addressed to the investigation of speech intelligibility under several acoustic conditions. At this aim, a binaural speech intelligibility model (BSIM) was investigated for speech intelligibility predictions in a real classroom. Predictions were performed within a joint project with the Oldenburg Universität (Germany) and were compared to the well-established room acoustic measures.

List of publications

As a result of the research that was carried out within these three years of Ph.D., several documentations were produced and are listed below. In particular, papers I to IV were published on or were submitted to international scientific journals and constituted the core of this dissertation.

Paper I	Minelli G., Puglisi G.E., Astolfi A., Acoustical parameters for learning in classroom: a review, Building and Environment 208, 1-15 (2022)
Paper II	Minelli G., Puglisi G.E., Astolfi A., A basic protocol for the acoustic characterization of small classrooms, JASA (under review)
Paper III	Astolfi A., Puglisi G.E., Murgia S., Minelli G., Pellerey F., Prato A., Sacco T., The influence of classroom acoustics on noise disturbance and well-being for first graders, Frontiers in Psychology 10, 1-20 (2019)
Paper IV	Minelli G., Puglisi G.E., Astolfi A., Haut C., Warzybok A., Binaural speech intelligibility in a real elementary classroom, Building and Environment (expected submission: mid-February 2022)

Other works containing partial results that were deepened in papers I to IV:

-Minelli G., Puglisi G.E., Astolfi A., Elementary classroom acoustics: what really matters, e-Euronoise, Madeira (Portugal), 25-27 October 2021

-Minelli G., Puglisi G.E., Astolfi A., Haut C., Warzybok A., Speech intelligibility in a real elementary classroom, 8th International Building Physics Conference, Copenhagen (Denmark), 25-27 August 2021

-Minelli G., Puglisi G.E., Astolfi A., Intelligibilità del parlato e benefici spaziali in aule scolastiche con e senza trattamento di correzione acustica, 47° Convegno nazionale Associazione Italiana di Acustica, Matera (Italy), 24-28 May 2021

-Astolfi A., Puglisi G.E., Minelli G., The effect of classroom acoustics on students' learning processes: selection of objective parameters and provision of a measurement protocol, e-Forum Acusticum, Lyon (France), 7-11 December 2020

-Di Blasio S., Puglisi G. E., Gervasi C., Castellana A., Murgia S., Minelli G., Vannelli B., Corbellini S., Carullo A., Astolfi A., A pilot study in primary school on the effect of noise monitoring system with lighting feedback on teachers' voice parameter, 23rd International Congress on Acoustics, Aachen (Germany), 9-13 September 2019

-Minelli G., Astolfi A., Puglisi G.E., Murgia S., Shtrepi L., Prato A., Sacco T., Measuring classroom acoustics with a systematic approach, 48th International Congress and Exhibition on Noise Engineering, Madrid (Spain), 16-19 June 2019

-Puglisi G.E., Minelli G., Astolfi A., Spatial benefits on speech intelligibility in real classroom acoustics under energetic and informational masking noise, 48th International Congress and Exhibition on Noise Engineering, Madrid (Spain), 16-19 June 2019

-Di Blasio S., Vannelli B., Shtrepi L., Puglisi G.E., Calosso G., Minelli G., Murgia S., Astolfi A., Long-term monitoring campaigns in primary school: the effects of noise monitoring systems with lighting feedback on noise levels generated by pupils in classrooms, 48th International Congress and Exhibition on Noise Engineering, Madrid (Spain), 16-19 June 2019

-Astolfi A., Puglisi G.E., Shtrepi L., Minelli G., Prato A., Sacco T., Effects of classroom acoustics on potential struggling first-grade readers, International Workshop on Neural Mechanisms Underlying Improved Speech Perception, Delmenhorst (Germany), 24-25 September 2018

-Astolfi A., Puglisi G.E., Minelli G., Murgia S., Prato A., Sacco T., Un protocollo per valutare l'acustica di aule scolastiche occupate, 45° Convegno nazionale Associazione Italiana di Acustica, Aosta (Italy), 20-22 June 2018

-Astolfi A., Puglisi G.E., Minelli G., Murgia S., Prato A., Sacco T., A protocol for the assessment of the acoustic quality of occupied school classrooms, 11th European Congress and Exposition on Noise Control Engineering, Crete (Greece), 27-31 May 2018

Thesis at a glance

The overall aim of this work is to contribute to expand the knowledge about classroom acoustics. Given the evidences about the influence of classroom acoustics on students' performances collected from literature studies, it attempts to identify what really matters in classroom acoustics. This passes through the design and the practical application of a basic measurement protocol for classroom acoustic characterization, through the administration of questionnaires on noise disturbance and well-being and through predictions of binaural speech intelligibility. The outcomes of this work constitute a base for the identification of tools, procedures and requirements for the effective design of school classrooms able to guarantee an adequate sound environment for educational facilities.

The thesis is organized in subsequent linked chapters and presents the main results that were achieved throughout the years by means of in-field experiments, and that were published on international peer-reviewed journals.

Chapter 1, Introduction, gives a brief overview of the Ph.D. research and a short insight in the reasons that led to develop this work, which were mainly recognized in the social impacts of the negative effects of poor classroom acoustics on students' performances. The general objectives and approach to research are also described in this section.

Chapter 2, A review to investigate the effect of the classroom acoustics on students' performances, collects the knowledge about the dependence between classroom acoustics and students' learning, speech intelligibility and perceptions, gained from published studies. A review procedure is applied to develop classroom acoustic guidelines for better learning performance for students under or over 12 years of age, and to identify thresholds that lead to worse performances.

Chapter 3, Characterizing classroom acoustics, focuses on the assessment of the acoustic quality of primary school classrooms. Firstly, a basic measurement protocol for classroom acoustic characterization was applied in 29 primary school classrooms. Secondly, the most important parameters for classroom acoustic characterization were identified through correlation and regression analysis. Thirdly, based on the collected data, thresholds for the acoustical parameters were identified and their accuracy and precision were tested to assess their ability to classify the acoustic quality as compliant or non-compliant.

Chapter 4, Investigating the effect of classroom acoustics on noise disturbance and well-being, involves the administration of questionnaires parallel to the performance of room acoustic and noise level measurements. Questionnaires on noise disturbance and well-being were administrated to about 330 first graders belonged to 20 primary school classrooms and their outcomes were evaluated accounting for the acoustic quality of the environment.

Chapter 5, Listening in challenging environments, focuses on the speech intelligibility objective and accurate assessment under realistic communication

situations, which implies considering the presence of reverberation and noise. A different evaluation of the acoustic quality of the classrooms is proposed, moving from the monaural to the binaural assessments.

Chapter 6, Final considerations, gives an overview on what was done and what is still needed based on the main findings of this thesis, which were found to be deeply connected.

Summary of publications

Hereby, the four papers that constitute the foundation of this Ph.D. thesis are shortly presented. Only two papers have been already published; of the remaining two, one is currently under review, and one is expected to be submitted by mid-February 2021. All were or will be submitted to international scientific peer-reviewed journals.

Paper I: Acoustical parameters for learning in classroom: a review
In this paper, a review on the reference values of the acoustical parameters that have the greatest influence on students' performance at different ages has been completed. Published studies from 2002 to 2020 were summarized, which focus on testing learning attainments and cognitive skills, speech intelligibility, and subjective perceptions under different classroom acoustic conditions. The results obtained were used to develop classroom acoustic guidelines for better learning performance for students under or over 12 years of age, and identified the thresholds that lead to worse performances.

Paper II: A basic protocol for the acoustic characterization of small classrooms
The present work was aimed to provide tools for easily characterize classroom acoustics through the practical application of a basic measurement protocol centered on a minimum number of parameters and positions. Measurements were performed in 29 occupied and unoccupied primary school classrooms belonging to 13 school building in Turin, which were assigned to the group of compliant or non-compliant classrooms based on the threshold for the acoustical parameters identified for the two groups.

Paper III: The influence of classroom acoustics on noise disturbance and well-being for first graders
In this work, questionnaires were administrated to about 330 pupils aged from 6 to 7 years belonging to 20 classes of 10 primary schools located in Torino (Italy). Questions included the happiness scale, subscales assessing self-esteem, emotional health, relationship at home and with friends, enjoyment of school, intensity and noise disturbance due to different sound sources, and quality of voice. The main findings of this focus highlighted that longer reverberation times, higher noise levels and degraded speech intelligibility reduce pupils' perception of having fun

and being happy with themselves. This conditions was also found to increase pupils' perception of noise intensity and disturbance.

Paper IV: Binaural speech intelligibility in a real elementary classroom

The aim of this study was to investigate the effects of binaural listening on the speech intelligibility in a real classroom. Different talker-to-listener distances and separation of noise and speech source were considered during the measurements carried out in one primary school classroom before and after its acoustical renovation. Predictions were obtained and compared to the typical room acoustic measures, as reverberation time, clarity and definition. The data analysis based on the binaural speech intelligibility predictions, highlighted the importance of a model able to deal with the binaural aspects of the auditory system.

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Chapter 1
Introduction

1.1. Brief overview of the Ph.D. research

The fundamental phases of the learning process take place in elementary classrooms, where speaking and listening are the primary communication modes.

Speech communication consists of a speaker that produces a speech to be delivered to a listener. The main goal of classroom design should be addressed to guarantee proper speech communication, in order to ensure that the speech produced by the speaker can be most clearly delivered to and thus being understood by the listener. The objective in classroom is to effectively communicate between the two main actors involved that are teachers and students. On one hand teachers should produce speech in an effective comfortable way and on the other side pupils need adequate speech intelligibility, learning and well-being. Both the actors need proper classroom acoustic conditions.

From the pupils perspective, poor acoustical design can be disruptive to the learning process and may negatively affect speech perception, student behavior, and educational outcomes (Klatte, Hellbrück, Seidel, and Leistner, 2010; Klatte, Lachmann, and Meis, 2010; Shield and Dockrell, 2008). The development of speech, language and cognitive abilities in children is influenced by the acoustic quality of a classroom. This is particularly true for children at the first stages of education, when their need to tune out competing sounds and tune into speech is the highest in order to establish the basis of the fundamental learning processes like reading and counting. In this context, good classroom acoustics supports the ability of children to reach linguistic maturity. Particularly, it allows to preserve the speech amplitude envelope, which affects the detection of the speech rhythm and prosody (Goswami, 2015), which is fundamental for children with reading impairments at the first grades of the primary school (Cardon, 2012). In turn, literature has consistently highlighted the positive effects of good acoustics on speech intelligibility, reading and cognitive abilities in general (Astolfi, Bottalico, and Barbato, 2012; Prodi, Visentin, and Feletti, 2013; Puglisi, Prato, Sacco, and Astolfi, 2018; Klatte, Bergström, and Lachmann, 2013). On the opposite, poor classroom acoustics can negatively affect speech intelligibility, cognitive skills, comprehension, academic performance and conversational interactions (Sato and Bradley, 2008; Shield and Dockrell, 2004; Jamieson, Kranjc, Yu, and Hodgetts, 2004; Klatte, Meis, Sukowski, and Schick, 2007; Klatte, Hellbrück, Seidel, and Leistner, 2010; Klatte, Lachmann, and Meis, 2010; McKellin, Shahin, Hodgson, Jamieson, Pichora-Fuller, 2011; Neuman, Wroblewski, Hajjcek, and Rubinstein, 2010; Shield and Dockrell, 2008; Stransfield, Berglund, Clarck, Lopez-Barrio, Fischer, Ohrström, Haines, Head, Hygge, van Kamp, and Berry, 2005; Yang and Bradley, 2009; Lewis, Valente, and Spalding, 2015), leading to perception of mental and physical discomfort, annoyance, headaches and increase in aggressiveness (WHO, 2014; Astolfi, Puglisi, Murgia, Minelli,Pellerey Prato, and Sacco, 2019; Vilcekova, Meciarova, Burdova, Katunska, Kosicanova, and Doroudiani, 2017), reducing children's well-being, attention and motivation

(Astolfi, Puglisi, Murgia, Minelli, Pellerey Prato, and Sacco, 2019; Picard and Bradley, 2001).

Concerns about acoustic conditions in schools have led many countries to the introduction of standards or guidelines on the acoustic design of schools (ANSI 12.60, 2010; BB93, 2015; AS/NZS 2107, 2000; AIJES S001, 2008; SIS SS 25268, 2007; UNI 11532-2, 2020). Nevertheless, national and international acoustical standards are not met by the majority of the classrooms (Shiled and Dockrell, 2004; Picard and Bradley, 2001; Astolfi and Pellerey, 2008; Ronsse and Wang, 2013) as they were built before the actual laws promulgation. In USA, 28 per cent of all schools across the country resulted to be unsatisfactorily noisy, with measured levels of around 73 dB(A) (Picard and Bradley, 2001). In London, the reported average internal noise level of 71 dB L_{Aeq} for 3 to 11 years of age pupils (Shield and Dockrell, 2004) exceeded the level recommended by the English standard Building Bulletin 93 (BB93, 2015). In Italy, less than 10% of schools at different levels (pre-schools, primary schools, lower and upper secondary schools) have acoustic protection against outdoor noise, while the Speech Transmission Index in unoccupied classrooms is poor in 31% of cases with ‘‘normal” vocal effort of the teacher, according to the classification given by the standard IEC 60268-16 (2020). Furthermore, agreement on preferred acoustical criteria for successful learning environment still lacks. These evidences leaded the development of this Ph.D. research, which has been carried out at Politecnico di Torino (Italy) in close cooperation between the Department of Energy. Also, a crucial impulse for the completion of this work was given by the Department of Medical Physics and Acoustics of the Oldenburg Universität (Germany) within an exchange research program that lasted four months in 2019-2020.

1.2. Social impact

The very first years of schooling are a crucial time in a child’s development because this period lays the foundations for the child’s learning and well-being throughout their life. The reading skills are the abilities that should be especially improved during this time, since they are directly related to cognitive abilities. It’s estimated that 70-80% of people with poor reading skills are likely to be dyslexic, according to the statistics of language learning disabilities. Statistics of 2020 also report that around 5-9% of the population has learning disabilities and that 8% of children aged 3-17 has learning disabilities. Among students with learning disabilities, those who do not meet the minimum requirements with regard to their academic progress are by far the most common (Büttner and Hasselhorn, 2011; Vaughn and Bos, 2014). Such students fail to develop the knowledge, skill, will, and self-regulation necessary to succeed in key subject areas. Oftentimes, they leave school without any kind of certificate and end up in danger of spending a lifetime in precarious employment relationships or dependent on social welfare benefits. (Grünke and Cavendish, 2016)

The poor acoustics of the majority of classrooms in Europe (Shield and Dockrell, 2004; Dockrell and Shield, 2006) can be seen as the primary cause for learning impairments. The difficulties encountered in classrooms characterized by excessive noise levels and reverberation time values are even greater for the hearing-impaired children, who struggle at every stage of their education with possible negative impacts on their education, employment and social interactions. WHO estimates that unaddressed hearing loss poses an annual global cost of US$ 980 billion, including health sector costs, costs of educational support, and societal costs. All these tools, can be part of prevention strategies to be used in common practices, in order to limit risk exposure and to prevent the disease from ever occurring. Recent releases of some standards have shown attention to the needs of the most vulnerable subjects, such as children with special needs, including new and more stringent requirements. The 2015, 2016 and 2020 updates of the BB93, DIN 18041, UNI 11532:2, respectively, define new requirements for classroom acoustic design which account for the presence of hearing-impaired and with learning disabilities children. New guidelines and recommendations on the acoustic design should account for these requirements.

1.3. Objectives

The need of identifying practical strategies to guarantee optimal conditions to maximize the acoustic comfort in classrooms for teaching and learning purposes, has been pointed out due to its tangible impact on society. To contribute to the design of these strategies, this Ph.D. work has been addressed to six main aspects:

(1) To review the state of the art on the effects of classroom acoustics on students' performance.

(2) To define a basic protocol for the acoustic characterization of classrooms that can be universally applied by technicians and practitioners.

(3) To identify the fundamental parameters for classroom acoustic characterization.

(4) To provide thresholds to classify the acoustic quality of classrooms as with compliant or non-compliant according to moderate or severe requirements.

(5) To investigate the association between objectively measured and subjectively perceived classroom acoustic conditions in the category of pupils.

(6) To obtain predictions for the evaluation of binaural speech intelligibility in noise, so that it can be used for design purpose.

1.4. Approach

The research questions that were introduced throughout the work were in some ways connected. They were all oriented to define tools, procedures and requirements for the enhancement of speech communication process in classrooms.

To deepen the aspect defined in paragraph 1.3, several measurement campaign in-field were carried out in these three years. Thanks to the collaboration with the

teachers, students and school administrators, I had the opportunity of performing monoaural acoustical measurements in 29 primary school classrooms in Torino. Moreover, questionnaires were administrated to about 330 pupils in some of the same schools, which gave the opportunity of making a step forward in the understanding of the acoustic comfort in learning environments. Binaural acoustical measurements were also performed in one additional classroom before and after an acoustic intervention and speech intelligibility predictions were performed on the acquired data.

After acquiring the experimental data from the questionnaires and acoustic measurements, the statistical analysis was performed. This approach, which was supervised by experts in the statistical field, allowed for the identification of trends and relationships that were aimed at improving significantly the existing knowledge.

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Chapter 2
A review to investigate the effect of classroom acoustics on students' performances

Objective	To review studies of the last 19 years investigating the effect of classroom acoustics on students' performances .
Outcome	The data from the reviewed studies are used to define classroom acoustic guidelines for better learning performance and thresholds that lead to worse performances.
Highlights	• Studies investigate different performances of students under specific acoustic conditions. • Most of the studies tested the effect of classroom acoustics on speech intelligibility. • Guidelines provide values for the parameters reverberation time, background noise level, signal-to-noise ratio and speech transmission index.
Notes	Parts of this chapter are submitted to Building and Environment as: ▪Minelli et al., "*Acoustical parameters for learning in classroom: a review*", Building and Environment, in press.

2.1. The review

This chapter represents a review that aims to summarize the state of the art of the last 19 years on the effect of classroom acoustics on students' learning attainments and, in a nutshell, based on the published studies, to identify the acoustical parameters and their values, which have the greatest influence on students' performance at different ages. The intent is to cover the review research gap after the milestone article by Picard and Bradley (2001) that includes data up to 2001. Two reviews have been taken as main references. In particular, Picard and Bradley (2001) represented the benchmark in terms of contents, while Reinten *et al.* (2017) was used for the methodology.

Picard and Bradley (2001) have published a major review of issues related to speech intelligibility in classrooms, which covers many aspects of noise and acoustics in the classroom. Reinten *et al.* (2017) suggests a conceptual framework able to show how the performance of people immersed in an office is influenced by room acoustics. These works served as a starting point for a review that could go beyond their contribution. Focusing on them, some lacks emerge. Picard and Bradley (2001) only considered studies dealing with speech intelligibility. Further limitations regard the publication date that dates back to 2001. Reinten *et al.* (2017) does not end up with the provision of values to be respected, and in any case the environment considered is the office.

Starting from these considerations, a review on the effects of classroom acoustics on learning, speech intelligibility and subjective perceptions has been conducted considering published studies from 2002 to 2020. The present work adds value to Picard and Bradley (2001) since:

- it updates the time window from 2002 to 2020;
- it includes studies focused on the relation between classroom acoustics and not only speech intelligibility, but also comprehension, learning attainments and subjective perception tests;
- it exclusively focuses on classroom acoustics environments that are ecologically valid, i.e., tests are performed directly in classroom or through laboratory reproductions based on realistic conditions.

This chapter is organized as follows. The next paragraphs present the main issues related to the known effects of classroom acoustics on speech intelligibility, learning and comprehension, and students' perceptions at different ages, since different age groups require different acoustic conditions. The methodology section presents the steps adopted for literature search, selection of the papers, tabulation and averaging of the results. This led to the provision of guidelines oriented to the design of classroom acoustics for better learning performance as well as to indication of worse classroom acoustics conditions that should be avoided in order to not incur in low learning attainments. The discussion is dedicated to the comparison with other studies that are important but that fell out of the rigorous

review of literature search. Finally, **Appendix A** presents extended information collected through the selected papers.

2.1.1. In seek of the preferred acoustical criteria

During the last forty years, many studies have been conducted aiming at identifying the preferred acoustical criteria that best enhance students' performance in educational facilities. In order to reach this goal, parameters related to reverberation, speech intelligibility and noise have been investigated by several researchers. In particular, reverberation in different sized environments has been analyzed by Bistafa and Bradley (Bistafa and Bradley, 2000a; Bistafa and Bradley, 2000b; Bistafa and Bradley, 2001) and Hodgson (Hodgson, 1999; Hodgson, 2001; Hodgson, 2002), who also proposed analytical, numerical, and empirical models that can be applied for simulations. The best acoustic conditions for speech intelligibility in small classrooms have been explored by Bradley (1986), Sato and Bradley (2008) and Hodgson and Nosal (2002). External and internal noise surveys have been conducted by Shield and Dockrell (Shield and Dockrell, 2004; Dockrell and Shield, 2004; Dockrell and Shield, 2006; Shield and Dockrell, 2008; Shield *et al.*, 2015; Connolly *et al.*, 2019). The effects of classroom acoustics on students´ performance was firstly investigated through the administration of standardized tests for the evaluation of children attainments in English, mathematics, and science (Shield and Dockrell, 2004), and then by the assessment of reading skills (Puglisi *et al.*, 2018), sentence and speech comprehension (Prodi *et al.*, 2019a), changes in attention level (Castro-Martinez *et al.*, 2016). Listening efficiency and the listening effort have been investigated by Prodi *et al.* (Prodi *et al.*, 2010; Prodi *et al.*, 2013; Prodi *et al.*, 2019b; Visentin *et al.*, 2019), defining listening efficiency as the combination of the accuracy of speech intelligibility and of the effort spent on achieving this goal (Prodi *et al.*, 2010) and referring listening effort to the resources or energy actually used by a listener to meet cognitive demands (Peelle, 2018). Furthermore, questionnaires have been administrated to detect the subjective impression of children of different age and to correlate them with acoustic indexes and students' performances. Noise ratings and school attitudes of primary school students have been collected and evaluated by Klatte Helburck *et al.* (2010). Noise disturbance had been also investigated by Astolfi *et al*. (2019) (see **Chapter 4**), as well as first graders' perception of their self-esteem, emotional health, relationship at home and with friends, enjoyment of school, and of the quality of teachers' voice in their classrooms.

Influence of classroom acoustics on different age groups

Adverse listening conditions determine challenging environments, with a greater effect on children than on adults (Neuman *et al.*, 2010; Yand and Bradley, 2009; Picard and Bradley, 2001; Wroblewski *et al.*, 2012). The difficulties related to the understanding of speech for elementary-grade children in unfavorable acoustic environments may be worsened by the fact that speech perception skills in

noise and reverberation are still developing at young ages, i.e., up to 11 years, and improves with age (Sato and Bradley, 2008; Neuman *et al.*, 2010). Research showed that a child's understanding of speech in noise and reverberation does not reach an adult level until the late teenage years (Nelson, 2003), with children under about 13 years of age being particularly susceptible. A recent work by Leibold and Buss (2019) even increased this age threshold to 14 years to consider the effective ability of correctly and easily discriminating speech from an informative noise source that is spatially separated with respect to the listener's head and from the speech source itself. Furthermore, children are more easily distracted by auditory events due to their less robust and less developed attentional abilities (Klatte *et al.*, 2013; Elliott, 2002). Younger children also are more annoyed by poor acoustics than older students (Minichilli *et al.*, 2018).

Influence of classroom acoustics on speech intelligibility

Most learning activities in classrooms involve oral communication, therefore the intelligibility of spoken words, which is defined as the percentage of correctly understood speech items with respect to the overall (IEC 60268-16, 2020), is very important for a successful development. Generally, it is lower than 100% when the competitive effect of the acoustic environment on speech is considered, and particularly when background noise and reverberation are present and do not comply with optimal acoustic conditions (Astolfi *et al.*, 2012).

Both Bradley and Hodgson (Bradley, 1986; Bradley *et al.*, 1999; Bradley *et al.*, 2002; Hodgson, 2002; Hodgson and Nosal, 2002) have carried out experimental and theoretical studies to investigate the relationship between background noise, reverberation time and speech intelligibility in classrooms. A general outcome is that acoustical condition in classroom should be designed based upon speech intelligibility and that noise is a highly critical factor in speech intelligibility. Bradley *et al.* (1999) found that ambient noise, rather than reverberation, was the most significant factor in understanding speech, and that the most important parameter for speech intelligibility is the signal to noise ratio. As far as speech intelligibility and noise are concerned, Klatte *et al.* (2007; 2010b) found that speech perception was more impaired by train sound and energetic classroom noise (without speech) than by informational background speech, but the latter was more detrimental to highly demanding tasks like those based on listening comprehension. Similarly, recent results of Puglisi *et al.* (2021) and MacCutcheon *et al.* (2019) found that informational masker has a more detrimental effect on speech intelligibility in comparison to energetic masker.

Influence of classroom acoustics on cognitive comprehension and learning attainments of children

Adverse acoustical conditions may impair performance in complex listening tasks even under conditions where individual items are perfectly intelligible (McCoy *et al.*, 2005), mainly due to an increase in listening effort (Klatte *et al.*,

2010a). Shield and Dockrell (2008) found that both external and internal noise have significant negative impacts on the academic performances of primary school children on standardized achievement tests of literacy, mathematics and science, and that intermittent rather than constant noise resulted to be more disturbing. They also negatively affect cognitive skills, i.e., short-term memory and sentence-comprehension (Klatte *et al.,* 2007), arousal, attention and informational processing (Szalma and Hancock, 2011). However, many studies have highlighted that the ability of storing unknown phonological forms in short-term memory is a precursor of vocabulary acquisition, in both mother and foreign language (Gathercole, 2006; Gathercole *et al.*, 2008). Reading skills are especially sensitive to chronic noise exposure in the learning environment (Mexwell and Evans, 2000; Haines *et al.*, 2001; Evand and Hygge, 2007). Students' interactions and collaborative learning in noisy settings worsen too (McKellin, 2011). Since ambient noise levels are higher in rooms with long reverberation times, some effects originally attributed to noise may primarily result from reverberation, with excessive noise levels as a consequence (Klatte *et al.*, 2010a). In this view, chronic effects of long reverberation time on children's learning and well-being at school result from the combined effects of noise and reverberation.

Influence of classroom acoustics on students' perception

Poor acoustics affects the emotional status of the students immersed in it. Adverse acoustic conditions can bring a children to feel angry or uncomfortable (Shield and Dockrell, 2004; Mexwell and Evans, 2000), thereby determining feelings of disturbance, annoyance (Astolfi *et al.*, 2019), depression, anxiety and stress (Sarlati *et al.*, 2014). On the contrary, in classrooms characterized by good classroom acoustics higher well-being, acoustical satisfaction and concentration can be achieved (Klatte *et al.*, 2010a; Neuman *et al.*,2010; Lewis *et al.*, 2015; Valente *et al.*, 2012). High levels of perceived disturbance and annoyance are reported by children in schools with high outdoor and indoor noise levels (Avsar and Gonullu, 2010), other students talking being cited as particularly disturbing (Astolfi and Pellerey, 2008; Connolly *et al.*, 2013). Higher background noise levels, and consequently lower speech-to-noise ratios, cause extra load on auditory information processing that forces students to a greater effort (Visentin *et al.*, 2019), leading to symptoms of fatigue, feeling heavy-headed, headache and difficulties in concentration (Vilcekova *et al.,* 2017). In addition to noise annoyance, poor classroom acoustics may, in the long term, impair social relations and school attitudes in the class (Klatte *et al.*, 2010a).

2.2. Method

2.2.1. Literature search

Reinten et al. (2017) has been taken as a reference for the methodology. In particular the search of the studies was carried out through the PICO strategy (Population Intervention Comparison and Outcome).

The Population was defined as the students performing tasks in classroom. The Intervention focused on classroom acoustics. The Outcome regarded students' performance.

Comprehensive literature searched were conducted using the computerized database Scopus (Elsevier, Amsterdam, The Netherlands). The following search strings were used: (pupil OR student OR children) AND (school OR classroom OR "learning environment") AND (acoustic* AND measure* OR survey OR "classroom acoustics" OR noise OR reverberation) AND (acoustic* AND measure* OR survey OR "classroom acoustics" OR noise OR reverberation) AND ("listening effort" OR learning OR performance OR attainment OR cognit* OR achievement OR skill). The studies could be identified through Scopus if the terms of the strings were present in the title, the abstract or the key word of the articles. In the present thesis, the search was extended by adding eight papers that have not been selected automatically, but that were found reading the studies identified by Scopus.

ResearchGate, Google, PubMed and Pico, i.e., a bibliographic search engine that gives a unique and integrated access to all the bibliographic resources of the Politecnico di Torino, were used to conduct further searches when the full-text of papers were not available in Scopus.

As aforementioned, the present review starts as an extension of the work of Picard and Bradley (2001), where only effects of classroom acoustics on speech intelligibility were investigated. In order to checks if some of the studies pre-2001 delt with classroom acoustics and students' performance, two more different searched have been carried out. Firstly, a new search was conducted through the same tools used in the study, that are the Scopus dataset and the selected terms; secondly, all the references cited in the work of Picard and Bradley have been checked one by one in sought of additional results other than speech intelligibility.

2.2.2. Studies selection

Initially, titles and abstracts of all papers identified were screened. For final inclusion, publications had to fulfil all the following criteria: 1) report significant correlation ($p<0.05$) between classroom acoustics and students' performances related to cognitive abilities, speech intelligibility or subjective perceptions; 2) involve subjects aged from 3 to 40 years; 3) present experiment with ecological validity; 4) be published in peer-reviewed scientific journals written in English. On the contrary, studies were excluded if they were not published in English, if they

were review papers or proceedings of conferences or if it was not possible to found their full-text. Further exclusions regarded publications for which the topic was not related to acoustics or to classroom environments, and papers that did not consider the listeners' perspective. Publications with non-mother tongue participants and with amplification systems were excluded too, as well as papers focused on the effect of aircraft or rail noise.

Figure 1 shows the process for identification of relevant publications. The literature search resulted in 817 potentially relevant publications. A total of 38 publications on the effects of classroom acoustics on students' performance met the inclusion criteria: Amlani, Russo, 2016; Astolfi *et al.,* 2019; Astolfi, Pellerey, 2007; Castro Martinez, 2016; Connolly *et al.,* 2019; Dos Santos *et al.,* 2013; Hurting *et al.,* 2016; Iglehart, 2019; Klatte *et al.,* 2010; Lam *et al*., 2018; Larsen, Vega, Ribera, 2008; Lewis *et al.,* 2015; MacCutcheon *et al*., 2019; McKellin *et al.,* 2011; Mealings *et al*., 2015; Mealing *et al.,* 2015b; Minichilli *et al.,* 2018; Nakeva von Mentzer *et al.,* 2018; Neave di Toro *et al*., 2017; Neuman *et al.,* 2010; Neuman *et al.*, 2012; Peng *et al.,* 2020; Peng, Wang, 2016; Peng, Wang, 2019; Polewczyk *et al.,* 2020; Prodi *et al.,* 2019; Prodi *et al.,* 2019b; Prodi *et al.,* 2013; Prodi, Visentin, 2015; Ronsse *et al.,* 2013; Seetha *et al*., 2008; Shield, Dockrell, 2008; Sogol *et al.,* 2014; Rabelo *et al.,* 2014; Valente *et al.,* 2012; Vilcekova *et al.,* 2017; Visentin *et al.,* 2019 ; Wròblewski *et al.,* 2012. Further eight papers were added as verification studies: Astolfi *et al.,* 2012; Jamieson, 2004; Klatte *et al.,* 2010b; Yang, Bradley, 2009; Prodi *et al*., 2010; Bradley, Sato, 2008; Prodi *et al.,* 2021; Prodi, Visentin, 2021.

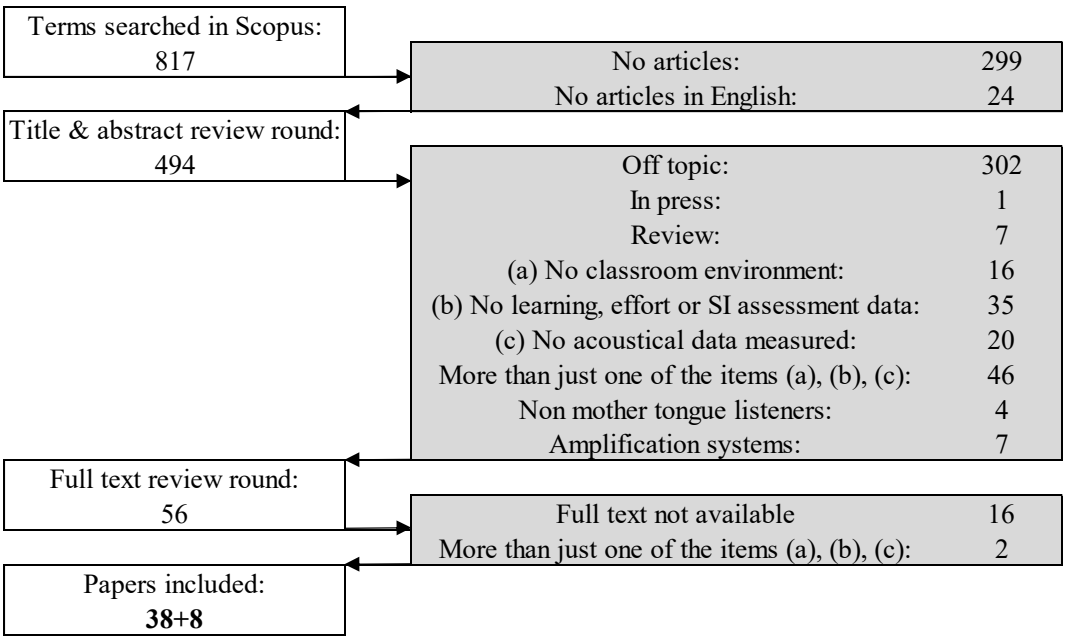

Figure 1. Flow chart of the process for identification of the included studies

2.2.3. Data extraction

Relevant data from the publications were extracted on subjects' personal factors, number of subjects, task category and type, performance measure, location of test administration, acoustical parameters and type of noise used during the experiment. Further information reported concerned, when available, the condition of occupation, the volume of the classrooms, the presence of an acoustic treatment, dB decay for reverberation time or frequency averaging of the acoustical parameters, standard deviation.

Specification of the provided information on subjects' personal factors

Age of participants and hearing sensitivity, i.e., Normal Hearing (NH) or Hearing Impaired (HI), were annotated. Experiments carried out with hearing impaired subjects were first considered, but their data were not used for the elaboration of the guidelines.

Specification of the provided information on tasks testing learning attainments, speech intelligibility and subjective perception

The tasks reported in the publications were classified in eleven typology: Word-Recognition (WR), Sentence-Recognition (SR), Sentence Comprehension (SC), Attention (Att), Memory (Mem), Information Processing (Info Proc), Collaborative Learning (Coll), Standardized Achievement Tests (SATs), Academic Achievement (Acad Ach), Dual Task Paradigm (DTP), and Questionnaires (Q). These eleven typology were traced back to three categories, of which two objective, i.e., Intelligibility and Cognitive, and one subjective, i.e., Perception. In particular, the WR and SR tasks referred to the objective category of Intelligibility, SC, Att, Mem, Info Proc, Coll, SATs, Acad Ach, and Dual Task Paradigm to the Cognitive objective category, while the Q tasks referred to the subjective category of Perception.

As far as intelligibility is concerned, Word-Recognition (WR) and Sentence-Recognition (SR) tests consisted in listening or reading words or sentences and repeating them orally or in writing or selecting on devices.

Concerning cognitive abilities, Sentence Comprehension (SC) tests consisted in listening or reading sentences and answering, orally or writing, to questions about them. Attention tests measured the level of attention through a questionnaire with words belonging and not belonging to the class but related to the subject or through the average of the times students look away. Memory (Mem) was tested through a pair of non-words, i.e., a word that has no semantic meaning, presented to children that had to mark a response sheet indicating if the non-words heard were mutually identical or different. Information Processing (Info Proc) tests consisted in reading a text or listening to an oral presentation and answering questions orally or in writing, assessing information contained explicitly in the text, ability to infer information not explicitly stated in the text or learning complex words. Collaborative learning (Coll) observed and recorded conversational interactions in

noisy classroom settings. Standardized Achievement Tests (SATs) and Academic Achievement (Acad Ach) were provided by the school and were investigated to assess how classroom acoustical environment impact student learning outcomes. Dual Task Paradigm (DTP) was used to assess Adaptive Pursuit Rotor (APR) tracing a dot as it continuously rotated around a fixed circle while listening and selecting among choices.

As far as perception is concerned, Questionnaires (Q) were administrated in the form of response sheets or oral interviews.

Considering the objective tasks, i.e., the outcome of the intelligibility and cognitive abilities tests, performances were measured in different ways. Accuracy (Acc) refers to the number of correct answers given; number of responses (n) is the total number of answers given, correct or incorrect; Listening Effort (LE) was assessed through response time or subjective ratings of effort, Response Speed (RS) recorded response latencies for questions or reading time for texts, Conversational Interactions (Conv Int) examined the sequencing, the inferencing, and the development of collaborative work.

As far as the subjective perceptions are concerned, they were tested through questionnaires on Well-Being (W-B), including questions about happiness, self-esteem, emotional health, relationships, enjoyment at school, mood, concentration, behavior, mental, physical and temporal demand, effort, frustration, perceived performance, depression, anxiety, stress; on Annoyance (Ann), assessing annoyance intensity, disturbance, frequency of occurrence of noise; or on Acoustical Quality (Ac Qual), where reverberation, intelligibility, teacher vocal effort, consequences of poor acoustics and satisfaction were investigated.

Specification of the provided information on acoustic parameters

The acoustical parameters considered in this work, which are the most occurrent in classroom acoustics studies, are the average reverberation time for the central octave bands, varying case by case from a minimum of 125 Hz to a maximum of 4 kHz, i.e., T_{mid}, the A-weighted sound pressure level of indoor noise acquired with students in silence or involved in classroom activities, i.e., L_{Neq}, the signal-to-noise ratio, i.e., SNR, the Speech Transmission Index, i.e., STI, the speech clarity and the useful-to-detrimental ratio averaged in the central octave bands 500÷1000 Hz, i.e., C50 and U50, respectively.

Further specifications refer to the type of noise. Informative Noise (IN) is intended as the anthropic sound generated by the talking of people present in the classroom itself or from the adjacent environments. Energetic Noise (EN) lacks in semantical content. Ambient Noise (AN) is meant as the typical noises of the built environment with heating, ventilation and air conditioning (HVAC) systems, of technological sounds, of typical classroom sounds such as moving chairs, scraping feet, coughing, leafing through papers, rattling with writing utensils, opening and closing school-bags, and of traffic noise from the outside.

2.2.4. Data analysis

Information has been filtered and grouped in terms of better and worse performance, as described hereafter. With the expression "better" and "worse" performances it is intended the set of acoustic and performances data that allows for better or worse intelligibility, cognitive and perception outcomes, respectively. The extent to which acoustic and performances data were defined as better or worse was determined based on the outcomes of each paper, that is, on the statistically significant differences among these two groups as declared by the respective Authors. While intelligibility, cognitive processes, or subjective perceptions, i.e., task categories, were not used for filtering results, data clustering used age groups.

Ranges of age groups were defined based on the cognitive development stages of Jean Piaget (1964), i.e., 5÷7 years, 8÷11 years, 12+ years. In the latter group, subjects were aged 12÷40 years accordingly to the available collected data and to the fact that from 12 years old on the listening abilities are comparable with adults (McCreery and Stelmachowizc, 2012).

The distinction between occupied and unoccupied conditions was omitted because results of the studies have been obtained assuming ad-hoc artificial research conditions in which reverberation and noise could be representative of both unoccupied and occupied conditions.

To subdivide the values of the acoustic parameters for classrooms grouped for better and worse performance, the following procedure has been adopted:

- When possible, one value of each acoustical parameter, i.e., one for better and one for worse learning performance, has been extracted from every selected article. The review procedure is based on the influence that classroom acoustics can have on some measure of human performance, i.e., speech intelligibility, learning or subjective perceptions. In the selected references, the type of performance differs case by case (as well as the tested acoustical measures). Only references reporting results in terms of students' performance that are significantly better or worse than others under specific acoustic conditions have been included. In some references a specific percentage of the change in the performance under the different acoustic conditions is indicated, e.g., in (Amlani and Russo, 2016) a 10% higher accuracy in word recognition task is reported, while others show a significant improvement or lowering of the performance without a precise quantification of their shift expressed in percentage, but that can be determined based on the data, as, e.g., in(Astolfi and Pellerey, 2008). This applied to both subjectively acquired data, based on questionnaires, and objectively measured performances. If studies reported more than one value, every data has been taken into account (Lam *et al.*, 2018; Neuman *et al.*, 2010), with an interval of 0.1 s for reverberation time that corresponds to the engineering-type accuracy of 10% (Astolfi *et al.*, 2008) with the assumption of an average reverberation time of about 1 s, 1 dB for

background noise level and SNR, 0.01 for STI, that represent each respective just noticeable difference (JND) (EN ISO 3382-2, 2008; Bork, 2000);

- When a range was given, the criterion for data processing differed depending on the specific parameter: for reverberation time and STI all the values have been considered (McKellin *et al.*, 2011; Rabelo *et al.*, 2014), for noise level all the values have been considered, with the intervals above specified, respectively. Reference (Dos Santos *et al.*, 2013) was an exception, as only the smaller value of the range has been included, given the very high value of the upper extreme that led to consider it an outlier;
- When some data has been translated in values "smaller or greater than", a single value, equal to the reported one, has been considered (Ronsse and Wang, 2013).

Median and interquartile range are assumed as measures of the central tendency and dispersion of the population, respectively, in the case of non-normal distribution of occurrences, as expected in the case of such a small database (Gibbons and Chakraborti, 2003).

2.2.5. Guidelines for better performances and detection of thresholds for worse performances

Starting from the median values of the acoustical parameters described above, guidelines for better performances and thresholds for worse performances have been derived. Particularly, values for better and worse learning attainments, speech intelligibility and subjective perceptions have been extracted under the following assumptions:

- Age clustering were distinguished under or over 12 y.o (thus dividing the sample almost equally between the two groups of age); these thresholds are used to distinguish the good practices for lower levels, i.e., primary grades, and higher levels, i.e., secondary grades;
- Occupied and unoccupied conditions were considered under a single overall value; this approach allowed to strengthen the results' consistency and to overcome singularities;
- The values of the guidelines for better learning performance and of the thresholds for worse learning performance derive from the previously described medians. Depending on the parameter, the values indicated for students under or over 12 year old have been chosen based on different approaches. First, roundings have been made taking into account the just noticeable difference (JND), which, in particular, for background noise level is equal to 1 dB according to EN ISO 3382-2, 2008. Second, more stringent values, or at least equal, were defined for the younger group of students with respect to the older one. In this sense, for students under 12 y.o. lower values of reverberation time and background noise level, and higher values of SNR and STI, were guaranteed, compared to those provided for students over 12 y.o. Third, it has

been checked that all the reference values could be respected at the design or verification phases, particularly the ones referred to the STI for which the highest values, close to 1, are difficult to be guaranteed (IEC 60268-16, 2020).

2.3. Results

2.3.1. Literature search results

The literature search led to 817 results, reduced to 518 when the document typology limitation to articles was applied, according to the procedure detailed in the methodology session. Further exclusions of documents not written in English lowered the number to 494, of which only 56 were considered as relevant to the research objective after the examination of their title and abstract. Particularly, based on title and abstract review, 302 have been considered off topic, 117 did not include one or more of the following items: classroom environment, learning, subjective perception or speech intelligibility data, acoustical data measured. Furthermore, 11 papers were excluded because listeners were non mother tongue and amplification systems were used during the experiments. After the full text screening, 18 articles were further excluded, of which 16 due to the unavailability of the text and 2 due to the absence of the items described above. It is remarkable as 16 texts resulted unavailable after careful and in-depth search in the search engines Scopus, PICO, ResearchGate, Google, PubMed. Finally, only 38 of the available studies measuring the effect of classroom sound environment on student performance was used out of 817, i.e., a small proportion equal to 5%.

As far as the further Scopus search to check pre-2001 studies is concerned, the majority of the articles (87%) were identified as off topic since they referred to a subject (e.g. neurology, psychiatry, otolaryngology, audiology) different from the one investigated. Those which were properly focused on architectural acoustics dealt with environment different than classrooms (2%) or were focused on hearing aid systems (5%) or on rail noise (1%). For part of the papers (5%), a full text was not available, thus it was not possible to carry on further analysis. As the aforementioned characteristics fall within the exclusion criteria presented in the study, the new papers found through Scopus for the period pre-2001 have been left out and have not been added to the review.

Relatively to the check of the references cited by Picard and Bradley, also in this case no paper was considered valid to be added to the analyses of the review under discussion as, again, their characteristics do not fall within the inclusion criteria. Indeed, the selection process required that the documents provided significant correlations between acoustical measures and learning, effort or speech intelligibility outcomes in order to be included, while most of the references in Picard and Bradley lack a room acoustic imprint and do not deepen the knowledge about the influence of the built environment on people rather than focusing on

understanding cognitive processes. Since the main objective of this document arose from the need to find the most relevant acoustical objective parameters for students' learning in classroom, works lacking information about acoustical measures or, on the contrary, works without results in terms of students' performances under specific room acoustic conditions have been considered out of the scope of the present work. Among the small portion of the references that present these characteristics in Picard and Bradley, only the minority reports information relating to performances other than speech intelligibility. However, they conclude by saying that the results between the conditions tested are not significantly different or they investigate the effects on the students performances of the exposure of noise of train or airplanes, and therefore can be omitted from this work. Other reasons for not adding references by Picard and Bradley to the present study refer to the fact that many articles deal with hearing impaired, hearing devices or amplification systems; others are reviews or not written in English, which constitute exclusion criteria.

2.3.2. Contents collected from the included studies

Table 1 is a summary of the contents collected from the papers included in the review. It reports the most meaningful information from each selected paper, relating to the subjects' personal factors, number of subjects, task category and type, performance measure, location of test administration and acoustical parameters.

Subjects' personal factors

From **Table 1** it emerges that 12% of the studies includes children from 5 to 7 years, 34% includes participants from 8 to 11 years, 54% takes in participants between 12 and 40 years. Even if not indicated, 66% of the studies considered normally-hearing students (NH), while 8% of the studies included hearing impaired participants (HI). When the hearing sensitivity was not provided it has been assumed being as NH.

Task category and type and performance measure

Intelligibility is investigated in 45% of papers, followed by subjective perceptions, which is investigated in 18% of the papers, and cognitive processes, investigated in 16% of the papers. 3% of the studies explore together the three categories, while two of the three categories are combined in the 13% of the cases, i.e., intelligibility and cognitive processes, or in the 3% of the cases, i.e., perception with intelligibility or perception with cognitive processes.

The task type of word-recognition emerges in 68% of the articles related to intelligibility performances, tested alone or in combination with cognitive and/or perception tasks; 32% of the studies used sentence-recognition, but one that is in combination with word-recognition. For both word-recognition and sentence-recognition tasks, accuracy is always tested, while only three studies, i.e., 12%, consider the number of responses (Connolly *et al.,* 2019; Mealings *et al.*, 2015a; Mealings *et al.*, 2015b), while the response speed has been considered in nine

studies (Lam *et al.,* 2018; Mealings *et al.*, 2015a; Mealings *et al.*, 2015b Nakevo von Mentzer *et al.*, 2018; Prodi, Visentin, and Feletti, 2013; Prodi and Visentin, 2015; Prodi *et al.*, 2019a; Prodi *et al.*, 2019b; Visentin *et al.*, 2019), i.e., 36% of the cases.

In the cognitive processes category, the type of the task administrated varies to a larger extent and spans from attention, memory, information processing, collaborative learning, sentence comprehension to academic achievement. Accuracy is evaluated in 83% of the studies, followed by response speed in 17% of the studies.

Subjective perception is always assessed through questionnaires. In particular, well-being, annoyance, acoustical quality and listening effort appears respectively 6, 6, 1, and 2 times out of 11 articles in this category.

Location of test administration

The 66% of the tests took place in real classroom, then 21% reproduced or simulated the classroom sound environment through earbuds, while 13% resorts to laboratories.

Half of the real classroom are traditional elementary classrooms, 25% are middle- and high-school classrooms characterized by regular rectangular geometry, both with an average volume of 216 (±59) m^3. Other typology of classrooms refers to university spaces, i.e., 17%, with an average volume of 200 (±86) m^3, to kindergarten environments, i.e., 8% with an average volume of 191 (±35) m^3, and to open plan classrooms, i.e., 8% with volumes of 470 m^3 and 1340 m^3 (Mealings *et al.*, 2015a; Mealings *et al.*, 2015b). Considering all the real classrooms together, with the exclusion of the open-plan environments, leads to an average volume of 216 (±61) m^3.

Laboratory refers to anechoic room (Lam *et al.*, 2018) or listening chamber (Valente *et al.*, 2012; Peng and Wang, 2016; Peng and Wang, 2019) at research facilities, i.e., universities and hospitals. These rooms are completely or partially covered by sound-absorbing panels and the classroom acoustic conditions are played back or simulated via loudspeakers, frontally or laterally placed at 1.5 m above the floor (Valente *et al.*, 2012; Peng and Wang, 2016; Peng and Wang, 2019) or hanging from the ceiling (Peng and Wang, 2016; Peng and Wang, 2019). Among studies that employ earbuds to play back the sound environment of the classroom, i.e., recorded or simulated, 75% used headphones while 25% used earphones.

Location of test administration, task category and age

Among the twenty-five studies that took place in real classrooms, six used cognitive tests, that were administrated to students of 5÷7 year old in one case (Klatte *et al.*, 2010a), of 8÷11 year old in four cases (McKellin *et al.*, 2011; Shield and Dockrell, 2008; Ronsse and Wang, 2013; Prodi and Visentin, 2019) and of 12+year old in three cases (McKellin *et al.*, 2011; Castro-Martinez *et al.*, 2016; Prodi and Visentin, 2019). Among the five studies performed in laboratory, four involved cognitive test, administrated to students of 8÷11 and 12+ year old, respectively in two (Lewis *et*

al., 2015; Valente *et al.*, 2012) and four (Lewis *et al*., 2015; Valente *et al.*, 2012; Peng and Wang, 2016; Peng and Wang, 2019) cases. Among the eight studies that used earbuds, in two cognitive tests were given and participants of 5÷7 y.o. were involved in one case (Nakeva von Mentzer *et al.*, 2018), of 8÷11 y.o. in both cases (Connolly *et al.*, 2019; Nakeva von Mentzer *et al.*, 2018) and of 12+ y.o. once (Connolly *et al.*, 2019).

Among the twenty-five studies that took place in real classrooms, fifteen used intelligibility tests, that were administrated to students of 5÷7 year old in six cases (Iglehart, 2019; Klatte *et al.*, 2010a; Mealings *et al.*, 2015a; Mealings *et al.*, 2015b; Prodi, Visentin, Feletti, 2013; Prodi *et al.*, 2019b), of 8÷11 year old in ten cases (McKellin *et al.*, 2011; Dos Santos *et al.*, 2013; Hurting *et al.*, 2016; Iglehart, 2019; Peng *et al.*, 2020; Prodi and Visentin, 2019; Prodi, Visentin, Feletti, 2013; Prodi *et al.*, 2019a; Rabelo *et al.,* 2014; Connolly *et al.*, 2019) and of 12+ year old in six cases (McKellin *et al.*, 2011; Iglehart, 2019; Larsen *et al.*, 2008; Prodi and Visentin, 2019; Prodi, Visentin, Feletti, 2013; Visentin *et al.*, 2019), while ten used questionnaires assessing subjective perceptions of students of 5÷7 y.o. in three cases (Klatte *et al.*, 2010a; Astolfi *et al.*, 2019; Polewczyk *et al.*, 2020), of 8÷11 y.o. in five cases (Klatte *et al.*, 2010a; Vilcekova *et al.*, 2017; Minichilli *et al.*, 2018; Peng *et al.*, 2020; Polewczyk *et al.*, 2020) and of 12+ y.o. in seven (Vilcekova *et al.*, 2017; Astolfi and Pellerey, 2008; Minichilli *et al.*, 2018; Sarlati *et al.*, 2014; Polewczyk *et al.*, 2020; Seetha *et al.*, 2008; Visentin *et al.*, 2019.

Acoustical parameters

Considering the three task categories of cognitive processes, intelligibility, and subjective perceptions, the acoustic parameters that occur mostly are T_{mid} (82%), L_{Neq} (61%) and SNR (34%). STI emerges to a less extent (21%), as well as C50 and SRM (5%), and U50 and SRT (3%). When only the speech intelligibility task category is considered, T_{mid} appears in most of the studies (86%), followed by L_{Neq} (50%) and SNR (46%). STI, SRM, C50 and SRT are considered to a less extent (17%, 8%, 4%, 4%, respectively). Considering cognitive processes, the same trend has shown where T_{mid} is the most recurrent parameter (83%), followed by L_{Neq} (75%), SNR (25%) and STI (8%). Subjective perception task category confirms the above results, with T_{mid} and L_{Neq} which report the larger number of occurrences (82%), followed by STI (27%), then SNR and C50 (18%), U50 (9%).

Type of noise

Table 1 and **Table A.1** in the Appendix A indicate the type of noise that occurred during the experimental activities. Particularly, in the latter indication concerning occupied and unoccupied conditions are reported, that shows as the most occurrent types of noise with students in the classrooms were IN (11 cases) and AN (15 cases), while EN was counted in few cases (3 cases). When the classroom was empty, AN occurred to a greater extent (14 cases), while IN and EN to a less extent (4 and 3 cases, respectively).

Table 1. Summary of the contents collected from the papers (REF) included in the review.

REF	Age	N	Task category and type		Performance measure	Location	Acoustical parameters
Amlani, Russo, 2016	8÷9	27	Int	WR	Acc	Eb	T_{mid}, L_{Neq}
Astolfi et al., 2019	6÷7	330	Perc	Q	W-B, Ann	Real	T_{mid}, L_{Neq}, C50, U50
Astolfi, Pellerey, 2007	16	1006	Perc	Q	Ann, Ac Qual	Real	T_{mid}, L_{Neq}, SNR, STI
Castro Martinez, 2016	22	141	Cogn	Attention	Acc	Real	T_{mid}, L_{Neq}
Conolly et al., 2019	11÷16	976	Cogn	Info Proc	Acc, n, RS	Eb	L_{Neq}
Dos Santos et al., 2013	8÷10	87	Int	WR	Acc	Real	L_{Neq}
Hurting et al., 2016	10	72	Int	WR	Acc	Real	T_{mid}, SNR
Iglehart, 2019	7÷16	10	Int	WR+SR	Acc	Real	T_{mid}, SNR
Klatte et al., 2010	7÷8	487	Int Cogn Perc	WR SC+Mem Q	Acc Acc W-B, Ann	Real	T_{mid}, L_{Neq}
Lam et al., 2018	18÷33	13	Int	WR	Acc, RS	Lab	T_{mid}, SNR, STI
Larsen, Vega, Ribera, 2008	18÷40	53	Int	WR	Acc	Real	T_{mid}, L_{Neq}
Lewis et al., 2015	8÷12	36	Int Cogn	SR Info Proc	Acc	Lab	T_{mid}, SNR
MacCutcheon et al., 2019	5÷7	39	Int	SR	Acc	Eb	T_{mid}, STI, SRM
McKellin et al., 2011	8÷12	24	Cogn, Int	Coll	Conv Inter	Real	T_{mid}, L_{Neq}
Mealing et al., 2015	5÷6	22	Int	WR	Acc, n, RS	Real	T_{mid}, L_{Neq}
Mealing et al., 2015b	5÷6	22	Int	WR	Acc, n, RS	Real	L_{Neq}
Minichilli et al., 2018	11÷18	503	Perc	Q	Ann	Real	T_{mid}, L_{Neq}
Nakeva von Mentzer et al., 2018	7÷9	27	Int Cogn	WR Acad Ach	Acc, RS Acc	Eb	SNR
Neave di Toro et al., 2017	18÷28	9	Int	SR	Acc	Eb	T_{mid}, SNR
Neuman et al., 2010	6÷12	63	Int	SR	Acc	Eb	T_{mid}, SNR
Neuman et al., 2012	6÷12	25	Int	SR	Acc	Eb	T_{mid}, SNR
Peng et al., 2020	11 8	32 87	Int Perc	WR Q	Acc Ann	Real	T_{mid}, L_{Neq}, C50, STI
Peng, Wang, 2016	24	47	Cogn	DTP (SR)	Acc	Lab	T_{mid}, L_{Neq}
Peng, Wang, 2019	24	47	Cogn Perc	DTP (APR) Q	RPM LE	Lab	T_{mid}, L_{Neq}, SNR
Polewczyk et al, 2020	7÷13	378	Perc	Q	W-B	Real	T_{mid}, STI
Prodi et al., 2019	11÷13	171	Cogn Int	SC WR	Acc, RS	Real	T_{mid}, L_{Neq}, STI
Prodi et al., 2019b	5÷7	117	Int	WR	Acc, RS	Real	T_{mid}, STI, SNR
Prodi et al., 2013	6÷12	741	Int	WR	Acc, RS	Real	T_{mid}, L_{Neq}
Prodi, Visentin, 2015	8÷10	530	Int	WR	Acc, RS	Real	T_{mid}
Ronsse et al., 2013	8÷11	n.a.	Cogn	SATs	Acc	Real	T_{mid}, L_{Neq}
Seetha et al., 2008	13÷17	150	Perc	Q	W-B, Ann	Real	L_{Neq}
Shield, Dockrell, 2008	8÷11	n.a.	Cogn	SATs	Acc	Real	L_{Neq}
Sogol et al., 2014	19÷25	250	Perc	Q	W-B	Real	T_{mid}
Rabelo et al., 2014	9	273	Int	WR	Acc	Real	T_{mid}, L_{Neq}, STI
Valente et al., 2012	8÷12	50	Cogn Int	SC SR	Acc	Lab	T_{mid}, SNR
Vilcekova et al., 2017	8÷15	34	Perc	Q	W-B	Real	L_{Neq}
Visentin et al., 2019	23÷28	13	Int Perc	WR Q	Acc, RS LE	Real	T_{mid}, L_{Neq}, STI
Wroblewski et al., 2012	7÷14	48	Int	SR	Acc	Eb	T_{mid}, L_{Neq}, SNR, SRM
Prodi et al., 2021	11÷13	171	Cogn	SC	Acc, RS	Real	T_{mid}, STI, SNR
Prodi, Visentin, 2021	11÷13	302	Int Cogn	SR SC	Acc, RS Acc, RS	Real	T_{mid}, C50, U50, STI, SNR
Astolfi 2012	7÷11	983	Int	WR	Acc	Real	T_{mid}, C50, STI, SNR
Jamieson, 2004	5÷8	40	Int	WR	Acc	Eb	SNR
Klatte et al., 2010b	7÷9	257	Int Cogn Perc	WR SC Q	Acc Acc Ann	Lab	T_{mid}, L_{Neq}, STI, SNR
Yang, Bradley, 2009	6÷11	217	Int	WR	Acc	Eb	T_{mid}, C50, SNR
Prodi et al., 2010	8÷10	80	Int	WR	Acc, LE, RS	Lab	T_{mid}, STI, SNR
Bradley, Sato, 2008	6÷11	840	Int	SR	Acc	Real	T_{mid}, L_{Neq}, SNR

Guidelines of classroom acoustics for better learning performance of students

The information collected in **Table 1** and **Extended Table 1** in **Appendix A** were filtered and grouped for different age groups in order to identify the acoustic conditions that led to better and worse performance of students. **Table 2** and **Table 3** report the values of the acoustical parameters extracted from every study grouped for the different age groups and for better and worse performance.

Table 2. Values of the acoustical parameters for better performance collected from each study.

Better performance				
Age	**T_{mid} [s]**	**L_{Neq} [dBA]**	**SNR [dB]**	**STI [-]**
5÷7	0.7 *(Astolfi et al., 2019)* 0.5 *(Prodi et al., 2019)* 0.4 *(Bradley, Sato, 2008)* 0.4, 0.7, 0.9, 1.6 *(Astolfi et al., 2012* 0.5÷0.6 *(Klatte et al., 2010)* 0.6 *(MacCutcheon et al., 2019)* 0.7 *(Mealings et al., 2015)* 0.35 *(Nakeva von Mentzer et al, 2018)* 0.3, 0.6, 0.8 *(Neuman et al., 2010)* <0.6 *(Neuman et al., 2012)* 0.6 *(Polewczyk et al., 2020)* 0.5 *(Klatte et el., 2010b)* 0,3÷0.9 *(Yang, Bradley, 2009))*	49 *(Astolfi et al., 2019)* 57 *(Mealings et al., 2015)* 55 *(Mealings et al.,2015b)* 22÷39 *(Klatte et al., 2010)* 55 *(Bradley, Sato, 2008)*	16 *(Prodi et al., 2019b)* 15, 18, 20 *(Bradley, Sato, 2008)* 0, +6 [43] 2, 5, 8 *(Astolfi et al., 2012)* 10, 12, 15 *(Neuman et al., 2010)* >6 *(Neuman et al., 2012)*	0.73 *(Prodi et al., 2019b)* 0.67 *(Astolfi et al., 2012)* 0.70 *(Polewczyk et al., 2020)* 0.72÷0.78 *(Klatte et el., 2010b)*
8÷11	0.3 *(Hurting et al., 2016)* 0.6 *(Lewis et al, 2015)* 0.6 *(Valente et al., 2012)* 0.4 *(Bradley, Sato, 2008)* 0.6 *(Prodi et al., 2010)* 0.69 *(Prodi et al., 2021)* 0.57, 0.69 *(Prodi, Visentin, 2021)* 0.4, 0.7, 0.9, 1.6 *(Astolfi et al., 2012)* 0.8 *(Amlani, Russo, 2016)* 0.3 *(Iglhart, 2019)* 0.5÷0.6 *(Klatte et al., 2010)* 0.7÷0.9 *(McKellin et al, 2011)* 0.3, 0.6, 0.8 *(Neuman et al., 2010)* <0.6 *(Neuman et al., 2012)* 0.6 *(Peng et al, 2020)* 0.6 *(Polewczyk et al., 2020)* <0.6 *(Ronsse et al., 2013)* 0.7÷0.9 *(Rabelo et al., 2014)* 0.0 *(Bradley, Sato, 2008)* 0.5 *(Klatte et el., 2010b)* 0,3÷0.9 *(Yang, Bradley, 2009)*	50÷80 *(Dos Santos et al., 2013)* 40 *(Amlani, Russo, 2016)* 22÷39 *(Klatte et al., 2010)* 40 *(Peng et al, 2020)* 35 *(Ronsse et al., 2013)* 55÷60 *(Rabelo et al., 2014)* 55 *(Bradley, Sato, 2008)*	12 *(Hurting et al., 2016)* 10 *(Lewis et al, 2015)* 10 *(Valente et al., 2012)* 15, 18, 20 *(Bradley, Sato, 2008)* 0, 6 *(Prodi et al., 2010)* 0, +18*(Prodi et al., 2021)* +18 *(Prodi, Visentin, 2021)* 2, 5, 8 *(Astolfi et al., 2012)* 18 *(Iglhart, 2019)* 10, 12, 15 *(Neuman et al., 2010)* >6 *(Neuman et al., 2012)* 5 *(Bradley, Sato, 2008)*	0.67 [47] 0.40, 0.47, 0.65 *(Prodi et al., 2021)* 0.65, 0.71*(Prodi, Visentin, 2021)* 0.58 *(Astolfi et al., 2012)* 0.75 *(Peng et al, 2020)* 0.70 *(Polewczyk et al., 2020)* 0.65÷0.70 *(Rabelo et al., 2014)* 0.72÷0.78 *(Klatte et el., 2010b)*
12÷18	0.5 *(Astolfi, Pellerey, 2007)* 0.7 *(Prodi et al., 2019)* 0.69 *(Prodi et al., 2021)* 0.57, 0.69 *(Prodi, Visentin, 2021)* 0.3 *(Iglhart, 2019)* ≤0.8 *(Minichilli et al., 2018)* 0.6 *(Polewczyk et al., 2020)* 0.0 *(Bradley, Sato, 2008)*	37 *(Astolfi, Pellerey, 2007)* 50 *(Conolly et al., 2019)* 41 *(Prodi et al., 2019)* 37 *(Minichilli et al., 2018)* 55 *(Bradley, Sato, 2008)*	19 *(Astolfi, Pellerey, 2007)* 0, +18*(Prodi et al., 2021)* +18 *(Prodi, Visentin, 2021)* 18 *(Iglhart, 2019)* 5 *(Bradley, Sato, 2008)*	0.70 *(Astolfi, Pellerey, 2007)* 0.65 *(Prodi et al., 2019)* 0.69 *(Prodi et al.,2021)* 0.40, 0.47, 0.65 *(Prodi et al., 2021)* 0.65, 0.71*(Prodi, Visentin, 2021)* 0.68 *(Minichilli et al., 2018)* 0.70 *(Polewczyk et al., 2020)*
19÷40	0.7, 1.1 *(Lam et al., 2018)* 0.8 *(Visentin et al., 2019)* 0.6 *(Prodi et al., 2010)* 1.2 (Castro Martinez, 2016) 0.5 *(Larsen, Vega, Ribera, 2008)* 0.3 *(Naeve di Toro et al., 2017)* <1.2 *(Peng, Wang, 2016)* 0.4 [26] 0.5 *(Klatte et el., 2010b)* 0,3÷0.9 *(Yang, Bradley, 2009)*	39 *(Visentin et al., 2019)* 34 *(Larsen, Vega, Ribera, 2008)* 38 *(Peng, Wang, 2016)* ≤38 *(Peng, Wang, 2019*	8, 15 *(Lam et al., 2018)* 20 *(Visentin et al., 2019)* ≥0 *(Naeve di Toro et al., 2017)* 21 *(Peng, Wang, 2019)*	0.57 *(Lam et al., 2018)* 0.67 *(Visentin et al., 2019)* 0.67*(Prodi et al., 2010)* 0.72÷0.78 *(Klatte et el., 2010b*

Table 3. Values of the acoustical parameters for worse performance collected from each study.

Worse performance				
Age	**T_{mid} [s]**	**L_{Neq} [dBA]**	**SNR [dB]**	**STI [-]**
5÷7	1.1 *(Astolfi et al., 2019)* 0.5 [29] 1.1 *(Klatte et al., 2010)* 0.7 *(Mealings et al., 2015)* 0.3, 0.6, 0.8 *(Neuman et al., 2010)* 0.8 *(Neuman et al., 2012)* 1.1 *(Klatte et el., 2010b)*1.2 [50]	50 *(Astolfi et al., 2019)* 68 *(Mealings et al., 2015)* 67 *(Mealings et al.,2015b)* 22÷39 *(Klatte et al., 2010)*	0 *(Prodi et al., 2019b)* -6 *(Prodi et al., 2010)* 10 *(Neuman et al., 2010)* <6 *(Neuman et al., 2012)* -3 *(Klatte et el., 2010b)* -2, 0, +2 *(Yang, Bradley, 2009)*	0.73 *(Prodi et al., 2019b)* 0.57 *(Klatte et el., 2010b)*
8÷11	1.2 *(Hurting et al., 2016)* 0.6 *(Valente et al., 2012)* 1.1 *(Prodi et al., 2010)* 0.57, 0.69 *(Prodi, Visentin, 2021)* 0.6 *(Amlani, Russo, 2016)* 0.9 *(Iglhart, 2019)* 1.1 *(Klatte et al., 2010)* 0.7÷0.9 *(McKellin et al., 2011)* 0.3, 0.6, 0.8 *(Neuman et al., 2010)* 0.8 *(Neuman et al., 2012)* 1.2 *(Peng et al, 2020)* 1.2÷2.6 *(Polewczyk et al., 2020)*	80÷114 *(Dos Santos et al., 2013)* 68÷74 *(McKellin et al., 2011)* 72 *(Shield, Dockrell, 2008)* 75 *(Vilcekova et al., 2017)* 39 *(Amlani, Russo, 2016)* 22÷39 *(Klatte et al., 2010)* 42 *(Peng et al, 2020)* 54 *(Ronsse et al., 2013)* 60÷74 *(Rabelo et al., 2014)* 70 *(Bradley, Sato, 2008)*	12 *(Hurting et al., 2016)* 7 *(Valente et al., 2012)* -12 *(Prodi et al., 2010)* 0, 6, 12 *(Prodi et al., 2010)* 0 *(Prodi, Visentin, 2021)* 0 *(Iglhart, 2019)* <10 *(Neuman et al., 2010)* <6 *(Neuman et al., 2012)* -10 *(Bradley, Sato, 2008)*-3 *(Klatte et el., 2010b)* -2, 0, +2 *(Yang, Bradley, 2009*	0.23 *(Prodi et al., 2010)* 0.4, 0.46 *(Prodi, Visentin, 2021)* 0.57 *(Peng et al, 2020)* 0.50 *(Polewczyk et al., 2020)* 0.47÷0.65 *(Rabelo et al., 2014)* 0.57 *(Klatte et el., 2010b)* 0.23 *(Prodi et al., 2010)*
12÷18	1.9 *(Astolfi, Pellerey, 2007)* 0.7 *(Prodi et al., 2019)* 0.57, 0.69 *(Prodi, Visentin, 2021)* 0.9 *(Iglhart, 2019)* >0.8 *(Minichilli et al., 2018)* 1.2÷2.6 *(Polewczyk et al., 2020)* 0.4 *(Bradley, Sato, 2008)*	41 *(Astolfi, Pellerey, 2007)* 70 *(COnolly et al., 2019)* 60 *(Prodi et al., 2019)* 73 *(Seetha et al., 2008)* 76 *(Vilcekova et al., 2017)* 57 *(Minichilli et al., 2018)* 70 *(Bradley, Sato, 2008)*	22 *(Astolfi, Pellerey, 2007)* 0 *(Prodi, Visentin, 2021)* 0 *(Iglhart, 2019)* -10 *(Bradley, Sato, 2008)*	0.60 *(Astolfi, Pellerey, 2007)* 0.65 *(Prodi et al., 2019)* 0.4, 0.46 *(Prodi, Visentin, 2021)* 0.40 *(Minichilli et al., 2018)* 0.50 *(Polewczyk et al., 2020)*
19÷40	0.7, 1.1 *(Lam et al., 2018)* 0.8 *(Visentin et al., 2019)* 1.1*(Prodi et al., 2010)* 2.0 (Castro Martinez, 2016) 0.8 *(Larsen, Vega, Ribera, 2008)* 0.8 *(Naeve di Toro et al., 2017)* >1.2 (*Peng, Wang, 2016)* 1.2 *(Peng, Wang, 2019)* >2.0 *(Sogol et al., 2014)*] 1.1*(Klatte et el., 2010b)* 1.9 *(Prodi et al., 2010)* 1.2 *(Yang, Bradley, 2009)*	62 *(Visentin et al., 2019)* 45 (Castro Martinez, 2016) 44 *(Larsen, Vega, Ribera, 2008)* >38 (*Peng, Wang, 2016)* 58 *(Peng, Wang, 2019)*	-1 *(Visentin et al., 2019)* 0, **6, 12** *(Prodi et al., 2010)* -3 *(Naeve di Toro et al., 2017)* 1 *(Peng, Wang, 2019)* -3 *(Klatte et el., 2010b)* 0, 6, 12 *(Prodi et al., 2010)* -2, 0, +2 *(Yang, Bradley, 2009*	<0.56 *(Lam et al., 2018)* 0.67 *(Visentin et al., 2019)* 0.23 *(Prodi et al., 2010)* 0.57 *(Klatte et el., 2010b)*

Figures 2 and **3** show the box-and-whisker diagrams while **Table 4** shows the median values together with their interquartile ranges of the acoustic parameters for classrooms grouped for better and worse performance across three age ranges, respectively (5÷7, 8÷11, 12+ y.o.), plus a global one, i.e., subjects from 5÷12+ y.o.

As expected, results show that students perform better with lower reverberation time and noise levels, and higher SNR and STI. Other parameters, i.e., C50, U50, SRM, were excluded from these diagrams and table due to the extremely scarce number of data that was found in the literature. Anyway, in these few cases, better performance was registered when C50, U50 and SRM were equal to or higher than around 3 dB (Astolfi *et al.*, 2019; Peng *et al.,* 2020), 0 dB (Astolfi *et al.*, 2019) and 3 dB (MacCutcheon *et al.*, 2019), respectively.

Younger students need lower reverberation time and noise levels and higher SNR and STI, compared to the older ones. However, the SNR values indicated in

Figures 2, 3 and in **Table 4** for better performance of 14 dBA for 5÷7-years-olds and of 11 dBA for 8÷11 y.o. children, lower than the 15 dBA for the elders, can be justified with the fact that younger children are noisier. In these terms, higher values of noise level during the first years of schooling are representative of the linear trend for measured levels in occupied classrooms to decrease with academic year (Picard and Bradley, 2001). Coherently, it is more likely to measure higher values of SNR in university classrooms or high school where the noise levels are lower than in elementary classrooms. The worse performance results support the previous observations, i.e., children from 8 to 11 y.o. make more noise than older students. In this case they are even noisier than the students in the younger group of 5 to 7 y.o. with respect to which they achieve a better performance even up to 62 dBA of noise thanks to their more developed cognitive abilities. Additional aspects to take into consideration when observing these singularities in **Table 4** are their interquartile ranges, that suggest a wide variability of the results.

Table 4 also shows guidelines for better learning performance and threshold values for worse performance derived from the overall results on which Authors made personal assumptions that are grouped for students <12 or ≥12 y.o. Here, each parameter behaves exactly as expected, i.e., reverberation time and noise levels increase with academic year while SNR and STI decrease, in fact poorer acoustic conditions are less detrimental to older students since they are able to adequately perform their tasks even in more adverse conditions. Guidelines for students <12 y.o. suggest T_{mid} equal to 0.6 s, background noise level $L_{Neq} \leq 35$ dBA, signal-to-noise ratio SNR ≥ 12 dBA and STI ≥ 0.65, for better performance. For students ≥12 y.o. T_{mid} equal to 0.7 s, $L_{Neq} \leq 40$ dBA, SNR ≥ 12 dBA and STI ≥ 0.60 are suggested. It is worthy to underline that the JND for the STI is 0.03 according to Bradley et al. (1999) and 0.05 according to Bork (2000), and thus the above reference values correspond to different acoustic conditions.

In the case of STI, it has been checked that all the reference values could be respected at the design or verification phases, particularly the ones referred to the STI for which the highest values, close to 1, are difficult to be guaranteed (IEC 60268-16, 2020). To this purpose, the relationships between STI, reverberation time and signal-to-noise ratio reported in Houtgast, Steeneken and Plomp (1980) and based on diffuse theory have been verified, and lower but most practicably reachable STI values have been proposed.

A worsening performance is indicated in cases of $T_{mid} \geq 1.2$ s, background noise level $L_{Neq} \geq 40$ dBA, signal-to-noise ratio SNR ≤ 5 dBA and STI ≤ 0.65, for students <12 y.o., while for students ≥12 y.o. it happens with $T_{mid} \geq 1.6$ s, $L_{Neq} \geq 60$ dBA, SNR ≤ -2 dBA and STI ≤ 0.60.

As far as background noise level is concerned, it can be drawn from data in **Table 1** and **Extended Table 1** in **Appendix A** that the above-mentioned levels are related to both ambient and informative noise.

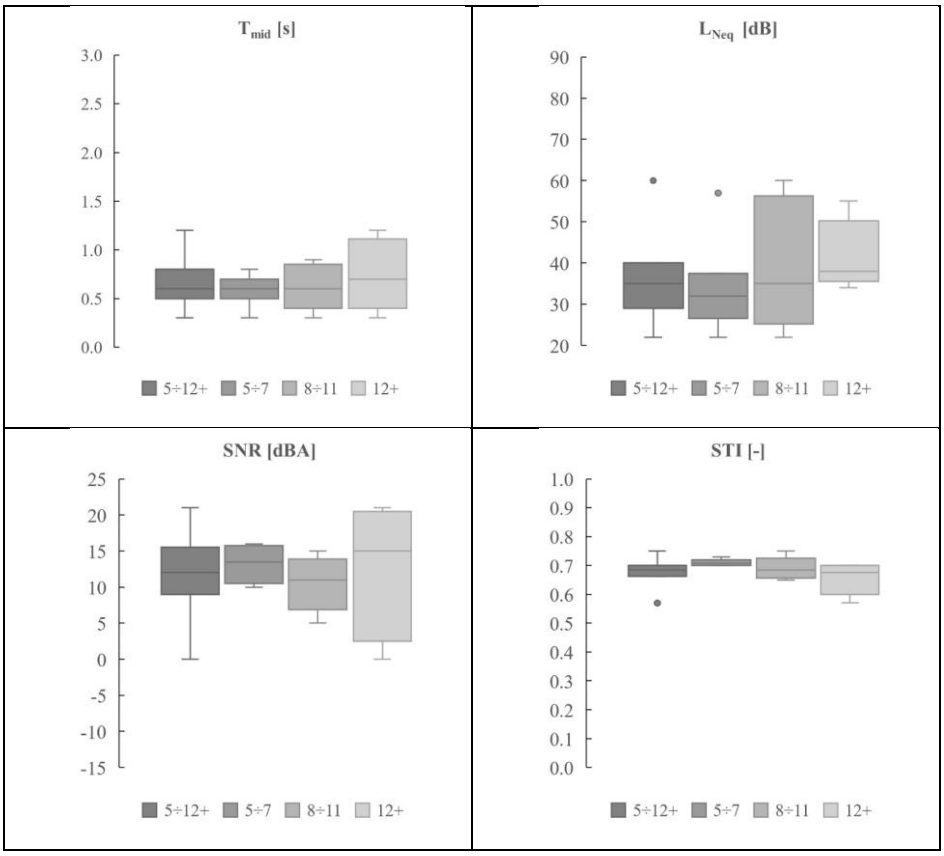

Figure 2. Box-and-Whisker diagrams for better performance.

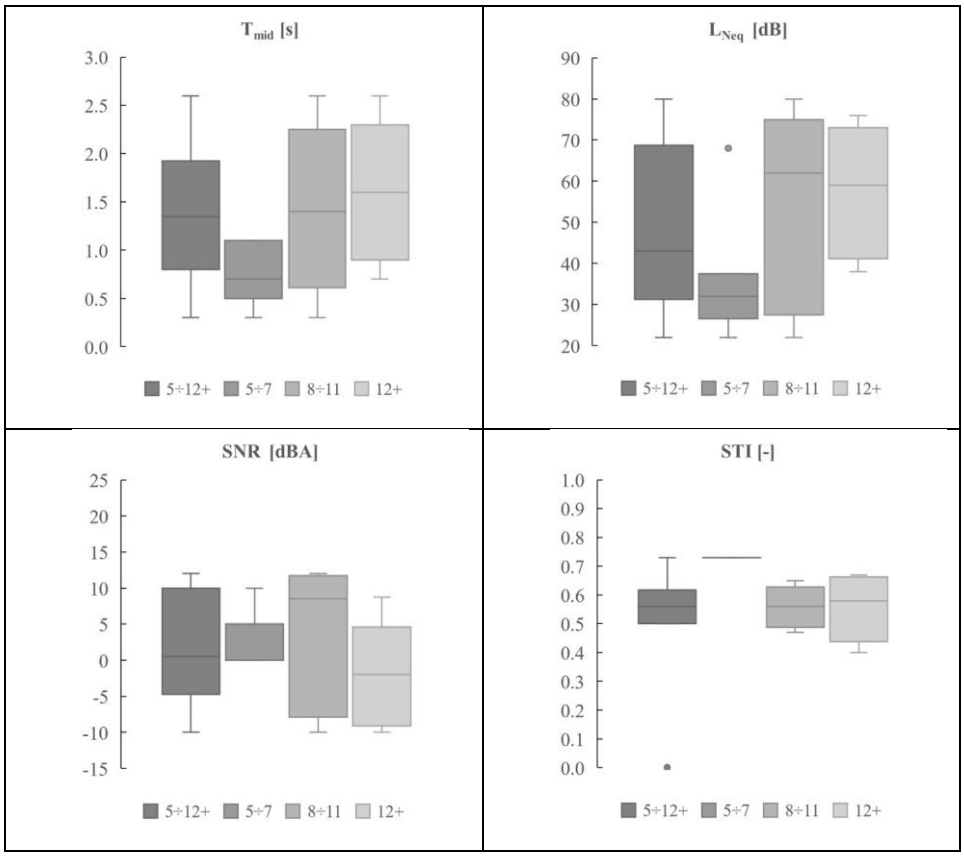

Figure 3. Box-and-whiskers diagrams for worse performance.

Table 4. Median values and interquartile ranges of the acoustic parameters for classrooms grouped for better (+) and worse (-) performance. Interquartile range is given in brackets.

	Age	**T_{mid} [s]**		**L_{Neq} [dBA]**		**SNR [dBA]**		**STI [-]**	
	Better performance (+)								
overall	global	0.6	(0.3)	35	(11)	12	(7)	0.69	(0.04)
	5÷7	0.6	(0.2)	32	(11)	14	(5)	0.72	(0.7)
	8÷11	0.6	(0.3)	35	(24)	11	(4)	0.69	(0.04)
	12+	0.7	(0.5)	38	(9)	15	(15)	0.68	(0.1)
Guidelines for better learning performance	<12	0.6		≤35		≥12		>0.65	
	≥12	0.7		≤40				>0.60	
	Worse performance (-)								
overall	global	1.4	(1.1)	43	(38)	1	(15)	0.56	(0.12)
	5÷7	0.7	(0.6)	32	(11)	5	n.a.	0.73	n.a.
	8÷11	1.4	(1.0)	62	(37)	9	(17)	0.56	(0.1)
	12+	1.6	(0.9)	59	(26)	-2	(9)	0.58	(0.18)
Thresholds for worse learning performance	<12	≥1.2		≥40		≤5		≤0.65	
	≥12	≥1.6		≥60		≤-2		≤0.60	

Table 5 reports the median values and the interquartile ranges of the acoustic parameters for classrooms grouped for better and worse performance by adding the eight extra papers to the considered database.

Focusing on the guidelines for better learning performances, the reverberation time, the signal-to-noise ratio and the STI have flattened out for all age groups and any distinction between conditions for students under or over 12 years of age are lost. Only the background noise level remains different for the two age group, and corroborates the previous outcome without the addition of the eight extra papers. In these terms, a reverberation time of 0.6 s, an SNR equal or higher than 10 dBA and an STI equal or higher than 0.65 are indicated for better performance for subjects aged from 5 to 40 years, while a background noise level equal or lower than 35 dBA and equal or lower than 40 dBA is reported for subjects < 12 and ≥12 years old, respectively.

Thresholds for worse learning performance return a more marked difference in acoustic conditions for the different age groups, highlighting that the youngers have more difficulties in more unfavorable conditions. In particular, performance get worse with $T_{mid} \geq 1.2$ s, background noise level $L_{Neq} \geq 40$ dBA, and STI ≤ 0.60, for students <12 y.o., while for students ≥12 y.o. it happens with $T_{mid} \geq 1.4$ s, $L_{Neq} \geq 60$ dBA, and STI ≤ 0.50. The same signal-to-noise ratio SNR ≤ 0 dBA should be avoided for both the age groups.

2.3.3. Discussion

Comparisons with Picard and Bradley (2001)

Picard & Bradley (2001) provide distinct guidelines for NH e HI students, but to the aim of the present comparison only data of NH students was considered. Also, as it is explained in the previous sections, it should be noted that the set of tasks in

this review are different and more comprehensive than those reported by Picard and Bradley (2001).

Table 5. Median values and interquartile ranges adding the eight extra paper to the database.

	Age	**T_{mid} [s]**		**L_{Neq} [dBA]**		**SNR [dBA]**		**STI [-]**	
	Better performance (+)								
overall	global	0.6	(0.2)	35	(11)	10	(7)	0.70	(0.09)
	5÷7	0.6	(0.3)	32	(10)	10	(6)	0.74	(0.03)
	8÷11	0.6	(0.2)	35	(12)	10	(6)	0.70	(0.09)
	12+	0.6	(0.2)	38	(7)	17	(8)	0.70	(0.09)
Guidelines for better learning performance	<12	0.6		≤35		≥10		≥0.65	
	≥12			≤40					
	Worse performance (-)								
overall	global	1.2	(06)	44	(19)	0	(5)	0.55	(0.09)
	5÷7	0.8	(0.3)	32	(19)	0	(8)	0.65	(0.08)
	8÷11	1.3	(0.6)	62	(28)	0	(4)	0.55	(0.08)
	12+	1.4	(0.6)	60	(13)	0	(6)	0.50	(0.10)
Thresholds for worse learning performance	<12	≥1.2		≥40		≤0		≤0.60	
	≥12	≥1.4		≥60				≤0.50	

Guidelines in **Table 4** suggest a reverberation time of 0.6÷0.7 s for students from 5 to 12+ years of age, that is 0.1÷0.2 s higher than the optimal 0.5 s recommended by Picard & Bradley (2001). Anyway, this value is derived from the global value of 0.6 s (±0.3) shown in **Table 4**, which takes into account subjects from 5 to 12+ years of age and that is compatible with the one reported by Picard & Bradley (2008).

As far as background noise level is concerned, L_{Neq}≤35 dBA and L_{Neq}≤40 dBA is advised for students <12 or ≥12 y.o., respectively, that is almost the same value of the correspondent values 34 dBA and 40 dBA proposed by Picard and Bradley (2001) for the same age ranges. The slight difference in the values for better performances could be due to the marginal contribution of the occupants in their research outcome.

The reference value of SNR ≥ 12 dBA proposed in these guidelines corroborates the outcome of Picard & Bradley (2001), who found that to obtain speech intelligibility higher than 80% for students 6÷12 y.o. an SNR higher than 12 dBA is necessary.

Classroom acoustic guidelines for better learning performance

On the base of the above stated results on the classroom acoustic guidelines for better learning performance, the comparison between values related to better speech intelligibility, cognitive performance and subjective perceptions are discussed below. Eight extra studies that have not been recognized during the search process, which are Astolfi *et al.* (2012), Jamieson (2004), Klatte *et al.* (2010b), Yang and Bradley (2009), Prodi *et al*. (2010), Bradley and Sato (2008), Prodi *et al.* (2021), Prodi and Visentin (2021), have been considered here to the aim of a verification process of the proposed guidelines. Nevertheless, by adding the eight extra studies

to the creation of the guidelines for better learning presented in **Table 4**, the results did not change significantly, apart from specific cases that will be discussed hereafter.

Reverberation time

As far as reverberation time is concerned, guidelines for better learning performance suggest a value of 0.6 s and of 0.7 s for students under and over 12 years of age, respectively. The value for students under 12 years originates from the studies by Klatte et al. (2010a), Valente et al. (2012), Peng et al. (2020) and Polewczyk et al. (2020), where higher accuracy in cognitive and intelligibility tasks can be achieved in classrooms characterized by a reverberation time of 0.6 s, particularly for students aged 5÷7, 8÷11. Studies by Lam et al. (2018) and Prodi and Visentin (2019) highlight the same outcome when reverberation time is 0.7 s for students over 12 years. However, studies by McKellin et al. (2011), Leibold and Buss (2019), Valente *et al.* (2012), Amlani and Russo (2016), Mealing *et al.* (2015a), Prodi and Visentin (2019), Visentin *et al.* (2019) involving subjects from 5 to 40 years of age, demonstrated that speech intelligibility is not very sensitive to small deviations from optimum reverberation time values (standard deviation ≤0.3 s in **Table 4**), since high performance is obtained in the range from 0.4 s to 0.9 s. This result corroborates studies by Astolfi *et al.* (2012), Klatte *et al.* (2010b), Yang and Bradley (2009), Prodi *et al*. (2010), Bradley and Sato (2008), Prodi *et al.* (2021), Prodi and Visentin (2021), that have not been recognized from the search methodology but that deal with performance of intelligibility, cognitive and subjective perceptions in classrooms. All these studies report the interval 0.3÷0.9 s of reverberation time as optimal for subjects' performance for both the age ranges under and over 12 years. As an example, in Astolfi *et al.* (2012) pupils from 7 to 10 years of age achieve high performance even with a reverberation time of 1.55 s.

Furthermore, the interval of 0.4÷0.9 s of reverberation time is adequate both to maximize speech intelligibility and to minimize vocal effort, as obtained averaging target values from recent studies (0.7 s in Yang and Bradley, 2009; 0.5÷0.6 s in Pelegrín-García *et al.,* 2014; 0.7 s in Puglisi *et al.,* 2017; and 0.8 s in Calosso *et al.,* 2017).

Students' subjective perceptions also support recommended reverberation time of 0.6 s (±0.3 s). In particular, questionnaires in Astolfi *et al.* (2019), Astolfi and Pellerey (2008), Minichilli *et al.* (2018), Peng *et al.* (2020) report higher well-being, acoustical satisfaction and concentration, as well as lower annoyance, in classrooms characterized by a reverberation time in the range of 0.5÷0.8 s.

Background noise level

Guidelines for background noise level for students <12 y.o. are in accordance with Shield and Dockrell (2008) and BB93 (2015), where the internal L_{Neq} value must be less than or equal to 35 dBA. This limit value can be related to both ambient and informative noise, in occupied and unoccupied conditions. Verification studies

further confirm that experiments were carried out with AN and IN to a greater extent (8 cases, i.e., Astolfi *et al.,* 2012; Jamieson, 2004; Klatte *et al.,* 2010b; Yang and Bradley, 2009; Prodi *et al*., 2010; Bradley and Sato, 2008; Prodi *et al.*, 2021; Prodi and Visentin, 2021; and 7 cases, i.e., Astolfi *et al.,* 2012; Jamieson, 2004; Klatte *et al.,* 2010b; Yang and Bradley, 2009; Prodi *et al*., 2010; Bradley and Sato, 2008; Prodi *et al.*, 2021, respectively), compared to studies with EN (1 case, i.e., Prodi and Visentin, 2021). Younger students need stricter recommendations, since they are more affected by noise in their cognitive (Peng and Wang, 2019; Prodi *et al.*, 2019a; Prodi *et al.*, 2021) and intelligibility (Peng and Wang, 2019; Bradley and Sato, 2008) tasks, as well as in their subjective perceptions (Minichilli *et al.*, 2018). It is particularly challenging to guarantee that kindergarten and 1st-grade students do not exceed the maximum noise level, as children in the first years of school would be among the noisiest groups. A slightly higher upper limit of 40 dBA is set for students ≥12 y.o. due that older students can still achieve better performances even under noisier conditions.

Last, background noise level should be not exceeded since it was found to have a larger detrimental effect on student performance than excessive reverberation (Bradley *et al.*, 1999). Indeed, L_{Neq} has a stronger effect than reverberation also on perceived listening effort (Peng and Wang, 2019).

Signal-to-noise ratio

Guidelines for better performance propose the same value of SNR for students aged from 5 to 12+ years. An SNR equal to or higher than 12 dBA was found as threshold to warrant better intelligibility, cognitive and subjective perception for children regardless of their age. Comparing this outcome with studies by Jamieson *et al.* (2004), Klatte *et al.* (2010b), Yang and Bradley (2009), Prodi *et al*. (2010), Bradley and Sato (2008), which have not been found within the search process, a significant difference was found as those studies distinguish median values of SNR for students under and over 12 years of age, i.e., 7 dBA and 4 dBA, respectively. Given the discrepancy of these studies with the ones proposed in the guidelines of **Table 4**, they have been added to the original data sample and this lead to a reduction of 2 dBA of the lowest admittable SNR value, i.e., 10 dBA instead of 12 dBA.

Speech Transmission Index

As far as the Speech Transmission Index is concerned, guidelines of the present study suggest that the younger children under 12 years of age need higher STI, i.e., ≥0.65, compared to older ones of 12+ years of age, that can still achieve excellent intelligibility with a lower STI, i.e., ≥0.60. This trend is confirmed by averaging the results of studies Astolfi *et al.* (2012), Klatte *et al.* (2010b), Yang and Bradley (2009), Prodi *et al*. (2010), where an STI of 0.70 for better performance is obtained for subjects under 12 years of age, while an STI of 0.67 is obtained for subjects aged 12 years or older. Furthermore, these results expand the overall indication of

IEC 60268-16 (2020), where STI from 0.6 to 0.64 is considered as good, from 0.65 to 0.76 as high and STI>0.76 as excellent.

2.3.4. Strengths and limitations

The findings of this study have to be seen in light of their strengths and limitations. The strengths consist in the inclusion of different task categories, taking together cognitive, intelligibility and subjective perception performances. Then, several age groups have been considered and differentiated guidelines based on these groups have been provided. From the methodological point of view, a systematic and objective review has been conducted for the selection and analysis of the references, that bring to guidelines derived from consistent data.

Nonetheless, these results must be interpreted with caution and a number of limitations should be borne in mind. The first limitation resides in the search strategy used, as the terms included to identify the literature papers limit the reference studies. As an example, some papers have been missed because the search method did consider only the words "acoustic* AND measure*" and not the word "acoustics" alone. Anyway, further 8 manuscripts have been considered in the verification phase. A second limitation consists in the fact that for some parameters the available data was not equal in number for the different age groups. Therefore, the obtained outcome is very robust in some cases, while a greater variability characterize few others. Finally, future studies should include non-mother tongue (Visentin *et al.*, 2019) and hearing impaired students (Iglehart, 2019), as well as students with other disabilities as autism (Alcantara *et al.*, 2004), in order to cover the needs of these vulnerable groups of learners that more and more often are included in regular classrooms together with mother tongue and normal hearing pupils.

As a final remark to the guidelines, it should be added that the provided reference values are interrelated but no theoretical calculations to figure out possible interrelations about better performance data, i.e., if they are coherent among them, has been carried out. These calculations could be based on diffuse field or modified diffuse field hypotheses or on geometrical acoustic models, that may not be accurate (Astolfi *et al.*, 2008; Labia *et al.*, 2020; Brinkmann *et al.*, 2019; Marbjerg *et al.*, 2018). In these terms, all the values in the guidelines should be respected. Anyway, it has been checked that all the reference values could be respected at the design or verification phases, particularly the ones referred to the STI for which the highest values, close to 1, are difficult to be guaranteed in everyday practice.

2.3.5. Conclusions

Indications to guarantee better performance were obtained from the literature studies. A reverberation time of 0.6÷0.7 s is adequate for students for every age, as well as an SNR equal to or over 12 dBA. L_{Neq} should not exceed 35 dBA and 40

dBA in classrooms attended by students under or over 12 y.o. An STI equal to or higher than 0.65 guarantees better performance for younger students while for older students this threshold lowers to 0.60.

Thresholds for worse performance in the case of poor acoustic conditions are also provided. They show that students under 12 y.o. cannot perform satisfactorily in a classroom characterized by a reverberation time equal to or over 1.2 s, noise levels reaching or exceeding 40 dBA causing an SNR equal to or lower than 5 dBA, and an STI equal to or lower than 0.65. Students aged 12+ y.o. lower their performance with a 1.6 s or higher reverberation time, at least 60 dBA noise levels measured inside the classroom and when the signal-to noise-ratio and STI are equal to or lower than -2 dBA and 0.60, respectively.

Appendix A
Extended Table 1

Table A.1. Extended Table 1. Occupational Condition, i.e. unoccupied (unocc) or occupied (occ), Type of noise and Detailed outcome of the study.

REF	Condition	Type of noise	Detailed outcome
Amlani, Russo, 2016	unocc	AN	In a classroom of 185 m^3, 10% higher accuracy without acoustic panels, $T60_{,unoccupied\ 0.5\text{-}4\ kHz}$ = 0.82 s, $L_{Neq_unoccupied}$= 40.1 dB(A) (vs $T60_{,unoccupied\ 0.5\text{-}4\ kHz}$ = 0.55 s, $L_{Neq_unoccupied}$ = 39.3 dB(A)). Performance decrease with the distance too (1.9 m > 3.6 m> 5.7 m> 7.2 m)
Astolfi et al., 2019	occ	AN	Lower annoyance and higher well-being can be achieved in the case B) (156 m^3) $T20_{,\ occ\ 0.25\text{-}2\ kHz}$ = 0.7 (±0.1) s, $L_{Neq_occ,\ sil}$= 49.4 (±5.4) dB(A), $C50_{,occ_ctr\ 0.5\text{-}1\ kHz}$ = 4.6 (±1.3) dB(A), $U50_{,occ_ctr\ 0.5\text{-}1\ kHz}$ = 1.9 (±1.9) dB(A) [vs case A) (238 m^3) $T20_{,\ occ\ 0.25\text{-}2\ kHz}$ = 1.1 (±0.2) s, $L_{Neq_occ,\ sil}$ = 50.6 (±2.8) dB(A), $C50_{,occ_ctr\ 0.5\text{-}1\ kHz}$ = 0.40 (±1.2) dB(A), $U50_{,occ_ctr\ 0.5\text{-}1\ kHz}$ = -1.3 (±0.9) dB(A)]
Astolfi, Pellerey, 2007	occ	AN	Higher acoustical satisfaction and concentration in renovated classrooms (215 ± 31 m^3) $T_{\ occ\ 0.5\text{-}2\ kHz}$ = 0.5 (±0.01) s, $L_{Neq_occ,\ sil}$= 36.8 (±2.3) dB(A), SNR= 19.2 (±3.7) dBA, STI= 0.7 (±0.06) [vs classrooms without acoustical treatment (212 ± 59 m^3) $T_{\ occ\ 0.5\text{-}2\ kHz}$ = 1.9 (±0.63) s, $L_{Neq_occ,\ sil}$ = 40.5 (±2.9) dB(A), SNR= 22.3 (±2.6) dBA, STI= 0.6 (±0.04)
Castro Martinez, 2016	unocc	AN	In a university classrooms of 240 m^3, higher attention after acoustical treatment $T_{unocc0.5\text{-}2\ kHz}$ =1.2 (±0.05) s, $L_{Neq_unocc,\ sil}$= n.a. (vs $T_{unocc0.5\text{-}2\ kHz}$ =2.0 (±0.05) s, $L_{Neq_unocc,\ sil}$= up to 45 dB(A))
Conolly et al., 2019	occ	EN, AN	Higher accuracy but slower response time in 50 dBA $L_{Neq_occupied_during\ lesson}$ compared to 70 dBA $L_{Neq_occupied_during\ lesson}$
Dos Santos et al., 2013	occ	n.a.	Higher accuracy in condition with $L_{Neq_occupied,lesson}$<51÷80 dBA compared to condition with $L_{Neq_occupied,lesson}$ >80÷114 dBA
Hurting et al., 2016	occ	EN	In traditional elementary classroom, with low T (0.3 s) higher accuracy when SNR=+12 dBA comparing to SNR=+3dBA; but with high T (1.2 s) higher accuracy when SNR=+3 dBA comparing to SNR=+12 dBA.
Iglehart, 2019	unocc	IN	In a classroom of 223 m^3, accuracy increases when the $T_{\ unocc,05\text{-}2\ kHz}$ decreases from 0.9 to 0.3 s; accuracy increases when the $T_{\ unocc,05\text{-}2\ kHz}$ decreases from 0.9 to 0.3 s and when SNR increases from 0 to 18 dB. Higher accuracy in a sound booth of 7 m^3 than those measured in the real classroom of 223 m^3 when T=0.3 s.
Klatte et al., 2010	unocc	AN	In primary classrooms of 231 m^3 (÷23 m^3) with low $L_{Neq,unocc_indoor}$ (22÷39 dBA) long reverberation ($T_{\ unocc,0.25\text{-}2\ kHz}$=1.06÷1.11 s) caused lower performance, higher annoyance of L_{Neq_indoor}, and less positive judgement of the relationships to peers and teachers compared to classrooms with good acoustics ($T_{\ unocc,0.25\text{-}2\ kHz}$=0.49÷0.6 s). When tested in their long reverberated classroom and then in a control classroom with low reverberation (0.5 s) recognition of noise-embedded words and storage of spoken nonwords in verbal working memory improved. Speech comprehension on the contrary was unaffected by reverberation.
Lam et al., 2018	occ	IN	Accuracy does not differ in (A)anechoic [STI=1], (B)reverberant only (250 m^3, $T_{\ occup,\ 0.5\text{-}2\ kHz}$= 1.1 s, SNR= 15 dB, STI 0.57) or (C)reverberant and noise (250 m^3, $T_{\ occup,\ 0.5\text{-}2\ kHz}$= 0.7, SNR= 7.5 dB, STI=0.57) condition when the speech intelligibility is high (>0.56). Faster responses (by 300 ms) in (A) anechoic condition compared to (B) and (C); (B) and (C) do not differ
Larsen, Vega, Ribera, 2008	unocc	AN	Higher accuracy in 111.6 m^3, $T_{unocc,\ 0.5\text{-}2\ kHz}$= 0.53 s, $L_{Neq_unocc,\ ambient}$= 34 dBA compared to 126.7 m^3, $T_{unocc,\ 0.5\text{-}2\ kHz}$= 0.76 s, $L_{Neq\ unocc\ ambient}$= 44 dBA
Lewis et al., 2015	occ	AN	In classrooms with V= 51 m^3 , T= 0.6 s, SNR= +10 dB, both normal hearing and mild to moderate hearing loss children performed at or near ceiling on the sentence-repetition task. In classrooms with V= 51 m^3 , T= 0.6 s, SNR= +10 dB poorer performance on the comprehension task compared to the sentence-repetition one. Children with normal hearing performed better than children with mild to moderate hearing loss and older children performed better than younger children
MacCutcheon et al., 2019	unocc	IN, EN	In typical classroom with $T_{30,\ 0.5\text{-}1\ kHz}$=0.6 s, better SRT for energetic maskers and separated (90°) conditions. In typical classroom with $T30_{,\ 0.5\text{-}1\ kHz}$=0.6 s, individual differences in memory span and language ability related to SRM advantages (spatial cues in separated conditions) with informational maskers.
McKellin et al., 2011	occ, unocc	IN	In classrooms with $T_{,unocc}$ =0.7÷0.9 s, $L_{Neq,occ_during\ lesson}$ noise levels (68 to 74 dBA) impeded the intended development of complex conversational interaction and collaborative learning
Mealing et al., 2015	occ, unocc	IN, AN	In an open-plan classroom 1340 m^3 (91 children in total) with $T_{,unocc}$ = 0.7 s, 22% higher accuracy and faster speed in the quiet condition compared with the noisy condition ($L_{Neq_occupied}$= 57 vs 68 dBA). Children's speech perception scores decrease by 26% for each doubling of the distance the child is seated away from the loudspeaker (from 1 m to 2 m, 4 m,..).
Mealing et al., 2015b	occ	IN, AN	The noise levels recorded during the test were higher the larger the classroom (216 m^3, 470 m^3, 1340 m^3, respectively $L_{Neq_occ,\ noisy\ activities}$= 55 dBA, 60 dBA, 67 dBA). Accuracy decreased by 14% and speed by 364 ms every 10 dBA increase of noise level. Accuracy decreased by 12% and speed by 844 ms for each doubling of distance the child was seated away from the loudspeaker (1 m, 2 m, 4 m, ..).
Minichilli et al., 2018	unocc	AN	Younger students are more affected by noise. Noise and annoyance perceived decreased with the increasing of classroom acoustics quality (lower external and internal $L_{N,eq}$, lower T). For most of the 28 classrooms $L_{Neq_external_unoccupied}$ >54 dBA, $L_{Neq_internal_unoccupied}$ >37÷57 dBA, $T_{\ unoccupied}$>0.8 s, STI=0.40÷0.68.

Nakeva von Mentzer et al., 2018	unocc	EN	In T=0.35 s, high accuracy both in quiet and in a +5 dBA SNR with four talker speech background, with better percent in quiet (95% vs 90%). Longer response times were evident in quiet. Higher speech intelligibility accuracy when higher lexical-access ability/academic achievement. Speech intelligibility accuracy well correlated with teachers' rating of children's concentration ability. Children rated with high concentration ability had the highest speech intelligibility scores in both quiet and four talker conditions, followed by children rated with high reading ability.
Neave di Toro et al., 2017	unocc	AN	In a university classroom of 228 m^3, at the back of the classroom a more favorable SNR-50 (from -3 to +18 dB) was needed as T increased from 0.3 to 0.6 to 0.8 s. Accuracy significant different comparing 0.3 s and 0.6 s, but not comparing 0.6 and 0.8 s. So: T≤0.6 s and SNR-50≥0 dB
Neuman et al., 2010	unocc	AN	In a classroom of 228 m^3 , the more reverberant the environment (from 0.3 to 0.8 s), at the back of the classroom the higher the SNR-50 required (from -6 to +21 dB): in particular, SNR-50>1÷5 for T=0.3 s, SNR-50>2÷6 for T=0.6 s, SNR-50>3÷7 for T=0.8 s. The younger the child (6 to 12), the higher the SNR required: SNR-50>6 for 5-7 y.o., SNR-50>5 for 8-11 y.o., SNR-50>2 for 12-18 y.o. To obtain average speech recognition scores of 95% at the back of the classroom, an SNR≥10 dB is required for all children at T=0.3 s, of ≥12 dB for children up to age 11 years at the T= 0.6 s, and of ≥15 dB for children aged 7 to 11 years at the 0.8-sec condition. The youngest children require even higher SNRs in the 0.8-sec condition.
Neuman et al., 2012	unocc	AN	In a classroom of 228 m^3 , higher accuracy in anechoic condition then when T60=0.6 s compared to 0.8 s, especially for children with cochlear implants; with T60=0.8 s a higher SNR-50 (10.25 dB) is required for better accuracy of children with cochlear implants (vs SNR-50=5.82 dB in anechoic condition).
Peng et al., 2020	unocc	AN	Higher speech intelligibility accuracy in treated classrooms A and B (averaged V=245±38 m^3, $T_{unocc,\ 0.5\text{-}4\ kHz}$= 0.6±0.1, $C50_{,\ 0.5\text{-}4\ kHz}$= 6.0±1.0 dBA, $L_{Neq,unocc}$= 39.5±1.0 dBA, STI=0.75±0.01) increased respectively by 7.5% and 4%, with a -0.61 s T, +6.4 dBA C50, -2.5 dBA L_{Neq}, +0.18 STI Even if between A and B acoustical indices and speech intelligibility scores do not differ, subjective perceptions do and in particular in A students express a greater improvement after treatment (Low frequency reverberation significantly influence speech perception)
Peng, Wang, 2016	unocc	AN	Recommended design criteria for spaces in which speech communication is important: L_{Neq}<48 dBA, T<1.2 s when Native English Talkers and Listeners, L_{Neq} <38 dBA, T<1.2 s when Talkers Both Native and Non-native and Listeners English native only
Peng, Wang, 2019	unocc	AN	Under different acoustic conditions ($T_{0.5\text{-}2\ kHz}$ (s): 0.4-1.2, L_{Neq} (dBA): 38,48,58, SNR (dB): +21, +11, +1) no significant performance change in the measured listening effort (adaptive pursuit rotor, APR) , but clearly in the transformed percent correct scores in rau for the speech comprehension(it worsened as the listening condition became more adverse). Adverse acoustics required more effortful listening as measured subjectively and L_{Neq} generally has a stronger effect than T on listening effort as measured by questionnaires
Polewczyk et al, 2020	unocc	n.a.	Significant improvement in performance and wellbeing after acoustic treatment (T from 1.2÷2.6 s to 0.6 s, STI from 0.5 to 0.7, classrooms of 94÷217 m^3). Positive changes in level of concentration, short memory capacity and pace of work. students can better hear and understand teachers' instructions and are much more capable of task fulfilling. clear reduction of aggression level.
Prodi et al., 2019	occ	IN, AN	In classroom of 155 m^3, $T_{0.5\text{-}2\ kHz}$=0.7 s, STI= 0.65 (in quiet), higher accuracy of speech intelligibility and Response Time of speech intelligibility and sentence comprehension in quiet condition (L_{Neq}=41 dBA), then with traffic noise (60 dBA) and worst with Classroom noise (60 dBA). Better performance for older children. The acoustic conditions that guarantee optimal speech intelligibility might not be equally adequate for SC.
Prodi et al., 2019b	occ	IN, AN	In an elementary classroom of V=166 m^3, $T_{0.5\text{-}2\ kHz}$= 0.5 s, STI_{quiet}= 0.73, background noise of working activity (0 dB SNR) worsened the pupils' performance and Response Times (only for 6Y and 7Y) compared to the "quiet classroom" condition (+16 dB SNR).
Prodi, Visentin, Feletti, 2013	occ	IN, AN	In classrooms 121÷187 m^3, $T_{occ,\ 0.5\text{-}1\ kHz}$= 0.6÷1.0 s, the "babble and activity noise" has the worst effect on performance whereas noise from the floor upstair (Tp) and external traffic noises (Tr) are less disruptive when the overall L_{Neq}=60 dBA.
Prodi, Visentin, 2015	occ	IN, AN	In classrooms 121÷187 m^3, $T_{occ,\ 0.5\text{-}1\ kHz}$= 0.6÷1.0 s, in the better listening conditions, the performance in the speech reception (accuracy and response time) worsens under traffic and babble noise, while in the worse listening conditions adaptation is observed for the traffic noise alone
Ronsse et al., 2013	unocc	AN	In classroom with $T_{occ,\ 0.5\text{-}1\ kHz}$ <0.6 s, $L_{Neq\ unocc\ heating\ and\ cooling\ systems\ active}$= 33÷54 dBA student reading and language subject areas may be negatively impacted by higher unoccupied L_{Neq} (when not controlling for the percent of students in each classroom receiving free or reduced-price lunches on achievement)
Seetha et al., 2008	occ	IN, AN	In classrooms where L_{Neq} = 73 dBA the noise affects students learning process and human health.
Shield, Dockrell, 2008	occ	IN, AN	External noise (L_{Neq} = 57 dBA) was found to have a significant negative impact upon performance, the effect being greater for the older children and for individual external events. Test scores were also negatively affected by internal classroom noise ($L_{Neq,occ}$=72.1 dBA).

Sogol et al., 2014	unocc[1]	n.a.	In university classrooms of 323 m^3 and 814 m^3 with T> 2 s, 36% of the students have suffered from severe and extreme anxiety.
Rabelo et al., 2014	unocc	IN, AN	Higher accuracy in speech intelligibility in classrooms with less noise (<60 dBA), a lower T30 (<0.88 s), and greater STI values (>0.65) with values ranging from 55÷74 dBA, 0.7÷2.1 s, 0.47÷0.70.
Valente et al., 2012	occ[2]	AN	In a room of 52 m^3, increasing background noise (+10 to +7 SNR dBA) and reverberation (0.6 to 1.5 s) degraded performance in comprehension tasks, compared to minimal differences in measures of sentence-recognition
Vilcekova et al., 2017	occ	IN, AN	The most concerns of occupants were about the acoustic discomfort (average L_{Neq} =75.5 dBA) leading to symptoms of fatigue, feeling heavy-headed, headache, difficulties in concentration, eyes and nose irritation, and sore throat.
Visentin et al., 2019	occ	EN, AN	In a university classroom of 197 m^3, $T30_{occ,0.5\text{-}2\ kHz}$= 0.83 s, $SNR_{_quiet}$=20.2 dB, $STI_{_quiet}$ =0.67, speech intelligibility was significantly worse in noisy (L_{Neq_noise} around 62 dBA) than in quiet (L_{Neq_quiet} =39 dBA) conditions and in fluctuating ($L_{Neq_fluctuating_noise}$=61 dBA) than in stationary noise ($L_{Neq_stationary_noise}$=63 dBA). Speech intelligibility was higher in the forward position (2.5m from the source vs 6 m). Higher subjective ratings (greater effort) in noisy than in quiet conditions and in the backward seating position.
Wroblewski et al., 2012	unocc	EN	In a classroom of 198 m^3, speech recognition decreased with noise level from 55 to 70 dB sound pressure level (SNR -10, -5, 0, +5 dB), in the reverberant conditions ($T_{unocc,0.125\text{-}4\ kHz}$=0.4 s vs 0.0 s) and with decreasing age. SRM (obtained by substracting mean individual scores under long-term average speech noise from those under modulated long-term average speech spectrum noise) in modulated noise relative to stationary noise decreased with SNR, age and was reduced by reverberation. In the nonreverberant condition ($T_{unocc,0.125\text{-}4\ kHz}$ = 0.0 s), participants showed similar amounts of SRM across ages.
Prodi et al., 2021	occ	IN, AN	In classrooms of around 150 m^3 and with $T_{mid,\ occ,\ 0.5\text{-}2\ kHz}$= 0.69 s, sentences were presented in three listening conditions, i.e. quiet, traffic noise, and classroom noise, corresponding to a STI of 0.65, 0.47, 0.40, and to a SNR of +18.1 dB, -0.4 dB, -0.3 dB, respectively. A ceiling effect is suggested by the results, with children achieving or nearing the maximum scores in all listening conditions, and for all sentence complexities. The pattern of performance at each age varied dependend on the combination of sentence complexity and listening condition.
Prodi, Visentin, 2021	occ	EN, AN	In two classroom of around 150 m^3 and $T_{mid,\ occ,\ 0.5\text{-}2\ kHz}$= 0.57 s, C50=5.4 dB, and $T_{mid,\ occ,\ 0.5\text{-}2\ kHz}$= 0.69 s, C50=2.4 dB, while in quiet conditions (U50=5.1, SNR=19.5 dB, STI=0.71, and U50=2.3 dB, SNR=18.1 dB, STI=0.65) a longer reverberation did not incur any significant changes in accuracy or RT, in classroom noise it had several effects (U50=-1.8, SNR=0.2 dB, STI=0.46, and U50=-3.5 dB, SNR=-0.3 dB, STI=0.40), depending on the task and the outcome measured. The effect was greater for accuracy in the speech perception task, and particularly for the younger pupils.
Astolfi 2012	occ	IN, AN	In classrooms 150÷245 m^3, $T30_{occ,\ 0.5\text{-}1\ kHz}$= 0.4÷1.6 s, $C50_{occ,\ 0.5\text{-}1\ kHz}$= -1.7÷10.7 dB, STI=0.1÷0.9, SNR of +6÷+26 dB for ambient noise, -16÷+18 dB for traffic noise, -15÷+20 dB for babble noise, -15÷+10 dB for fan-coil noise, -20÷+5 dB for impact noise. 7 y.o. pupils understood fewer words in the lowest STI range (0.15-0.8) than 8-10 y.o. pupils, whereas an Intelligibility Score of around 97% was achieved by all the grades with a STI of 0.9. In the presence of traffic noise, which resulted the most interfering noise, a decrease in RT from 1.6 to 0.4 s determined an Intelligibility Score increase on SNR(A), which varied from 13% to 6%, over the S/N(A) range of -15 to +6 dB, respectively. In the case of babble noise, the same decrease in reverberation time leads to a negligible variation in IS over similar S/N(A) range.
Jamieson, 2004	occ	IN, AN	In classrooms with ambient background noise between 60 dBA and 70 dBA, four conditions of SNR were created: Quiet, 0 dB, -6 dB, -12 dB. Speech intelligibility declined as the SNR decreased. Kindergarten and grade 1 children were especially affected by noise in the -6 dB SNR.
Klatte et al., 2010b	occ	IN, AN	In two virtual classroom of 230 m^3 with $T30_{0.25\text{-}2\ kHz}$=0.47 s, STI= 0.72-0.78 vs $T30_{0.25\text{-}2\ kHz}$ =1.1 s, STI=0.57-0.67 performance was measured with different background noises (silence, background speech and classroom noise without speech) and SNR. Better performance in silence (L_{Aeq}<55 dBA) and with SNR > +1. Children´s ratings of the sound-induced disturbance were low overall and uncorrelated to the actual disruption.
Yang, Bradley, 2009	unocc	IN, AN	In classrooms with T60=0.3 s, 0.6 s, 0.9 s, 1.2 s, only the 1.2 s reverberation time condition showed a significant reduction in mean speech intelligibility score.
Prodi et al., 2010	occ, unocc	IN, AN	Better performances in classrooms with RT=0.6 s, SNR=0 dBA, +18 dBA, STI= 0.40, 0.47, 0.65
Bradley, Sato, 2008	occ	IN, AN	In classrooms with volumes 198 m^3, $T60_{0.5\text{-}1\ kHz}$= 0.41(±0.09) s, $C50_{0.5\text{-}1\ kHz}$=9.51(±2.26) s, the results indicates that +15 dB SNR is not adequate for the youngest children.

[1] Simulated through geometrical acoustics software.

[2] Calculated through Sabine formula.

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Chapter 3
Characterizing classroom acoustics

Objective	To provide tools to easily characterize primary school classroom acoustics and to promote the design of adequate sound environment for educational facilities.
Outcome	Provision of a basic measurement protocol and identification of the fundamental parameters for classroom acoustic characterization. Thresholds to classify the acoustic quality as compliant or non-compliant are also provided.
Highlights	• Measurement campaigns were carried out in 29 occupied and unoccupied primary school classrooms in Turin. • Background noise level in silence and during group activities, reverberation time, speech clarity, useful-to-detrimental ratio and speech level, were acquired along the main axis of the classroom and in one or two positions offset to the axis. • Classrooms compliant and non-compliant with the standards were identified based on a cut-off value of occupied reverberation time set to both 0.8 s and 0.6 s, and threshold for the other acoustical parameters were also identified. • Speech clarity measured in the middle of the room and reverberation time are detected as the parameters which can be used alternatively for the rigorous and fast characterization of classroom acoustics.
Notes	Parts of this chapter have been published in: ▪Minelli et al., "*A basic protocol for the acoustic characterization of small classrooms*", JASA, (under review).

3.1. The need of simplification in acoustic characterization

In **Chapter 2**, evidences on the impacts of classroom acoustics on students' learning processes, especially from the first years of schooling onward, were given. As far as the students are concerned, i.e., from the listeners' perspective, it is mandatory to guarantee speech comprehension, above all at the lowest level of education, during the time in which brain plasticity is still high (Cardon et al., 2012; Stiles, 2000), since the classroom sound environment plays a crucial role in the learning process and the cognitive development of young children (Tierney and Nelson, 2009). In these terms, the acoustic quality of classrooms affects the students' performance, as has already been underlined in many studies (Ronsse and Wang, 2013; Valente et al., 2012; Visentin et al., 2019; Peelle, 2018; Prodi et al., 2010; Prodi et al., 2013; Prodi et al., 2015; Prodi et al., 2019a; Prodi et al., 2019b; Puglisi et al., 2018; Puglisi et al., 2021). Classroom acoustics does not affect only students but also teachers that are immersed in it for most of the time during their everyday life. As far as the teachers are concerned, i.e., from the speakers' perspective, it is mandatory to reduce their vocal effort and load, in order to prevent voice disorders and to preserve vocal health (Castellana et al., 2018; Carullo et al., 2015; Puglisi et al., 2015a; Puglisi et al., 2017). Indeed, dysphonic voice has significant and negative effect on both speech intelligibility and listening easiness mainly in noise conditions and high reverberated environments (Bottalico et al., 2021). Classroom acoustics also have consequences on the occupants' well-being and in particular on feelings of joy (Astolfi et al., 2019), comfort or discomfort (Astolfi and Pellerey, 2008; Minichilli et al., 2018), on aggression levels (Polewczyk and Jarosz, 2020), as well as on personal relationships (Klatte et al., 2010).

Based on these premises, this chapter represents an attempt to practically answer to the following question: "what are the optimal acoustic conditions for speech communication and learning in classrooms?". In particular, the scope of the present work has been to identify the basic parameters and their optimal values necessary to define the acoustic quality of parallelepipedal shaped primary school classrooms with medium volumes, i.e., between 100 and 290 m^3. The study arises from the awareness that many of the available indexes and parameters used for classroom acoustic characterization are closely correlated. On the basis of this knowledge, which is well-supported by literature, there is a need to advance such characterization practices by simplifying the measurement protocols in order to save time and to allow wide experimental campaigns to be made to certify a higher number of classrooms. To this aim, 29 primary classrooms in Turin, Italy, which are heterogeneous in terms of building typologies and acoustic conditions, have been considered in this study. The database used in Astolfi *et al.* (2019) (see **Chapter 4**) has been enlarged in this work, although the same protocol was used.

This chapter is organized as follows. Firstly, the optimal values for reverberation time, noise levels, speech clarity and useful-to-detrimental ratio found in literature are reported, and reasons for a basic protocol for the in-field characterization of classroom acoustics are given. The methodology section follows and describes the schools and classrooms involved in the study, the procedures applied for the measurements of background noise level during silent and group activities, reverberation times, speech clarity, useful-to-detrimental ratio and speech levels, and the statistical analysis carried out. This led to the subdivision of the classrooms in two consistent two groups, qualified as compliant or non-compliant with the standard, on the basis of a cut-off value of the occupied reverberation time, which was set at both 0.8 s and 0.6 s considering moderate or severe acoustic requirements, respectively. Thresholds were also identified for the other acoustic parameters for the two groups and their accuracy and precision was tested. Correlation and regression analyses allowed for the identification of the fundamental parameters from which the others can be derived. Finally, **Appendix B** reports the graphs of the reverberation times and speech clarity measured in each classrooms, while **Appendix C** deepens issues related to sound propagation.

3.1.1. Optimal values for classroom acoustics

Reverberation

There is still a lack of agreement on the optimal reverberation time since various target values have been proposed. In the following, apart from where it is otherwise specified, the reverberation time and the other quantities are intended as in occupied conditions, that is, in the condition experienced by the pupils in the classrooms. Several studies suggest that a lower reverberation is synonymous of higher acoustical quality. According to Picard and Bradley (2001), a shorter reverberation time leads to a greater toleration to background noise, and values of between 0.4 s and 0.5 s are thus preferable. In a recent review by Minelli *et al.* (2021) (see **Chapter 2**), a reverberation time of 0.6 s was found to guarantee a better learning performance for 5 to 11 year old students, and this reverberation time was found to increase to 0.7 s for students over 12 years old. Yang and Bradley (2009) suggested an acceptable reverberation time for students aged 6 to 11 and adults of 0.3 s to 0.9 s, with the ideal values being around 0.7 s. Moreover, Hodgson and Nosal (2002) proposed reverberation times in the range of 0.1 s to several seconds, when the dominant source of interfering sounds is nearby children.

These wide optimal ranges are also supported by several recent studies that have found a range of 0.4 s to 0.8 s to be adequate, not only to maximize speech intelligibility, but also to minimize vocal effort. Puglisi *et al.* (2017) found the optimal reverberation time for speech in primary school classrooms to be equal to about 0.7 s, while Pelegrín-García *et al.* (2014) found it to be in the range of 0.5 s to 0.6, while Calosso *et al.* (2017) found it to be equal to about 0.8 s in secondary school classrooms. Nevertheless, it is worth mentioning that the range from 0.7 s to

0.9 s, even though well within the range of measured classroom conditions in many studies (Mealings, 2016), is greater than the upper limit of most standards and recommendations (Mealings, 2016; NAL, 2016), including the influential ANSI S12.6:2010, and the associated ASA publications "*Classroom Acoustics I: a resource for creating learning environments with desirable listening conditions*" and "*Classroom acoustics for architects: a comparison booklet for ANSI/ASA S12.60 Part 1 and 2*", which recommend a reverberation time in unoccupied conditions of 0.6 s. In the UK, Building Bulletin 93 (BB93:2015) established a maximum mid-frequency unoccupied reverberation time for primary schools equal to or less than 0.6 s, which can rise to 0.8 s in the case of refurbishments and for secondary school students. For comparison purposes, the unoccupied values should be reduced by about 10% in order to obtain occupied values (Astolfi *et al.*, 2019) (see **Chapter 4**), which also depend on the age of the occupants. A maximum reduction of 0.1 s was applied to the reference values listed above, that is, the optimal occupied reverberation time was 0.5 s, as recommended in the ANSI S12.6:2010 standard and in BB93:2015, and which can rise to 0.7 s in the case of refurbishments or for older students. Nevertheless, if a tolerance is assumed in the definition of a target value of the reverberation time (UNI 11532-2:2020; DIN 18041:2016), which is almost equal to 0.1 s in this RT range, the maximum admittable limit values in occupied conditions again become equal to 0.6 s and 0.8 s, in the case of primary school classrooms and for refurbished rooms or older students, respectively. It could be important to introduce the issues of uncertainty into the measurement results (UNI 11532-2:2020; DIN 18041:2016), as well as introducing the accuracy of prediction (Hodgson, 1996; Bistafa and Bradley, 2000) and of the tolerance (UNI 11532-2:2020; DIN 18041:2016), into future standards. Recent standards have in fact adopted this approach to define the optimal reverberation times in classrooms. A reverberation time of 0.6±0.1 s, for medium frequencies in occupied conditions, is optimal according to the DIN 18041:2016 and UNI 11532-2:2020 standards, for about 200 m^3 rooms, which are named A3, that is, rooms dedicated to communication, with several people speaking simultaneously in the classroom.

The requirements are even stricter when children with special hearing and communication needs are included in mainstream classrooms (Greenland and Shield, 2019). In this case, other issues, apart from optimal values, should be included to control the low-frequency reverberation time as well as for the use of face masks as a regular habit as a result of the ongoing COVID-19 pandemic (Bottalico *et al.*, 2020).

Noise

Ambient noise in classrooms is more annoying than reverberation and leads to a greater impairments of speech recognition when it is very high (Picard and Bradley, 2001). Thus, most of the studies have so far been focused on the impact of noise on the performances, annoyance and well-being of people in these

environments. Shield and Dockrell (2008) found that pupils aged from 7 to11 failed to meet the British government's literacy and numeracy targets when the background noise level (L_{N90}) exceeded 50 dB(A) for 90% of the measurement period. This value corresponds to an equivalent continuous background noise level L_{Neq} of 64 dB(A) when pupils are engaged in silent activities and when differences between L_{N90} and L_{Neq} of about 14 dB, as measured by Shield and Dockrell (2004), are considered. However, according to a recent review on optimal acoustic conditions for learning in classrooms, lower values are recommended, that is, a maximum background noise level of 35 dB(A) is advised for students younger than 12 years old in schools (Minelli *et al*., 2021) (see **Chapter 2**), which is almost the same 34 dB(A) value that Picard and Bradley (2001) proposed in the former review for the same age group in empty rooms or with silent occupants.

Several countries have introduced standards and guidelines to regulate noise control with reference to empty buildings. The American ANSI S12.60:2010 standard requires a maximum noise level in unoccupied conditions of 35 dB(A). The British BB93:2015 standard applies the same limit for new buildings but increases it up to 40 dB(A) in the case of refurbishment. The Italian UNI 11532-2:2020 standard sets the highest admitted noise level at 38 dB(A) for smaller volumes than 250 m^3, while 41 dB(A) is recommended for volume equal to or larger than 250 m^3, respectively.

Speech intelligibility

As far as speech intelligibility is concerned, according to formula (3) in Bradley (1986), the recommended speech clarity, C50, should be greater than 2±1 dB and 4±1 dB at mid-frequencies for small classrooms with reverberation times of 0.8 s and 0.6 s, respectively, and a 1-kHz useful-to-detrimental ratio, U50, of 1.0 dB is recommended overall for a high level of speech intelligibility.

Bradley *et al.* (1999) showed that useful-to-detrimental ratios, speech transmission index measures, and values of the articulation loss of consonants, are all accurate predictors of speech intelligibility. Moreover, they stated that U50, as obtained from measured C50, averaged over the four octaves from 500 Hz to 4 kHz and A-weighted SNR, as well as other variations of U50 with respect to the frequency averaging, are equivalent for assessing speech intelligibility. As can be seen in FIG. 3 in Sato and Bradley (2008), U50 values higher than 4 dB ensure a speech intelligibility that is almost equal to 100%.

3.1.2. Reasons for a basic protocol for the in-field characterization of classroom acoustics

The acoustic measurement procedures and instruments for classrooms have not been fully standardized, and the research findings result from a heterogeneous sample of in-field methods. For example, Bradley *et al.* (1999) provided a measured 1 kHz reverberation time using an omnidirectional source and four receivers in occupied classrooms while the children were silent, whereas Sato and Bradley

(2008) used a directive source under both occupied and unoccupied conditions to measure the reverberation time in the frequency range between 0.25-4 kHz and 0.5-2 kHz, respectively.

An in-depth comparison of the literature has revealed that:

(i) the equipment and measurement positions considered in the studies differ from case to case;

(ii) the details on the measurement procedures, e.g., the recording time for the noise level measurement (Bradley, 1986; Sato and Bradley, 2008; Pelegrìn-Garcia *et al.*, 2012; DIN 18041:2016) the activities carried out in the classroom during measurements (Bradley, 1986; Sato and Bradley, 2008) and the height or precise position of the equipment (Bradley, 1986; Sato and Bradley, 2008; DIN 18041:2016; EN ISO 3382-2:2008) are not always described completely in the published studies;

(iii) the values of the specific parameters are often indicated in different ways, i.e., as the frequency range, dB weighting, averages, statistical analyses.

All this makes it difficult, or even impossible, to perform a comparison of the results. Furthermore, despite the large amount of evidence on the link between classroom acoustics and students' performance, there is still a lack of agreement on the preferred acoustical criteria to guarantee good speech intelligibility in educational facilities (Picard and Bradley, 2001). Moreover, the adopted measurement procedures are all time-demanding, although most of the parameters are closely correlated (Astolfi *et al.*, 2019, see **Chapter 4**; Bradley, 1986).

This work stems from the need to have comfortable teaching and learning environments, and it is an attempt to identify the minimum number of parameters that best characterize classroom acoustics, together with their optimal values. It is aimed at providing a basic measurement protocol, based on a minimum number of parameters and measurement positions, for educational facilities. To this aim, the following questions arose:

a. How many parameters are needed, as a minimum, to characterize classroom acoustics?
b. How many measurement points need to be set in a classroom?
c. Do we really need to carry out measurements under occupied conditions?
d. What are the thresholds for compliant and non-compliant classroom acoustics in primary schools?

To answer these questions, we measured the acoustical parameters along the main axis and in one or two positions offset to each axis in 29 primary school classrooms in Turin, Italy. One listener position was chosen far from the source, at the rear of the classroom and offset to the axis, to account for the most disadvantaged conditions for speech intensity and directivity. We carried out statistical analyses, including correlations and regression analyses, on the collected data. We then divided the classrooms into two consistent groups based on their compliance with an arbitrary reverberation time threshold, which was chosen among the maximum admittible values in the case of moderate and severe

requirements, respectively. Given the strong correlation among the measured quantities, we also derived thresholds for the other parameters, which can be used alternatively to qualify classroom acoustics as compliant or non-compliant for the two requirements. The main objective of this research has been to allow acousticians to characterize classroom acoustics using just one or two measured parameters, since all the others are closely correlated. These steps have led to the creation of a basic protocol that can be applied when performing acoustic measurements in traditional frontal-teaching primary classrooms and which can be used effectively to guide any future interventions.

3.2. Method

3.2.1. Schools and classrooms

Table 6 shows the features of the 29 first-grade classrooms belonging to 13 primary schools in Turin that were involved in this study. The majority of the pupils were 6 years old. The locations, periods of construction and architectural features of the schools differ. Moreover, they were built between 1846 and 1975, and are scattered over the city of Turin, in neighborhoods characterized by low or medium volumes of traffic (Uk Department of Transport, 2012).

Each classroom is identified with a code (ID) made up of a letter that indicates the school and a number that indicates the classroom. The classroom volumes vary between 105 m^3 and 290 m^3, and all the classrooms, except one (G1), have a rectangular shape. The average height of the classrooms ranges from 3.0 m to 5.3 m, and the ceilings are flat or vaulted. The floor finishes are venetian tiles, except for in one case (H1), which is instead in linoleum. The furniture consists of desks and chairs, bookshelves and blackboards. Some classrooms have undergone acoustic correction interventions. Table 1 shows the number of pupils in each classroom, and this number refers to those that were present during the measurements.

3.2.2. Characterization of the classroom acoustics

We performed the acoustic measurements in one-day in each school in the last two months of the school year, over three scholastic years, that is, from 2017 to 2019. We carried out the measurements under occupied conditions, with an average number of 19 children per class. We also measured the reverberation time under empty conditions, at the end of each session.

The pupils were seated in the traditional teaching layout (in rows facing the teacher's desk) in all the classrooms, with three or four rows of desks in each classroom, which were sometimes joined. The teacher's desk was parallel to one of the shorter walls in each room, except for in E2, where the teacher's desk and the blackboard were parallel to the longer side of the room, for teaching purposes. We

identified the main axis in each classroom, starting from the center of the wall behind the teacher's area.

Table 6. Features of the classrooms. V means the ceiling was vaulted, C means it was coffered, and F means it was flat. CC indicates the school was in the city center, PP means it was in the proximity of parks, and SC means it was in a suburban city setting.

	Classrooms					Schools		
ID	Volume [m^3]	No. of Pupils during the measurements	School facing onto	Ceiling shape	Acoustic treatment	Year of construction	Location	Traffic volume
A1	194	15	street	F	Yes	1846	CC	low
A2	261	18	street	V	Yes	1846	CC	low
A3	283	19	street	V	Yes	1846	CC	low
A4	233	21	street	V	Yes	1846	CC	low
A5	264	23	street	V	Yes	1846	CC	low
B1	203	22	street	F	Yes	1904	SC	low
B2	201	17	street	F	Yes	1904	SC	low
C1	123	12	street	F	No	1966	SC	low
D1	255	18	street	V	No	1891	SC	low
D2	252	21	courtyard	F	No	1891	SC	low
E1	236	19	courtyard	V	No	1882	CC	medium
E2	236	21	courtyard	V	No	1882	CC	medium
F1	279	18	courtyard	F	No	1913	SC	medium
F2	261	18	courtyard	F	No	1913	SC	medium
G1	136	8	courtyard	F	No	1975	PP	low
G2	106	19	courtyard	F	No	1975	PP	low
G3	138	16	courtyard	F	No	1975	PP	low
H1	133	21	courtyard	F	No	1968	SC	low
H2	132	23	courtyard	F	No	1968	SC	low
H3	140	20	courtyard	F	No	1968	SC	low
H4	132	20	courtyard	F	No	1968	SC	low
I1	237	8	courtyard	C	No	1909	PP	low
I2	215	12	courtyard	C	No	1909	PP	low
L1	241	22	courtyard	F	No	1921	SC	low
L2	264	25	courtyard	F	No	1921	SC	low
L3	255	21	courtyard	F	No	1921	SC	low
M1	207	21	courtyard	V	No	1874	CC	low
N1	210	21	courtyard	V	No	1887	CC	medium
O1	260	21	courtyard	F	No	1903	SC	low

Measurements, set-up and equipment

Figure 4 shows the standard measurement setup used in each classroom. The measurement equipment consisted of a TalkBox acoustic stimulus generator (NTi Audio, Schaan, Liechtenstein) which, according to the datasheet provided by the manufacturing company (NTi Audio TalkBok operating manual, 2020), presents a standardized voice-like acoustical signal emission of the human voice according to IEC 60268-16:2020, and of a calibrated-class-1 sound level meter (SLM, model XL2 by Nti Audio, Schaan, Liechtenstein). The TalkBox was positioned at a height of 1.5 m from the floor at the position typically occupied by the teacher during lessons. The SLM was located at a height of 1.1 m from the floor, in different positions over the pupils' seating area, which were selected case by case, in order to acquire acoustic stimuli for the extraction of several parameters. Positions 1, 2 and 3, along the main axis of each classroom, were representative of the first, central and last row of desks, respectively, and two off axis positions, i.e., points 4 and 5, were then added. Off-axis point 4 represents listeners in the classroom that do not benefit from the direct sound of the teacher's voice on the axis. However, when the TalkBox directivity patterns (NTi Audio TalkBok operating manual, 2020) and the

directivity pattern of the human talker (Chu and Warnock, 2002) were compared, we detected small differences at an azimuth angle of 30° on the horizontal plane around the source, which corresponds to the largest space deviation that was obtained during the measurements. The differences were lower than 1 dB, up to the octave band center frequencies of 4 kHz and were ~6 dB at 8 kHz. In the case of humans talking, we obtained the octave-band speech levels relative to those measured directly in front of the talkers by averaging the three one-third-octave band values included in each octave band. Such a process should be considered when measurements are carried out with TalkBox, even though only small differences are shown for the octave bands, which are the most important values because of their contribution to speech intelligibility, i.e. from 0.5 kHz to 4 kHz (IEC 60268-16:2020; Steeneken and Houtgast, 1999; ANSI S3.5:1997).

The SLM was also positioned at the reference position (ref), which was the same in each classroom, as we used the measurement at this position to compare the speech level value at 1 m from the source for all the case studies. We positioned the source at a distance of at least 1 m from the blackboard wall and at a height of 1.5 m from the floor to ensure that the reference position was the same in each classroom. Positions 1, 2, 3, 4 and 5 were not fixed and differed slightly from classroom to classroom, depending on the size of the rooms. Position 5 was only used for the measurement of background noise. However, the SLM was positioned at least 1 m from any surface for each measurement.

We used a wooden clapper, which we located randomly in two positions in each classroom, in combination with three microphone positions, as a sound source for the measurement of the reverberation time in unoccupied conditions Puglisi *et al.*, 2017). The results obtained in occupied conditions were obtained as the average of the measurement positions when we used the TalkBox as the sound source. However, since the radiation of the wooden clapper is within the directivity of a standard omni-directional sound source for higher frequencies than 0.5 kHz (Papadakis and Stavroulakis, 2019), and the compatibility of a reverberation time obtained with an omnidirectional sound source and a source with the similar directivity to a human talker has already been proved, albeit with slight differences at low frequencies (Astolfi *et al.*, 2008), the use of the two procedures should not have implied any significant differences, except for the lowest frequency range. Furthermore, an ad hoc comparison, performed in a small unoccupied university classroom, revealed a perfect matching between the two measurement procedures, with only slight differences below 0.125 kHz.

We chose the measurement positions to be representative of the distribution of the whole seating area of the pupils, considering the first (receiver 1), central (receiver 2) and last rows of desks (receiver 3). These positions are all on the central axes of the classrooms. They receive the best possible frequency distribution of the direct sound from the source but, since they are farthest from the walls, they are affected less by the reflections from the walls. We added another measurement position (receiver 4) to consider the most disadvantaged seat in each classroom, that

is, at the back of the room, at the widest possible angle from the source axis, on the right-side, close to the window. However, the overall A-weighted difference in speech level between position 3 (on the axis) and 4 (at a maximum of 30° off the axis) was found to be –0.2 dBA at the same distance from the source under anechoic conditions (Chu and Warnock, 2002), and façade reflections could further reduce this gap.

According to UNI 11532-2:2020, only positions 2 and 4 are mandatory in classrooms smaller than 250 m^3 to characterize the acoustics of the room. Moreover, position 4 should be chosen as close as possible to an HVAC unit, if present.

Another measurement position, which is closer to the source but at a wider azimuth angle from the axis, could also be considered. With reference to the typical classroom layout, the maximum azimuth angle that we encountered in the classrooms was 45°, and this was found in correspondence to the first row of pupils (receiver 1). The drop in value measured in this condition, due to speaker's directivity, was -0.6 dBA, with maximum differences of ~ -1 dB in the octave bands, which are the most important for speech intelligibility (IEC 60268-16:2020; Steeneken and Houtgast, 1999). These slight differences in the speaker's level, due to directivity, were compensated for by the reflections from the wall and by the higher speech intensity, due to the shorter distance than that of receiver 4. For these reasons, we only considered receiver 4 as a disadvantaged receiver position that had to be included in the measurement set-up.

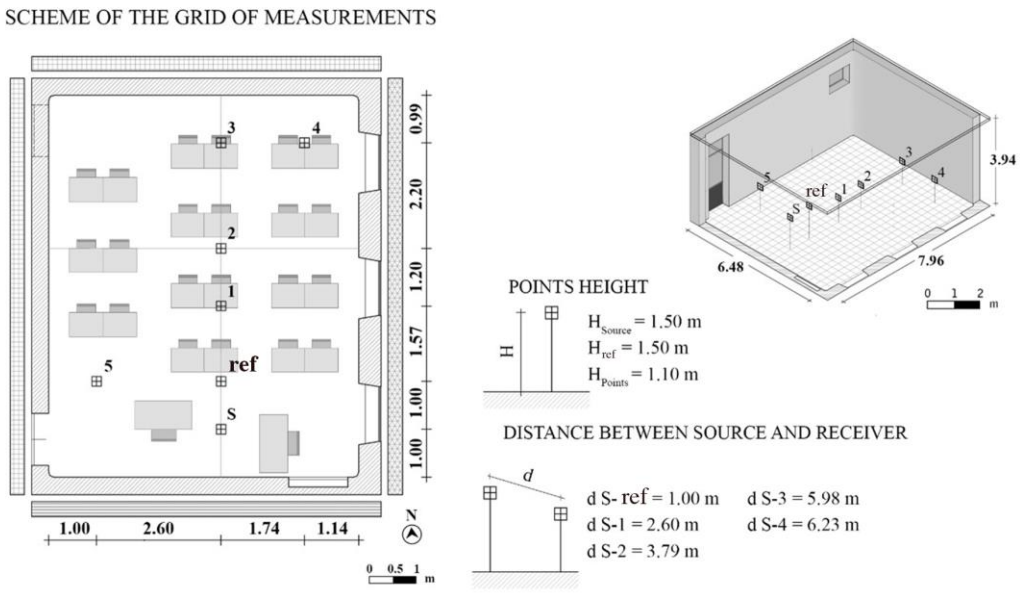


Figure 4. Measurement set-up in a typical classroom.

Reverberation time (T20, s) and speech clarity (C50, dB) were measured according to ISO 3382-2 (2008) and ISO 3382-1 (2009), respectively. Room impulse responses were acquired from three repeated exponential sine sweep

signals, which were emitted by the TalkBox and recorded by the SLM at each measurement point. The sweep signals were generated with a sample frequency of 44.1 kHz and a resolution of 16 bits. They were designed to cover a range of 0.05–2 kHz and to have a duration of 3 s each, based on the assumption that in cases with moderate background noise, as in the classrooms under study, it is normally a safe practice to use sweeps with a length of two to four times the expected longest reverberation time (ISO 18233, 2006). Particularly, the SLM was moved along the main axes in the receiver positions ref, 1, 2, 3, and 4. Frequency averages were calculated according to DIN 18041 (2016) in the range 0.25–2 kHz for T20 and according to ISO 3382-1 (2009) in the range 0.5–1 kHz for C50.

T20 in unoccupied conditions, $T20_{_e}$, where the subscript "e" is for empty, was measured with a wooden clapper, i.e., two wooden boards hinged together, according to the ISO 3382-2 (2008), as described in Puglisi et al. (2017). The measurement method in the empty condition was different compared to the one in the occupied condition; however, the two procedures can be considered equivalent in the frequency range of interest as described in Puglisi et al. (2018). Values of $T20_{_e}$, were averaged between 0.5 and 1 kHz, in order to be compared with the Italian technical standard UNI 11367 (2010). However, $T20_{_e}$ was also averaged between 0.25 and 2 kHz ,$T20_{_e\ 0.25\text{-}2\ kHz}$, with the aim to force comparison between occupied and empty T20 values applying the same frequency averaging. This range was chosen because of its greater similarity to the wider range provided by the most recent UNI 11532-2:2020 standard for both the reverberation time under occupied and unoccupied condition.

Background noise level (L_N, dBA) was considered in terms of indoor A-weighted equivalent sound pressure level (L_{Aeq}). Repeated measurements were performed based on 3-min acquisitions (Puglisi et al., 2015a), with windows and doors closed to ensure that no external unforeseen noises influenced them, except the typical ones related to traffic and roads. For this measure, the SLM was located in two or three positions in each classroom, which alternatively corresponded to positions 2, 4, and 5, as presented in **Figure 4**. Noise measurements were carried out with children in silence, L_{N_sil}, and with the children performing group activities, L_{N_gr}, in order to be representative of typical classroom scenarios. Both the mentioned conditions were guaranteed with the help of the teacher who asked the children to keep silent and then to speak as they were in a traditional group lesson.

The speech signal (L_S, dBA) was measured to characterize the propagation of a voice signal in each classroom. The TalkBox was positioned in S according to **Figure 4**, and then it was set to emit a voice signal with a "normal" vocal effort, i.e., corresponding to 60 dBA at 1 min anechoic conditions to comply with ANSI S3.5 (1997). The speech signals were acquired as an equivalent A-weighted continuous sound pressure level at the SLM, having the source switched on for the receiving positions ref, 1, 2, 3, and 4.

The ratio of useful to detrimental energy (U50, dB) was calculated to consider both the effect of the acoustics of the environment and the effect of the signal-to-noise

ratio on speech intelligibility (Bradley et al., 1999). It is obtained in terms of ratio between useful and detrimental energy, i.e., noise and reverberation. Particularly, it is obtained for each position, from C50, L_S, and L_{N_sil} values. U50 was then averaged between 500 and 1,000 Hz ($U50_{0.5\text{-}1\ kHz}$), as it is derived from a C50 value that exhibits the same span of frequency averaging.

Overall, the acoustic parameters that are distance dependent (i.e., C50, L_S, and U50) were measured point by point as described above, but then the acquired measures were processed to have single values that are useful for an effective comparison across classes. In particular, for C50 and U50, the values measured across the classroom were averaged together to have a spatial mean, excluding the reference point (ref in **Figure 4**), being hereafter reported to as "M" in the parameters' symbols. Such a value was found to be not so different from the central value, i.e., the value measured at position 2 in **Figure 4**, which is hereafter reported as "ctr" as subscript for C50 and U50, as underlined in Puglisi et al. (2018). Furthermore, L_S values, which were measured on the axis in front of S (i.e., acquisitions in points ref, 1, 2, and 3) were associated to obtain its slope per double distance (in decibels per double distance) (Astolfi et al., 2008), which is hereafter referred to as "m" in the parameters symbols.

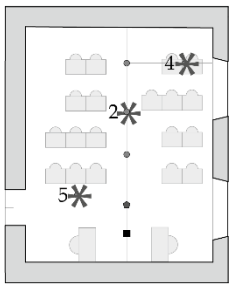
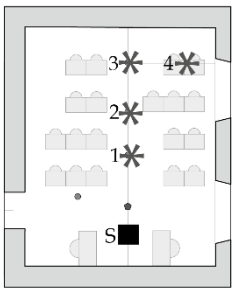
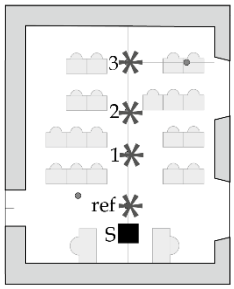
Table 7 summarizes the characteristics of the source stimuli, the acquisition intervals, the acoustical parameters, and the references and/or standards considered for the measurements. The schemes of the measurement positions for the different parameters shown in **Table 7** were all applied for a full classroom acoustic characterization. The measurement method refers to occupied classrooms, although we also measured the reverberation time under unoccupied conditions.

3.2.3. Statistical Analysis

The statistical analysis was carried out with SPSS (IBM Statistics 20, IBM, Armonk, NY, the USA). Since the distribution of the database resulted to be non-normal, once we had checked it, assuming the Lilliefors correction with the Shapiro-Wilk test, we used non-parametric methods to analyze the data. We investigated any correlations between the acoustic parameters by means of Spearman's rho (Croux and Dehon, 2010), and further analyzed those with a p-value < 0.01 through linear regression analysis.

We then divided the classrooms into two groups, starting from a reference T20 value chosen arbitrarily from among the ones identified as thresholds for evaluating the compliance or non-compliance of the classroom acoustic conditions with the literature or with the considered standards. In this way, the classroom acoustics were classified as compliant (C) or non-compliant (NC) with the requirement. We assessed the significance of the differences between the values of the parameters in the two groups by means of the Mann–Whitney U Test (MWU), a test that is used for two groups of independent observations. Only the parameters with a p-value below 0.05 were considered significantly different between the two groups.

Table 7. Measurement set-up with the positions of SLM (✳) and the source (■), the characteristics of the source stimuli, acquisition intervals, parameters, and the considered reference or standard.

Scheme 1		Scheme 2				Scheme 3	
							
Source stimuli							
Children in silence inside the classroom	Children performing group activities inside the classroom	Three repeated 3 s exponential sine sweeps emitted by Talkbox in S or in 2 randomly chosen wooden clapper source positions and no. 3 microphone positions (6 source-receiver pairs) for $T20_{e}$				Speech signal with a "normal" vocal effort emitted by Talkbox in S	
Measurement positions							
SLM at a height of 1.1 m from the floor at positions 2, 4 and 5		SLM at a height of 1.1 m from the floor at positions 1, 2, 3 and 4				SLM at a height of 1.1 m from the floor in 1, 2 and 3; SLM at 1.5 m from the floor in the ref	
Acquisition interval							
3 minutes in each position		15 seconds for each position				20 seconds for each position	
Parameter, averaging, symbol							
Single value for each classroom		Single value for each classroom Frequency average (0.25-2 Hz)	(0.5-1 Hz)	(0.5-1 Hz)	(0.5-1 Hz)	Single value for each classroom	
L_{N_sil} (dBA)	L_{N_gr} (dBA)	T20 (s)	$T20_{e}$ (s)	$C50_{ctr}$, $C50_{M}$ (dB)	$U50_{ctr}$, $U50_{M}$ (dB)	L_{S_ref} (dBA)	mL_{S} (dBA/dd)
Reference or standard							
Puglisi *et al.*(2015b)		DIN 18041:2016, ISO 3382-2:2009	UNI 11367:2010, Puglisi *et al.*(2017)	ISO 3382-1:2009	Bradley (1986)	n.a.	n.a.

Once subdivided the classrooms between the two groups on the basis of the reverberation time thresholds, we resort to the receiver operating characteristic (ROC) approach three times. Firstly, the area under the curve (AUC) of each of the other acoustical parameter was inspected to assess its overall summary accuracy to classify cases between the groups of classrooms compliant (C) or non-compliant (NC) with the threshold. AUC ranges from 0.5 to 1.0: an AUC near to 1 indicates a strong ability of the parameter to separate those classrooms compliant with the thresholds from those which do not comply, while an AUC close to 0.5 means that the parameter has a poor capability to discriminate between the two groups.

Relative to the values in between, an AUC greater than 0.9, 0.8, 0.7 and 0.6 reflects an excellent, good, fair and poor diagnostic ability of a binary classifier system at the variation of the discriminant threshold, respectively. Secondly, the analysis of the ROC curves allowed for the identification of the most suitable threshold value for the other investigated acoustical parameters, based on the Minimum Squared Distance (MSqD). The MSqD is the minimization of the squared distance from the ROC curve to the upper-left corner of the chart, that is the theoretical optimum in which all the classrooms are correctly attributed to the C or NC groups (Hajian-Tilaki, 2018). Thirdly, the accuracy and precision of the thresholds identified through the MSqD from the ROC curve were then tested to assess their ability to classify the acoustic quality of the classrooms as either C or NC (Zou *et al.*, 2007). In order to perform these analyses, the values of the parameters were indicated as follows:

- True Positive (TP), when the classification was C and the value of the specific parameter was correctly identified in the C group;
- True Negative (TN), when the classification was NC and the value of the specific parameter was correctly identified in the NC group;
- False Positive (FP), when the classification was C and the value of the specific parameter was identified in the NC group;
- False Negative (FN), when the classification was NC and the value of the specific parameter was identified in the C group.

Accuracy, $\frac{TP+TN}{TP+FP+TN+FN}$, is the percentage of positive and negative predictions that were correct and responded to the question: "how many classrooms have been correctly labeled out of all the 29 classrooms?". Precision, $\frac{TP}{TP+FP}$, is the percentage of positive predictions that were correct and responded to the following question: "how many of those classrooms that have been labeled as compliant classrooms, i.e., C, actually respect the threshold?".

3.3. Results

3.3.1. Measurement results

Table 8 shows the results of the acoustic measurements in the primary school classrooms, while **Table 9** reports the descriptive statistics of the acoustical parameters, considering all the classrooms together. The measured acoustical parameter range covers a wide span of values for all the considered parameters and represents most of the classroom environment typologies (Secchi *et al.*,2017). T20 ranges from 0.5 s to 1.4 s, $C50_{_M}$ ranges from -2.2 dB to 7.6 dB, while $U50_{_M}$ ranges from -2.2 dB to 6.5 dB. The reverberation time for classroom A2 under unoccupied condition $T20_{_e}$ is lower than T20 under occupied conditions, for both the frequency averaging, that represents an anomaly.

Table 8. The acoustic parameters measured for each classroom. Standard deviations are indicated in brackets, when available; n.a. stands for not available. It is also indicated whether the classrooms belonged to the compliant group, i.e., C, or to the non-compliant group, i.e., NC, in the case of groupings (a) and (b). The values that do not comply with the threshold, i.e., False Positive (FP) and False Negative (FN), based on the different groups, are highlighted in bold when considering (a), in italics when considering (b), and in bold italics if the value does not comply with the (a) or (b) subdivisions.

ID	Acoustical parameters											Group	
	T20 [s]	$T20_{e}$ [s]	$T20_{e,\ 0.25\text{-}2\ kHz}$ [s]	L_{N_sil} [dBA]	L_{N_gr} [dBA]	L_{s_ref} [dBA]	mL_S [dBA/dd]	$C50_{M}$ [dB]	$C50_{ctr}$ [dB]	$U50_{M}$ [dB]	$U50_{ctr}$ [dB]	T20≤0.8 s (a)	T20≤0.6 s (b)
A1	0.9 (0.02)	**0.9** (0.04)	***1.0*** (0.04)	51.7	n.a.	61.3	-1.9	1.3 (1.2)	1.0	-1.2 (1.0)	-1.1	NC	NC
A2	1.0 (0.06)	***0.8*** (0.06)	***0.9*** (0.17)	49.0	**64.7**	61.2	-2.4	2.2 (1.8)	0.0	0.2 (1.1)	-1.3	NC	NC
A3	0.8 (0.06)	*0.8* (0.05)	*0.8* (0.08)	38.4	61.8	60.3	-2.0	*4.1* (0.9)	*5.1*	3.8 (0.9)	4.8	C	NC
A4	0.7 (0.03)	*0.7* (0.06)	*0.7* (0.09)	47.1	**69.2**	61.3	-1.6	*4.7* (1.4)	*4.4*	3.4 (1.4)	3.4	C	NC
A5	0.7 (0.04)	*0.8* (0.06)	*1.0* (0.29)	46.3	**78.4**	61.0	-2.3	*5.4* (0.4)	*4.8*	3.9 (0.6)	3.5	C	NC
B1	0.5 (0.01)	0.6 (0.07)	0.6 (0.13)	49.3	66.3	60.8	-2.1	7.6 (1.5)	7.3	4.0 (1.9)	2.9	C	C
B2	0.5 (0.09)	0.5 (0.02)	0.6 (0.17)	39.9	66.3	61.7	-2.6	7.0 (1.0)	8.1	6.5 (0.9)	7.3	C	C
C1	0.7 (0.03)	0.9 (0.03)	*0.9* (0.09)	49.3	62.2	62.8	-1.6	3.3 (0.8)	2.8	2.2 (0.6)	1.9	C	NC
D1	1.3 (0.05)	1.4 (0.06)	1.4 (0.06)	51.2	**68.0**	63.0	-1.8	-0.1 (0.6)	-0.6	-1.6 (0.8)	-2.1	NC	NC
D2	1.3 (0.10)	1.4 (0.01)	1.5 (0.09)	52.0	n.a.	62.7	-2.1	-0.1 (1.0)	0.0	-1.6 (1.3)	-1.6	NC	NC
E1	1.2 (0.06)	1.3 (0.06)	1.4 (0.22)	54.0	**66.6**	62.1	-1.4	1.1 (0.9)	0.7	-1.2 (0.6)	-1.5	NC	NC
E2	1.0 (0.08)	**1.0** (0.15)	1.2 (0.15)	54.3	73.7	61.5	-1.9	2.7 (1.0)	***3.8***	-0.9 (0.8)	0.0	NC	NC
F1	1.2 (0.03)	1.5 (0.01)	1.5 (0.10)	52.0	75.1	62.1	-1.7	-0.3 (1.8)	1.1	-2.2 (1.6)	-0.9	NC	NC
F2	1.4 (0.13)	1.7 (0.03)	1.7 (0.07)	52.0	73.8	62.9	-1.8	-0.1 (1.2)	-1.1	-1.8 (1.3)	-2.7	NC	NC
G1	0.9 (0.05)	1.2 (0.07)	1.2 (0.11)	51.5	72.2	62.3	-2.1	2.6 (1.0)	**3.3**	**0.9** (0.9)	**1.3**	NC	NC
G2	0.6 (0.01)	*0.9* (0.01)	0.9 (0.09)	51.9	65.3	60.7	-0.8	*2.9* (0.9)	3.3	0.8 (0.6)	1.4	C	C
G3	0.7 (0.05)	*0.8* (0.04)	*0.8* (0.16)	52.5	63.5	n.a.	0.0	*4.4* (0.3)	*4.7*	n.a.	n.a.	C	NC
H1	0.7 (0.03)	*0.8* (0.03)	*0.9* (0.07)	51.6	**71.9**	61.5	-1.1	*3.6* (0.2)	*3.9*	1.5 (0.1)	1.4	C	NC
H2	0.6 (0.08)	0.9 (0.04)	0.9 (0.09)	55.9	68.1	62.4	-2.2	5.3 (0.3)	5.9	**-0.7** (0.5)	**-1.0**	C	C
H3	0.7 (0.04)	1.0 (0.19)	*1.0* (0.00)	45.5	63.9	62.9	-1.8	*3.8* (0.3)	*3.8*	3.2 (0.5)	3.0	C	NC
H4	0.7 (0.03)	*0.8* (0.04)	*0.8* (0.08)	53.1	65.5	62.9	-2.1	*4.1* (0.6)	*3.6*	0.7 (0.6)	**-0.1**	C	NC
I1	1.3 (0.10)	1.3 (0.07)	1.4 (0.12)	45.7	**59.9**	61.9	-1.6	-2.2 (0.2)	-1.1	-1.7 (0.3)	-2.6	NC	NC
I2	1.1 (0.03)	1.3 (0.03)	1.4 (0.24)	42.3	71.1	63.3	-2.3	0.0 (0.9)	-0.3	-0.2 (0.9)	-0.5	NC	NC
L1	0.9 (0.05)	n.a.	n.a.	47.9	**67.4**	61.1	-1.9	1.6 (1.0)	1.0	0.3 (1.1)	0.0	NC	NC
L2	1.0 (0.04)	1.2 (0.02)	1.3 (0.13)	46.0	71.6	62.0	-2.2	0.5 (2.0)	0.6	-0.2 (2.1)	-0.1	NC	NC
L3	1.0 (0.05)	1.3 (0.04)	1.2 (0.03)	43.0	81.3	62.6	-2.3	0.8 (0.7)	0.7	0.5 (0.7)	0.3	NC	NC
M1	0.9 (0.04)	1.1 (0.06)	1.2 (0.09)	52.0	81.9	63.0	-1.7	2.1 (1.3)	2.3	0.4 (0.9)	0.5	NC	NC
N1	1.1 (0.05)	1.1 (0.04)	1.2 (0.19)	54.3	76.1	63.9	-1.4	1.4 (0.7)	0.9	-1.0 (1.0)	-1.4	NC	NC
O1	1.0 (0.04)	1.1 (0.04)	1.1 (0.08)	49.6	76.7	62.3	-1.9	2.3 (1.1)	2.4	0.5 (0.7)	**0.7**	NC	NC

Table 9. Descriptive statistics of the acoustical parameters for all the classrooms. Standard deviations are indicated in brackets. The percentiles were calculated using Tukey's hinges.

Parameter	Average	25th Percentile	50th Percentile	75th Percentile
T20 [s]	0.9 (0.3)	0.7	0.9	1.1
$T20_{_e}$ [s]	1.0 (0.3)	0.8	1.0	1.3
$T20_{_e,\ 0.25\text{-}2\ kHz}$ [s]	1.1 (0.3)	0.9	1.1	1.4
L_{N_sil} [dBA]	48.9 (4.6)	46.0	49.6	52.0
L_{N_gr} [dBA]	70 (6.0)	65.5	69.2	73.8
$Ls_{_ref}$ [dBA]	62.1 (0.9)	61.5	62.1	62.9
mL_s [dBA/dd]	-1.8 (0.6)	-2.2	-1.9	-1.6
$C50_{_M}$ [dB]	2.6 (2.4)	0.8	2.7	4.1
$C50_{_ctr}$ [dB]	2.6 (2.5)	0.7	2.8	3.9
$U50_{_M}$ [dB]	0.8 (2.2)	-0.9	0.5	2.2
$U50_{_ctr}$ [dB]	0.8 (2.4)	-0.9	0.4	1.9

Regarding the background noise level when the pupils were silent, L_{N_sil}, the lowest measured level was 38.4 dB(A), which means that, all the classrooms recorded values above the limit of 35 dB(A) stated in the ANSI S12.60:2010 standard as the threshold value, as well as in BB93:2015, and also suggested in Minelli *et al.* (2021) (see **Chapter 2**) for a better learning performance. Only one classroom complied with the limit value of 38 dB(A), according to the UNI 11532-2:2020 standard, while all the classrooms were found to be well below the value of 64 dB(A) L_{Neq}, and thus meet the British government's targets pertaining to literacy and numeracy (Shield and Dockrell, 2008).

For the speech level, $L_{S,}$ measured at receiver 3, in correspondence to the last row of desk, on the axis, and at receiver 4, at the same distance, but with a maximum off axis azimuth angle of 30°, which is not shown in Table 3, it may be useful to report that the average difference across all the classrooms was found to be – 0.6 dB (st. dev. 1 dB). The greater drop, with respect to the expected differences in the case of a human source, could be due to the higher directivity of TalkBox.

3.3.2. Relationships between the acoustical parameters

Table 10 shows the two-tailed significant correlations between the acoustical parameters measured in the classrooms and the results that corroborate the outcomes that had already been found in Astolfi *et al.* (2019) (see **Chapter 4**). Here the parameter $T20_{_e\ 0.25\text{-}2\ kHz}$ was not considered for the analysis, because of its compatibility with $T20_{_e.}$

First, a strong negative relationship can be observed between the reverberation time under occupied conditions T20, and the C50 and U50 speech intelligibility indexes, an outcome which seems to suggest that it is necessary to use only one

quantity to characterize classroom acoustics. This outcome also confirms the results of the previous study by Bradley (1986), where it is indicated that many of the early/late ratio values can be predicted from the measured reverberation times with a root mean square (rms) error of just over 1 dB.

Second, the positive and significant correlation between T20 and $T20_{_e}$ suggests the necessity of only characterizing classrooms under empty conditions, with a consequent reduction in the efforts necessary to carry out acoustic measurements in such an environment.

Third, the very close connection between the central and mean values of both the C50 and U50 quantities indicates that only one measurement in the center of the room need to represent the behavior of the whole classroom, in terms of speech intelligibility, as already shown by Puglisi *et al.* (2018).

Table 10. Correlation matrix of the acoustical parameters measured in the classrooms. Spearman correlation coefficients with two ** indicate significant relationships, with a p-value < 0.01.

	T20	$T20_{_e}$	L_{N_sil}	L_{N_gr}	L_{S_ref}	mL_S	$C50_{_M}$	$C50_{_ctr}$	$U50_{_M}$	$U50_{_ctr}$
T20		.865**					-.934**	-.892**	-.823**	-.802**
$T20_{_e}$					.586**		-.905**	-.804**	-.809**	-.730**
L_{N_sil}									-.489**	
L_{N_gr}										
L_{S_ref}										
mL_S										
$C50_{_M}$								.934**	.861**	.807**
$C50_{_ctr}$									.777**	.829**
$U50_{_M}$										.945**
$U50_{_ctr}$										

Figure 5 shows the results of the regression analyses of the correlations and quantifies the relationship between the parameters. High R^2 values are found for all the significant correlations, except for L_{S_ref} and T20, for which the relationship is weak. As far as the behavior of L_{S_ref} is concerned, a clear relationship does not appear for reverberation time increases from 0.5 s to 1.4 s, even though the tendency is coherent with what can be expected, i.e., lower L_{S_ref} values are related to lower reverberation time values, while the contribution of the environmental reflections increases the level of the signal emitted by the source for higher reverberation times.

It is possible to assume, from the graphs in **Figure 5** and the correlations in **Table 10**, that classroom acoustics can be fully characterized from just a single measure, e.g., T20 or $C50_{_ctr}$, since it would be possible to estimate the other parameters through robust equations.

C50 in the central position in occupied settings, i.e., $C50_{_ctr}$, can be considered as one of the most effective quantities for measurements inside a classroom to

investigate classroom acoustics. It is preferable to T20 and U50, because of its easier measurement procedure, which only requires the acquisition of the impulse response for one source-to-listener path. T20, on the other hand, requires more than one receiver to calculate the spatial average, while U50, even though referring to the central position, i.e., $U50_{ctr}$, requires the measurement of the impulse response, the level of the signal and the background noise level. This is obviously valid for conditions in which the background noise when the pupils are silent is as low as in the present study, that is, it does not affect speech intelligibility to any great extent.

As far as the relationship between T20 and $T20_e$ is concerned, a close correlation can be observed in **Figure 5**, which suggests that only the empty condition is needed to be considered for an experimental survey.

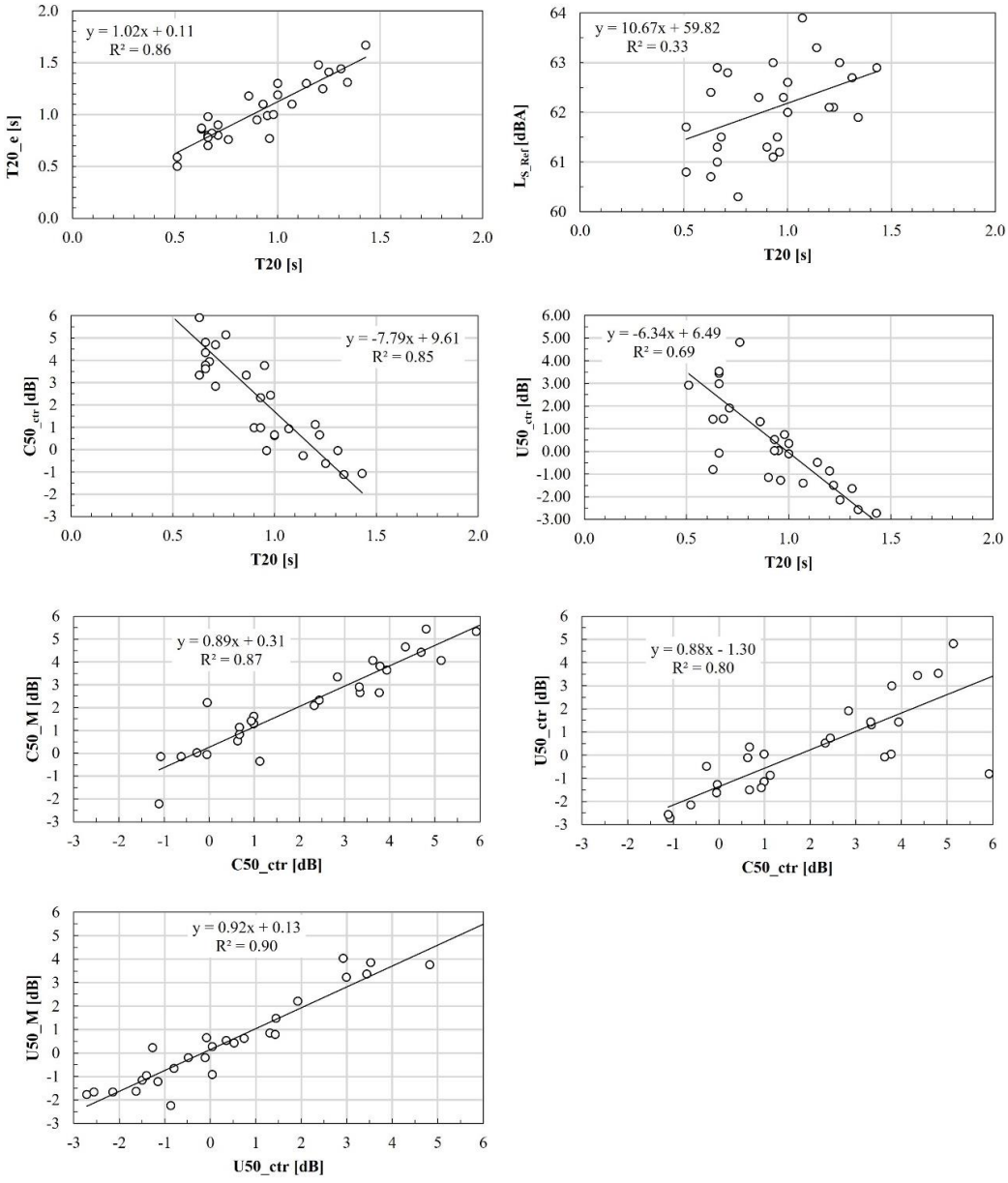


Figure 5. Regression lines of the significant correlations shown in Table 10. The determination R2 coefficient confirms the close relationship between the parameters in most of the considered cases.

3.3.3. Compliant and non-compliant classrooms

In order to categorize a certain classroom as belonging to an acceptable or non-acceptable ranking, i.e., classrooms compliant (C) or non-compliant (NC), the classrooms were subdivided into two groups twice, i.e., assuming arbitrary T20 cut-off values of 0.8 s (a) and of 0.6 s (b), respectively. The objective was to ascertain the threshold that divides C from NC for each acoustical parameter in both of these cases.

The T20 cut-off value of 0.8 s was chosen as being representative of moderate requirements for classroom acoustics since: (i) it is toward the upper range of admittable reverberation times in comfortable classrooms used for learning (Yang and Bradley, 2009; Hodgson and Nosal, 2002), (ii) it is the optimal value advised in the case of the refurbishment of primary school classrooms and it is recommended for older pupils (BB93:2015), and (iii) it is also recommended for speaking to older pupils (Calosso *et al.*, 2017). The same T20 threshold of 0.8 s was used in Astolfi *et al.* (2019) (see **Chapter 4**) to discriminate between compliant and banon-compliant acoustics classrooms. In Astolfi *et al.*, 2019, the pupils' perception of noise disturbance and their sense of fitting in at school differed significantly for the two groups, and the average subjective score was higher in NC than in C for the former and lower for the latter, respectively.

On the other hand, a T20 value equal to 0.6 s is the cut-off value that is required in the case of more severe classroom acoustics requirements. It was chosen since: (i) it is recommended in the most recent standards on classroom acoustics, such as the DIN 18041:2016 and the UNI 11532-2:2020 standards, (ii) there is evidence that 0.6 s is the optimal value to guarantee a better learning performance for primary school students (Minelli *et al.*, 2021) (see **Chapter 2**). A reverberation time (T_{soll}) of 0.6±0.1 s, from 0.250 kHz to 4 kHz, is considered optimal, according to the DIN 18041:2016 and UNI 11532-2:2020 standards, for rooms dedicated to communication with the simultaneous presence of several people speaking in the classroom, as is the case during primary school lessons. This time was calculated with the formula $T_{soll} = \left(0.37 \lg \frac{V}{m^3} - 0.17\right)$, together with the range of ±20%, when the average volume (V), that is, of about 210 m^3 of the 29 classrooms in **Table 6**, was considered.

The boxplots in **Figure 6** graphically show the results of grouping (a) and **Table 11** shows the threshold values for each parameter. $T20_{_e\ 0.25\text{-}2\ kHz}$ was not represented by the boxplots, instead it was inserted in Table 11.

As can be seen from **Figure 6** and **Table 11**, there is no significant difference between the C and NC groups for the L_{N_sil}, L_{S_ref} or mL_S parameters, since the results of the Mann–Whitney U Test (MWU) are greater than 0.05.

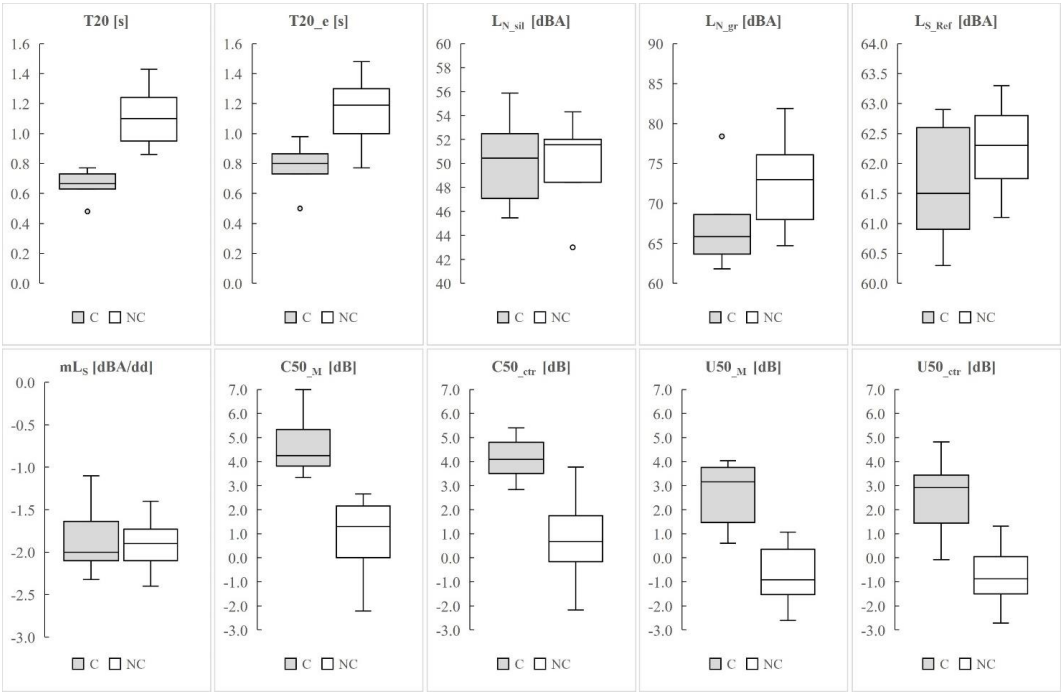


Figure 6. Boxplots of each parameter for the two groups based on the grouping (a). C stands for compliant classrooms and NC stands for non-compliant classrooms.

Table 11. Descriptive statistics of the acoustical parameters with a subdivision into C and NC for grouping (a). Standard deviations are indicated in brackets; the values in bold are the ones used for the calculation of the threshold, while n.a. stands for "not available". The percentiles were calculated using Tukey's hinges. The p-values that were obtained with the MWU test are also shown.

		Average	25th Percentile	50th Percentile	75th Percentile	p-value
T20 [s]	C	0.6 (0.1)	0.6	0.7	0.7	0.00
	NC	1.1 (0.2)	1.0	1.0	1.2	
$T20_{e}$ [s]	C	0.8 (0.1)	0.7	0.8	0.9	0.00
	NC	1.2 (0.2)	1.1	1.2	1.3	
$T20_{e,\ 0.25\text{-}2\ kHz}$ [s]	C	0.8 (0.1)	0.7	0.9	0.9	0.00
	NC	1.3 (0.2)	1.1	1.3	1.4	
L_{N_sil} [dBA]	C	48.0 (5.3)	45.9	49.3	51.8	0.48
	NC	49.7 (4.3)	46.0	51.3	52.0	
L_{N_gr} [dBA]	C	67.2 (4.7)	64.6	66.3	68.6	0.02
	NC	72.3 (6.1)	68.0	73.0	76.1	
Ls_ref [dBA]	C	61.7 (1.0)	60.9	61.5	62.6	0.09
	NC	62.4 (0.7)	62.0	62.3	63.0	
mL_s [dBA/dd]	C	-1.7 (0.8)	-2.2	-2.0	-1.6	0.85
	NC	-1.9 (0.3)	-2.2	-1.9	-1.7	
$C50_{M}$ [dB]	C	4.7 (1.5)	3.7	4.1	5.4	0.00
	NC	1 (1.4)	-0.1	1.0	2.2	
$C50_{ctr}$ [dB]	C	4.8 (1.7)	3.7	4.4	5.5	0.000
	NC	0.9 (1.5)	-0.3	0.7	2.3	
$U50_{M}$ [dB]	C	2.6 (2.0)	1.1	3.2	3.8	0.00
	NC	-0.6 (1.0)	-1.7	-0.6	0.4	
$U50_{ctr}$ [dB]	C	2.6 (2.3)	1.4	2.9	3.5	0.00
	NC	-0.7 (1.3)	-1.5	-0.7	0.4	

The boxplots in **Figure 7** graphically show the results of grouping (b) that was made by imposing T20 equal to or below 0.6 s and then higher than 0.6 s to attribute classrooms to the C and NC groups, respectively. Once the classrooms had been assigned to the C and NC group on the basis of the T20 criterion, the descriptive statistics were calculated for each parameter as shown in **Table 12**. Again, $T20_{e\ 0.25\text{-}2\ kHz}$ was not represented by the boxplots, instead it was inserted in Table 12.

Table 12 shows that the two C and NC groups are once again not significantly different for the L_{N_sil}, L_{S_ref}, or mL_S parameters, as resulting from the MWU test. Moreover, no significant differences are found for the L_{N_gr}, $U50_{_M}$ or $U50_{_ctr}$ parameters as their p-value is greater than 0.05.

Table 13 shows the AUC and the threshold values of the acoustical parameters obtained for the two groupings (a) and (b), which were used to subdivide the classrooms into C and NC. By comparing the thresholds in **Table 13** with the optimal values of the acoustical parameters reported in literature (see Section 3.1.1), it is possible to label the two groups of classrooms as compliant (C) or non-compliant (NC), respectively, considering the upper limit of the admissible values in the case of T20 for C. The close correlation between the parameters determines the pairing of the thresholds for the two groups with the optimal values.

As far as grouping a) is considered, a maximum AUC is shown for the parameter $C50_{_M}$. High values of AUC are also reported for $C50_{_ctr}$, $U50_{_M}$ and $T20_{_e}$ that reveal an excellent ability of the parameters to discriminate the classrooms between the two groups. This ability lowers in the case of $U50_{_ctr}$ and L_{N_gr} parameters, being good and fair respectively. Focusing on the thresholds identified through the MSqD from the ROC curve, classrooms with a higher T20 than 0.8 s, a higher $T20_{_e}$ than 0.9 s and a higher L_{N_gr} than 67 dB(A) are labeled as NC, which are also classrooms with a lower $C50_{_M}$ and $C50_{_ctr}$ than 3 dB, and with a lower $U50_{_M}$ and $U50_{_ctr}$ than 1 dB. On the other hand, values that are below the T20, $T20_{_e}$ and L_{N_gr} thresholds, and which are over the C50 and U50 thresholds, are labeled as C. Thresholds for the L_{N_sil}, L_{S_ref} or mL_S parameters are not given since they did not significantly differ between NC and C, as shown in **Table 11**.

As far as grouping b) is considered, the AUC values derived from the ROC analysis are generally lower compared to grouping a). The greater values of AUC are shown for $C50_{_M}$ and $C50_{_ctr}$ that have an excellent ability to separate the classrooms that comply with the threshold from those that do not comply, followed by the $T20_{_e}$ parameter that can do the same in a good way. Analyzing the MSqD from the ROC curve, the $T20_{_e}$ threshold results to be lower than or equal to 0.9 s, while values higher than or equal to 5 dB or to 6 dB have been found for $C50_{_M}$ and $C50_{_ctr}$, respectively. Thresholds for the parameters L_{N_sil}, L_{S_ref}, mL_S, L_{N_gr}, $U50_{_M}$ or $U50_{_ctr}$ are not given since the NC and C groups of classrooms do not differ significantly.

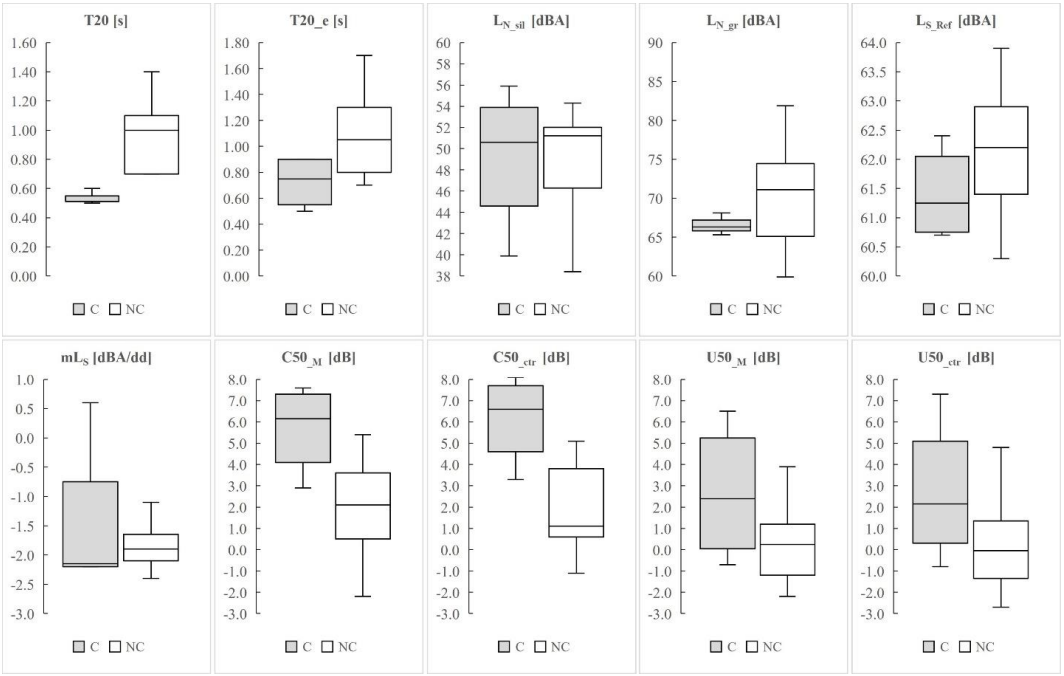


Figure 7. Boxplots of each parameter for the two groups, based on the subdivision (b). C stands for compliant classrooms and NC stands for non-compliant classrooms.

Table 12. Descriptive statistics of the acoustical parameters with a subdivision into C and NC, based on a T20 lower than or equal to 0.6 s, according to grouping (b). Standard deviations are indicated in brackets, the values in bold are the ones used for the calculation of the threshold, while n.a. stands for "not available". The percentiles were calculated using Tukey's hinges. The p-values that were obtained with the MWU test are also shown.

		Average	25th Percentile	50th Percentile	75th Percentile	p-value
T20 [s]	C	0.6 (0.1)	0.5	0.6	0.6	0.001
	NC	1.0 (0.2)	0.7	1.0	1.1	
$T20_{_e}$ [s]	C	0.7 (0.2)	0.6	0.8	0.9	0.029
	NC	1.1 (0.3)	0.8	1.1	1.3	
$T20_{_e,\ 0.25\text{-}2\ kHz}$ [s]	C	0.8 (0.2)	0.6	0.8	0.9	0.012
	NC	1.2 (0.3)	0.9	1.2	1.4	
L_{N_sil} [dBA]	C	49.2 (6.8)	44.6	50.6	53.9	0.874
	NC	49.3 (4.1)	46.3	51.2	52.0	
L_{N_gr} [dBA]	C	66.5 (1.2)	65.8	66.3	67.2	0.275
	NC	70.3 (6.3)	65.1	71.1	74.5	
Ls_ref [dBA]	C	61.4 (0.8)	60.8	61.3	62.1	0.115
	NC	62.1 (0.9)	61.4	62.2	62.9	
mL_s [dBA/dd]	C	-1.4 (1.4)	-2.2	-2.2	-0.8	0.575
	NC	-1.9 (0.3)	-2.1	-1.9	-1.7	
$C50_{_M}$ [dB]	C	5.7 (2.1)	4.1	6.2	7.3	0.009
	NC	2.0 (1.9)	0.5	2.1	3.6	
$C50_{_ctr}$ [dB]	C	6.2 (2.1)	4.6	6.6	7.7	0.009
	NC	1.9 (2.0)	0.6	1.1	3.8	
$U50_{_M}$ [dB]	C	2.6 (3.2)	0.1	2.4	5.3	0.088
	NC	0.3 (1.9)	-1.2	0.3	1.2	
$U50_{_ctr}$ [dB]	C	2.7 (3.4)	0.3	2.2	5.1	0.123
	NC	0.2 (2.0)	-1.4	-0.1	1.4	

Table 13 also reports the accuracy and precision of the thresholds identified through the MSqD from the ROC curve for each acoustical parameter in labeling the classrooms in the two categories. **Table 8** shows the values that do not comply with the threshold of the specific parameters, i.e., False Positive (FP) and False Negative (FN), which are in bold, in italics or in bold italics, on the basis of a group belonging to (a) or (b).

As can be seen from **Table 13**, clustering (a) shows a 100% accuracy and precision of the threshold values for $C50_{_M}$ and $U50_{_M}$. This accuracy refers to the capability of the threshold to correctly assign the classrooms to the C or NC groups, while precision only implies the correct assignment of the classrooms to the C group. This means that all the classrooms attributed to the NC group have a lower $C50_{_M}$ value than 3 dB and a lower $U50_{_M}$ value than 1 dB, while all the classrooms attributed to the C group have a $C50_{_M}$ value higher than or equal to 3 dB and a $U50_{_M}$ value higher than or equal to 1 dB. In other words, focusing on $C50_{_M}$ and $U50_{_M}$, all of the 29 classrooms have been correctly assigned to the NC or C groups, thus these thresholds are 100% able to correctly qualify the acoustics of the classroom. Furthermore, it implies that the assessment of either $C50_{_M}$, $U50_{_M}$ or T20, on the basis of which the grouping a) was carried out, provides a correct classroom acoustics qualification, and it is therefore necessary to measure only one of these three parameters to correctly qualify the acoustic of the entire classroom. The accuracy and precision of the thresholds of the L_{N_gr}, $U50_{_ctr}$ and $T20_{_e}$ parameters do not reach 100%, and remain around 70%, 80% and 90%, respectively. The lowest percentages of the classifiers are shown for the L_{N_gr} threshold, which has been found to be able to correctly subdivide the classrooms into the two groups only 20 times out of 27 (74%), while 4 classrooms out of 12 of those assigned to the C group exceeded the L_{N_gr} threshold thus they were wrongly assigned to the C group. This means that evaluating the acoustics of the classroom using the L_{N_gr}, $U50_{_ctr}$ or $T20_{_e}$ parameters could lead to incorrect attributions, therefore the measurement of another parameter, i.e., T20, $C50_{_M}$ or $U50_{_M}$, would be necessary to achieve a more certain characterization. $C50_{_ctr}$ is not always able to correctly subdivide the 29 classrooms into the two C and NC groups, since its accuracy is around 90%. On the other hand, $C50_{_ctr}$ can correctly label the classrooms that comply with the requirement, as demonstrated by its 100% precision.

For grouping (b), a 100% accuracy and precision percentage are only shown for the thresholds $C50_{_ctr}$. The percentages of the classifiers of the $T20_{_e}$ and $C50_{_M}$ parameters are generally lower than those obtained with grouping (a), thus showing a reduction in the ability of the respective thresholds to correctly classify the classrooms as C or NC. The minimum value shown in **Table 13** is the accuracy of $T20_{_e}$ that is able to accurately subdivide the classrooms into the two groups 19 times out of 28 (68% accuracy), followed by the 75% precision of the $C50_{_M}$ threshold indicating that 3 classrooms out of 4 were precisely assigned to the C group.

Relative to the comparison between $T20_{_e}$ and $T20_{_e\ 0.25\text{-}2\ kHz}$, **Table 13** shows that averaging the reverberation time in empty condition between 0.25 and 2 kHz led to the identification of a slightly higher threshold for both moderate and severe requirements, and that it is equal to 1 s. This threshold demonstrates higher values of accuracy and precision in the case of grouping (a), which on the contrary are lower for grouping (b).

In short, **Table 13** shows, in bold, the thresholds of the parameters that can be used alternatively to characterize classroom acoustics, according to the different level of performance required in the classroom, that is, moderate performance, as with grouping (a), or severe performance, as with grouping (b). In the case of moderate requirements, such as for the refurbishment of existing classrooms or in the case of older pupils (BB93:2015), as well as in the case of specific requirements for voice support (Calosso *et al.*, 2017), where a slightly higher reverberation time than 0.6 s is required, thresholds (a) are preferable. In this case, the parameters that are preferable to use alternatively for classroom acoustic characterization are T20, $T20_{_e}$ or $T20_{_e\ 0.25\text{-}2\ kHz}$, $C50_{_M}$, $C50_{_ctr}$ and $U50_{_M}$. In the case of a severe performance requirement, that is, in the case of the respect of standard requirements, thresholds (b) are advised. T20, $C50_{_M}$ and $C50_{_ctr}$ result to be the most accurate and precise parameters for an alternative use to fully characterize classroom acoustics for both moderate and severe requirements.

Table 13 also shows the paucity of cases belonging to the C group for the second grouping (b). A similar amount of data is needed for both groups to improve the statistical analysis and to have more robust results, like those in the case of grouping (a).This will be one of the aims of future research and it will be achieved by boosting the sharing of acoustical measures across Europe, since Italian schools are generally hosted in typical Southern European buildings, which have high ceilings and plaster walls, and are thus associated with higher reverberation time values.

Table 13. Area under the curve (AUC), thresholds identified through the minimum squared distance from the ROC curve and their accuracy and precision for groupings (a) and (b). The parameter data that can be used alternatively to characterize classroom acoustics, according to the different levels of performance required in the classroom, are shown in bold.

Grouping		$T20_{_e}$ [s]	$T20_{_e,\ 0.25\text{-}2\ kHz}$ [s]	L_{N_gr} [dBA]	$C50_{_M}$ [dB]	$C50_{_ctr}$ [dB]	$U50_{_M}$ [dB]	$U50_{_ctr}$ [dB]
(a) T20≤0.8 s	AUC	**0.95**	**1.00**	0.77	**1.00**	**0.98**	**0.95**	0.90
	Threshold for C classrooms	**≤0.9**	**≤1.0**	≤67	**≥3**	**≥3**	**≥1**	≥1
	Accuracy	**89% (25/28)**	**93% (26/28)**	74% (20/27)	**100% (29/29)**	**93% (27/29)**	**100% (28/28)**	86% (24/28)
	Precision	**92% (11/12)**	**100% (12/12)**	67% (8/12)	**100% (12/12)**	**100% (12/12)**	**100% (11/11)**	82% (9/11)
(b) T20≤0.6 s	AUC	0.85	0.90		**0.91**	**0.92**		
	Threshold for C classrooms	≤0.9	≤1.0		**≥5**	**≥6**		
	Accuracy	68% (19/28)	57% (16/28)		**93% (27/29)**	**100% (29/29)**	n.a.	n.a.
	Precision	100% (4/4)	50% (2/4)		**75% (3/4)**	**100% (4/4)**		

3.4. Discussion on the thresholds for compliant and non-compliant classroom acoustics

According to grouping (a), which is intended for classrooms with moderate acoustic requirements, the classrooms need to ensure a T20 value equal to or lower than 0.8 s, a $T20_{_e}$ value equal to or lower than 0.9 s, or $C50_{_M}$ and $C50_{_ctr}$ values equal to or higher than 3 dB. These classrooms should also implicitly guarantee $U50_{_M}$ and $U50_{_ctr}$ values equal to or higher than 1 dB and an L_{N_gr} value equal or lower than 67 dBA. Since most of the quantities are correlated, compliant classrooms should respect most of these limits.

An agreement has also been found between the obtained thresholds and the optimal values reported in various research studies. As far as an optimum reverberation time is concerned, Yang and Bradley (2009) stated that acceptable reverberation times in classrooms, during lessons, should be about 0.3 s to 0.9 s, while Hodgson and Nosal (2002) demonstrated that when the dominant sources of interfering sounds are nearby children, nonzero reverberation times should be in the range of 0.1 s to several seconds. To corroborate this, Bradley *et al.* (1999) found that to have good speech intelligibility in classrooms, room acoustics is less important than the signal-to-noise ratio (S/N). This usually implies that guaranteeing high signal-to-noise ratios, i.e., S/N>15 dB, is more important than guaranteeing an optimal reverberation time, especially if an adequate S/N is not guaranteed first. The C50 and U50 target values found in this work agree with those obtained by Bradley (Bradley, 1986; Bradley *et al.*, 1999), who recommended a greater C50 than 2±1 dB at mid frequencies for small classrooms with a reverberation time of 0.8 s, and a 1 kHz U50 optimum of 1 dB for very good speech intelligibility.

On the other hand, on the basis of grouping (b), if severe acoustic requirements are needed for classrooms, to respect the standards for new schools, and for the optimal support of the teacher's voice (Puglisi *et al.,* 2017), classrooms should guarantee a T20 value equal to or lower than 0.6 s or a $C50_{_ctr}$ value equal to or higher than 6 dB. These classrooms should also implicitly guarantee a $T20_{_e}$ value equal to or lower than 0.9 s and a higher $C50_{_M}$ value than 5 dB. These thresholds are intended as the upper limits, with the admitted tolerance already included, in agreement with the UNI 11532-2:2020 and DIN 18041:2016 standards.

However, as has emerged from literature, an ideal approach to the acoustical design of classrooms should be organized considering the priorities. First, such a design is needed to control anthropic noise sources, in terms of sound power emission, through strategies of behavioral engagement, for example (Di Blasio *et al*., 2019); second, the teachers' voice should be supported with reflected sound, which can be achieved as a result of an optimized classroom layout. Design criteria should not specify the maximum reverberation time, but rather a range of acceptable values, which should be about 0.7 s and 0.8 s to guarantee beneficial conditions for voice production (Puglisi *et al.*, 2017; Calosso *et al.*, 2017).

3.5. Conclusions

This work stems from the need to have comfortable teaching and learning environments, and it represents an attempt to identify the minimum number of parameters that best characterize the acoustics of primary school classrooms, together with their optimal values. To do this, a comprehensive protocol for systematic acoustic measurements in small environments was provided and applied in 29 classrooms. A survey allowed us to answer the research questions listed in the introduction of the present article and which are reported below.

a. How many parameters are needed, as a minimum, to characterize classroom acoustics?

The obtained results show that most of the usually considered parameters are closely correlated. Reverberation time, T20, or speech clarity in the central point, $C50_{ctr}$, in occupied conditions, can both be used as the most representative parameters to characterize classroom acoustics, at least under occupied conditions with the pupils silent, and with a lower background noise level than 56 dB(A), that is the maximum level recorded in the classrooms. Therefore, using either T20 or C50, it is possible to estimate the useful-to-detrimental ratio, U50, which is the parameter that is most closely related with speech intelligibility, as it accounts for both noise and room acoustic defects. The noise level in silent conditions, L_{N_sil}, the slope per double distance of the speech level, mL_S, and the speech level in the reference point (@ 1 m from the source), L_{S_ref} , have not emerged as primary parameters to characterize classroom acoustics.

b. How many measurement points are needed in a classroom?

In order to reduce the measurement points to a minimum number, it is advisable to first characterize classrooms by means of the speech clarity parameter in the central position, $C50_{ctr}$. A spatial average is needed for T20.

c. Do we really need to carry out measurements under occupied conditions?

Only the reverberation time was measured in both occupied and unoccupied conditions, and these times resulted to be positively and significantly correlated. $T20_e$ was also significantly correlated with the C50 and U50 parameters, although we only measured these parameters in occupied conditions. As a result of these measurements, it is possible to state that it is sufficient to measure T20 in unoccupied conditions, using a procedure that gradually becomes smoother and faster, and from which the other related parameters can be estimated.

d. What are the thresholds for compliant and non-compliant classroom acoustics in primary schools?

New thresholds for classroom acoustic parameters, which discriminate the acoustic quality of primary school classrooms compliant and non-compliant, are here proposed on the basis of two different groupings, one that considers moderate classroom acoustic requirements and the other that considers severe ones. The obtained threshold values, which are supported by literature and subjective data, are

intended as the upper limit and they include the tolerance range. The new thresholds for moderate requirements are:

- 0.8 s and 0.9 s for the reverberation time under occupied and unoccupied conditions, respectively;
- 67 dB(A) for the noise level during group activities;
- 3 dB for speech clarity, when considered both as a spatial average and as a single value in the central position;
- 1 dB for the useful-to-detrimental ratio, when considered both as a spatial average and as a single value in the central position.

The thresholds for severe requirements are:

- 0.6 s and 0.9 s for the reverberation time in occupied and unoccupied conditions, respectively,
- 5 dB for speech clarity, when considered both as a spatial average and as a single value in the central position.

Moderate limits are intended for older pupils and for refurbishment, whereas severe limits are intended for younger pupils and in the case of new schools. Both limits also support the teacher's voice in the classrooms. However, the new thresholds for the acoustical parameters beyond reverberation time that we found in this study for both moderate and severe requirements are not definitive being not based on studies testing performance or subjective perception of pupils. Instead, the present work rather focuses on a methodology which allows to identify acoustical parameters alternative to the reverberation time and their optimal values, that depend on the collected data and on the imposed cutoffs. The main result of the work in fact suggests that more convenient parameters, such as clarity in the central position of the classroom, can replace reverberation time, which implies a more laborious measurement procedure, to classify classroom acoustics as compliant or non-compliant.

In conclusion, the aim of this work has been to promote a holistic approach to classroom acoustics, which considers the needs of both the pupils and the teachers, as well as practical classroom refurbishment needs. Furthermore, it has drawn attention to the concepts of admittable tolerance and accuracy in prediction and uncertainty in the measurement results, and it has stressed the greater importance of increasing the speech signal-to-noise ratio than pursuing the acoustic requirements of a room. Severe requirements are advised for the case of younger pupils, which should be even more severe when children with special hearing and communication needs are included in mainstream classrooms. Moderate requirements should be considered to help teachers suffer less from vocal illnesses and to make interventions on existing classrooms cheaper and more affordable. Many classrooms could be renovated through this approach and using this essential protocol, as the main problems of non-compliance arise for existing classrooms and not for new buildings, which, unfortunately, are far fewer in number.

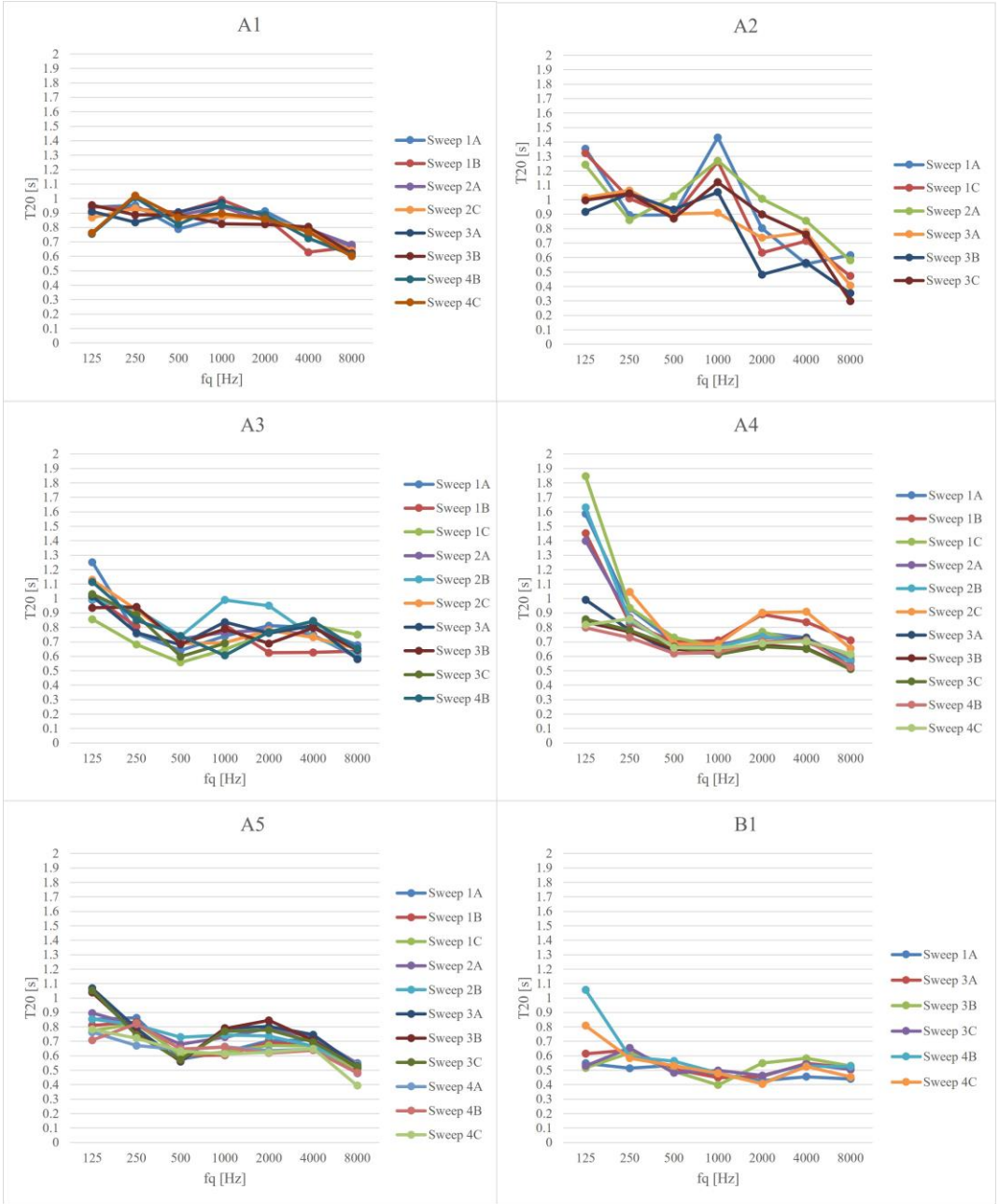
Appendix B
Graphs of T20 and C50

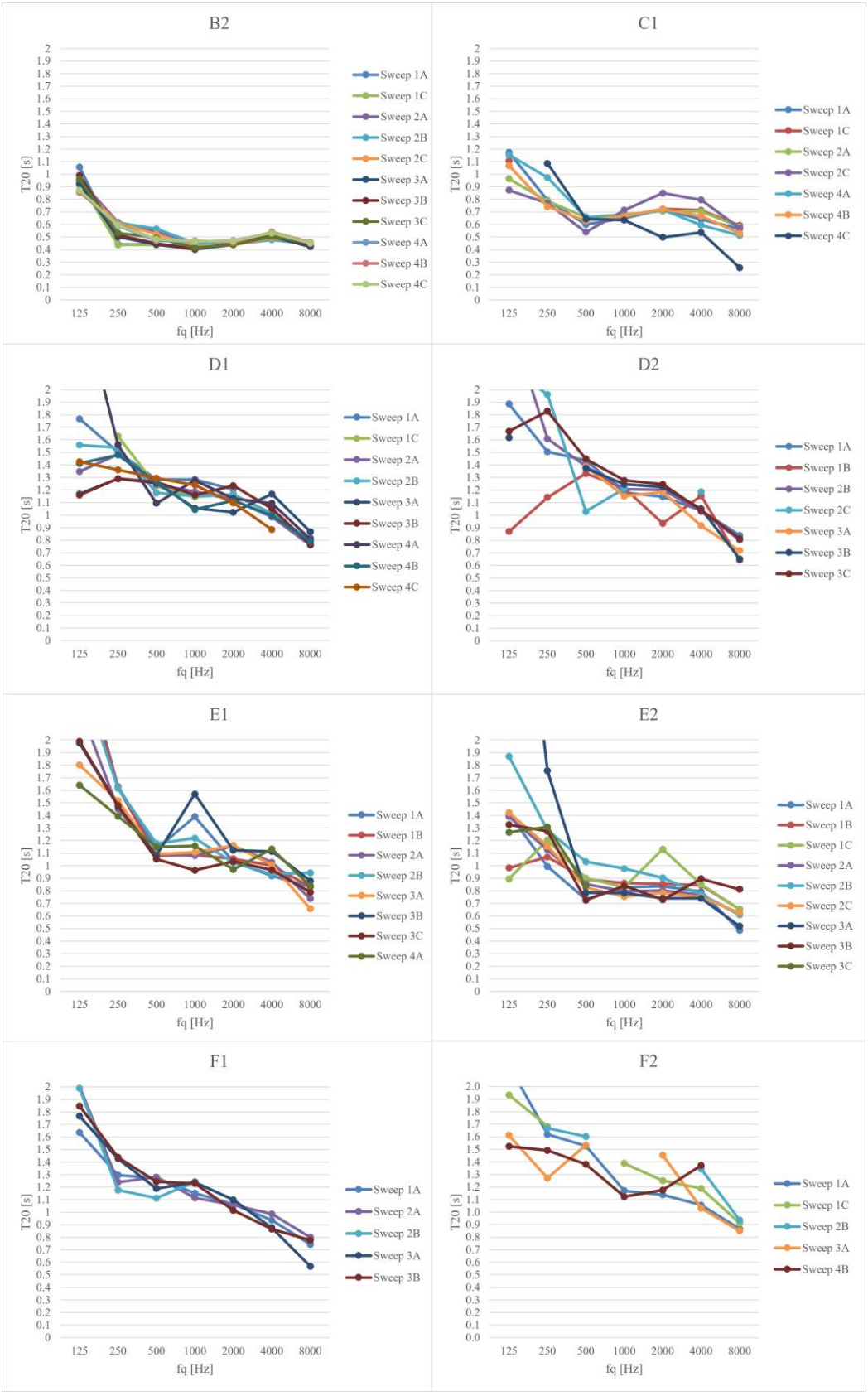
B.1. Inspection of the data

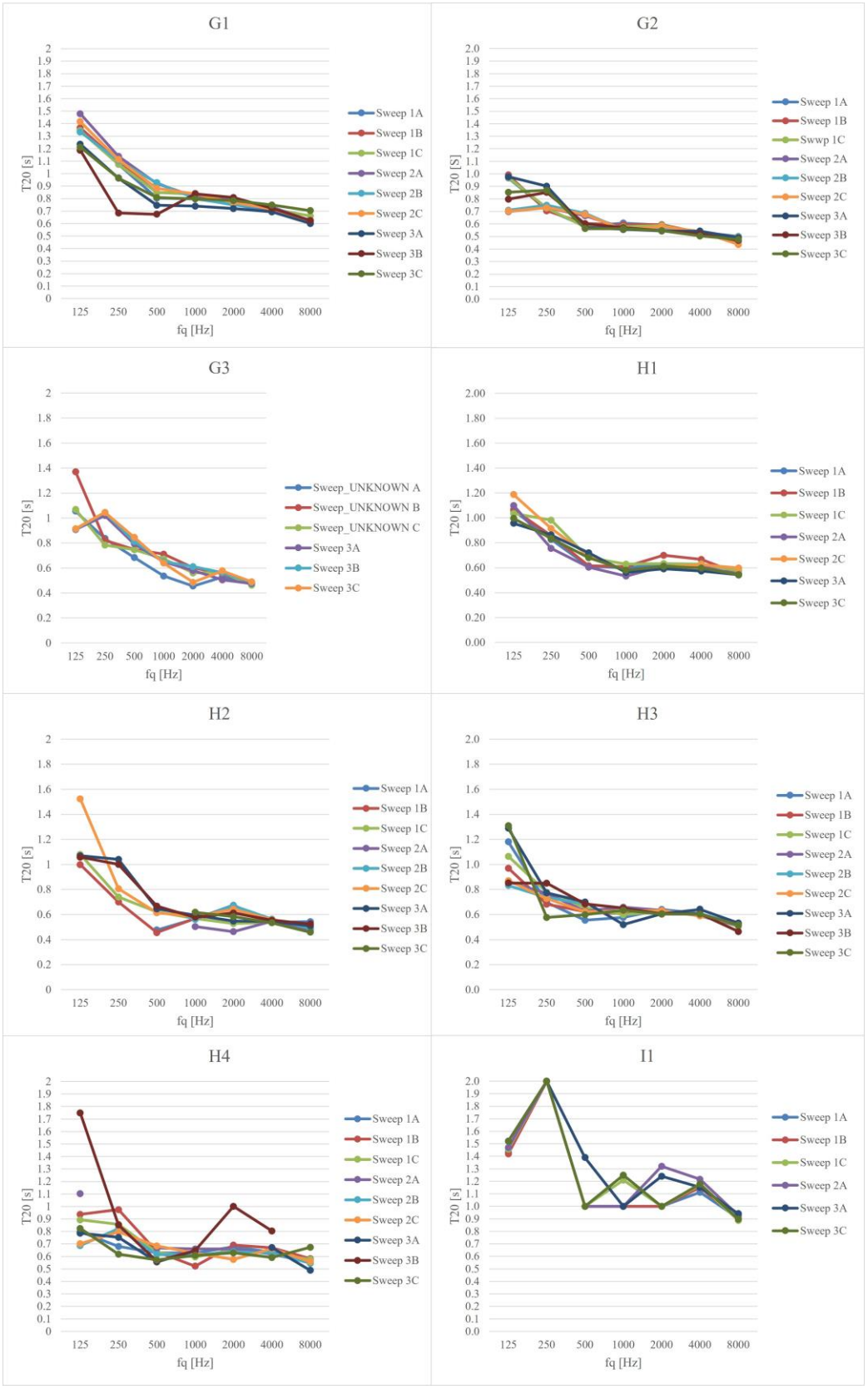
The data acquired through the application of the measurement protocol described in **Chapter 3** have been inspected and anomalous data have been excluded from the database before starting any analysis. In this Appendix the graphs of reverberation time and speech clarity are reported.

B.1.1. Graphs of reverberation time, T20

Reverberation time in occupied condition was measured along the main axes in positions ref, 1, 2, 3, and 4 through the recording of three repeated exponential sine sweep signals in each position. **Figure B.1** shows the results of the measurement of reverberation time in each position, when available, and in each classroom.




B2
T20 [s]
fq [Hz]
125 250 500 1000 2000 4000 8000
Sweep 1A
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
Sweep 4A
Sweep 4B
Sweep 4C
C1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1C
Sweep 2A
Sweep 2C
Sweep 4A
Sweep 4B
Sweep 4C
D1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 3A
Sweep 3B
Sweep 4A
Sweep 4B
Sweep 4C
D2
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
E1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 2A
Sweep 2B
Sweep 3A
Sweep 3B
Sweep 3C
Sweep 4A
E2
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
F1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 2A
Sweep 2B
Sweep 3A
Sweep 3B
F2
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1C
Sweep 2B
Sweep 3A
Sweep 4B


G1
T20 [s]
fq [Hz]
125 250 500 1000 2000 4000 8000
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
G2
T20 [S]
fq [Hz]
Sweep 1A
Sweep 1B
Swwp 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
G3
T20 [s]
fq [Hz]
Sweep_UNKNOWN A
Sweep_UNKNOWN B
Sweep_UNKNOWN C
Sweep 3A
Sweep 3B
Sweep 3C
H1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2C
Sweep 3A
Sweep 3C
H2
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
H3
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
H4
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
I1
T20 [s]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 3A
Sweep 3C

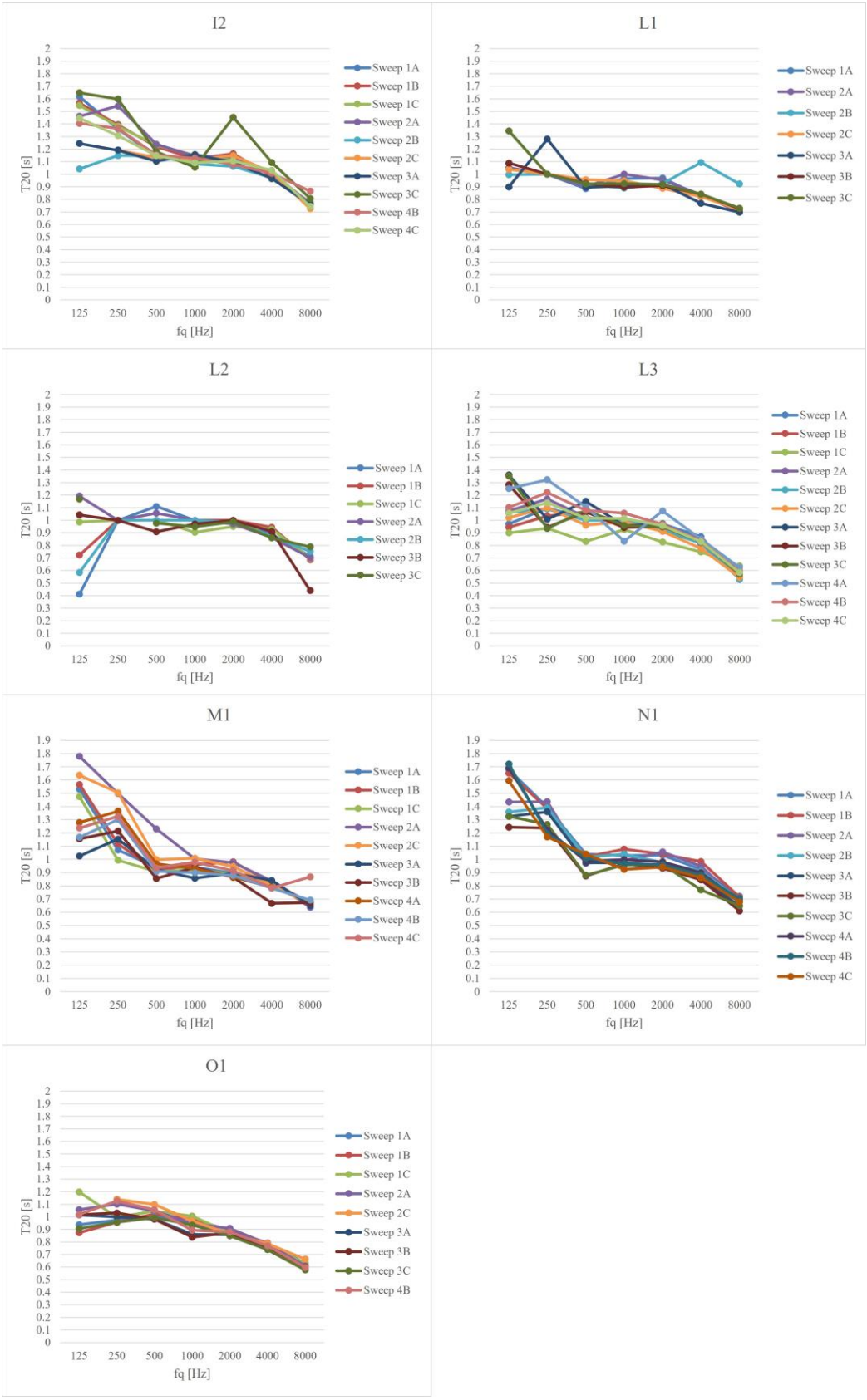
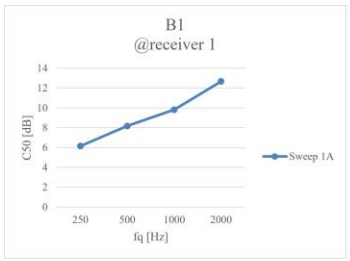


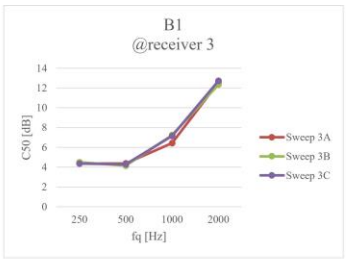
Figure B.1. Graphs of measured reverberation time in occupied condition, T20, for each classroom, position, and emitted exponential sine sweep. The number following the word "Sweep" refers to the position of acquisition, while the letter A, B, or C indicates the first, second or third exponential sine sweep emitted in the same position, respectively.

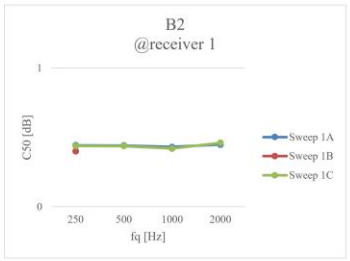
B.1.2. Graphs of speech clarity, C50

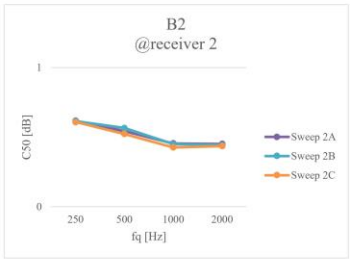
Speech clarity was measured along the main axes in positions ref, 1, 2, 3, and 4 through the recording of three repeated exponential sine sweep signals in each position. **Figure B.2** shows the results of the measurement of speech clarity, C50, in positions 1, 2, and 3, when available, for each classroom.

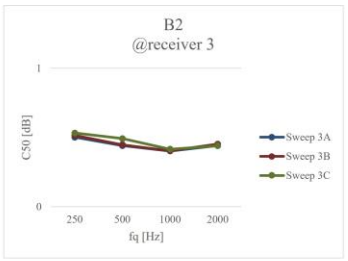


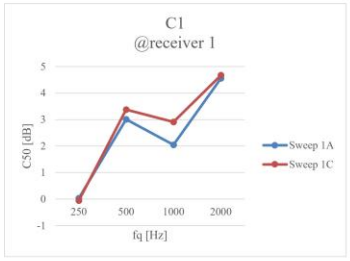

B1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A

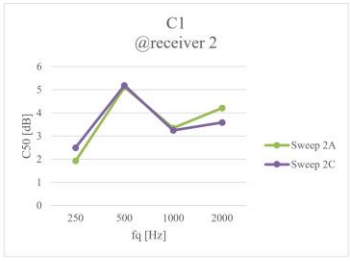

B1
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

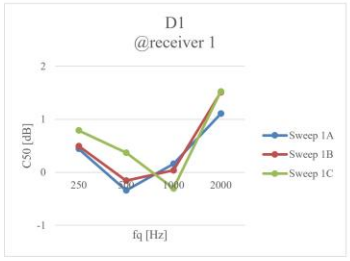

B2
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

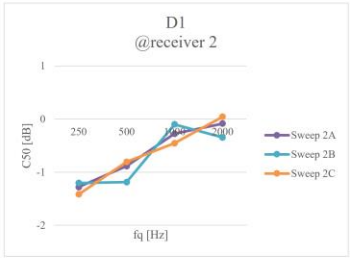

B2
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C

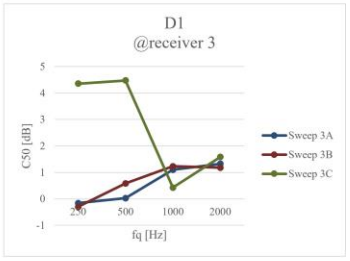

B2
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

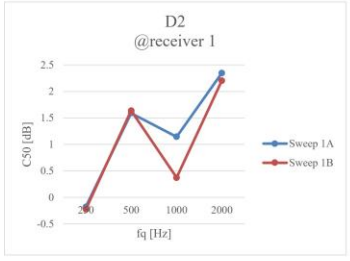

C1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1C

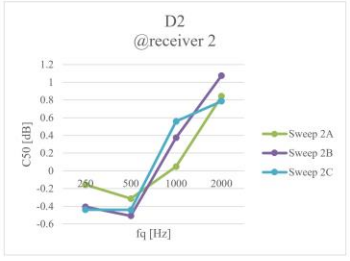

C1
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2C

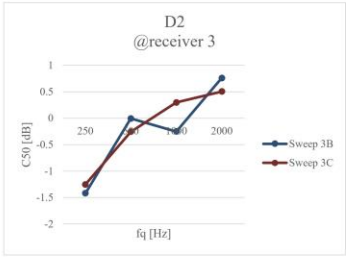

D1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

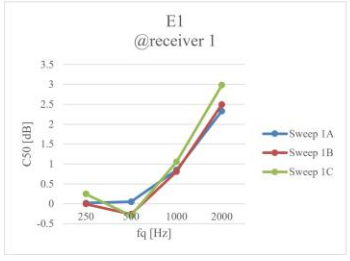

D1
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C

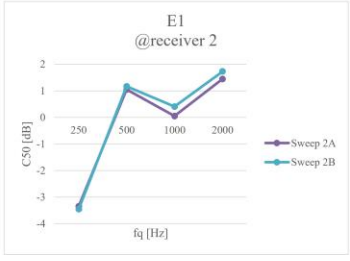

D1
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

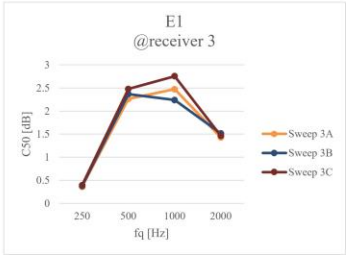

D2
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B

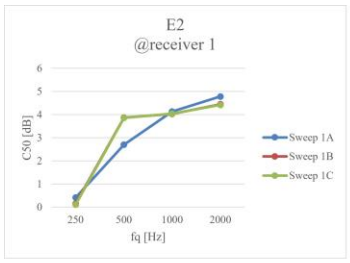

D2
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C

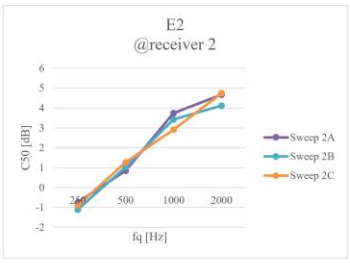

D2
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3B
Sweep 3C

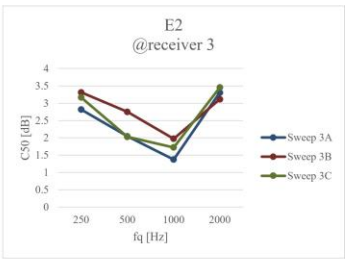

E1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

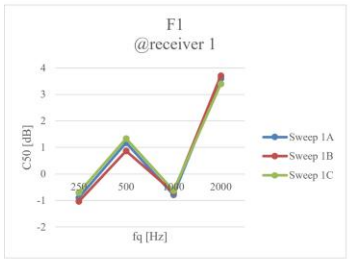

E1
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B

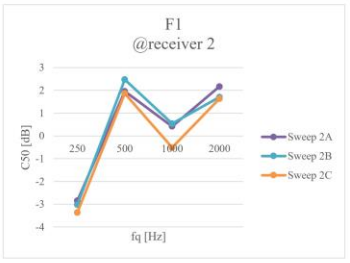

E1
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

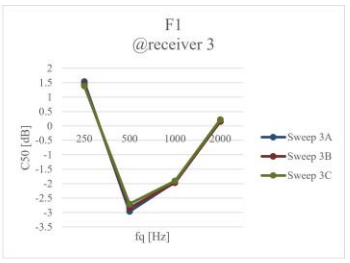

E2
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

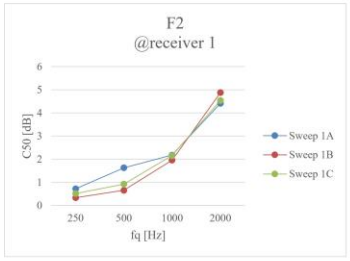

E2
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C

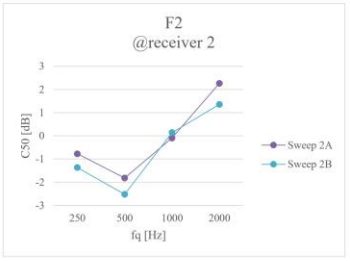

E2
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

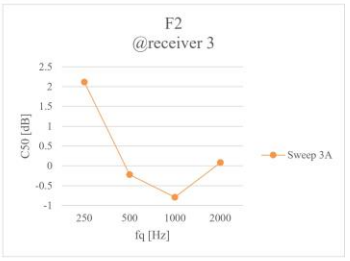

F1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

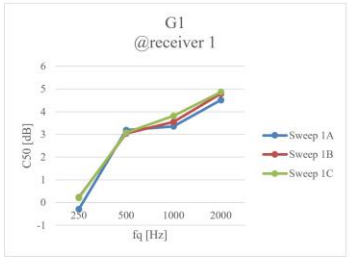

F1
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C

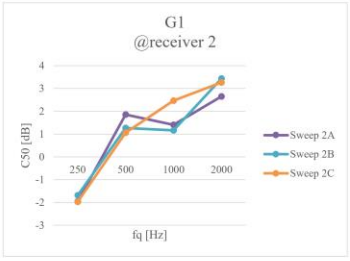

F1
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

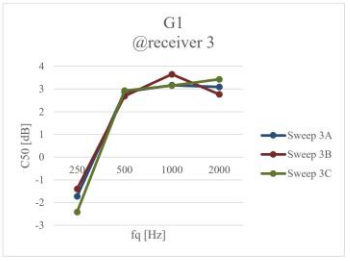

F2
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

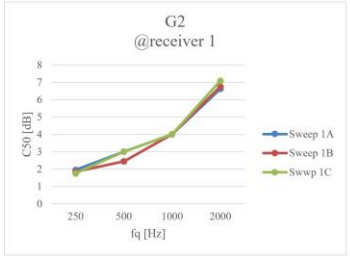

F2
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B

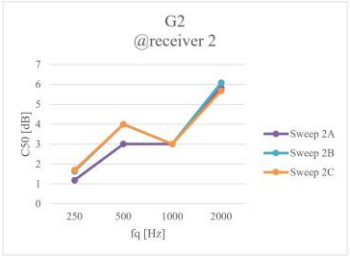

F2
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A

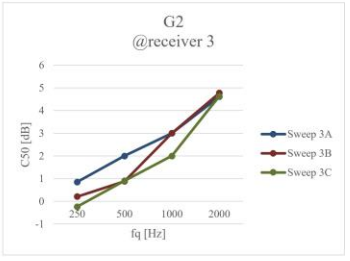

G1
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C

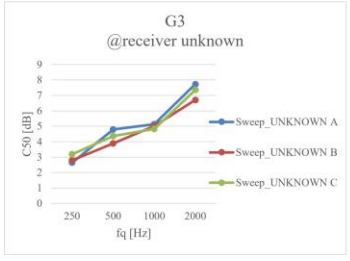

G1
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C


G1
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C

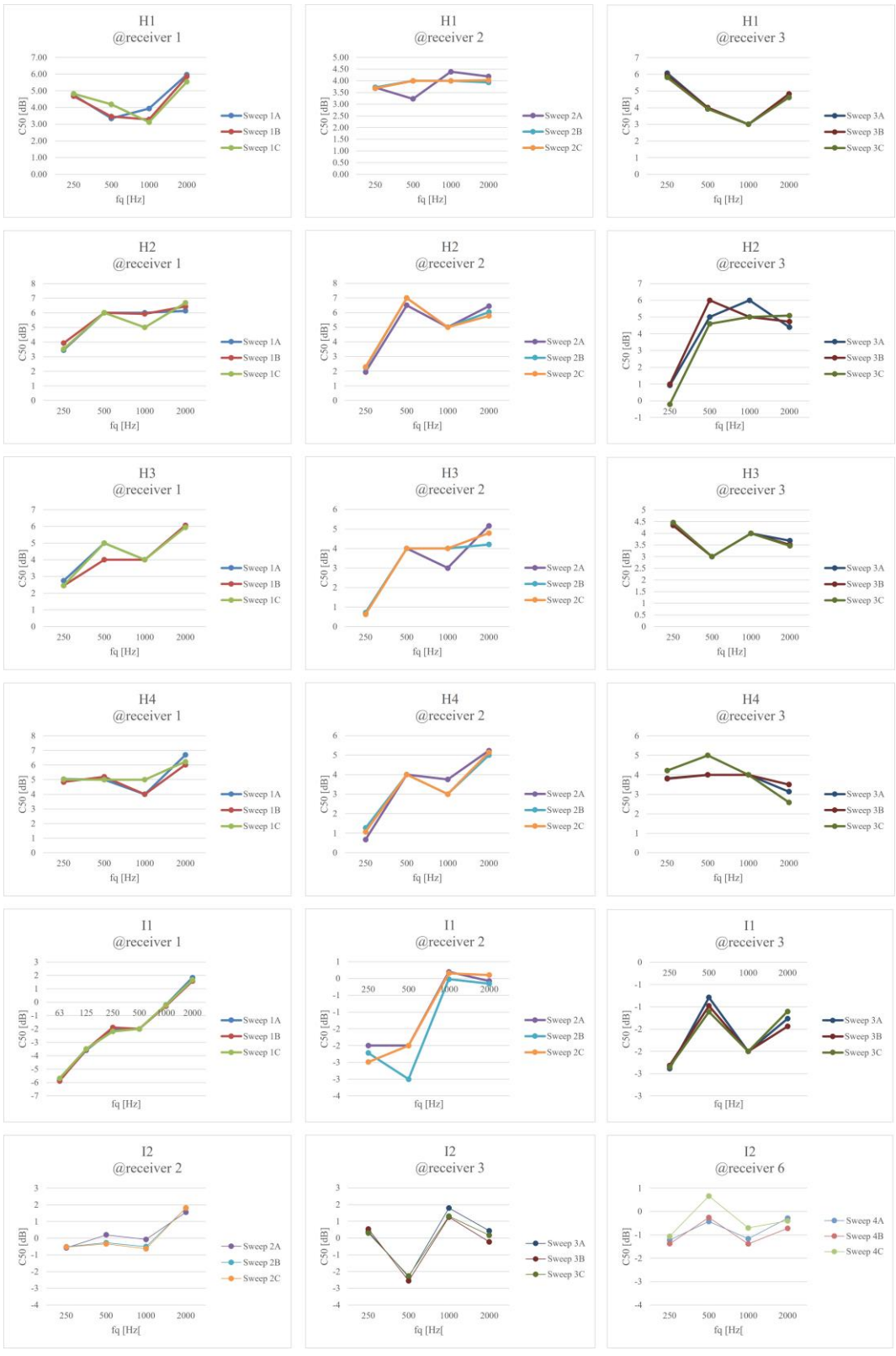

G2
@receiver 1
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Swwp 1C


G2
@receiver 2
C50 [dB]
fq [Hz]
Sweep 2A
Sweep 2B
Sweep 2C


G2
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C


G3
@receiver unknown
C50 [dB]
fq [Hz]
Sweep_UNKNOWN A
Sweep_UNKNOWN B
Sweep_UNKNOWN C


G3
@receiver 3
C50 [dB]
fq [Hz]
Sweep 3A
Sweep 3B
Sweep 3C


H1 @receiver 1
H1 @receiver 2
H1 @receiver 3
H2 @receiver 1
H2 @receiver 2
H2 @receiver 3
H3 @receiver 1
H3 @receiver 2
H3 @receiver 3
H4 @receiver 1
H4 @receiver 2
H4 @receiver 3
I1 @receiver 1
I1 @receiver 2
I1 @receiver 3
I2 @receiver 2
I2 @receiver 3
I2 @receiver 6
C50 [dB]
fq [Hz]
Sweep 1A
Sweep 1B
Sweep 1C
Sweep 2A
Sweep 2B
Sweep 2C
Sweep 3A
Sweep 3B
Sweep 3C
Sweep 4A
Sweep 4B
Sweep 4C

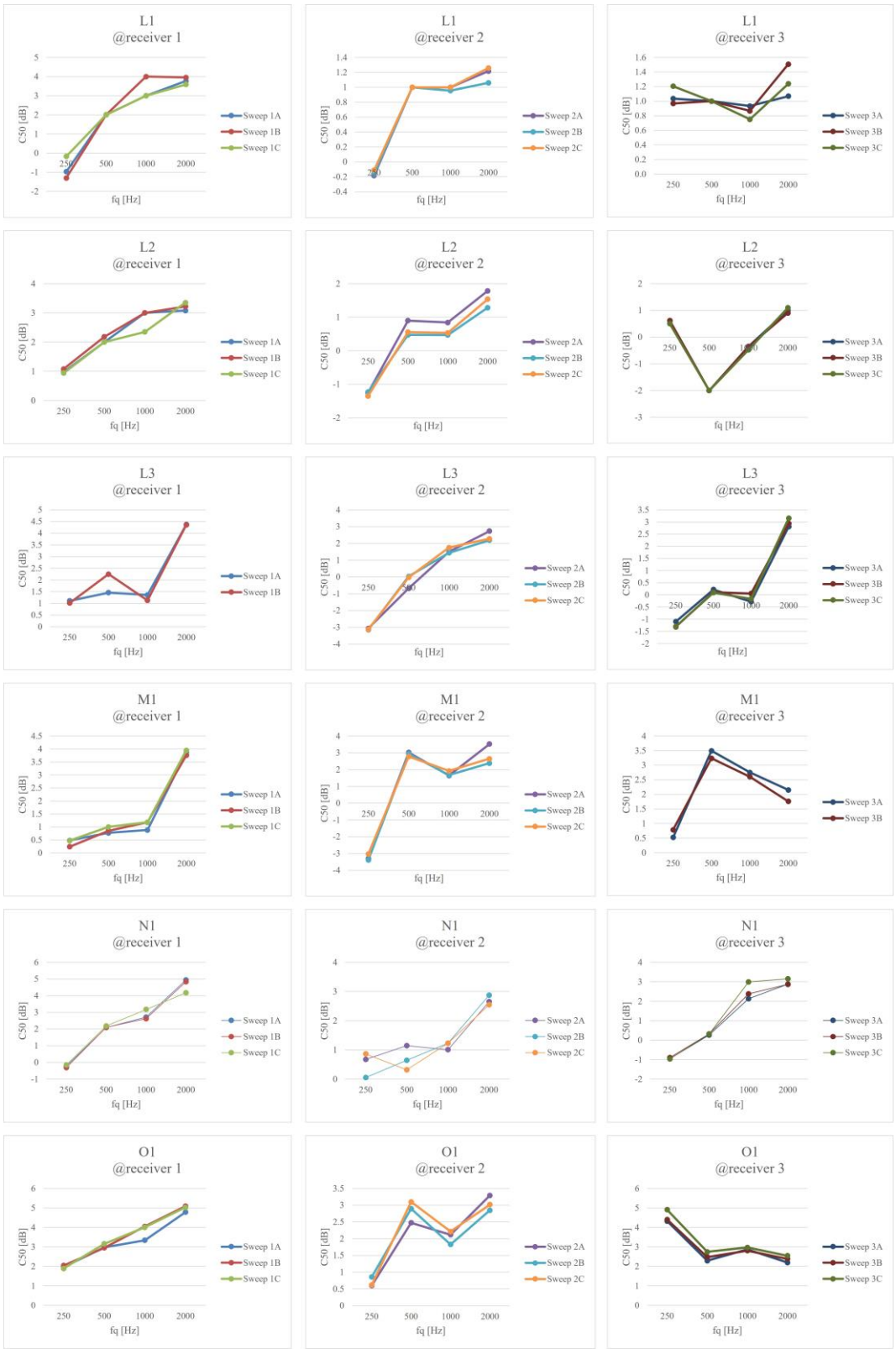


Figure B.2. Graphs of measured speech clarity, C50, for each classroom, position, and emitted exponential sine sweep. The number following the word “Sweep” refers to the position of acquisition, while the letter A, B, or C indicates the first, second or third exponential sine sweep emitted in the same position, respectively.

Appendix C
Insights on sound propagation for a different design approach

C.1. Speech level propagation

The propagation of the speech level, L_S, along the main axis of the classroom does not differ for C and NC for both subdivision (a) and (b), as described in **Chapter 3**. This emerges from the boxplots in **Figure 6** and **Figure 7** and from the p-value in **Table 11** and **Table 12**. It is also shown in **Figure C.1** hereafter. The following section focus only on the subdivision (a), since the classes assigned to C and NC are more equally distributed in number. **Figure C.2** graphically represents the L_S regression lines for C and NC classrooms considering subdivision (a) and obtained by averaging the speech levels at different distances from the source for the two groups of classrooms. Particularly, the slopes per double distance of the speech level, mL_S, in NC, represented by a reverberation time of 1.1 s as average, and in C, with a reverberation time of 0.7 s as average, is almost the same and it is around -2 dB/dd in both the conditions. This result was unexpected since different values were expected in C and NC, so further analyses concerned the slope of the parameter sound strength (G).

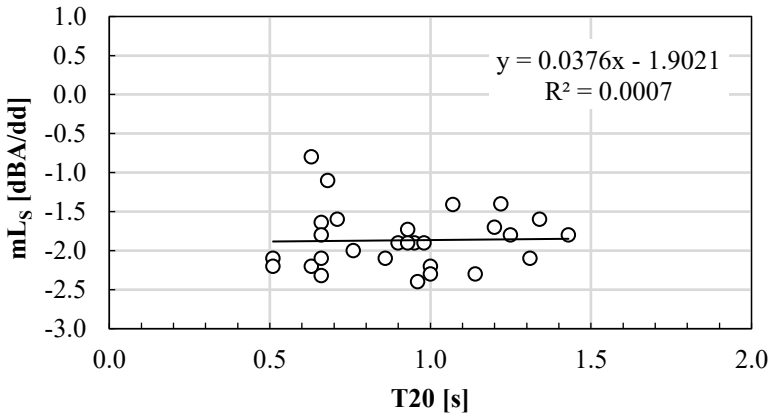


Figure C.1. Regression line between slope per double distance of the speech level and reverberation time.

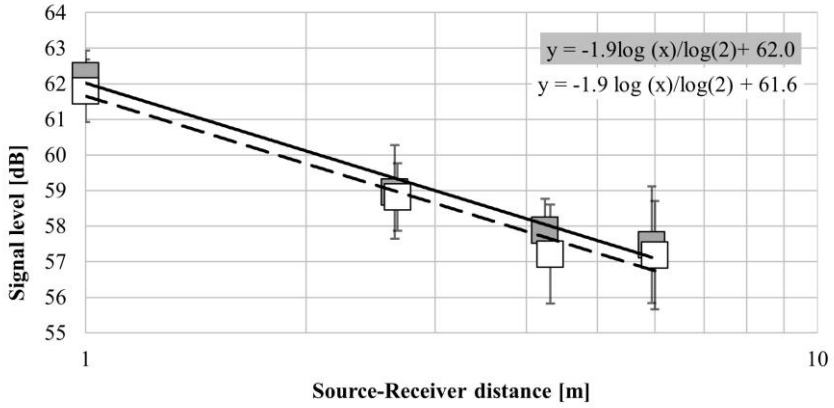


Figure C.2. Regression lines of the propagation of the speech level along the main axis, L_S, in NC (gray square and solid line) and C classrooms (white squares and dashed line). The regression lines are obtained considering the L_S mean values for the positions ref, 1, 2, and 3.

G represents the logarithmic ratio of the sound energy of the measured impulse response to that of the response measured in a free field at a distance of 10 m from the sound source (Sato and Bradley, 2008; ISO 3382-1:2009). Its components G_{50}, G_{late} and G_{tot}, being referred to the first 50 ms of the sound energy, to the sound tail after 50 ms, and to the total sound energy, respectively, have been examined in terms of slope per double distance. G values have been calculated with Adobe Audition Aurora plug-in (http://pcfarina.eng.unipr.it/Aurora_XP/index.htm), in agreement with the procedure described in Sato and Bradley (2008). A calibration file, which consisted in the impulse response recorded at the reference position of classroom A1 and muted in its late component, was used for the calculation.

G_{tot}, G_{50} and G_{late} have been represented in C and NC along the main axis of the classrooms in **Figure C.3**. The same slope of -2 dB/dd was obtained in the case of G_{tot}, in both C and NC. From the graph it is also visible that the slope of the G_{50} is the same, and it is around – 3 dB/dd, in C and NC. Instead, the slope of the G_{late} differs in the case of C and NC acoustics and it is -0.6 dB/dd and -0.9 dB/dd, respectively.

It is important to observe that in the case of NC acoustics at the back of the room, i.e., at the position that is more distant from the source, values of G_{50} and G_{late} are very similar, or cohincident. For good speech intelligibility G_{50} should be larger than G_{late}, particularly at more distant listening positions (Sato and Bradley, 2008).

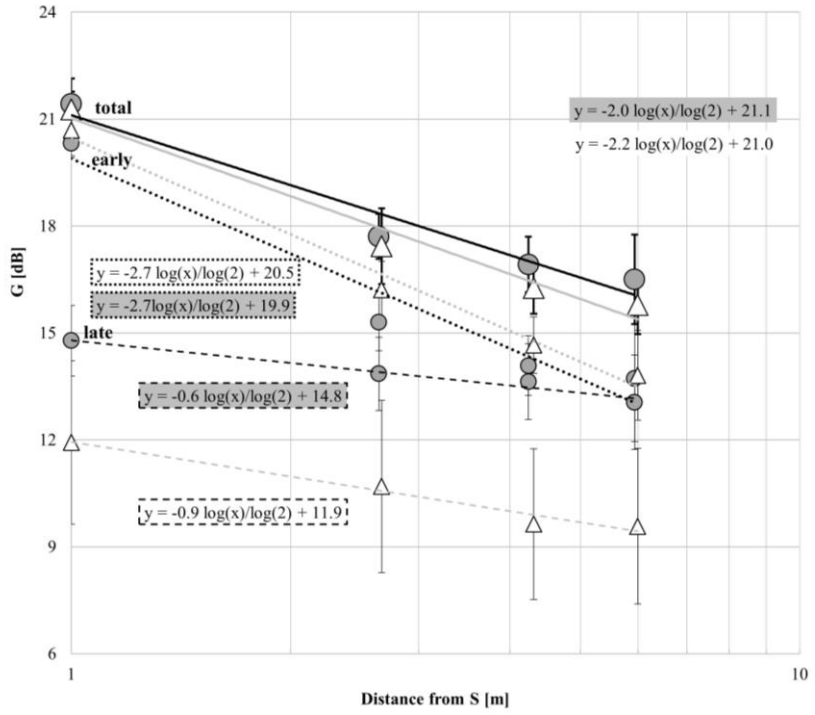


Figure C.3. Regression lines of the propagation along the main axis of G_{tot} (solid line), G_{50} (round dot line) and G_{late} (dashed line) in classrooms with NC (values are grey circles and regression lines are black) and C (values are white triangles and regression lines are light grey). The regression lines are obtained considering the G mean values for the positions ref, 1, 2, and 3.

C.2. A different design approach

As indicated in **Chapter 3,** design criteria should not specify maximum reverberation time, but a range of acceptable values. In order to identify an optimal reverberation time range, Sato and Bradley (2008) proposed an approach that would aim to optimize conditions at a 6 m distance from the teacher, that is the more distant listening location in a typical elementary school classroom. The proposed design approach rely on the interrelations between reverberation time, useful-to-detrimental ratio and G_{50} and G_{late}. In particular, they selected the optimal reverberation time as the one that maximizes the difference between G_{50} and G_{late} at the farthest listening positions from the teacher and that maximizes U50. They based their study on calculated values, while in this study we refer to measured values.

Hereafter, a replication of the design approach proposed by Sato and Bradley (2008) is given based on the dataset presented in **Chapter 3** and in the present **Appendix C. Figure C.4** and **Figure C.5** show the relationships between T20 and G_{tot}, G_{50}, G_{late}, and U50, respectively. The graph in **Figure C.4** identifies the optimal reverberation time range, that is between 0.6 s and 0.9 s, based on the difference between G_{late} and G_{50} at 6 m distance from the teacher, i.e., at the back of the classroom. Particularly, it has been safely assumed that G_{late} should be from 3 dB to 6 dB lower than G_{50} in any position inside the classroom, especially at the farthest listening locations from the speech source. 3 dB are equivalent to halving G_{50} energy, while 6 dB maximizes the difference between G_{late} and G_{50} without lowering too much the reverberation time, which should be avoided. On the other side, the graph in **Figure C.5** shows that the central value of this optimal range, equal to 0.75 s, corresponds to U50 of 1 dB, that according to Bradley et al.(1999) is the minimum value for optimal speech intelligibility in classrooms. This results corroborates the outcomes of other studies that found a 0.75 s reverberation time as optimal to support speech intelligibility (Yang and Bradley, 2009) and vocal effort (Puglisi *et al*, 2017; Calosso *et al.*, 2017) in classrooms.

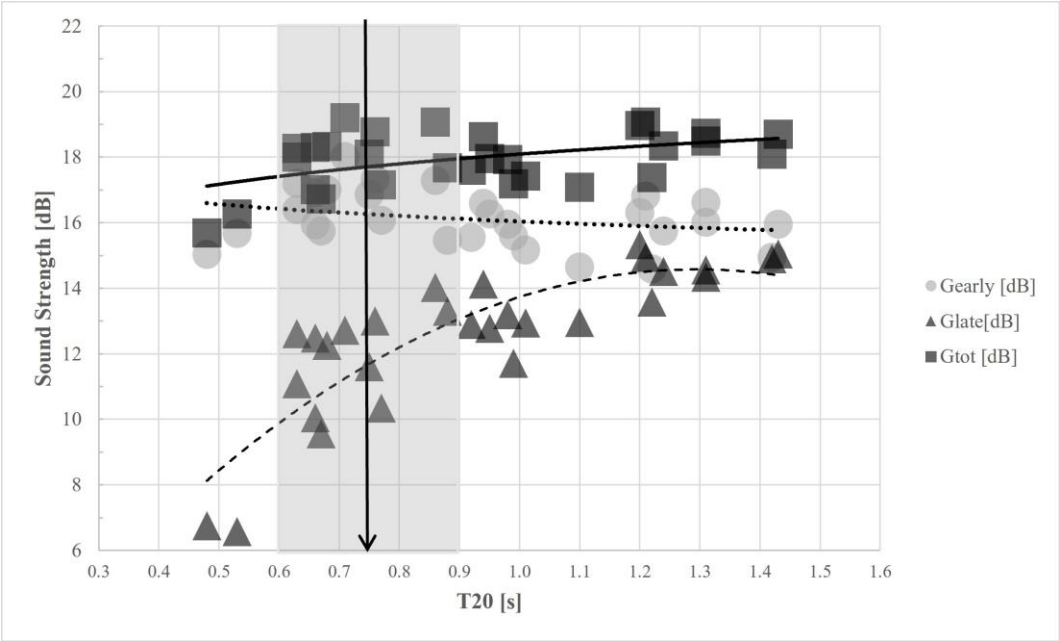


Figure C.4. Relationships between T20 and G_{tot}, G_{50}, G_{late}. The shaded area indicates the range of optimal reverberation time referred to the difference between G_{late} and G_{50} from 3 to 6 dB.

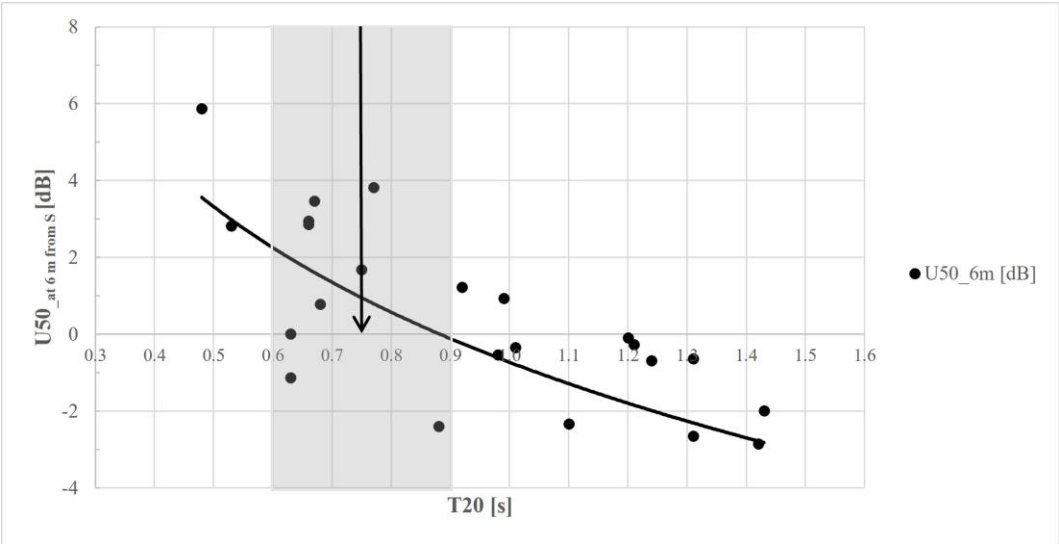


Figure C.5. Relationship between T20 and U50. The shaded area indicates the range of optimal reverberation times referred to the differences between G_{late} and G_{50} from 3 to 6 dB. The arrow highlights the optimal reverberation time of 0.75 s which is related to optimal U50 equal to 1 dB.

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Chapter 4
Investigating the effect of classroom acoustics on noise disturbance and well-being

Objective	To investigate the effect of classroom acoustics on noise disturbance and well-being for pupils aged 6 to 7 years through questionnaires and acoustical measurements.
Outcome	Poor classroom acoustics bring pupils to a reduced perception of having fun and being happy with themselves and it is related to an increased perception of noise intensity and disturbance.
Highlights	• About 330 pupils aged 6 to 7 years and belonged to 20 classes participated in the study. • Questions included the happiness scale, subscales assessing self-esteem, emotional health, relationship at home and with friends, enjoyment of school, intensity and noise disturbance due to different sound sources, and quality of voice. • Background noise level in silence and during group activities, reverberation time, speech clarity, useful-to-detrimental ratio and speech level, were acquired along the main axis of the classroom and in one or two positions offset to the axis.
Notes	Parts of this chapter have been published in: ▪Astolfi et al., "*Influence of classroom acoustics on noise disturbance and well-being for first graders*", Frontiers in Psychology 2019, 10: 2736.

4.1. A pilot study to investigate the effects of classroom acoustics on the perceived well-being and noise disturbance in first graders

From **Chapter 2**, it is clear that unfavorable acoustics in classroom not only determines challenging environments for children and affect their learning process, especially at the lowest grades of education, but poor acoustics also affects the emotional status of the students immersed in it. Research has widely focused on the effects that classroom acoustics has on the teaching and learning process, but few studies have investigated the perception of noise disturbance at school and the influence of poor acoustics on pupil's well-being. Particularly, no study has investigated, with in-classroom surveys, children wellbeing at school. Another important lack in the literature is the investigation of fundamental aspects of school life at the lowest grade of primary education, i.e., for most of the countries in Europe from 6 to 7 years. It is in the early childhood that the neuroplasticity of the human brain cortex is still high, and interventions can produce more positive effects. At the cortical level, various sensory and cognitive systems interact and adjust functional properties based upon experience and learning (Cardon *et al.,* 2012). This chapter is thus dedicated to the description of a pilot study to investigate to which extent classroom acoustics affects the perceived well-being and noise disturbance in children. To this aim, room acoustic measurements were performed in 20 primary classrooms in Turin, Italy, and questionnaires have been administrated to about 330 pupils aged 6 to 7 years. The database used in this chapter is part of that used in **Chapter 3**.

This chapter is organized as follows. The next paragraphs present the main findings about the children perception of the sound environment at school and about the associations between noise annoyance and well-being, based on which the need to investigate the effect of poor acoustics on noise disturbance and well-being at school emerges. The methodology section presents the participants, schools and classrooms involved in the present study. Then the questionnaires administrated to the participants are described, together with the applied statistical analysis. Significance of the differences and correlation analysis allowed for the identification of the effect of classroom acoustics on well-being and noise disturbance on children.

4.1.1. Children perception of the sound environment at school

Together with the presence of noise sources as distractors for children's ability to understand, the subjective perception of the sound environment makes it very different the way listeners experience their everyday living spaces. Brännström *et al.* (2017) investigated on the 9- to 13-year-old children's personal ratings of perceived noise in order to improve the classrooms' design. They found that children were more annoyed to noise in tasks where the demands of verbal

processing are higher. Dockrell and Shield (2004) administered a survey on the perception of noise in schools to children of grades 2 and 6. The more the external noise level increased, the more they were annoyed and the less they reported to be able to hear the teacher speaking inside the classroom. Astolfi and Pellerey (2008) assessed the subjective and objective environmental quality in classrooms involving 1,006 high school students with an average age of 16.1 years. They found that students reported to be strongly annoyed by noise sources internal in the classroom, i.e., other students talking in the classroom, and as a side effect of poor classroom acoustics on the overall perception of the school environment, students reported a decrease in their ability to concentrate.

Association between noise annoyance and well-being

Extensive literature on the subjective perception of the sound environment, especially with surveys in-field, is anyway lacking so far on the possible comorbidities that go beyond the students' performance at school. Well-being relates to the way people feel and function, thus it impacts people's daily life. Particularly, research should thus focus on the assessment of the association between the perception of sound environment at school, in terms of noise annoyance, and of the wide concept of personal well-being. In fact, as the concept of well-being is composed of three main aspects, that is, subjective, psychological, and social well-being (Ryff and Singer, 1998; Diener, 2006; Keyes, 2013), it can be assumed to be strongly linked to the experience of everyday life situations and circumstances. While noise annoyance has become recognized as an important environmental stressor, its association to well-being has hardly been studied.

Some researchers found no association between noise from airplane and traffic and children well-being. In particular, chronic aircraft noise exposure resulted associated with high levels of noise annoyance but not to mental health problems in over 300 children aged 8–11 years (Haines *et al.,* 2001). Mental health is defined by World Health Organisation (WHO, 2014) as "a state of well-being in which every individual realizes his or her own potential, can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to her or his community." Also, Stansfeld *et al*. (2009) reported no association between either aircraft or road traffic noise exposure and the Strengths and Difficulties Questionnaire (SDQ) total score, in more than 2,000 children aged 9–11 years. This questionnaire is a largely used psychometrically valid instrument to assess mental health of children aged 3–16 years, but the drawback of this tool is that for younger children, it has to be filled in by parents at home (Goodman, 2001).

On the opposite, Crombie *et al.* (2011) showed association between noise and mental health. Particularly, they found a relationship between road- and aircraft-generated noise and the incidence of mental problems in 9- to 10-year-old children. Lim et al. (2018) have found that high noise levels and high noise sensitivity determine less mental health of children and adolescents and that the effects of these noise-related variables depend on socioenvironmental factors. At school, Klatte and

Hellbrück (2010) found that the children from classrooms with poor acoustics reported a higher burden of indoor noise in the classrooms and judged their relationships to their peers and teachers less positively than children from classrooms with good acoustics. As a further study, Stansfeld *et al.* (2000) reviewed a set of studies on the relationship between noise and mental health. They found, as a general result, that noise was associated with stress-related factors of mental health (e.g., self-reported stress, sociability, and behaviors) and with well-being in children.

Other researchers investigated physiological symptoms of mental health, such as Evans *et al.* (2001) who found that children who lived in noisier areas had elevated resting systolic blood pressure and 8-h overnight urinary cortisol. Moreover, under laboratory conditions, they found that children from noisier neighborhoods showed elevated heart rate reactivity to reading tests. Similarly, Wålinder *et al.* (2007) studied the physiological and psychological stress reactions of children in relation to classroom noise. They reported that equivalent noise levels in classrooms, in the range between 59 and 87 dB(A), were significantly related to an increased prevalence of symptoms of fatigue and headache and to a reduced diurnal cortisol variability, indicating that noise should be focused on as a risk factor for children's well-being in the school environment.

As comorbidities, the exposure to road traffic noise in both residential and school areas was found to be associated in children aged between 7 and 11 years with emotional symptoms (Dreger *et al.,* 2015) and hyperactivity and inattention (Forns et al., 2016; Hjortebjerg et al., 2016).

Need to investigate the effect of BA at school on noise disturbance and well-being for first graders

Going beyond the available knowledge is therefore necessary, especially to understand if poor acoustics and other factors at school, where children spend most of their time, directly influence their harmonic growth, learning, and well-being. The research should be focused at the lowest grades of education, when interventions can be more effective for children. In addition, subjective outcomes should be acquired by children themselves at school, while they are having classes, in order to catch their feeling while they are immersed in the classroom environment. Most of the previous studies on well-being for children aged less than 11 years are instead based on questionnaires administrated to parents or filled in by parents or children at home, and to the authors' knowledge, only few works are available so far in literature that carried out well-being and noise disturbance surveys with first graders at school. And few studies compared results from questionnaires with acoustic measures of noise, room acoustics, and speech intelligibility. This comparison is essential for planning future interventions and increase learning and well-being of children.

This chapter is thus dedicated to the description of a pilot study to investigate to which extent classroom acoustics affects the perceived well-being and noise

disturbance in children. Noise disturbance has been used in this study, instead of noise annoyance, as noise annoyance is a multifaceted concept that could be more complicated for children as it includes, beside noise disturbance, interferences with some activities, nuisance, unpleasantness, and other factors (Guski *et al.,* 1999; Di Blasio *et al.,* 2019). The purposes of the adopted approach, which was based on the combination of objective and subjective measurements, can be summarized in three main points:

(i) assessment of classroom acoustics of first graders at school;
(ii) assessment of the perceived well-being and noise disturbance at school;
(iii) association between classroom acoustics, perceived wellbeing, and noise disturbance. To reach the proposed objectives, room acoustic measurements were performed, and noise levels were monitored during classes. Then, based on the work by Sabri et al. (2015), questions on the perceived well-being inside the classroom environment were designed, containing information on emotional well-being (self-esteem, emotional health, and resilience), friends and family (quality of the relationship), satisfaction of school, and life satisfaction. To build a questionnaire oriented to investigating a multidimensional measure of school-related quality of life, based on Dockrell and Shield (2004) and Astolfi and Pellerey (2008), the abovementioned information was integrated with questions on the perceived noise disturbance.

4.2. Method

4.2.1. Participants

During a meeting for the presentation of the research project, teachers and parents have been informed about the project goal and the scientific evidence of the relationship between acoustics and subjective perceptions and well-being. Only pupils with parental consent were involved in this study, resulting in 367 students from 20 first-grade classes belonging to 10 primary schools in Turin. In the classes, a total number of pupils in the range between 8 and 25 was present. Subjects aged 6 represented 62% of the total, while 37% was aged 7 and only 1% was 8 years old. There were more males (54%) than females (45%). The overall sample consisted of 77% Italian mother tongue (MT) pupils, while 23% used other primary languages in their family context (e.g., Romanian, Moroccan, English, German, Spanish, Albanian, and Arabic). Furthermore, some subjects declared to speak a second language besides Italian. Table 1 shows the sociodemographic characteristics of the considered sample. Twenty-seven subjects were excluded from the data analysis because of cognitive or hearing deficits proved by the school administration through an official medical certificate or due to incorrect completion of the questionnaire.

4.2.2. Schools and classrooms

Table 14 reports information about the school buildings and classes involved in the research project. Database in **Chapter 3** expanded the one used in this study, so the 20 classes described hereafter coincide with their homonymous in **Chapter 3**. Schools differed in location, period of construction, and architectural features. They are scattered in the city of Turin, in neighborhoods characterized by "low" or "medium" volume of traffic depending on the road typology as defined by the UK Department of Transport (2012), i.e., local road for local traffic or road intended to connect different city areas but not intended to provide largescale transport links. In the case of medium volume of traffic, classrooms were not directly facing the road, but a courtyard or a corridor was present in between. In the case of low volume of traffic, most of the classrooms faced the road. The presence or absence of an acoustic treatment (AT) in the classrooms ("yes" or "no") was based on the presence or absence of whatever sound-absorbing material.

4.2.3. Acoustic measurements

Acoustic parameters and adopted protocol

Acoustic measurements were performed as described in **Chapter 3**. They were performed within 1 day approximately in the last 2 months of the school year. Measurements were carried out under occupied conditions, with the number of children inside being on average 18 across all classes. The adopted protocol regarded the acquisition of acoustic parameters that are useful to characterize the classroom's response to easy listening (Minelli et al., 2019).

Measurement results

Table 15 shows the acoustic parameters grouped for compliant (C) and non-compliant (NC) classrooms, i.e., with occupied reverberation time in or out of the optimal range of 0.5–0.8 s, respectively. Here the values already presented in **Chapter 3** are reported again for ease of comparison along this chapter. A good agreement is shown between occupied, T20, and unoccupied reverberation times, T20_e, even though in the case of the unoccupied condition, optimal values are too low compared to the measured values. For the classrooms A2, A3, C1, E1, and I1, T20_e is surprisingly lower or equal to T20. This strange behavior is due to the different frequency range assumed for the averaging, which is only confined to 0.5–1 kHz in the case of the empty room.

Optimal values are shown for speech intelligibility expressed by the parameters C50 and U50, in the C classrooms, as well as lower values of noise level during group activity, L_{N_gr}, that is strictly related to reverberation time. In contrast, noise level in silence, L_{N_sil}, does not show decreased values in NC.

No such clear tendency is shown for the parameters related to the speech level, L_{S_ref} and mL_S, with reverberation time, even though the expected values should be lower in C and higher in NC. In the case of the slope of the speech signal, mL_S,

higher values (or lower if the slope is taken in absolute value) mean values closer to zero, i.e., absence of slope due to a more uniform acoustic field.

Table 14. Description of the classrooms considered in terms of students and building features. Schools were identified based on their neighbourhood quality (i.e. "district real estate value", from OICT 2019, which was € for the property value interval of 1.000-1.500 €/m2 ; €€ for 1.500-2.000 €/m2; €€€ for 2.000-2.500 €/m2; €€€€ for 2.500-3.000 €/m2; €€€€€ for 3.000-3.500 €/m2), the presence of acoustic treatment, the year of construction and the traffic volume. IDs refer to schools (capital letters) and classrooms (number).

ID	Classroom volume (m^3)	Classes		Schools			
		Male pupils (%)	Italian mothertongue (%)	Year of construction	Acoustic treatment	District real estate value (€)	Traffic volume
A1	194	60	67	1846	Yes	€€€€€	low
A2	261	50	61	1846	Yes	€€€€€	low
A3	283	58	79	1846	Yes	€€€€€	low
B1	203	50	91	1904	Yes	€€€€€	low
C1	123	58	33	1966	No	€	low
D1	255	67	72	1891	No	€€€€	low
D2	252	57	76	1891	No	€€€€	low
E1	236	68	74	1882	No	€€€	medium
E2	236	62	67	1882	No	€€€	medium
F1	279	61	67	1913	No	€€€€	medium
F2	261	56	44	1913	No	€€€€	medium
G1	136	75	75	1975	No	€€€	low
G2	106	58	95	1975	No	€€€	low
H1	133	57	76	1968	No	€€€€	low
H2	132	48	87	1968	No	€€€€	low
H3	140	50	90	1968	No	€€€€	low
H4	132	50	85	1968	No	€€€€	low
I1	237	13	100	1909	No	€€€	low
L1	241	45	86	1921	No	€€€	low
L2	264	52	96	1921	No	€€€	low

Table 15. Acoustic parameters for compliant and non-compliant classrooms. L_{N_sil} is the noise acquired with students in silence, L_{N_gr} is the noise acquired with students doing group activities; L_{s_ref} is the signal measured at the reference point. The slope of a parameter per double distance is referred to with "m" (e.g. mL_S); the mean distribution of a parameter in the classroom is referred to with "M" (e.g. $U50_{_M}$); the value of a parameter measured in the center of the classroom is referred to with "ctr" (e.g. $U50_{_ctr}$). Standard deviations are indicated in brackets when available. Not available measures are marked as NA. Values in bold are compliant with the optimal values in occupied conditions.

ID	Acoustical parameters									
	T20_e (s)	**T20 (s)**	**L_{N_sil} (dBA)**	**L_{N_gr} (dBA)**	**L_{S_ref} (dBA)**	**mL_S (dBA/ dd)**	**$C50_{_ctr}$ (dB)**	**$C50_{_M}$ (dB)**	**$U50_{_ctr}$ (dB)**	**$U50_{_M}$ (dB)**
Non-compliant classrooms										
A1	1.0 (0.04)	0.9 (0.04)	51.7	NA	61.3	-1.9	1.0	1.3 (1.2)	-1.1	-1.2 (1.0)
A2	**0.8** (0.06)	0.9 (0.18)	49.0	64.7	61.2	-2.4	0.0	2.2 (1.8)	-1.3	0.2 (1.1)
D1	1.4 (0.06)	1.2 (0.31)	51.2	68.0	63.0	-1.8	-0.6	0.0 (0.9)	-2.1	-1.5 (1.0)
D2	1.4 (0.01)	1.3 (0.25)	52.0	NA	62.7	-2.1	0.0	-0.3 (1.1)	-1.6	-1.8 (1.4)
E1	1.2 (0.06)	1.2 (0.11)	54.0	66.6	62.1	-1.4	0.7	1.1 (0.9)	-1.5	-1.2 (0.6)
E2	1.0 (0.01)	0.9 (0.08)	54.3	73.7	61.5	-1.9	3.8	2.7 (1.0)	0.0	-0.9 (0.8)
F1	1.5 (0.01)	1.2 (0.12)	52.0	75.1	62.1	-1.7	1.1	-0.3 (1.8)	-0.9	-2.2 (1.6)
F2	1.7 (0.03)	1.4 (0.33)	52.0	73.8	62.9	-1.8	-1.1	-0.1 (1.2)	-2.7	-1.8 (1.3)
G1	1.2 (0.07)	0.9 (0.05)	51.5	72.2	62.3	-2.1	3.3	2.6 (1.0)	1.3	0.9 (0.9)
I1	1.3 (0.07)	1.4 (0.07)	45.7	59.9	61.9	-1.6	-2.2	-2.2 (0.2)	-2.6	-2.6 (0.2)
L1	NA	1.0 (0.05)	47.9	67.4	61.1	-1.9	1.2	1.6 (1.0)	0.0	0.4 (1.1)
L2	1.2 (0.02)	1.1 (0.07)	46.0	71.6	62.0	-2.2	0.6	0.5 (2.0)	-0.1	-0.2 (2.1)
Compliant classrooms										
A3	**0.8** (0.05)	**0.8** (0.05)	38.4	61.8	60.3	-2.0	**5.1**	**4.1** (0.9)	**4.8**	**3.8** (0.9)
B1	**0.6** (0.07)	**0.5** (0.05)	49.3	66.3	60.8	-2.1	**7.3**	**7.6** (1.5)	**2.9**	**4.0** (1.9)
C1	0.8 (0.03)	**0.8** (0.12)	49.3	62.2	62.8	-1.6	2.8	**3.3** (0.8)	**1.9**	**2.2** (0.6)
H1	0.8 (0.03)	**0.7** (0.20)	51.6	71.9	61.5	-1.1	**3.8**	**3.6** (0.2)	**1.4**	**1.5** (0.2)
H2	0.9 (0.04)	**0.6** (0.08)	55.9	68.1	62.4	-2.2	**5.4**	**5.3** (0.2)	-1.0	-0.8 (0.5)
H3	1.0 (0.03)	**0.7** (0.04)	45.5	63.9	62.9	-1.8	**3.8**	**3.8** (0.3)	**3.0**	**3.2** (0.3)
H4	0.8 (0.04)	**0.7** (0.07)	53.1	65.5	62.9	-2.1	**3.5**	**4.1** (0.6)	-0.1	0.6 (0.6)
G2	0.9 (0.01)	**0.6** (0.01)	51.9	65.3	60.7	-0.8	**3.5**	2.9 (0.9)	**1.4**	0.8 (0.7)

4.2.4. Questionnaires

Two questionnaires have been designed in order to evaluate children subjective perception of well-being and noise disturbance while in classroom. In both cases, questions have been adapted for children of 6 years old, taking into account readability, comprehension and ease of administration of the document. An Italian translation of the questionnaire developed by Sabri *et al.* (2015), suitable for young people with special educational needs (SENs), was done and then used as the questionnaire for perceived well-being assessment, while the questionnaire on noise disturbance was adapted on the base of the work by Dockrell and Shield (2004) and by Astolfi and Pellerey (2008). Priority has been given to reduce to minimum the number of questions and to limit the number of statements to the most relevant. The translation of instructions and items was made using a back-to-back translation, that is, this procedure was used to validate that the translation content did not deviate significantly from the original. Initially, the English version was translated into Italian, then it was translated back to English and this back translation checked with the original for inconsistencies. The back translation was judged to be consistent with the original English version.

The structure of the questionnaire with the items to be answered is shown in **Table 16**, while **Appendix D** reports the printed version of the administrated questionnaire, which has been enriched with illustrations, both in the original language of administration, i.e., Italian, and translated in English. It was administrated inside the classrooms where the didactic activity takes place every day, while researchers of the Polytechnic of Turin and teachers assisted the compilation: in particular each question was read by a child in turn who was then asked to explain its meaning. If it was unclear or not understood by all, an intervention by the teacher was required in order to clarify the question. Questionnaires were filled in during sessions of about 40 min each, with a break in between, along 1 day either in May 2017 or in May 2018. Approval to conduct the present study was granted by the Politecnico di Torino Ethics Committee.

The well-being questionnaire started with an introductory section that consists in five items on sociodemographic information such as age, gender, number of people living at home, the quietest place known by the individual, primary language spoken in family. Finally, the last item of the section and the questionnaire is an open question where the child is asked to report an opinion about the feelings of their school sound environment. Then the questionnaire presents five sections: (1) self-esteem; (2) emotional health; (3) relationship at home and with friends; (4) enjoyment of school; (5) scale of happiness. Sections 1–4 consist in three questions each, where a three-point ordinal scale allows to choose the accordance among the options (a) yes, (b) not sure or (c) no. For section 5 the evaluation scale consists in a 11-point scale, where pupils had to put a cross on the number of an illustrated stair corresponding to their perceived level of happiness. A visual feedback with sketches and emoticons helped in the compilation of the questionnaire. The noise

questionnaire contained three sections: (1) perceived disturbance of specific noise sources (i.e., traffic, car sirens, internal noise, and natural noise), (2) perceived intensity and disturbance of noise during school activities performed either in silence or in group, (3) perceived voice quality under two situations, that is, while a classmate asks a question or while the teacher explains. The described sections were associated with three-point ordinal scales of evaluation, in which the judging items typically varied from the less (left) to the most (right) disturbing/annoying response. A "not at all" answer was not contemplate due to the fact that the scale was limited to three points. As it is visible from the full survey in **Appendix D**, questions Q1_N, Q2_N, Q3_N and Q4_N, were introduced by a "pre-question" asking if the student heard a certain noise while in classroom. Only students that responded yes to the "pre-question" proceeded indicating if they were disturbed a little, quite or a lot. In these terms, being a little disturbed by a noise heard in the classroom, such as that from traffic or from radios in an adjacent environment, was considered more probable than not at all. As in the well-being questionnaire, figures and emoticons were used to make it easier to identify the type of noise being investigated and a symbology that facilitated the indication of the perceived disturbance. Finally, the last item of the questionnaire consisted in an open question where the child was asked to optionally add comments.

4.2.5. Statistical analysis

The statistical analysis was carried out with SPSS (IBM Statistics 20, IBM, Armonk, NY, United States). In order to detect and eliminate outliers from the original sample, two different methodologies have been applied, one that refers to the well-being answers and the other based on the noise answers. As far as the well-being answers, pupils have been divided in two groups based on the Q13_WB answer, i.e., the happiness scale, through a 2-means cluster analysis. Particularly, unhappy children have been considered for answers from 0 to 6, and happy children for answers from 7 to 10. This subdivision was motivated by the assumption that the happiness status of the children could influence the responses given to the questionnaires, so differences have been investigated. Then, a logistic regression has been carried out considering the membership in the group as the response variable and the others well-being answers as explicative variables, and the Cook's distance, for every pupil has been obtained. The Cook's distance measures inconsistence between the response variables and the explicative ones. All the pupils with a Cook's distance higher than 0.15 have been recognized as outliers. As far as the noise answers is concerned, outliers have been automatically recognized for each class, by the corresponding box-plots related to the means of the answers from Q1_N to Q10_N.

Table 16. Administered questionnaires on the perceived well-being and noise disturbance, with scales and labels question by question

Topic	ID	Questions	Scale	Labels
Well-being				
Self-esteem	Q1_WB	I am proud of myself	1-3	Yes (1) Not sure (2) No (3)
	Q2_WB	I'm serene	1-3	
	Q3_WB	I have a lot of fun	1-3	
Emotional health	Q4_WB	Lots of things about me are good	1-3	
	Q5_WB	I feel pleased with myself	1-3	
	Q6_WB	I am a cheerful child	1-3	
Relationship at home and with friends	Q7_WB	My home is a good place to relax	1-3	
	Q8_WB	I enjoy myself with my friends	1-3	
	Q9_WB	My friends help me if I need it	1-3	
Enjoyment of school	Q10_WB	I like being in school	1-3	
	Q11_WB	I feel safe at school	1-3	
	Q12_WB	I feel like I fit in at school	1-3	
Scale of happiness	Q13_WB	Put a cross on the number corresponding to your degree of happiness	0-10	Not happy (0) Happy (10)
Noise				
Traffic disturbance	Q1_N	How much traffic noise disturb you?	1-3	A little (1) Quite (2) A lot (3)
Sirens disturbance	Q2_N	How much ambulance, firemen and police sirens disturb you?	1-3	
Disturbance from internal noises	Q3_N	How much sounds of radios or recorders coming from other classrooms or from the corridor disturb you?	1-3	
Rain disturbance	Q4_N	How much rain noise, if it's raining outside, disturb you?	1-3	
Intensity and disturbance during silent task	Q5_N	The noise present when you perform a task in silence seems you...	1-3	Low (1) Medium (2) High (3)
	Q6_N	How much does this noise disturb you?	1-3	A little (1) Quite (2) A lot (3)
Intensity and disturbance during group activity	Q7_N	The noise present when you're working in a group seems to you...	1-3	Low (1) Medium (2) High (3)
	Q8_N	How much does this noise disturb you?	1-3	A little (1) Quite (2) A lot (3)
Quality of voice	Q9_N	How do you hear the teacher's voice if you are in silence while she is talking?	1-3	Good (1) Quite good (2) Bad (3)
	Q10_N	How do you hear your classmate's voice if he or she is answering to the teacher?	1-3	

In the current sample, the Cronbach's a values of 0.69 and 0.71 have been obtained from the answers to the two questionnaires on well-being and noise disturbances, respectively, thus showing the internal consistency of both the questionnaires, i.e., a good intercorrelations among test items in each set of questions. But, being the two values not sufficiently close to unity, they also reveal that the two sets of items actually measure several unrelated latent constructs. This fact confirms that both questionnaires are suitable to capture different aspects of well-being and of noise disturbances, in the form they were designed.

Non-parametric methods have been used to analyze data obtained with ordinal scales, as in the case of this study (Sigel and Castellan, 1988). The significance of the differences between happy and unhappy children in compliant and non-compliant classrooms related to several factors concerning well-being and noise, as well as the differences between males and females, was assessed with the Mann–Whitney U Test (MWU), a test that is used for two groups of independent observations.

The relationships between the well-being and noise disturbance scores and the acoustic parameters were also investigated through the nonparametric and non-linear correlation estimator Spearman's rho (Croux and Dehon, 2010). The same approach was applied to investigate relationships between the issues concerning the school context, the MT percentage and the subjective outcomes and the classrooms characteristic acoustic parameters. However, the results of these latter correlations should be treated with caution, since the not acoustical factors, i.e., the traffic volume, the district real estate value and the mother tongue percentage, could affect the data in complex ways that such analytical tools are not able to control. In paragraph 4.5 "Strengths and limitations of the study" alternative statistical tools to be applied in future studies are given.

In order to perform a more robust correlation analysis, the acoustic parameters have been previously analyzed with respect to their expected relationships with the parameter Reverberation time, T20. All the acoustic parameters for each classroom, except L_{Neq_sil}, have been related to T20 through a linear regression, and the classrooms that did show evident anomalous tendencies have been considered outliers and thus canceled from the database. From zero to three classroom values for each parameter have been canceled from the original database. The anomalies were due to non-uniform reverberant sound field in the classroom caused by concentration due to vaulted ceilings, shape of the room, causalities in the measurements and so on.

4.3. Results

After the removal of outliers, a final sample of 326 questionnaires was used for the subjective analyses. The students were almost equally subdivided between males (54%) and females (46%), and 79.0% were Italian. A reduced sample of 296 students, corresponding to the happy children, were also used for the correlation between the subjective and objective acoustic data and between the subjective data and the classes and schools' characteristics. Unhappy children have been removed from this analysis in order to have a more homogeneous sample.

A preliminary analysis has been made in order to get differences between males and females on the single questions, considering the whole sample of children after the removal of the outliers. Apart from the questions Q5_WB (pleasances with himself or herself) and Q6_WB (cheerfulness), for which a statistical significant difference has been found between males and females according to the MWU test, and lower average scores have been gathered by males for both the questions, no difference has been found for the other well-being and noise disturbance aspects. Females have been found less pleased with themselves and less cheerful than males.

The main statistical analyses have then been carried out and the results commented in the paragraphs below. In particular, the research questions were explained through the following outcomes:

- Comparison between subjective responses on well-being and noise disturbance in compliant and non-compliant classroom acoustics for all the students (**Table 17**), for happy students (**Table 18**) and for unhappy students (**Table 19**);
- Comparison between subjective responses on well-being and noise disturbance for happy and unhappy students in C classrooms (**Table 20**) and NC classrooms (**Table 21**);
- Correlation matrix of the perceived well-being and noise disturbance scores of happy children with the classes and schools characteristics (**Table 22**);
- Correlation matrix of the acoustic parameters (**Table 23**);
- Correlation matrix of the perceived well-being and noise disturbance scores of happy children with the acoustic parameters (**Table 24**).

Standard deviations in **Tables 17** and **Table 20** are quite high considering the 1–3 points scale of the adopted questionnaires. However, they are proportionally comparable to those reported in literature for children aged from 6–7 to 10–11 years in Dockrell and Shield (2004), and in the range 9–13 years in Brännström *et al.* (2017), which adopted 1–5 points scales.

As far as the correlation analysis is concerned, some of the correlation coefficients shown in **Tables 23** and **Table 24** are low in absolute value, leading anyway to weak but statistically significant relationships according to the size of the samples.

4.3.1. Effect of poor classroom acoustics on well-being and noise disturbance for happy and unhappy children

Table 17 shows higher mean values, which corresponds to worse conditions, in NC compared to C, with significant differences according to the MWU Test, for the answers to the question Q12_WB related to the enjoyment of school, and particularly to the fitting in at school. The same occurs for the answers to the questions Q7_N, Q8_N, and Q9_N, which relate to noise disturbance during silence tasks, and to intensity and disturbance during group activity, respectively. The results highlight as noise in classrooms with higher reverberation, either from outdoor or indoor, can be perceived as more disturbing being more amplified by reverberation.

The same results that concern noise disturbance have also been found for happy students, as shown in **Table 18**, while **Table 19** shows as for unhappy students the main problem in NC only concern serenity (Q2_WB), pleasances with himself or herself (Q5_WB) and fitting in at school (Q12_WB).

Tables 20 and **Table 21** show the comparison between happy and unhappy students' subjective responses on the perceived well-being and noise disturbance, in C and NC classroom, respectively. Seven out of twelve well-being items have been judged significantly worse by unhappy students in C, compared to eleven out of twelve in NC, thus suggesting as poor classroom acoustics determines less well-being that C.

Table 17. All students' subjective responses on the perceived well-being and noise disturbance, with the sample being grouped per classroom acoustics (i.e. compliant and non-compliant classrooms). Mean (M), standard deviation (St.dev.) and the 95% confidence interval (95% C.I.) values are provided, and the p-values of significance for the differences between the two acoustic conditions, according to the MWU Test. Any statistically significant differences, with p-value < 0.05, are reported in bold.

Topic	ID	Scale	Compliant classrooms (N=139)			Non-compliant classrooms (N=187)			MWU p-value
			M	St.dev.	95% C.I.	M	St.dev.	95% C.I.	
Well-being									
Self-esteem	Q1_WB	1-3	1.24	0.50	1.15-1.32	1.25	0.55	1.17-1.33	0.86
	Q2_WB	1-3	1.43	0.71	1.32-1.55	1.56	0.76	1.45-1.67	0.11
	Q3_WB	1-3	1.19	0.52	1.11-1.28	1.23	0.54	1.16-1.31	0.35
Emotional health	Q4_WB	1-3	1.30	0.55	1.21-1.39	1.34	0.60	1.26-1.43	0.64
	Q5_WB	1-3	1.21	0.47	1.13-1.29	1.32	0.61	1.23-1.41	0.12
	Q6_WB	1-3	1.20	0.50	1.12-1.28	1.24	0.55	1.16-1.32	0.56
Relationship at home and with friends	Q7_WB	1-3	1.28	0.59	1.18-1.38	1.28	0.62	1.19-1.37	0.72
	Q8_WB	1-3	1.12	0.34	1.06-1.17	1.16	0.46	1.09-1.22	0.70
	Q9_WB	1-3	1.32	0.63	1.22-1.43	1.30	0.56	1.23-1.38	0.86
Enjoyment of school	Q10_WB	1-3	1.25	0.56	1.15-1.34	1.41	0.75	1.30-1.51	0.09
	Q11_WB	1-3	1.41	0.65	1.30-1.52	1.40	0.63	1.31-1.49	0.91
	Q12_WB	1-3	1.26	0.56	1.16-1.35	1.42	0.70	1.32-1.53	**0.03**
Scale of happiness	Q13_WB	0-10	9.24	1.83	8.94-9.55	9.28	1.99	9.00-9.57	0.51
Noise									
Traffic disturbance	Q1_N	0-3	1.88	0.87	1.65-2.10	1.89	0.84	1.67-2.11	0.92
Sirens disturbance	Q2_N	0-3	1.90	0.83	1.72-2.08	1.88	0.78	1.72-2.05	0.93
Disturbance from internal noises	Q3_N	0-3	1.83	0.81	1.66-2.00	1.75	0.75	1.60-1.90	0.56
Rain disturbance	Q4_N	0-3	1.72	0.74	1.57-1.88	1.83	0.91	1.67-1.99	0.58
Intensity and disturbance during silent task	Q5_N	1-3	1.42	0.67	1.31-1.53	1.53	0.74	1.42-1.64	0.18
	Q6_N	1-3	1.28	0.57	1.19-1.38	1.52	0.76	1.41-1.63	**0.01**
Intensity and disturbance during group activity	Q7_N	1-3	1.93	0.80	1.79-2.06	2.14	0.77	2.03-2.25	**0.02**
	Q8_N	1-3	1.74	0.78	1.61-1.88	1.97	0.83	1.85-2.09	**0.02**
Quality of voice	Q9_N	1-3	1.29	0.61	1.19-1.40	1.25	0.55	1.17-1.33	0.65
	Q10_N	1-3	1.58	0.71	1.46-1.70	1.53	0.74	1.43-1.64	0.37

Table 18. Happy students' subjective responses on the perceived well-being and noise, with the sample being grouped per classroom acoustics (i.e. compliant and non-compliant classrooms). Mean (M), standard deviation (St.dev.) and the 95% confidence interval (95% C.I.) values are provided, and the p-values of significance for the differences between the two acoustic conditions, according to the MWU Test. Any statistically significant differences, with p-value < 0.05, are reported in bold.

Topic	ID	Scale	Compliant classrooms (N=124)			Non-compliant classrooms (N=172)			MWU p-value
			M	St.dev.	95% C.I.	M	St.dev.	95% C.I.	
Well-being									
Self-esteem	Q1_WB	1-3	1.22	0.49	1.13-1.30	1.22	0.53	1.16-1.91	0.80
	Q2_WB	1-3	1.43	0.73	1.30-1.56	1.50	0.73	1.81-2.59	0.31
	Q3_WB	1-3	1.14	0.45	1.06-1.22	1.19	0.48	1.24-2.19	0.15
Emotional health	Q4_WB	1-3	1.26	0.52	1.17-1.35	1.33	0.59	1.21-1.86	0.35
	Q5_WB	1-3	1.22	0.49	1.13-1.30	1.28	0.57	1.29-2.18	0.35
	Q6_WB	1-3	1.10	0.31	1.05-1.16	1.15	0.41	1.82-2.71	0.43
Relationship at home and with friends	Q7_WB	1-3	1.23	0.54	1.14-1.33	1.24	0.57	1.25-2.22	0.89
	Q8_WB	1-3	1.09	0.31	1.03-1.14	1.12	0.39	1.18-2.02	0.68
	Q9_WB	1-3	1.27	0.57	1.17-1.37	1.24	0.47	1.53-2.47	0.77
Enjoyment of school	Q10_WB	1-3	1.22	0.53	1.12-1.31	1.35	0.70	1.55-2.59	0.14
	Q11_WB	1-3	1.31	0.59	1.20-1.41	1.30	0.54	2.21-2.73	0.81
	Q12_WB	1-3	1.23	0.52	1.13-1.32	1.33	0.61	2.20-3.00	0.11
Noise									
Traffic disturbance	Q1_N	0-3	1.87	0.87	0.62-1.01	1.94	0.83	0.00-0.44	0.65
Sirens disturbance	Q2_N	0-3	1.86	0.84	0.86-1.25	1.90	0.77	0.00-0.94	0.68
Disturbance from internal noises	Q3_N	0-3	1.79	0.83	0.93-1.31	1.74	0.76	0.46-1.54	0.78
Rain disturbance	Q4_N	0-3	1.74	0.75	0.92-1.29	1.84	0.91	1.11-2.17	0.67
Intensity and disturbance during silent task	Q5_N	1-3	1.38	0.63	1.27-1.49	1.49	0.72	1.49-2.38	0.19
	Q6_N	1-3	1.26	0.56	1.16-1.36	1.50	0.76	1.33-2.14	**0.01**
Intensity and disturbance during group activity	Q7_N	1-3	1.91	0.80	1.77-2.05	2.12	0.79	2.14-2.66	**0.03**
	Q8_N	1-3	1.72	0.79	1.58-1.86	1.94	0.83	1.86-2.67	**0.03**
Quality of voice	Q9_N	1-3	1.27	0.59	1.16-1.37	1.23	0.53	1.14-1.79	0.74
	Q10_N	1-3	1.50	0.65	1.39-1.62	1.52	0.73	1.28-2.15	0.78

Table 19. Unhappy students' subjective responses on the perceived well-being and noise disturbance, with the sample being grouped per classroom acoustics (i.e. compliant and non-compliant classrooms). Mean (M), standard deviation (St.dev.) and the 95% confidence interval (95% C.I.) values are provided, and the p-values of significance for the differences between the two acoustic conditions, according to the MWU Test. Any statistically significant differences, with p-value < 0.05, are reported in bold.

Topic	ID	Scale	Compliant classrooms (N=15)			Non-compliant classrooms (N=15)			MWU p-value
			M	St.dev.	95% C.I.	M	St.dev.	95% C.I.	
Well-being									
Self-esteem	Q1_WB	1-3	1.40	0.63	1.08-1.72	1.53	0.74	1.16-1.91	0.64
	Q2_WB	1-3	1.47	0.64	1.14-1.79	2.20	0.77	1.81-2.59	**0.01**
	Q3_WB	1-3	1.67	0.82	1.25-2.08	1.71	0.91	1.24-2.19	0.96
Emotional health	Q4_WB	1-3	1.67	0.62	1.35-1.98	1.53	0.64	1.21-1.86	0.52
	Q5_WB	1-3	1.13	0.35	0.96-1.31	1.73	0.88	1.29-2.18	**0.03**
	Q6_WB	1-3	2.00	0.93	1.53-2.47	2.27	0.88	1.82-2.71	0.54
Relationship at home and with friends	Q7_WB	1-3	1.67	0.82	1.25-2.08	1.73	0.96	1.25-2.22	0.96
	Q8_WB	1-3	1.33	0.49	1.09-1.58	1.60	0.83	1.18-2.02	0.47
	Q9_WB	1-3	1.80	0.86	1.36-2.24	2.00	0.93	1.53-2.47	0.55
Enjoyment of school	Q10_WB	1-3	1.50	0.76	1.10-1.90	2.07	1.00	1.55-2.59	0.12
	Q11_WB	1-3	2.27	0.46	2.04-2.50	2.47	0.52	2.21-2.73	0.26
	Q12_WB	1-3	1.50	0.76	1.10-1.90	2.62	0.77	2.20-3.00	**0.00**
Noise									
Traffic disturbance	Q1_N	0-3	2.00	1.00	0.87-3.00	1.00	0.00	/	0.12
Sirens disturbance	Q2_N	0-3	2.22	0.67	1.79-2.66	1.50	1.00	0.52-2.48	0.14
Disturbance from internal noises	Q3_N	0-3	2.09	0.54	1.77-2.41	1.88	0.64	1.43-2.32	0.42
Rain disturbance	Q4_N	0-3	1.56	0.73	1.08-2.03	1.77	0.93	1.27-2.27	0.66
Intensity and disturbance during silent task	Q5_N	1-3	1.73	0.88	1.29-2.18	1.93	0.88	1.49-2.38	0.52
	Q6_N	1-3	1.47	0.64	1.14-1.79	1.73	0.80	1.33-2.14	0.36
Intensity and disturbance during group activity	Q7_N	1-3	2.07	0.80	1.66-2.47	2.40	0.51	2.14-2.66	0.24
	Q8_N	1-3	1.93	0.70	1.58-2.29	2.27	0.80	1.86-2.67	0.21
Quality of voice	Q9_N	1-3	1.53	0.74	1.16-1.91	1.47	0.64	1.14-1.79	0.89
	Q10_N	1-3	2.20	0.86	1.76-2.64	1.71	0.83	1.28-2.15	0.13

Table 20. Subjective responses on the perceived well-being and noise disturbance of students in compliant classrooms only, with the sample being grouped per happiness (i.e. happy and unhappy). Mean (M), standard deviation (St.dev.) and the 95% confidence interval (95% C.I.) values are provided, and the p-values of significance for the differences between the two happiness conditions, according to the MWU Test. Any statistically significant differences, with p-value < 0.05, are reported in bold.

Topic	ID	Scale	Happy subjects (N=124)			Unhappy subjects (N=15)			MWU p-value
			M	St.dev.	95% C.I.	M	St.dev.	95% C.I.	
Well-being									
Self-esteem	Q1_WB	1-3	1.22	0.49	1.13-1.30	1.40	0.63	1.08-1.72	0.18
	Q2_WB	1-3	1.43	0.73	1.30-1.56	1.47	0.64	1.14-1.79	0.58
	Q3_WB	1-3	1.14	0.45	1.06-1.22	1.67	0.82	1.25-2.08	**0.00**
Emotional health	Q4_WB	1-3	1.26	0.52	1.17-1.35	1.67	0.62	1.35-1.98	**0.00**
	Q5_WB	1-3	1.22	0.49	1.13-1.30	1.13	0.35	0.96-1.31	0.59
	Q6_WB	1-3	1.10	0.31	1.05-1.16	2.00	0.93	1.53-2.47	**0.00**
Relationship at home and with friends	Q7_WB	1-3	1.23	0.54	1.14-1.33	1.67	0.82	1.25-2.08	**0.01**
	Q8_WB	1-3	1.09	0.31	1.03-1.14	1.33	0.49	1.09-1.58	**0.00**
	Q9_WB	1-3	1.27	0.57	1.17-1.37	1.80	0.86	1.36-2.24	**0.00**
Enjoyment of school	Q10_WB	1-3	1.22	0.53	1.12-1.31	1.50	0.76	1.10-1.90	0.07
	Q11_WB	1-3	1.31	0.59	1.20-1.41	2.27	0.46	2.04-2.50	**0.00**
	Q12_WB	1-3	1.23	0.52	1.13-1.32	1.50	0.76	1.10-1.90	0.10
Noise									
Traffic disturbance	Q1_N	0-3	1.87	0.87	0.62-1.01	2.00	1.00	0.87-3.00	0.79
Sirens disturbance	Q2_N	0-3	1.86	0.84	0.86-1.25	2.22	0.67	1.79-2.66	0.19
Disturbance from internal noises	Q3_N	0-3	1.79	0.83	0.93-1.31	2.09	0.54	1.77-2.41	0.18
Rain disturbance	Q4_N	0-3	1.74	0.75	0.92-1.29	1.56	0.73	1.08-2.03	0.47
Intensity and disturbance during silent task	Q5_N	1-3	1.38	0.63	1.27-1.49	1.73	0.88	1.29-2.18	0.11
	Q6_N	1-3	1.26	0.56	1.16-1.36	1.47	0.64	1.14-1.79	0.11
Intensity and disturbance during group activity	Q7_N	1-3	1.91	0.80	1.77-2.05	2.07	0.80	1.66-2.47	0.47
	Q8_N	1-3	1.72	0.79	1.58-1.86	1.93	0.70	1.58-2.29	0.24
Quality of voice	Q9_N	1-3	1.27	0.59	1.16-1.37	1.53	0.74	1.16-1.91	0.07
	Q10_N	1-3	1.50	0.65	1.39-1.62	2.20	0.86	1.76-2.64	**0.00**

Table 21. Subjective responses on the perceived well-being and noise disturbance of students in non-compliant classrooms only, with the sample being grouped per happiness (i.e. happy and unhappy). Mean (M), standard deviation (St.dev.) and the 95% confidence interval (95% C.I.) values are provided, and the p-values of significance for the differences between the two happiness conditions, according to the MWU Test. Any statistically significant differences, with p-value < 0.05, are reported in bold.

Topic	ID	Scale	Happy subjects (N=172)			Unhappy subjects (N=15)			MWU p-value
			M	St.dev.	95% C.I.	M	St.dev.	95% C.I.	
Well-being									
Self-esteem	Q1_WB	1-3	1.22	0.53	1.16-1.91	1.53	0.74	1.16-1.91	**0.03**
	Q2_WB	1-3	1.50	0.73	1.81-2.59	2.20	0.77	1.81-2.59	**0.00**
	Q3_WB	1-3	1.19	0.48	1.24-2.19	1.71	0.91	1.24-2.19	**0.01**
Emotional health	Q4_WB	1-3	1.33	0.59	1.21-1.86	1.53	0.64	1.21-1.86	0.12
	Q5_WB	1-3	1.28	0.57	1.29-2.18	1.73	0.88	1.29-2.18	**0.02**
	Q6_WB	1-3	1.15	0.41	1.82-2.71	2.27	0.88	1.82-2.71	**0.00**
Relationship at home and with friends	Q7_WB	1-3	1.24	0.57	1.25-2.22	1.73	0.96	1.25-2.22	**0.01**
	Q8_WB	1-3	1.12	0.39	1.18-2.02	1.60	0.83	1.18-2.02	**0.00**
	Q9_WB	1-3	1.24	0.47	1.53-2.47	2.00	0.93	1.53-2.47	**0.00**
Enjoyment of school	Q10_WB	1-3	1.35	0.70	1.55-2.59	2.07	1.00	1.55-2.59	**0.00**
	Q11_WB	1-3	1.30	0.54	2.21-2.73	2.47	0.52	2.21-2.73	**0.00**
	Q12_WB	1-3	1.33	0.61	2.20-3.00	2.62	0.77	2.20-3.00	**0.00**
Noise									
Traffic disturbance	Q1_N	0-3	1.94	0.83	0.00-0.44	1.00	0.00	/	0.05
Sirens disturbance	Q2_N	0-3	1.90	0.77	0.00-0.94	1.50	1.00	0.52-2.48	0.28
Disturbance from internal noises	Q3_N	0-3	1.74	0.76	0.46-1.54	1.88	0.64	1.43-2.32	0.53
Rain disturbance	Q4_N	0-3	1.84	0.91	1.11-2.17	1.77	0.93	1.27-2.27	0.81
Intensity and disturbance during silent task	Q5_N	1-3	1.49	0.72	1.49-2.38	1.93	0.88	1.49-2.38	**0.04**
	Q6_N	1-3	1.50	0.76	1.33-2.14	1.73	0.80	1.33-2.14	0.19
Intensity and disturbance during group activity	Q7_N	1-3	2.12	0.79	2.14-2.66	2.40	0.51	2.14-2.66	0.22
	Q8_N	1-3	1.94	0.83	1.86-2.67	2.27	0.80	1.86-2.67	0.14
Quality of voice	Q9_N	1-3	1.23	0.53	1.14-1.79	1.47	0.64	1.14-1.79	0.05
	Q10_N	1-3	1.52	0.73	1.28-2.15	1.71	0.83	1.28-2.15	0.34

4.3.2. Effect of classes and school characteristics on well-being and noise disturbance

Table 22 shows the most significant correlations between the perceived well-being and noise disturbance answers related to the happy children and the classes and schools characteristics, even if correlations are not the best tool to investigate such different and multi-layered data as anticipated in paragraph 4.2.5 "Statistical analysis" and discussed in paragraph 4.5 "Strengths and limitations of the study". To this analysis' aim, correlations were run between individual subjective responses (i.e., on perceived well-being and noise disturbance) and overall classes and schools characteristics, as specific objective data did not differ from pupil to pupil. Only Spearman correlation coefficients with p-values lower than 0.01 are shown. All the relationships are coherent among them, but the most interesting ones deserve some comments that are reported below:

- The percentage of Italian MT children is negative related to the reverberation time in the empty classrooms, $T20_e$, to the background noise level with the children in silence, L_{N_sil}, and to the traffic volume (TV), thus indicating as schools with a higher percentage of MT children have better acoustics. Indeed, mother tongue children, whose families have more choice where to send them to school due to a privileged economic status, more probably attend schools located in districts with better environmental conditions, as lower traffic volume, which means lower noise levels inside the classrooms. This is also confirmed by the lower perception of intensity and disturbance of noise in quiet (Q5_N and Q6_N, respectively), when the MT are higher. Moreover, MT is negatively related to the feeling of being pleased with themselves (Q5_WB), thus suggesting as a higher MT is related to higher well-being.
- The district real estate value (DV) is negatively related to the TV and to the acoustic parameters T20_e and L_{N_sil}, and it is also positively related to the presence of AT. These results suggest as richer districts allows for schools with better acoustics. DV is also negatively related to the goodness of the children' s relationships at home and with friends (Q7_WB and Q9_WB), generally indicating that growing in poorer districts can bring to less well-being.
- High TV determines lower serenity and increases noise disturbance, as shown from the positive relationships of TV with the feeling of being serene (Q2_WB) and with the perception of disturbance of noise from outdoor and indoor (Q1_N, Q2_N, Q3_N, and Q6_N).
- Acoustic treatments is negatively related to the reverberation time in the empty classrooms, T20_e, and to the background noise level with the children in silence, L_{N_sil}, as expected.

Table 22. Correlation matrix of the perceived well-being and noise disturbance scores of the happy children with the classes' and the schools' characteristics (with MT being mother tongue, DV being district real estate value, TV being traffic volume, AT being acoustic treatment) and the reverberation time and the background noise level in the empty classrooms, i.e. $T20_{_e}$ and $L_{N_sil,}$ respectively. Spearman correlation coefficients are given for significant relationships with p-value < 0.01.

ID	Question or parameter	Classes and schools characteristics			
		MT	DV	TV	AT
MT	Mother tongue percentage	1			
DV	District real estate value		1		
TV	Traffic volume	-0.54	-0.22	1	
AT	Acoustic treatment		0.75	-0.27	1
T20_e (s)	Reverberation time in	-0.31	-0.44	0.56	-0.63
L_{N_sil}	Noise level in silence	-0.36		0.55	-0.35
Q1_WB	Proudness				
Q2_WB	Serenity			0.21	
Q3_WB	Fun				
Q4_WB	Hold many positive things about himself/herself				
Q5_WB	Gladness	-0.18			
Q6_WB	Cheerfulness				
Q7_WB	Relax at home		-0.18		
Q8_WB	Enjoinment with friends				
Q9_WB	Get help from friends		-0.21		
Q10_WB	Pleasure of being at school				
Q11_WB	Safety at school				
Q12_WB	Fit in at school				
Q1_N	Traffic disturbance			0.28	
Q2_N	Sirens disturbance			0.22	
Q3_N	Disturbance from internal			0.21	
Q4_N	Rain disturbance				
Q5_N	Intensity during silent task	-0.20			
Q6_N	Disturbance during silent	-0.19		0.16	
Q7_N	Intensity during group				
Q8_N	Disturbance during group				
Q9_N	Quality of the teacher's				
Q10_N	Quality of the classmates'				

4.3.3. Relationship between acoustic parameters and subjective outcomes

Correlations between acoustic parameters

Table 23 shows the correlations between the acoustic parameters measured in the classrooms. Only Spearman correlation coefficients with p-value less than 0.01 are shown. Very high relationships are shown between the acoustic quantities, as expected. Particularly most of the quantities are very well related to the reverberation time T20, both empty and occupied.

The parameters L_{N_sil}, L_{N_gr}, L_{S_ref}, and mL_S are positive related to the reverberation time, that is when T20 is higher they are higher, as expected, and negatively related to C50 and U50. A very tight connection is shown between central and mean values of the quantities C50 and U50, thus bringing to the practical conclusion that only one measurement in the center of the room can well describe the behavior of the whole classroom in terms of speech intelligibility, as already shown by Puglisi *et al.* (2017). U50_ctr is also well related to C50_ctr, which suggests the use of only one quantity instead of two to represent speech intelligibility.

Table 23. Correlation matrix of the acoustical parameters measured in the classrooms. Spearman correlation coefficients are given for significant relationships with p-value < 0.01.

	Acoustical parameters									
	T20_e (s)	**T20 (s)**	**L_{N_sil} (dBA)**	**L_{N_gr} (dBA)**	**L_{S_ref} (dBA)**	**mL_S (dBA/dd)**	**$C50_{ctr}$ (dB)**	**$C50_M$ (dB)**	**$U50_{ctr}$ (dB)**	**$U50_M$ (dB)**
T20_e (s)	1									
T20 (s)	0.86	1								
L_{N_sil} (dBA)	0.27		1							
L_{N_gr} (dBA)	0.64	0.48	0.49	1						
L_{S_ref} (dBA)	0.73	0.59	0.35	0.40	1					
mL_S (dBA/dd)	0.57	0.51			0.36	1				
$C50_{ctr}$ (dB)	-0.84	-0.90		-0.36	-0.55	-0.46	1			
$C50_M$ (dB)	-0.88	-0.96		-0.56	-0.48	-0.48	0.91	1		
$U50_{ctr}$ (dB)	-0.71	-0.87	-0.36	-0.46	-0.65	-0.30	0.90	0.82	1	
$U50_M$ (dB)	-0.84	-0.90	-0.37	-0.67	-0.62	-0.46	0.80	0.93	0.89	1

Correlations between acoustic parameters and well-being and noise disturbance scores

In order to choose among the most important objective quantities to be measured in a classroom it is useful to look at the results in **Table 24**, which shows the correlation matrix of the perceived well-being and noise disturbance scores for the happy children with the acoustic parameters. Most of the results are coherent

and meaningful and can be useful to understand more about the relationships between environmental factors and children perception and behavior. The following interesting outcomes can be drawn:

Generally, a positive relationship between disturbance from noise coming from outside the classroom, and in particular from traffic (Q1_N) and from adjacent rooms and corridor (Q3_N), and the noise level measured when the children were in silence, L_{N_Sil}, has been found, well underling as poor sound insulation is related to higher sound levels in classrooms and consistent higher noise disturbance.

The higher is the slope of the speech level along the central line of the classroom, mL_S, or the lower is the slope when taken in absolute value, the higher is the perceived noise intensity and noise disturbance when the children are doing a task in silence (Q5_N and Q6_N, respectively). This is explainable considering that with higher values of speech slope the room is more reverberant and the speech level at the back of the classroom less clear, as well the noise is higher compared to less reverberant rooms.

The higher the values of speech Clarity, C50, and Useful-to-detrimental-energy ratio, U50, both at the central position and average across the classroom, the lower are the noise intensity and disturbance scores Q3_N, Q5_N, Q6_N, Q7_N, and Q8_N. This means that good speech intelligibility corresponds to low noise disturbance both in the case of working in silence and in the case of group activity.

As far as well-being is concerned, it is shown that the feeling of having fun is well related to higher values of speech intelligibility, in terms of U50_ctr, and the feeling of being happy of herself or himself is well related to lower values of mL_S, i.e., in rooms with higher slope of L_S, which means with less reverberation, children are happier with themselves.

A particular remark is related to the parameter L_{N_gr}, which is unexpected negative related to the well-being aspect "proudness of myself." It means that the higher the level of noise during the group activity the higher is the proudness of the children. This result can be explained from the psychological point of view, as children were very happy while doing a lot of noise and they could be proud of having done it.

With the aim to further clarify the relationships between subjective and objective parameters, **Figures 8** and **Figure 9** show, as example, the regression lines between the average values across classes of the answers to the questions Q3_N and Q5_N and the acoustic parameters L_{N_sil} and mL_S, respectively. These relationships have been chosen as they show two of the highest correlation coefficients in **Table 24**.

Table 24. Correlation matrix of the perceived well-being and noise disturbance scores for the happy children with the acoustical parameters. Spearman correlation coefficients are given for significant relationships with p-value < 0.01.

ID	Question	Acoustical parameters								
		T20 (s)	**L_{N_sil} (dBA)**	**L_{N_gr} (dBA)**	**L_{S_ref} (dBA)**	**mL_S (dBA/dd)**	**$C50_{_ctr}$ (dB)**	**$C50_{_M}$ (dB)**	**$U50_{_ctr}$ (dB)**	**$U50_{_M}$ (dB)**
Q1_WB	Proudness			-0.18						
Q2_WB	Serenity									
Q3_WB	Fun								-0.16	
Q4_WB	Hold many positive things about himself/herself									
Q5_WB	Gladness					0.18				
Q6_WB	Cheerfulness									
Q7_WB	Relax at home									
Q8_WB	Enjoinment with friends									
Q9_WB	Get help from friends									
Q10_WB	Pleasure of being at school									
Q11_WB	Safety at school									
Q12_WB	Fit in at school									
Q1_N	Traffic disturbance		0.30	0.33						
Q2_N	Sirens disturbance									
Q3_N	Disturbance from internal noises		0.26							-0.22
Q4_N	Rain disturbance									
Q5_N	Intensity during silent task					0.28				-0.17
Q6_N	Disturbance during silent task					0.22	-0.17	-0.17	-0.16	-0.18
Q7_N	Intensity during group activity	0.16			0.18		-0.17		-0.24	-0.17
Q8_N	Disturbance during group activity								-0.19	
Q9_N	Quality of the teacher's voice									
Q10_N	Quality of the classmates' voice									

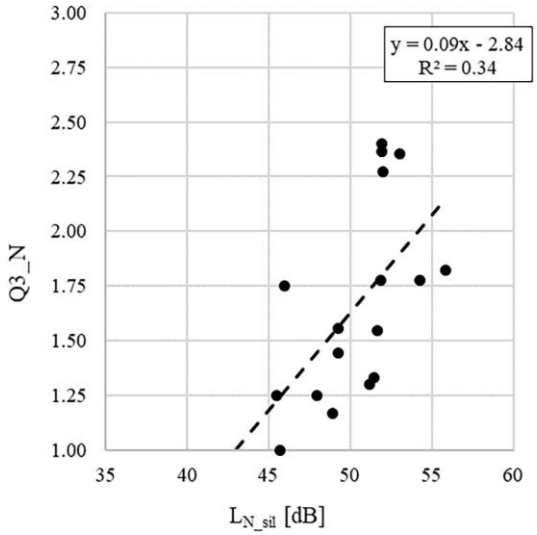


Figure 8. Linear regression graph showing the dependency of the average values across classes of the answers to the question Q3_N (i.e., "How much sounds of radios or recorders coming from other classrooms or from the corridor disturb you?") on the noise level measured with children in silence, L_{N_sil}.

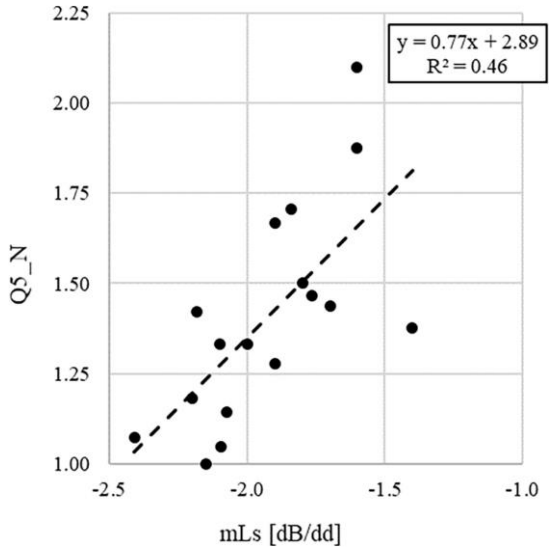


Figure 9. Linear regression graph showing the dependency of the average values across classes of the answers to the question Q5_N (i.e., "The noise present when you perform a task in silence seems you.") on the slope of the voice signal, mL_S.

4.4. Discussion

In-field studies on the effects of classroom acoustics on the perception of noise disturbance are only a few in the available literature. Furthermore, no study has investigated the perception of well-being at school and its relationships with acoustics. The present study has aimed at investigating three main aspects that are lacking in the available literature so far:

(i) the influence of classroom acoustics non-compliant with the standards on perceived well-being and noise disturbance for happy and unhappy children;
(ii) the influence of class and school characteristics on perceived well-being and noise disturbance;
(iii) the relationships between classroom acoustic parameters and perceived well-being and noise disturbance scores.

4.4.1. Role of classroom acoustics non-compliant with the standard on well-being and noise disturbance for happy and unhappy children

The classrooms involved in the study are representative of the typical acoustic quality available in the majority of Italian schools, with reverberation times under occupied conditions ranging from 0.5 to 1.4 s. Therefore, they could be grouped under C and NC labels depending on their performance in agreement with recent studies, which suggest an optimal reverberation time range between 0.5 and 0.8 s to account for both speaking and listening premises at the same time. Based on the C and NC clustering of classrooms, the data from subjective questionnaires administrated to the pupils were analyzed to understand the extent to which C and NC have an influence on the perception of well-being and noise disturbance at school. The presented results highlight that outdoor and indoor noise in NC is perceived as more disturbing than in C, being significantly amplified by the higher reverberation. These outcomes corroborate previous studies that proved outdoor and indoor noise sources to be the most annoying for children of grades 2 and 6 (Dockrell and Shield, 2004) and high school students (Astolfi and Pellerey, 2008), respectively. This study has shown that the 90.8% of the involved pupils reported to be happy. The subgroup of 9.2% of unhappy pupils has shown that the significant detrimental effect of NC was on the perception of serenity, self-pleasances, and fitting in at school, and not on increased noise disturbance. Overall, unhappy pupils have judged worse a higher number of well-being items in NC compared to C, confirming the need of C quality in classrooms to enhance well-being at school. This is consistent with a previous study by Klatte and Hellbrück (2010), who found that children attending classes under NC conditions judged their relationships to their peers and teachers less positively than did children from C classrooms.

4.4.2. Effect of classes and school characteristics on well-being and noise disturbance perception

School and classroom characteristics need to be accounted for in a study that investigates the subjective perception as it may be influenced by the subjects' background, origins, and features. Therefore, objective information was collected that consisted in student and building features, the presence of AT, the year of construction, and the TV. However, the presented study investigated their relationship with the subjective outcomes and the classroom acoustic parameters through correlations, that could not be the best one when investigating such different and multi-layered data. Thus, the results of these correlations, that are commented in this paragraph, should be treated with caution and not intended as definitive. Future studies will apply to the present dataset more sophisticated statistical tools that could disclose the contribution of the not acoustical factors in the variance of the data.

In classrooms with better acoustics, a higher percentage of mother-tongue-speaking children was present. Such a result was corroborated by the lower perception of noise intensity and disturbance in quiet. Moreover, the students' feature of being speakers of the MT resulted in a higher feeling of being pleased with themselves. These outcomes suggest that being speakers of the MT is a child characteristic that brings more chances of attending C classes, being less disturbed, and having more well-being.

As far as school features are concerned, richer districts presented better acoustic conditions, resulting in turn in the fact that richer districts also revealed a greater perception of well-being.

Higher TVs were found to determine lower serenity and increase in noise disturbance. This outcome agrees with many studies, among which Klatte and Hellbrück (2010), Crombie *et al.* (2011), and Lim *et al.* (2018), who proved a significant association between noise exposure to noise and high levels of noise annoyance, as well as decreased well-being, but all the studies took into account children older than 6–7 years old and were mostly based on questionnaires that were not filled in directly by children at school.

4.4.3. Relationships between classroom acoustic parameters and well-being and noise disturbance scores

Overall, very high relationships were found between the acoustic quantities, corroborating past results (Bradley, 1986; Sato and Bradley, 2008; Yang and Bradley, 2009). The perceived noise intensity and disturbance were found to be strongly positively related to the slope of speech level along a classroom's main axis (mL_S) and strongly negatively related to speech clarity (C50) and the ratio of useful to detrimental energy (U50), both at the central position and on average across the classroom. These coherent outcomes are dependent on the reverberation time, which directly affects the uniformity of the sound energy in the room and

increases the noise level: the higher is the reverberation time in the room, the higher is the speech slope along the main axis (or lower when it is considered in absolute values) and the lower are the values of speech clarity and the ratio of useful to detrimental energy. Much should then be done in the acoustic design of classrooms to guarantee optimal distribution of parameters across all the listening positions. Promising results are achieved by combining the use of absorptive and diffusive surfaces (Choi, 2014), even though the perceptive effect of diffusive linings is still under research (Shtrepi *et al*., 2015, 2016, 2017).

The very high correlation between speech clarity and the ratio of useful to detrimental energy and the tight connection between central and mean values suggest the adoption of only one of the two indexes measured in the central position of the room to evaluate the classroom speech intelligibility. This outcome is in agreement with the results found by Puglisi *et al*. (2017), who suggested to measure clarity in the middle of the classroom to characterize its average behavior in terms of speech intelligibility. U50 in the central position of the classroom was also strongly related to the feeling of having fun. A strong positive relationship was found for mL_S and the feeling of children of being happy with themselves; that is, the higher the slope (or the lower in absolute value), the higher is the feeling of being unpleased with oneself. To the authors' knowledge, no studies are available in literature that considered the influence of speech intelligibility parameters and the effect of reverberation on the perceived well-being of young children. Anyway, the obtained results on the influence of acoustics on well-being at school are in line with those from Wålinder *et al*. (2007), who found that noise can be considered as a risk factor for the children's well-being in the school environment because it has primary consequences on the increased prevalence of symptoms of fatigue and headache.

Furthermore, the noise levels measured inside the classrooms were found to be significantly correlated with the perception of outdoor noise sources, in particular from traffic and from adjacent rooms and corridor. This relationship supports the need of an accurate acoustic design of classrooms with a focus on the enhancement of sound insulation as suggested in Secchi *et al.* (2017), as it is related to higher sound levels in classrooms and consistent with higher noise disturbance.

4.5. Strengths and limitations of the study

The present study confirms the association between poor classroom acoustics and noise disturbance for children at school. The main strength of the study is that the acoustic parameters needed to discriminate C and NC were measured accurately, on the basis of referred protocols, and considers all the classroom acoustic aspects. In addition, this is the first study that examines the combined effect of noise disturbance and well-being perception of first graders at school. On the one side, the wide range of classroom acoustic conditions chosen for the study, ranging from 0.5 to 1.4 s of reverberation time, has ensured the covering of most of the

current classrooms' features. On the other side, the school characteristics sufficiently covered most of the school buildings of a typical town.

There are also several limitations in the present study. The selection of the schools depended on their willingness to participate in the research, which was part of a wider study on the assessment and strengthening of the reading abilities of first graders (Astolfi *et al.,* 2018b). Furthermore, the teachers of first graders volunteered to participate in the study, probably due to an already existing interest in the strengthening of the reading abilities of the pupils. The influence of the acoustic environment on the children's abilities was only proposed as a secondary outcome to the teachers. All the invited children of the classrooms (with the consent of their legal guardians) agreed to participate in the study.

Well-being was measured using an Italian translation of the questionnaire developed by Sabri *et al.* (2015), suitable for young people with SENs. It was selected as it was validated for children aged 6–7 years old and because it was especially designed for wellbeing investigations at school. The questionnaire included many items which may have affected their completion rate, especially for first graders. The items were a priori explained to the children by an experimenter, who was always the same, but this could have biased the answers, involuntarily.

In addition, the questionnaires filled in by children with hearing impairment (HI) or with SENs identified by the teachers were excluded, and these data have not been used for further analyses. It is well known that children with HI or SENs are more susceptible to the adverse effects of NC, and future studies need to survey this fragile group of pupils. Moreover, because this is a cross-sectional study, the causality of the association cannot be univocally determined. To investigate temporal changes in noise disturbance and well-being also for particular groups of children, as well as to infer causality, longitudinal studies are needed based on a larger population. Additional information on parent's and family conditions, both related to economic and educational issues and on well-being and noise disturbance perceived at home, should have been acquired.

The relationships between the issues concerning the school context, the MT percentage and the subjective outcomes and the classrooms characteristic acoustic parameters have been investigated through simple tool correlations, that could not be the best tool to investigate such different and multi-layered data. In order to control the effects that the not acoustical factors, i.e., the traffic volume, the district real estate value and the mother tongue percentage, could have on the outputs, more sophisticated tools could be used. In this perspective, future studies will perform more advanced level of analyses with the application of statistical mixed models, as the generalized linear mixed model (GLMM), that are able to take into account the influence of both fixed and random effects. In particular, MT, DV, TV and AT, will be considered as fixed effects, and individual participants as random effects. Fixed effects are explanatory variables that affect the average response of all the outcomes and provide estimates of the average rate of change of the population, instead random effects present the general variability among the subjects. The

model will allow to identify the weight that the variables have on predictions of the subjective outcomes, that will be considered as dependent variables.

An unexpected result consisted in the strong relationship that was found between L_{N_gr} and the well-being aspect "proudness of myself," as it was found that pupils were prouder of themselves as the level due to activity noise was higher in the classroom. This outcome should be deepened from a psychological point of view rather than an acoustic point of view, as it may be that due to the excitement of children when they were asked to be noisy, the measurement condition was biased. Thus, a proposal for the future is to measure other noise levels in the classrooms, related to real noise situations during lessons; however, it is needed to adopt an effective measurement procedure that avoids external influences on the behavior of pupils.

4.6. Conclusion

In the present study, subjective outcomes on the assessment of perceived well-being and noise disturbance at school for first graders were related to classroom acoustics characteristics and to classes and schools features.

The findings of this pilot study, which involved 326 first graders in their own classrooms, suggest that long reverberation times, which are associated with poor classroom acoustics as they generate higher noise levels and degrade speech intelligibility, bring pupils to a reduced perception of having fun and being happy with themselves. Furthermore, classroom acoustics non-compliant with the standard is also related to an increased perception of noise intensity and disturbance, particularly in the case of traffic noise and noise from adjacent school environments.

Finally, an analysis of the perception of well-being and noise disturbance depending on the self-judgment of pupils on being happy or unhappy was performed. Happy pupils reported a higher perception of noise disturbance under poor classroom acoustic conditions, whereas unhappy pupils reported only complaints in classroom acoustics non-compliant with the standard with respect to the perception of pleasances with himself or herself and of fitting in at school.

Appendix D
Questionnaires on well-being and noise disturbance administrated to pupils in classrooms

Table D.1. Italian (original) version of the well-being questionnaire administrated to children in classrooms.

Il benessere dei bambini a scuola

SCUOLA..... *PRIMARIA*

CLASSE.....

DATA.....

NOME E COGNOME.....

MISSIONE BENESSERE

LO SCOPO DELLA NOSTRA RICERCA E' CAPIRE COME VALUTI IL TUO BENESSERE
CI VUOI AIUTARE? COMPILA IL SEGUENTE QUESTIONARIO PER NOI.



0.a. QUANTI ANNI HAI? _____

0.b. SONO ... UN BAMBINO  ○ UNA BAMBINA  ○

0.c. QUANTE PERSONE VIVONO IN TOTALE A CASA TUA?_____

0.d. QUAL E' IL POSTO PIU' TRANQUILLO CHE CONOSCI?_____

0.e. CHE LINGUA PARLI A CASA?_____

1

1. QUANTO SEI D'ACCORDO CON OGNI AFFERMAZIONE?

		 SI	 NON SO	 NO
A	SONO ORGOGLIOSO DI ME STESSO	○	○	○
B	SONO SERENO	○	○	○
C	MI DIVERTO MOLTO	○	○	○

3. QUANTO SEI D'ACCORDO CON OGNI AFFERMAZIONE?

		 SI	 NON SO	 NO
A	MOLTE COSE DI ME SONO POSITIVE	◯	◯	◯
B	SONO CONTENTO DI ME STESSO	◯	◯	◯
C	SONO UN BAMBINO ALLEGRO	◯	◯	◯

4. QUANTO SEI D'ACCORDO CON OGNI AFFERMAZIONE?

		SI	NON SO	NO
A	CASA MIA È UN BUON POSTO PER RILASSARSI	◯	◯	◯
B	MI DIVERTO CON I MIEI AMICI	◯	◯	◯
C	I MIEI AMICI MI AIUTANO SE NE HO BISOGNO	◯	◯	◯

4. QUANTO SEI D'ACCORDO CON OGNI AFFERMAZIONE?

		 SI	 NON SO	 NO
A	MI PIACE STARE A SCUOLA	○	○	○
B	MI SENTO SICURO A SCUOLA	○	○	○
C	MI SENTO A MIO AGIO A SCUOLA	○	○	○

5. QUANTO SEI FELICE?

METTI UNA CROCE SUL NUMERO

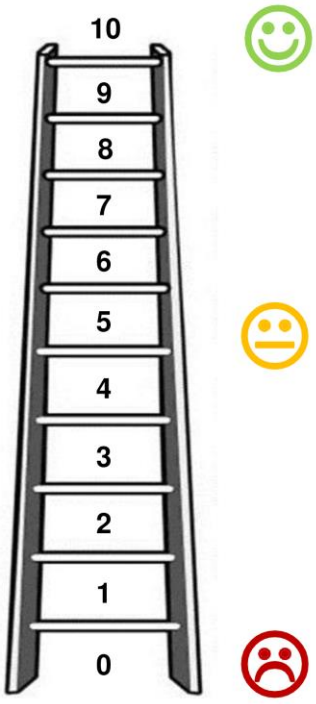


Table D.2. Italian (original) version of the questionnaire on noise disturbance administrated to children in classrooms.

La qualità acustica nelle aule scolastiche

SCUOLA.....

PRIMARIA

CLASSE.....

DATA.....

NOME E COGNOME.....

MISSIONE RUMORE

LO SCOPO DELLA NOSTRA RICERCA E' CAPIRE QUANTO SENTI BENE NELLA TUA AULA. CI VUOI AIUTARE? COMPILA IL SEGUENTE QUESTIONARIO PER NOI.



1

1. QUANDO SEI IN CLASSE, SENTI..



		SI	NO
A	IL RUMORE DEL TRAFFICO?	◯	◯



		POCO	ABBASTANZA	MOLTO
B	**SE SI**, QUANTO TI DISTURBA QUESTO RUMORE?	◯	◯	◯

2. QUANDO SEI IN CLASSE, SENTI..



		SI	NO
A	LE SIRENE DI AMBULANZA, VIGILI DEL FUOCO O DI POLIZIA?	◯	◯

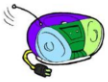


		POCO	ABBASTANZA	MOLTO
B	**SE SI** QUANTO TI DISTURBA QUESTO RUMORE?	◯	◯	◯

3. QUANDO SEI IN CLASSE, SENTI..



		SI	NO
A	SUONI DI TELEVISIORI, RADIO O REGISTRATORI PROVENIENTI DA ALTRE AULE O DAL CORRIDOIO?	○	○



		POCO	ABBASTANZA	MOLTO
B	**SE SI**, QUANTO TI DISTURBA QUESTO RUMORE?	○	○	○

4. QUANDO SEI IN CLASSE, SENTI..



		SI	NO
A	IL RUMORE DELLA PIOGGIA SE ALL'ESTERNO PIOVE?	○	○



		POCO	ABBASTANZA	MOLTO
B	**SE SI**, QUANTO TI DISTURBA QUESTO RUMORE?	○	○	○

5. QUANDO SEI IN CLASSE...



		BASSO	MEDIO	ALTO
A	IL RUMORE PRESENTE QUANDO ESEGUI UN COMPITO IN SILENZIO TI SEMBRA..	◯	◯	◯



		POCO	ABBASTANZA	MOLTO
B	QUANTO DI DISTURBA QUESTO RUMORE?	◯	◯	◯

6. QUANDO SEI IN CLASSE...



		BASSO	MEDIO	ALTO
A	IL RUMORE PRESENTE QUANDO STAI LAVRANDO IN GRUPPO TI SEMBRA..	◯	◯	◯



		POCO	ABBASTANZA	MOLTO
B	QUANTO TI DISTURBA QUESTO RUMORE?	◯	◯	◯

7. SEI IN CLASSE. COME SENTI LA VOCE DELLA MAESTRA SE..



		BENE	ABBASTANZA BENE	MALE
A	SIETE TUTTI IN SILENZIO MENTRE LEI SPIEGA?	○	○	○

8. SEI IN CLASSE. COME SENTI LA VOCE DEL TUO COMPAGNO SE..



		BENE	ABBASTANZA BENE	MALE
A	LUI O LEI STA RISPONDENDO ALLA MAESTRA?	○	○	○

9. VUOI AGGIUNGERE QUALCOSA?

_____

_____

_____

_____

_____

_____

GRAZIE PER IL TUO AIUTO A QUESTA RICERCA.
PER FAVORE, RESTITUISCI IL QUESTIONARIO ALLA TUA MAESTRA.

Table D.3. English (translated) version of the well-being questionnaire.

Children well-being at school

SCHOOL..... *PRIMARY SCHOOL*

CLASSROOM.....

DATE.....

NAME AND SURNAME.....

WELL-BEING MISSION

THE AIM OF OUR RESEARCH IS TO UNDERSTAND HOW DO YOU RATE YOUR WELL-BEING. WOULD YOU LIKE TO HELP US? FILL IN THE FOLLOWING QUESTIONNAIRE.



0.a. HOW OLD ARE YOU? _____

0.b. I AM ... A BOY  ○ A GIRL  ○

0.c. HOW MANY PEOPLE LIVE IN YOUR HOUSE IN TOTAL?_____

0.d. WHAT IS THE QUIETEST PLACE THAT YOU KNOW?_____

0.e. WHAT LANGUAGE DO YOU SPEAK AT HOME?____

1

CHILDREN well-being at school

PRIMARY SCHOOL

1. HOW MUCH DO YOU AGREE WITH EACH STATEMENT?

		 YES	 NOT SURE	 NO
A	I AM PROUD OF MYSELF	○	○	○
B	I'M SERENE	○	○	○
C	I HAVE A LOT OF FUN	○	○	○

Children well-being at school

PRIMARY SCHOOL

2. HOW MUCH DO YOU AGREE WITH EACH STATEMENT?

		 YES	 NOT SURE	 NO
A	LOTS OF THINGS ABOUT ME ARE GOOD	○	○	○
B	I FEEL PLEASED WITH MYSELF	○	○	○
C	I AM A CHEERFUL CHILD	○	○	○

3. HOW MUCH DO YOU AGREE WITH EACH STATEMENT?

		 YES	 NOT SURE	 NO
A	MY HOME IS A GOOD PLACE TO RELAX	○	○	○
B	I ENJOY MYSELF WITH MY FRIENDS	○	○	○
C	MY FRIENDS HELP ME IF I NEED IT	○	○	○

4. HOW MUCH DO YOU AGREE WITH EACH STATEMENT?

		 YES	 NOT SURE	 NO
A	I LIKE BEING IN SCHOOL	○	○	○
B	I FEEL SAFE AT SCHOOL	○	○	○
C	I FEEL LIKE I FIT IN AT SCHOOL	○	○	○

5. HOW HAPPY ARE YOU?

PUT A CROSS ON THE NUMBER CORRESPONDING TO YOUR DEGREE OF HAPPINESS

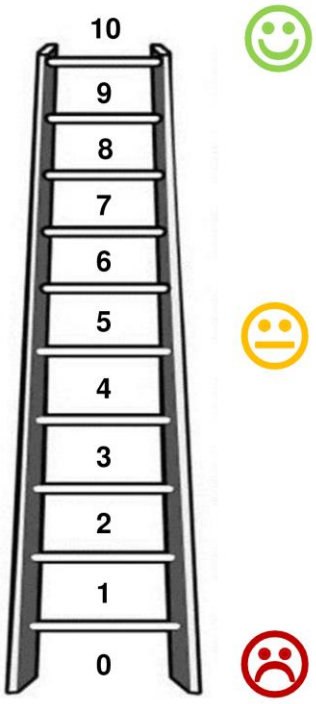


Table D.4. English (translated) version of the well-being questionnaire.

Acoustic quality in school classrooms

PRIMARY

SCHOOL.....

CLASSROOM.....

DATE.....

NAME AND SURNAME.....

NOISE MISSION

THE AIM OF OUR RESEARCH IS TO UNDERSTAND HOW WELL YOU CAN HEAR IN YOUR CLASSROOM. WOULD YOU LIKE TO HELP US? PLEASE, FILL IN THE FOLLOWING QUESTIONNAIRE.



1

Acoustic quality in school classrooms

PRIMARY

1. WHEN YOU ARE IN CLASSROOM, DO YOU HEAR..



		YES	NO
A	TRAFFIC NOISE?	○	○



		A LITTLE	QUITE	A LOT
B	**IF YES**, HOW MUCH DOES THIS NOISE DISTURB YOU?	○	○	○

2. WHEN YOU ARE IN CLASSROOM, DO YOU HEAR..



		YES	NO
A	AMBULANCE, FIREMEN AND POLICE SIRENS?	○	○

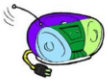


		A LITTLE	QUITE	A LOT
B	**IF YES,** HOW MUCH DOES THIS NOISE DISTURB YOU?	○	○	○

3. WHEN YOU ARE IN CLASSROOM, DO YOU HEAR...



		YES	NO
A	SOUNDS OF RADIOS OR RECORDERS COMING FROM OTHER CLASSROOMS OR FROM THE CORRIDOR?	○	○



		A LITTLE	QUITE	A LOT
B	**IF YES**, HOW MUCH DOES THIS NOISE DISTURB YOU?	○	○	○

4. WHEN YOU ARE IN CLASSROOM, DO YOU HEAR...



		YES	NO
A	RAIN NOISE, IF IT IS RAINING OUTSIDE?	○	○



		A LITTLE	QUITE	A LOT
B	**IF YES**, HOW MUCH DOES THIS NOISE DISTURB YOU?	○	○	○

5. WHEN YOU ARE IN CLASSROOM...



		LOW	MEDIUM	HIGH
A	THE NOISE PRESENT WHEN YOU PERFORM A TASK IN SILENCE SEEMS YOU..	◯	◯	◯



		A LITTLE	QUITE	A LOT
B	HOW MUCH DOES THIS NOISE DISTURB YOU?	◯	◯	◯

6. WHEN YOU ARE IN CLASSROOM...



		LOW	MEDIUM	HIGH
A	THE NOISE PRESENT WHEN YOU'RE WORKING IN GROUP SEEMS TO YOU..	◯	◯	◯



		A LITTLE	QUITE	A LOT
B	HOW MUCH DOES THIS NOISE DISTURB YOU?	◯	◯	◯

7. HOW DO YOU HEAR THE TEACHER' VOICE IF..



		GOOD	QUITE GOOD	BAD
A	YOU ARE IN SILENCE WHILE SHE IS TALKING?	○	○	○

8. HOW DO YOU HEAR YOUR CLASSMATE'S VOICE IF..



		GOOD	QUITE GOOD	BAD
A	HE OR SHE IS ANSWERING TO THE TEACHER?	○	○	○

9. WOULD YOU LIKE TO ADD SOMETHING?

_____

_____

_____

_____

_____

_____

THANK YOU FOR YOUR HELP IN THIS RESEARCH.

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Chapter 5
Listening in challenging environments

Objective	To investigate the effect of real complex acoustic scenarios on speech intelligibility for adults through predictions of binaural speech intelligibility in classrooms.
Outcome	The binaural speech intelligibility model (BSIM) is a very useful tool to save time and obtain intelligibility predictions without involving people to test.
Highlights	• Objective acoustical measurements were carried out in one Italian primary school classroom before and after the acoustical treatment. • Binaural speech intelligibility predictions are compared to the well-established room acoustic measures. • The importance of a model able to deal with the binaural aspects of the auditory system is shown.
Notes	Parts of this chapter are submitted as proceedings to IBPC 2021 as: ▪Minelli et al., "*Binaural Speech Intelligibility in a real primary school classroom*", IBPC 2021, proceedings.

5.1. Introduction

So far, **Chapter 2**, **Chapter 3** and **Chapter 4** dealt with guidelines and thresholds for the acoustical parameters that can guarantee better learning performances or proper acoustics in classroom. However, they refers to a monoaural listening perspective that does not reflects real complex acoustic scenarios. It is the case of realistic spatial configurations of speakers and listeners that occur in classroom and that may result in improved or degraded speech communication. This chapter constitute an attempt to contribute to the understanding of the mechanisms underlying speech intelligibility in real complex acoustic scenarios as classrooms, taking into account binaural hearing.

The chapter is organized as follows. Firstly, the switch from monoaural to binaural indices of speech intelligibility is presented together with the introduction of binaural listening processes. Studies on binaural speech perception and their outcome follow, giving particular attention to the description of the configurations adopted in the experiments and of the type of noise used. Then, models to predict binaural speech intelligibility are reported together with the reasons to use one of them in the present study. The methodology section describes the two classroom involved in the present study, the monoaural and binaural acoustical measurements carried out and the binaural speech intelligibility model used. The results provide information on the effects of reverberation and spatial separation on speech intelligibility.

5.1.1. From a monoaural to a binaural perspective

Speech intelligibility is defined as the percentage of the proportion of speech that is understood by a listener in BS EN IEC 60268-16 (2020). Speech intelligibility has been investigated in monoaural conditions in a large number of studies. The Articulation Index (AI) (ANSI, 1969), the Speech Intelligibility Index (SII) (ANSI, 1997), which are based on the signal-to-noise ratios in different spectral bands, and the Speech Transmission Index (STI) (IEC 60268-16, 2020), that can rate between 0 and 1 and is a complex measure of the quality of speech transmission, are some of the monoaural objective indices used for the description of speech intelligibility. However, speech intelligibility is also assessed through measures simpler than the STI, such as clarity, definition or useful-to-detrimental ratio that consider the reflections reaching the listener's ears within a certain time interval after the direct sound as useful (Bradley, 1986; Bradley *et al.,* 2003).

The above-mentioned measures are essentially monoaural models and thus cannot forecast potential advantages given by binaural listening processes. Indeed, the cocktail party effect (Cherry, 1953; Conway *et al*., 2001) describes that although speech intelligibility in classroom is often corrupted by ambient noise and reverberation, listeners can focus on a specific speech signal even in challenging sound environments, because speech intelligibility depends on the spatial configuration of the sources and can benefit of binaural listening thanks to spatial

hearing (MacCutcheon *et al.,* 2019). In fact, the auditory system uses several different cues for locating sound source, such as time and level differences between both ears. In particular, the interaural time difference refers to the difference in arrival time of a sound between two ears due to the differing relative proximities of the ears to the sound source (Zurek, 1993), while the interaural level difference is the difference in loudness and frequency distribution between the two ears, as the level of the sound is highest for the ear that is closer to the sound source.

Investigating the speech recognition threshold (SRT) and the spatial release from masking (SRM)

The ability to separate speech (target) from noise (masker) is an essential auditory skill required in everyday communication by children. For example, children in classroom should separate the speech of the teacher from noisy backgrounds generated by traffic or other pupils inside the environment. Enhanced intelligibility is reached through the use of the difference in location between a target and a masker, that is called spatial release from masking (SRM) (Bronkhorst, 2000). SRM is commonly defined as the difference between the speech recognition threshold (SRT) obtained in a co-located condition, i.e., when the target and the masker are directly ahead or behind the listeners' head, and the SRT obtained in a spatially separated condition, i.e., when either the target or the masker or both are off axis with respect to the listener's head (Westerman and Buchholz, 2015). SRT is the signal-to-noise ratio (SNR) yielding a certain percentage of correct recognition scores, such as 50% speech intelligibility, i.e., SRT50 (in dB SNR).

Many studies investigated speech perception in environments characterized by the presence of noise. In particular, such studies mostly explored the SRM benefit of spatially separating in angle the source in anechoic or semi-anechoic conditions. Platte and Vom Hövel (1980), Plomp and Mimpen (1981), Duquesnoy (1983), Bronkhorst and Plomp (1988), Peissing and Kollmeier (1997), measured the largest release from masking of up to 12 dB when the masker is positioned behind the listener's head with an angle of 120°. Wagener *et al*. (2007) obtained an SRM between 7 dB and 10 dB when the noise source was shifted from a frontal to a rear collocation, that is from 0° to 90° with respect to the listener's head, accounting for the outcomes of test administrated in different languages, i.e., German, Dutch, British English, and Swedish. Dirks and Wilson (1969) showed that an SRM of up to 7.5 dB occurs in the case the target and the masker are spatially separated with and angle of 90°, considering a 50% of speech intelligibility level. Contrariwise, when the noise and speech sources were co-located, the SRM was about 1 dB, which is negligible since it corresponds to the just noticeable difference (JND) in sound intensity (EN ISO 3382-2:2008). Reverberation and real complex acoustic scenarios have started to be included only in a few experiments, though, in order to not make the study too complex, most still account for the effect of the noise source from a single location at a time.

Speech intelligibility has also been investigated in terms of difference in distance considering the spatial configuration of target, noise and listener position. Westermann and Buchholz (2015) obtained better (i.e., lower) speech recognition thresholds of up to 10 dB considering a target-to-receiver distance of 0.5 m while moving a masker with informational content on axis at increasing distances compared to SRTs with larger target-to-receiver distances. Conversely, speech intelligibility was not significantly enhanced when the masker-to-receiver distance was kept at 0.5 m and the distance between listener and target on axis was changed. Puglisi *et al.* (2021) found higher (i.e., worse) SRT80s of up to 3 dB with increasing target-to-listener distance from 1.5 m to 4 m, both in classrooms with a reverberation time of 0.4 s and 3.1 s.

Informational vs energetic masking noise

The type of noises also affects speech perception differently, based on their characteristics, and in the literature are often categorized as energetic versus informational masking (Brungart, 2001; Lecumberri *et al.,* 2010). Energetic masking noise (EN) and informational masking noise (IN) present several differences:

- From a cognitive point of view, EN occurs because of overlap between target and masker at a peripheral stage in the auditory pathway, while the subsequent effects of interaction occurring at a central stage are related to IN, as defined by Pollack (1975);
- The spectral distribution of EN is comparable to white noise or to a speech-modulated noise, while IN has a spectrum that changes based on the characteristics of the talker(s) it refers to (e.g. male-adults IN will have higher occurrences at lower frequencies than children IN).
- IN has an informational content that EN does not have, hence it is confusing and distracting for a listener, who can more likely fail in segregate the target and the masker because of similarity and because of stealing of attention (Kidd *et al.*, 2005).

The effect of informational masking on speech intelligibility inside an auralized cafeteria environment was explored by Westermann and Buchholz (2015b) in terms of SRT values. A distance of 2 m between listeners and a target was considered while the informational maskers were distributed through the environment in co-located or separated positions with respect to the listener. The separated positioning of the masker brought an improvement of 8 dB of SRTs compared to the co-located condition. Peng *et al.* (2018) virtually simulated the acoustics of two classrooms with reverberation time of 0.4 s and 1.1 s for the examination of its effect in combination with IM on SRM of adults and children. Children showed lower, i.e., worse, results in terms of SRMs than adults and did not exhibit significant differences between the two classrooms. On the contrary, adults performed better in the classroom with shorter reverberation time. These results were corroborated by their subsequent study (Pen *et al.* , 2021), where an immaturity in using binaural

cues for speech-in-noise perception was found until at least 10-12 years old even in mild reverberation. Puglisi *et al.* (2021) investigated to which extent reverberation and IM and EM noise affect SRT80s under very good and very poor classroom acoustics, involving adult listeners. As far as reverberation is considered, worse, i.e., higher, SRT80s in the more reverberant classroom with both IM and EM were found; referring to the type of noise, SRT80s in the case of IM were higher by 7 dB SNR in comparison to EM.

Binaural speech intelligibility prediction models through the years

Binaural speech intelligibility has been also investigated through prediction models (Levitt and Rabiner, 1967; Vom Hövel, 1984, Zurek, 1990; Levandier and Culling, 2010; Van Wijngaarden and Drullman, 2008). Among the most recent, Beutelmann and Brand (2006) found high correlations between predicted and measured SRT for different spatial configurations of noise and speech source in anechoic and reverberant rooms. The model was extended by Beutelmann *et al.* (2010), bringing to a mean absolute prediction error of 3 dB considering normal-hearing subjects. Since the latter model could not satisfactorily predict the effect of late reflections on speech intelligibility, Rennies *et al.* (2014) evaluated three extensions. In any case, all the above mentioned models can make prediction only accounting for EM noise.

Reasons for the use of a binaural speech intelligibility prediction models in the present study

A lack of high accuracy of speech intelligibility prediction models with respect to real acoustic conditions emerges, particularly considering the combined effect of reverberation and noise (Puglisi *et al.* 2021). In order to validate the accuracy of speech intelligibility prediction models, there is a need for field measurements in real acoustic conditions that consider the combination of reverberation and noise. Hence, to go beyond the available knowledge in the field, an experiment based on ecological acoustic conditions was performed. Two typical Italian primary school classrooms were considered, and predictions of speech intelligibility considering normal-hearing adults were performed.

The aim of the study was to objectively assess binaural speech intelligibility and monaural room acoustic parameters in the two classrooms. It was investigated to which extent reverberation and noise affect speech intelligibility under good and poor acoustics by measuring the signal-to-noise ratio yielding 80% correct recognition scores (i.e., Speech Recognition Threshold, SRT80 in dB SNR). Only stationary, speech-shaped energetic masking (EM) noise was considered. Then, the SRM both for close and far target-to-receiver distances were obtained.

5.2. Methods

5.2.1. Classrooms

Monoaural and binaural acoustical measurements were carried out in two classrooms belonging to the same school building located in Torino (Italy). The school is a three-story building that dates back to the early twentieth century. While the architectural features (i.e., geometry, finishes) of the two classroom were identical, they differed in acoustical properties due to an acoustical treatment applied to one of them. In the following, they will be considered as a one classroom before and after acoustic treatment, referred to as *ante operam* (AO) and *post operam* (PO) conditions, respectively. **Figure 10** and **Figure 11** consist of pictures of the AO and PO conditions, respectively. In particular, the classrooms present a rectangular plan of dimensions of 6.7 m x 8.4 m, and a volume of around 258 m^3. Both the classrooms are located at the ground floor of the school building. The environment is characterized by the presence of three windows facing the school courtyard adjacent to a road with medium volume of traffic; the floor's finishes are mainly made of venetian tiles, while the walls and the ceiling are covered by a plaster in the case of AO condition. The furniture consists of student's desks and chairs, bookshelves, and blackboards. In the PO classroom, the acoustical treatment involved the addition of absorbent panels in glass fiber ($\alpha_{0,5\text{-}1kHz}$ = 1) on the left longitudinal (9.7 m^2) and rear (16.2 m^2) walls, and of a countertop in glass fiber ($\alpha_{0,5\text{-}1kHz}$ = 0,95) on the ceiling (56.3 m^2).



Figure 10. Pictures of the classroom ante operam (AO)



Figure 11. Pictures of the classroom post operam (PO)

Measurements were performed out of school time and 23 children sitting at their desks were simulated with the 100% polyester fiber panels (0.6 m x 0.6 m x 0.05 m each).

5.2.2. Acoustic measurements

Monoaural measurements

Monoaural measurements were carried out according to the protocol proposed in **Chapter 3** and with the aim to characterize the acoustics of the room. A calibrated NTi XL2 (NTi Audio, Schaan, Liechtenstein), sound level meter and a NTi Audio TalkBox (NTi Audio, Schaan, Liechtenstein) source were used for the measurements. **Figure 12** shows that recordings were performed for four receiver positions along the central axis at a distance of 1 m, 2.2 m, 3.6 m, and 6.2 m from the source and with a height of 1.2 m from the floor. The TalkBox source laid always in the same position and was placed on the central axis of the classroom at 1 m from the frontal wall and at 1.5 m from the floor. Room impulse responses were acquired from exponential sine sweep signals emitted by the TalkBox and recorded by the sound level meter.

Reverberation time (T30, s) was averaged over a frequency range from 250 Hz to 2 kHz, while the early decay time (EDT, s), speech clarity (C50, dB) and definition (D50, dB) were averaged over a frequency range from 500 Hz to 1 kHz, all according to UNI 11532-2 (2020). Calculated parameters were compared to the recent recommendations for an optimal occupied classrooms. An optimal reverberation time should be around 0.5 s (UNI 11532-2, 2020), EDT between 0.3 s and 0.7 s (Bradley, 2011), C50 greater than approximately 2 dB (UNI 11532-2, 2020), and D50 in a range of 0.86 to 1.0 for an excellent acoustics (Marshall, 1994).

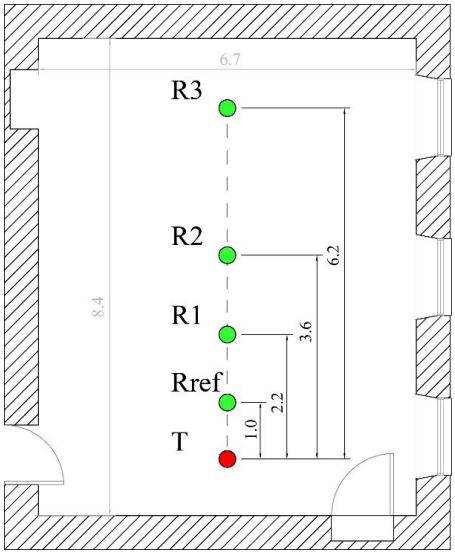

Figure 12. Spatial configuration for monoaural measurements of targets (T, solid red circles) and receiver (R, solid green circles) in the two geometrically identical classrooms. Geometrical dimensions of the rooms are also provided.

Binaural measurements

Binaural room impulse response (BRIRs) were recorded with a Brüel & Kjær (B&K) Head and Torso Simulator (HaTS) using an NTi Audio TalkBox source with speech directivity pattern for talker-related BRIRs and a Larson Davis Omnidirectional (Dodecahedral) sound source for a masker-related BRIRs. **Figure 13** shows the equipment used for the measurement of the binaural room impulse responses.



Figure 13. Equipment used for the binaural measurement in classroom. The TalkBox, the HaTS and the Dodecahedral sound source are visible in the picture.

Figure 14 show the measurement chain for the acquisition of the binaural room impulse responses. As it is visible from the image, the HaTS ears are connected to the first sound card (a), from whose channel 1 (CH1) and channel 2 (CH2) are coupled to line right (R) and left (L) of the second sound card (b). From this second sound card (b) two cables come out: the first connects from the line out to the Dodecahedral, the second is connected directly to the pc via usb. Finally, the Dodecahedral is connected to an amplifier.

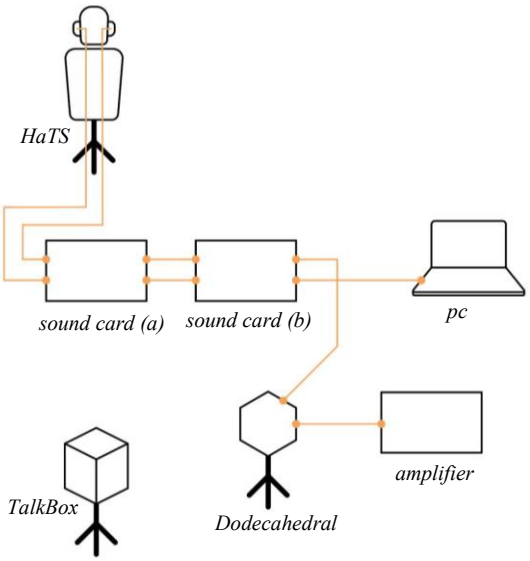

Figure 14. Scheme of the measurement chain for the acquisition of the binaural room impulse responses.

In order to focus on such aspects as the influence of the acoustical treatment on speech recognition and the SRM as a measure of binaural speech processing, some conditions were kept constant: in particular, the sound pressure level and configuration of the target speaker (T), the head orientation and height of the receiver (R), the sound pressure level and typology of noise of the masking noise source (M) never changed during the measurement campaigns.
The speech source position (T) was fixed at 1.5 m height and at 1 m from the rear wall on the central axis of the classroom. The receiver's ears were at 1.5 m from the floor and it was placed at three distances from the T, namely at 1.5 m, 4.0 m and 6.5 m, referred in the following to as $T_{1.5}$, $T_{4.0}$ and $T_{6.5}$, respectively. Finally, the noise source was set at 1.5 m height in six positions that differed in angular position (0°, 180°, and 120°) and/or distance (1 m, 1.5 m. 2.5 m) with respect to the receiver.
Figure 15 and **Table 25** show the configurations of the binaural acoustical measurements, where:
i) the left side scheme shows the close target-to-receiver distance ($T_{1.5}$) corresponding to the first raw of student's desk. It is the most advantaged acoustic condition under evaluation. The positions of the noise source consider several distances (1.0, 2.5, and 5 m) and 2 azimuths(120° and 180°). The effect of increasing noise distance can also be evaluated, in agreement with literature studies such those of Westermann & Buchholz who studied the effect of noise distance on axis (from 1 m to 10 m). The two azimuths are considered in order to evaluate influence of reverberation and noise distance on SRM. It is expected that the SRM will be reduced in reverberated conditions compared to the anechoic conditions from the literature. Furthermore, it is expected that SRM will decrease with increasing distance between noise and receiver;
ii) the central scheme shows the conditions with the far target-to-receiver distance of 4 m ($T_{4.0}$) and corresponds to the central raw and is assumed to be the most disadvantaged condition for the students. Again, the noise source is placed at several distances (1, 2.5 and 4 m) and 3 azimuths (0°, 120° and 180°). These configurations allow evaluating differences in intelligibility when the noise source is located in front and in back of a listener which may introduce spectral cues resulting in speech intelligibility differences (14). Also, the SRM is examined and compared across the three target-to-receiver distances;
iii) the right-side scheme shows the very far target-receiver position ($T_{6.5}$). It corresponds to the last row of student's desk and it is assumed that, although the target-to-receiver distance increases, intelligibility can be improved compared to T4.0 due to the speech reflections of the rear wall. In line with conditions described above, the noise source is placed at several distances (1 m, 2.5 m, 5 m, and 6.5 m) and at 2 azimuths (120° and 0°) in order to examine the effect of increasing noise distance and SRM for a receiver located far away from the target speech.

5.2.3. Binaural speech intelligibility model

BSIM model

The binaural speech intelligibility model (BSIM, Beutelmann *et al.,* 2010) was used to predict SRTs for the different receiver and noise source positions in the two acoustical environments (AO and PO). The model requires to separate speech and noise signals for each ear. For that, the corresponding BRIRs were convolved with the speech and noise signal. First, the signals are filtered using a gammatone filterbank (Hohmann, 2002) ranging from 146 Hz to 8300 Hz in 30 ERB spaced frequency bands simulating the frequency selectivity of the human auditory system.

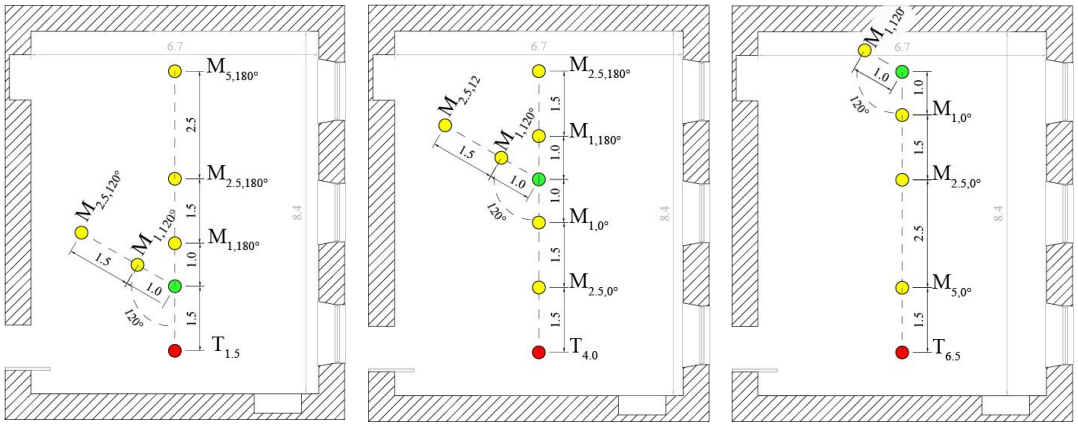

Figure 15. **S**chemes of the three different configurations. In each scheme the solid red circle represents the target position (T), the solid green circle identifies the receiver position (R), while the masker positions (M) are indicated by solid yellow circles. Specification of linear and angular distance from the receiver are indicated in subscript for target and maskers: for example, $T_{1.5}$ indicates that the target is 1.5 m away from the receiver, while $M_{5,180°}$ indicates that the position of the masking is 5 m away from the receiver and with an angle of 180°.

Table 25. Target- and masker-receiver distances and masker azimuth for the three experimental conditions.

	Configuration	Target-receiver distance	Masker-receiver distance	Masker azimuth	Condition
scheme i)	$T_{1.5}M_{1,\ 120°}$, $T_{1.5}M_{2.5,\ 120°}$	1.5 m	1 m, 2.5 m	120°	separated
	$T_{1.5}M_{1,\ 180°}$, $T_{1.5}M_{2.5,\ 180°}$, $T_{1.5}M_{5,\ 180°}$	1.5 m	1 m, 2.5 m, 5 m	180°	co-located
scheme ii)	$T_{4.0}M_{1,\ 120°}$, $T_{4.0}M_{2.5,\ 120°}$	4 m	1 m, 2.5 m	120°	separated
	$T_{4.0}M_{1,\ 180°}$, $T_{4.0}M_{2.5,\ 180°}$	4 m	1 m, 2.5 m	180°	co-located
	$T_{4.0}M_{1,\ 0°}$, $T_{4.0}M_{2.5,\ 0°}$	4 m	1 m, 2.5 m	0°	co-located
scheme iii)	$T_{6.5}M_{1,\ 120°}$	6.5 m	1 m	120°	separated
	$T_{6.5}M_{1,\ 0°}$, $T_{6.5}M_{2.5,\ 0°}$, $T_{6.5}M_{5,\ 0°}$	6.5 m	1 m, 2.5 m, 5 m	0°	co-located

Then, binaural processing is considered by applying the Equalization-Cancellation (EC, Durlach, 1963) mechanism. In the EC mechanism, the interaural level differences (ILD) and the interaural time differences (ITD) are equalized in each frequency band, independently. In a next step, the equalized left ear channel is subtracted from the equalized right ear channel (or vice versa). The equalization of the ITD and ILD is optimized such that the SNR is maximized after applying the cancellation step. However, the accuracy of the equalization is limited by internal noise. If the target and noise signals differ in their interaural parameters, which is the case if they are spatially separated from each other, the SNR can be substantially improved due to constructive interferences in the target signal and more important, destructive interferences in the noise signal. . In the next step, the EC-maximized SNRs are compared to the monaural SNRs of the left and the right ear in each

frequency band. The maximum SNR of all three alternatives is considered for further processing.. In a last step, the speech intelligibility index (SII, ANSI 1997) performs a weighting of the SNRs in each frequency band to mirror human speech perception. Afterwards, the speech-weighted SNRs are integrated over frequency and transformed to an index value between 0 and 1, which can then be mapped to SRTs.

Calibration

In order to transfer an SII into an SRT, a reference condition needs to be defined and calibrated in the BSIM which requires an empirical SRT. Usually the reference condition corresponds to anechoic co-located target and masker sources placed in from of the listener at the same distance (Beutelmann *et al.,* 2010; Haut and Brand, 2018). Here, a different approach was used, because the acoustical sources for speech and noise were not the same (Talkbox vs. dodecahedron). Instead, the BSIM was calibrated to the PO condition were the speech was coming from the target source position and the noise was located 1 m behind the listener (M3). This situation is most similar to an anechoic situation typically used for calibration since the binaural effects are almost neglectable and the target is not influenced by reverberation due to a very short target-receiver distance. The calibration obtained in this situation was kept constant across room acoustic scenarios and target/masker combinations.

The reference SII was set to 0.22, which corresponds to empirical SRT in anechoic and co-located speech/noise situations (Beutelmann *et al.,* 2010; Rennies *et al.,* 2014; Wagner et al., 2020). It is important to note that the relative differences across conditions which are of main interest here are not affected by choosing the reference SII.

5.3. Results

5.3.1. Classroom acoustics results

Table 26 shows the measured values of the acoustic parameters for both AO and PO conditions. The acoustic conditions in the PO condition agree with the standard with respect to all the parameters investigated. Reverberation time ($T30_{0.25\text{-}2\ kHz}$) is in its optimum range according to the DIN 18041(2016) standard and UNI 11532-2 (2020) indication for rooms named A3, that is, rooms dedicated to lesson and communication between teacher and students. Early decay time ($EDT_{0.5\text{-}1\ kHz}$) also is in the range provided by Bradley (2011). Clarity value ($C50_{0.5\text{-}1\ kHz}$) complies to the UNI 11532-2 (2020) standard for classrooms with volumes lower than 250 m^3 and Definition value is in the optimal range suggested by Marshall (1994). After the acoustical treatment the values of the parameters were improved: in fact, reverberation decreases parallel to the increase of speech clarity and definition. On the contrary, the obtained data in AO do not meet the aforementioned standards.

To further characterize the acoustics of the two classrooms, **Table 26** also reports the critical radius (r_c) and the corresponding five-time distance. The critical radius of each room was calculated as $r_c=\sqrt{0.0032V/T}$, where V is the volume of the room and T represents its reverberation time. It indicates the distance from a source at which the direct and reverberant field are equivalent in terms of intensity. A suggested by Houtgast *et al*. (1980), speech intelligibility remains constant and depends only on the reverberant field if the distance exceeds five times the critical radius, i.e., $0.3\sqrt{V/T}$.

In both classrooms the target-to-receiver distances and noise-to-receiver distances are larger than the critical radius. In the AO condition the critical radius is exceeded five times for one receiver position and for two noise-to-receiver distances. This highlight that in the AO condition the reverberant field is predominant.

Table 26. Descriptive statistics of the acoustical parameters measured in the ante operam (AO) and post operam (PO) conditions. Standard deviations are indicated in parentheses. Values that meet the standards are highlighted in bold.

Condition	$T30_{0.25\text{-}2\ kHz}$ [s]	$EDT_{0.5\text{-}1\ kHz}$ [s]	$C50_{0.5\text{-}1\ kHz}$ [dB]	$D50_{0.5\text{-}1\ kHz}$ [%]	Critical radius (r_c) [m]	$0.3\sqrt{V/T}$ [m]
AO	1.4 (0.1)	1.4 (0.1)	-1.1 (2.3)	44 (12.8)	0.8	4.1
PO	**0.4 (0.0)**	**0.3 (0.1)**	**10.6 (3.2)**	**90 (5.0)**	1.4	7.6
Optimum range	0.5	0.3÷0.7 s	≥2.0	86÷100	n.a.	n.a.
Reference	UNI 11532-2, 2020	Bradley, 2011	UNI 11532-2, 2020	Marshall, 1994	Houtgast et al., 1980	

5.3.2. Binaural speech intelligibility results

Effect of classroom acoustics

Figure 16, **Figure 17** and **Table 27** show the intelligibility benefits of the PO intervention for all target and masker combinations. An improvement of speech intelligibility after acoustical treatment ranges from predicted SRT improvements (ΔSRT) of 6.4 dB SNR to 17.3 dB SNR and is observed in all the target-masker configurations. Greater benefits of about 9 – 17 dB SNR are in the spatially separated noise position for all target-to-receiver distances. The benefit is larger when the masker is closer to the receiver (at 1 m = 15.2 dB SNR, at 2.5 m = 12.3 dB SNR). SRT benefits are obtained also for the co-located noise positions of 0° and 180°. In these cases, there is no influence of the masker distance, i.e., SRT benefit does not change with increasing the masker distance. When noise is co-located, the receiver positions at 1.5 away from the target source shows SRT benefit of about 9.2 dB, which decreases to about 6.4 dB at 4.0 m away from the target and then it increases to 13.6 dB for the far-far receiver position at 6.5 m from the target. Larger benefit for the $T_{6.5}$ could be due by the stronger influence of the absorbing panels on the rear wall for the far-far target-to-receiver distance; on the contrary, in AO the noise signal is reflected by the rear wall and delayed to the listener, that

receive simultaneously the covered speech signal, arriving later because of the greater distance.

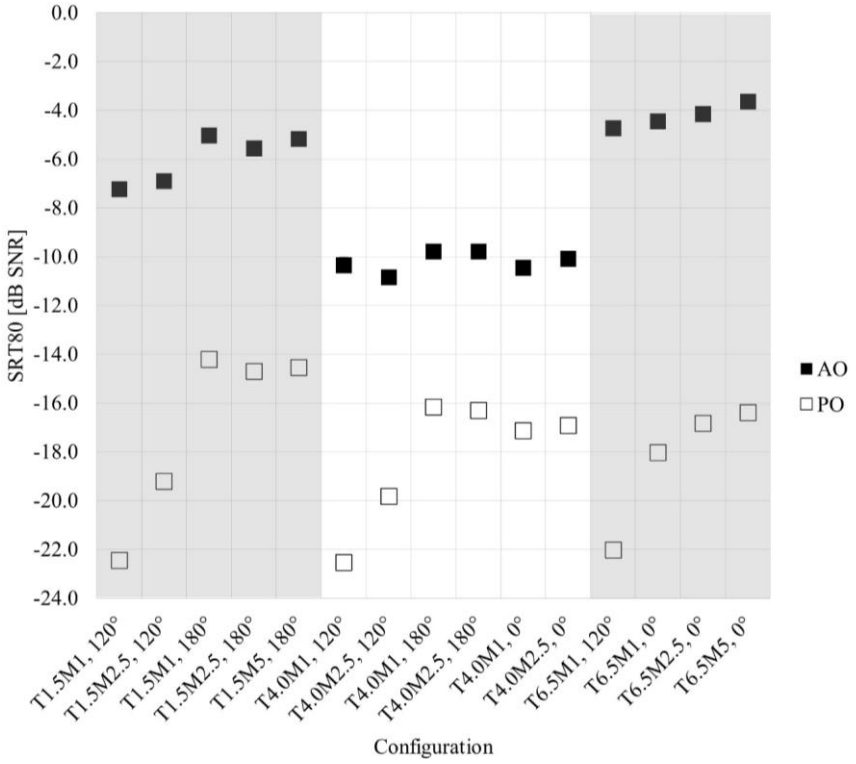

Figure 16. Obtained speech reception thresholds (SRT80s) in AO and PO conditions, considering the positions of target-to-receiver ($T_{1.5}$, $T_{4.0}$, $T_{6.5}$) and the masker-to-receiver distance (N_1, $N_{2.5}$, N_5) and angle (0°, 120°, 180°).

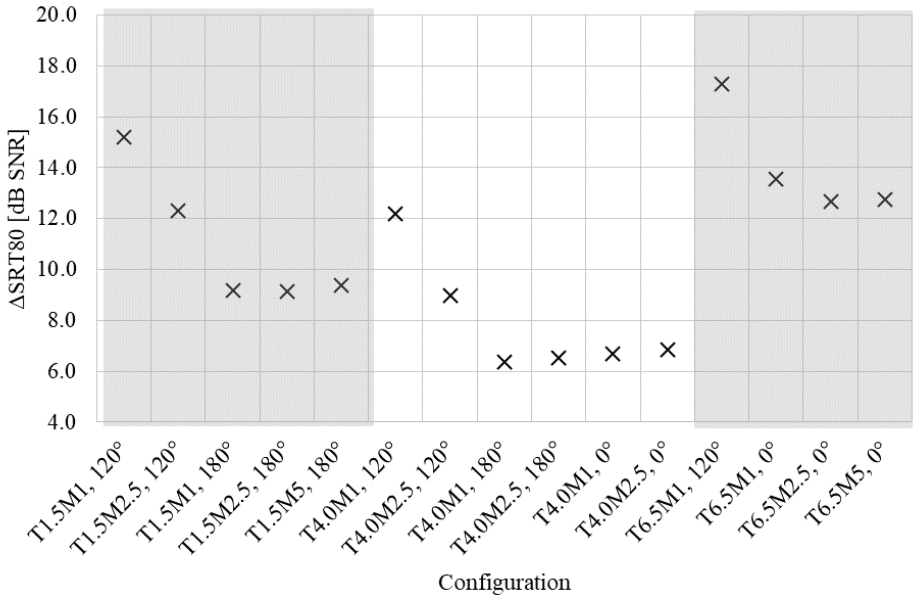

Figure 17. Difference between the obtained speech reception thresholds (SRT80s) in AO and PO conditions, considering the positions of target-to-receiver ($T_{1.5}$, $T_{4.0}$, $T_{6.5}$) and the masker-to-receiver distance (N_1, $N_{2.5}$, N_5) and angle (0°, 120°, 180°).

Table 27. Differences in speech recognition thresholds (ΔSRT80s) predicted in the AO condition minus the PO condition.

	Configuration	SRT80 [dB SNR]		ΔSRT80 [dB SNR]
		AO	PO	(AO-PO)
scheme i)	$T_{1.5}M_{1,\ 120°}$	-7.2	-22.5	15.2
	$T_{1.5}M_{2.5,\ 120°}$	-6.9	-19.2	12.3
	$T_{1.5}M_{1,\ 180°}$	-5.0	-14.2	9.2
	$T_{1.5}M_{2.5,\ 180°}$	-5.6	-14.7	9.1
	$T_{1.5}M_{5,\ 180°}$	-5.2	-14.5	9.4
scheme ii)	$T_{4.0}M_{1,\ 120°}$	-10.3	-22.5	12.2
	$T_{4.0}M_{2.5,\ 120°}$	-10.8	-19.8	9.0
	$T_{4.0}M_{1,\ 180°}$	-9.8	-16.2	6.4
	$T_{4.0}M_{2.5,\ 180°}$	-9.8	-16.3	6.5
	$T_{4.0}M_{1,\ 0°}$	-10.5	-17.1	6.7
	$T_{4.0}M_{2.5,\ 0°}$	-10.1	-16.9	6.8
scheme iii)	$T_{6.5}M_{1,\ 120°}$	-4.7	-22.0	17.3
	$T_{6.5}M_{1,\ 0°}$	-4.5	-18.0	13.6
	$T_{6.5}M_{2.5,\ 0°}$	-4.1	-16.8	12.7
	$T_{6.5}M_{5,\ 0°}$	-3.6	-16.4	12.7

Generally, the predicted results of this study confirmed the observation from the literature (Rennies *et al.,* 2011; Beutelmann *et al.,* 2010; Puglisi *et al.,* 2021) where SRTs increased (got worse) with the degree of reverberation. This trend is also in agreement with the results of Peng *et al.* (2021) that demonstrated SRT worsening when increasing reverberation from 0.4 to 1.1 s, that is exactly the two reverberation time considered in the present study, considering 7-12 year old children. Also for the monaural acoustic measures, substantial improvement for short reverberation time was observed (**Table 26**). In this study, D50 values were better in all the frequency bands for the PO condition (AO/PO 125 Hz: 0.33/0.58, 250 Hz: 0.44/0.80, 500 Hz: 0.44/0.87, 1000 Hz: 44/95, 2000 Hz: 59/95, 4000 Hz: 67/96, 8000 Hz: 87/97), which correctly predict better intelligibility in the PO condition in agreement with Beutelmann and Brand (2006) and Beutelmann *et al*. (2010). However, application of the objective acoustical measures is limited to co-located conditions since they cannot account for the binaural aspects. In contrast, BSIM can account for binaural processing and assess speech intelligibility not only for co-located conditions but also for different spatial configurations of target and masker which reflects better real listening conditions.

Spatial release from masking in angle

Figure 18 shows that, in general, the benefit of SRM in angle is greater in PO than in AO and ranges from 2.9 to 8.3 dB SNR, with the greatest benefit in $T_{1.5}M_{1,180°\text{-}120°}$ in PO. Moving the masker from 0° to 120° results in lower benefits than moving it from 180° to 120°, in both AO and PO conditions. The SRMs for the AO range between -0.1 and 2.2 dB indicating that reverberation strongly degrades the binaural cues that are used to improve speech intelligibility in spatially separated conditions. Reverberation decorrelates the signals at the left and right ear and by that the human binaural system is not able to exploit the binaural cues. In a consequence, SRTs in co-located and spatially separated conditions are similar leading to no or strongly reduced SRM. Focusing only on the configurations with the masker at 1 m from the receiver, the binaural release from masking is in the range of 6 dB for the PO condition, while it is very much reduced (0.7 dB) for the AO. It demonstrates how important is reverberation for the binaural aspects and quantifies how big can be the benefit from acoustical treatment in terms of SRM. This has very important implications for the acoustical design and treatment of classrooms. The binaural aspects have a crucial role in source segregation, enabling focus on the speech target and at the same time supressing the interfering sources. It is, however, only possible in the classrooms with a good acoustics.

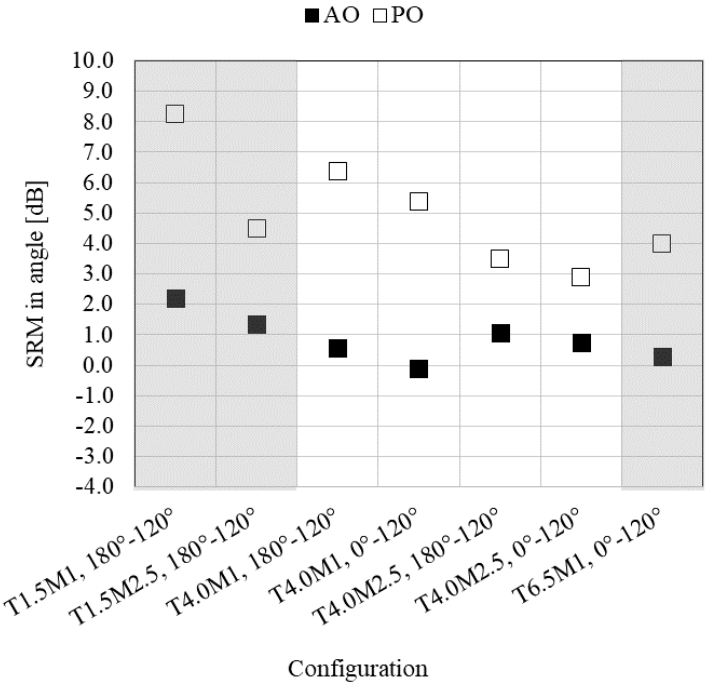

Figure 18. Spatial release form masking (SRM) of close target and masker ($T_{1.5}M_{1,180°\text{-}120°}$), close target and far masker ($T_{1.5}M_{2.5,\ 180°\text{-}120°}$), far target and close masker ($T_{4.0}M_{1,\ 180°\text{-}120°}$; $T_{4.0}M_{1,\ 0°\text{-}120°}$), far target and far masker ($T_{4.0}M_{2.5,\ 180°\text{-}120°}$; $T_{4.0}M_{2.5,\ 0°\text{-}120°}$), very far target and close masker ($T_{6.5}M_{1,\ 0°\text{-}120°}$). Black squares indicate the AO condition, while the white ones are for the PO condition.

Finally, the predicted SRM in this study are compared to the data from literature obtained in the anechoic conditions with a speech source in front of the listener and

varying azimuth of a noise source (Bronkhorst, 2000). According to expectations, anechoic SRMs are higher (better) than those in real rooms. For a noise azimuth of 120°, up to 13 dB SRT improvement can be obtained in anechoic condition (Bronkhorst, 2000) whereas it is reduced to about 6 dB in rooms with a good acoustics as indicated by the results of PO condition, and is almost absent in rooms with high reverberation time (AO condition). It is in line with other studies examining SRM under reverberant conditions (Beutelmann and Brand, 2006; Beutelmann *et al.,* 2010). For example, as shown in Beutelmann and Brand (2006), where room acoustic of an office and of a cafeteria were considered, and in Beutelmann *et al.* (2010), where a classroom, a listening room and a church were investigated, the SRM at 120° was in the range of about 2-8 dB, i.e., substantially lower (worse) than in an anechoic condition. Puglisi *et al.* (2021) considered two classroom with a reverberation time of 0.4 s and 3.1 s and obtained SRMs of 2.8 dB and -0.2 dB, respectively, considering a target positioned 1.5 m from the receiver and an energetic masking noise source at 1 m from the receiver. The average SRM obtained in the classroom with 0.4 s reverberation time was equal to 1.7 (±2.3) dB, while the one obtained in the classroom with 3.1 s reverberation time was equal to 0.2 (±0.8) dB. However, Peng *et al.* (2021) observed that, considering IM and reducing reverberation time of two virtual acoustic classrooms from 1.1 s to 0.4 s, significant SRM improvements were shown only for adult listeners but not for 7-12 year old children. These improvements were about 11-13 dB SMR with the lower reverberation time and about 10 dB SMR with the higher one, for adults, while for children they ranged from 3 to 8 dB SMR for both the conditions.

Spatial release from masking in distance

The SRM in distance was determined only for the cases in which the noise source was separated, i.e., masker at 120° azimuth, in order to focus on the condition where receiver can benefit more from binaural cues and to understand the influence of reverberation. The far distance between noise and receiver is always 2.5 m compared to 1 m, as the only azimuth condition considered is the separated one of 120°.

Figure 19 shows that, in general, the benefit of SRM in distance is greater in PO than in AO and that it is on average equal to 3 dB and -0.1 dB, respectively. In agreement with **Table 27** and the critical radius, in the PO condition the noise level is mainly due to the direct sound when the masker is at 1 m from the listener, while it is due to the direct plus the reverberant contributions when the masker is at 2.5 m. In the AO condition, the noise level is due to the direct plus reverberant contribution when the masker is at 1 m or at 2.5 m from the listener.

In the configuration with the target close to the receiver, i.e., at 1.5 m from the listener, SRM in PO conditions resulted to be of 3.3 dB. This predicted value of SRM in distance corroborates results by Puglisi *et al.* (2021), which found an average SRM in distance across subjects of 3.1 dB in the same target-receiver-masker configuration for a classroom with an equal reverberation time of 0.4 s.

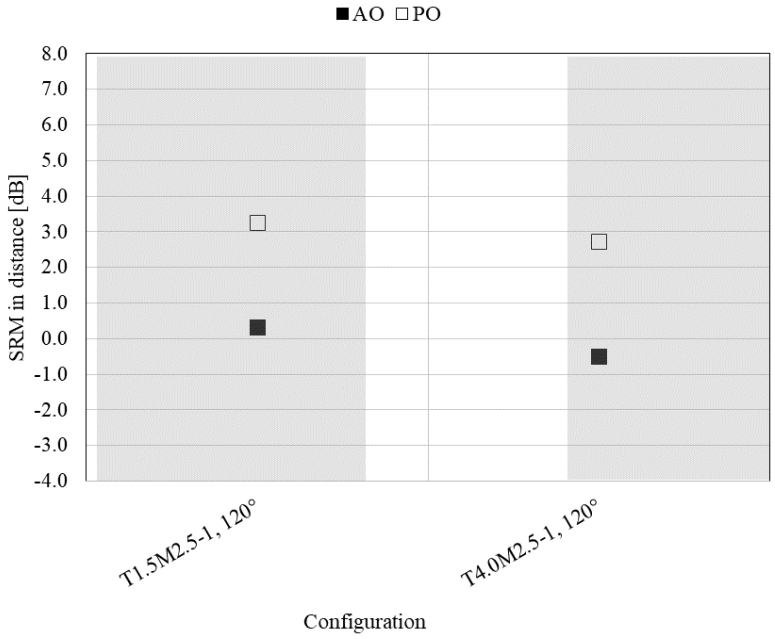

Figure 19. SRM in distance in the case of close target and separated masker ($T_{1.5}M_{120°}$) and far target and separated masker ($T_4M_{120°}$).

5.4. Discussion

5.4.1. Classroom acoustics and speech intelligibility

The results of the monoaural acoustic parameters show that only the PO condition agrees with the standards, while the AO condition presents an acoustics not adequate. The sound propagation can be negatively affected by the presence of large volume and reflective surfaces that characterized the historical building such the one considered in this study. The AO condition in fact refers to the classroom without an acoustic treatment able to decrease the unwanted sound tail and to support the useful early reflections. Conversely, the PO condition is characterized by the presence of a recent acoustic treatment that covers the walls and the ceiling, making the classroom compliant also with the recently updated requirements in the Italian standard UNI 11532-2:2020.

The acoustics parameters T30 and C50 are correlated to speech intelligibility as indicated by other studies in classrooms (Yang and Bradley, 2009; Bradley *et al*., 1999), however additional investigation concerning binaural indices is necessary. Measured and predicted SRT were found to be significantly correlated by Rennies *et al.* (2011), the latter being obtained from a binaural speech intelligibility model based on Definition, D50, that is exactly related to C50 as shown in EN ISO 3382-2:2008.

5.4.2. Effect of reverberation on speech intelligibility

As an overall effect, longer reverberation time degrades speech intelligibility, as shown by the increase in the SRT80s values in the AO condition compared to

the PO condition. Particularly, under long reverberation time, SRT80s were higher by 10.6 dB SNR on average when reverberation times of 1.4 s and 0.4 s are considered. This result agrees with the review of Bronkhorst (2000) that found an increase by up to 10 dB SNR of SRTs due to the adverse effect of reverberation on speech intelligibility. A lower SRT difference, i.e. around 2.5 dB SNR, was found reducing reverberation time from 1.1 s to 0.4 s by Peng *et al.* (2021), when considering IM and both adults and 7-12 year old children. The reduction of intelligibility with the increase of reverberation was demonstrated by other studies (Astolfi *et al.,* 2012; Prodi *et al.,* 2013; Visentin *et al.,* 2018). Nábělek and Robinson (1982) observed that listeners' ability to discriminate speech in quite was significantly reduced by reverberation, regardless of their age. These outcomes were corroborated by Beutelmann *et al.* (2010) who conducted experiments in an office and in a cafeteria and found higher SRT with longer reverberation time.

5.4.3. Effect of spatial separation of noise on speech intelligibility

Listener's ability to discriminate speech from noise when such sources are spatially separated, both in angle and in distance, can lead to a higher speech intelligibility under competitive noise.

Considering the SRM in angle, decrease in SRTs, i.e., positive effects, of up to 12 dB when the noise source is spatially separated and at 120° from the listener are reported in a widereaching review by Bronkhorst (2000). These positive effects can be compromised by reverberation, as reported in the review, that included experiments carried out in anechoic conditions with energetic maskers. Real acoustic scenarios with reverberation and informative content of speech and noise should be investigated in field studies in order to test the accuracy of speech intelligibility prediction models (Rennies *et al.,* 2011; Beutelmann *et al*., 2010). The work by Peng *et al.* (2021) embraced this direction, since it investigated the role of informational masking in modulating SRM of adults and children in two virtually reproduced realistic reverberant environments. Only the SRM improvements moving the masker from a collocated position to a 90° separated position of the adults were significant, and they were around 10 dB with a reverberation time of 1.1 s and around 13 dB with a reverberation time of 0.4 s.

The results of this study are in the range of those presented in literature. For the PO condition results show an SRM equal to ~6 dB when the energetic masker noise source is at 1 m from the listener. This value is barely lower to the findings of Bronkhorst (2000) and Dirks and Wilson (1969), since they measured SRM up to 7.5 dB to yield SRT50 under anechoic condition when the energetic masker noise was separated from the speech source with an angle of 90°. Beutelmann *et al.* (2006) considered a stationary speech-shaped noise in different environments, i.e., anechoic condition, cafeteria, and office. They founded an SRM of 12 dB in anechoic condition when the noise was at 100° from the receiver, that was reduced to about 3 dB in the office for different noise azimuth and to about 6 dB in the cafeteria. In the present study, in the case of AO condition, SRM in angle resulted

to be equal to ~0 dB when the distance between masker and receiver was 1 m. In these terms, the spatial release from masking in angle in AO was not remarkable and corroborated the results by Ahrens *et al.* (2019) who did not found significant SRM when energetic noise occurred under long reverberation times.

As far as SRM in distance is concerned, a major and recent reference in the available literature is related to Puglisi *et al.* (2021), who found that, in a classroom with reverberation time of 0.4 s, the spatial advantage given by moving an energetic masking noise source from 1 m to 2.5 from the receiver and being the target source 1 m apart corresponds to ~3 dB. The same result is found in the present study in the PO condition, i.e., in a classroom with a similar reverberation time.

5.5. Strength and limitations

The principles underlying the processing of complex auditory scenes by humans are not yet fully understood. Particularly, a lack of field studies that investigate the effect of noise, reverberation and spatial configurations emerges. The present study makes use of acoustical measurements and predictive tools to bring new insights into the research field, which needs to be further investigated in light of more than a few aspects. First, the speech intelligibility predictive model by Beutelmann *et al.* (2010) used in the present study served for exploring the negative effect of reverberation on SRT and SRM under energetic masking noise. It and the other available predictive tools provided by Beutelmann and Brand (2006), and Rennies *et al.* (2014) do not account for informational content of noise, so they could be used to evaluate the effects originating by the energetic masking and by that help to interpret the condition with informational masking. However, the predictive models of speech intelligibility should be implemented thanks to in-field studies considering ecological acoustic aspects that are fundamental in real complex acoustic scenarios, such as informative maskers and the increasing deterioration of the speech signal by reverberation with increasing distance. In this way, simulation tools for accurate, effective and preliminary classroom acoustic design would be available. Second, the SRT and SRM results obtained in the present study refer to normal-hearing adult listeners. The aforementioned implemented predictive models should also account for the auditory processing of young children and hearing-impaired subjects, that can have a lower ability of isolating a target from a spatially separated masker speech. Third, the present study considers only two classroom acoustic conditions, that is before and after the acoustic correction intervention, so only the effect of two reverberation times is taken into account. Future studies should include a broader variety of reverberation times so that its effect on speech intelligibility in combination with noise could be deeper understood. Furthermore, future studies should focus on additional parameters apart from reverberation time, such as speech clarity, gain or direct-to-reverberation ratio, since they play an important role in the achievement of a proper acoustic design. This is evidenced by recent updates of the standards DIN

18041:2016 and UNI 11532-2:2020, where the use of absorbing panels in combination with scattering surfaces is recommended for the enhancement of classroom acoustics.

5.6. Conclusions

The goal of the present work was to investigate the binaural aspects of the auditory system of adult normal-hearing listeners through predictions of binaural speech intelligibility in classrooms with and without acoustical treatment when an energetic masking noise is used. The results showed that:

- the predicted SRTs are lower (better) in the acoustically treated room; predictions were consistent also with D50 checked in each frequency band;
- when considering the noise source position spatially separated from the listener's head, SRTs are lower (better) than those with the noise source spatially co-located;
- SRM in angle improves substantially as less reverberation directly influences the listeners ability to benefit from interaural differences between the target and the interfering signal;
- when the separated noise source is moved to a closer position to the listener, SRM improves in a similar way both with a closer or larger distance between target and receiver in the acoustically treated room.

However, these results should be evaluated in light of the fact that the BSIM model used in the present study was developed for normal-hearing adults which is also fed with acoustical data relating to adult anthropometry. Thus they could be not perfectly fit to describe the children behavior in the challenging binaural scenarios of the classrooms, who showed a more protracted trajectory in reaching the maturity in using spatial hearing for speech-in-noise understanding.

As an overall conclusion, guaranteeing optimal acoustic condition in classrooms is mandatory for good speech intelligibility. This can be pursued also in existing classrooms with a proper retrofit through the addition of absorbing material on the walls and on the ceiling. Furthermore, BSIM is a very useful tool to save time and obtain intelligibility predictions without involving people to test. The power of such a tool could become primary in the process of architectural design. Using a simulation software it can be possible to create a new environment and then directly obtain prediction on intelligibility. In case of interventions on already existing rooms, it is useful to obtain feedback on the best possible interventions without going on place.

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Chapter 6
Final considerations

6.1. Final remarks

In this final chapter, a summary and a brief discussion of the main findings is presented based on the aspects that constituted the objectives of this Ph.D. research. Also, an insight in the possible future applications of the obtained outcomes is given.

Objective 1: to review the state of the art on the effects of classroom acoustics on students' performance.

In **Chapter 2**, a review on studies published from 2002 to 2020 investigating the effect of classroom acoustics on students' performance at different ages is described.

With the aim to update and extend the outcomes of the previous review article by Picard and Bradley (2001), the present review procedure is based on the effect classroom acoustics can have on learning attainments and cognitive skills, speech intelligibility, and subjective perceptions under different classroom acoustic conditions. Only 38 papers out of the 56 containing empirical findings on the influence of acoustical parameters on students' performance were considered, as the remaining 18 lacked ecological validity or did not respond to the selection criteria. Studies were only included if they considered normal hearing subjects and typical lesson settings provided in classrooms without an amplification system. Thus, the studies selected involved subjects between 5 and 40 years old. The values of the acoustical parameters that led to better or worse learning performance were tabulated and the distribution of occurrences was created. The median and interquartile range for the distribution of occurrences were used to describe the central tendency and dispersion and analyzed considering two different age groups. The results obtained were used to develop classroom acoustic guidelines for better learning performance, and to identify the thresholds that lead to worse performances. Both guidelines and thresholds provide values for students under or over 12 years of age, since the need of a higher acoustical quality of younger students emerged from the considered studies. In particular, a reverberation time of 0.6 s, a signal-to-noise ratio equal to or over 12 dBA, a background noise level equal to or lower than 35 dBA and an speech transmission index equal to or higher than 0.65 are recommended for students under 12 y.o., that correspond to a reverberation time of 0.7 s, a signal-to-noise ratio equal to or over 12 dBA, a background noise level equal to or lower than 40 dBA and a speech transmission index equal to or higher than 0.6 for students over 12 y.o. In order to avoid worse learning performance for students under 12 y.o. values of reverberation time and background noise level should not exceed 1.2 s and 40 dBA, respectively, as well as signal-to-noise ratio and speech transmission index should not be lower than 5 dBA and 0.65, respectively. For students over 12 y.o. reverberation time and background noise level should not exceed 1.6 s and 60 dBA, respectively, as well as signal-to-noise ratio and speech transmission index should not be lower than -2

dBA and 0.60, respectively. However, these results should be evaluated in light of the fact that the identification of an optimal reverberation time range would be preferable than the indication of a single value and that excessive background noise level was found to have a larger detrimental effect on student performance than excessive reverberation.

Objective 2: to define a basic protocol for the acoustic characterization of classrooms that can be universally applied by technicians and practitioners.

In **Chapter 3** and **Chapter 4** a systematic approach for the measurement of the acoustical quality of parallelepipedal shaped primary school classrooms with medium volumes, i.e., between 100 and 290 m^3, is given.

Background noise level during silent and group activities, reverberation times, speech clarity, useful-to-detrimental ratio and speech levels were measured along the main axis and in one or two positions offset to each axis in 29 primary school classrooms in Turin, Italy. Measurements were carried out under occupied conditions, with 19 children per class on average. Reverberation time was measured also in empty conditions at the end of each session. The equipment consisted in a TalkBox source, in a calibrated-class-1 sound level meter and in a wooden clapper. The TalkBox was located in a position typically occupied by the teacher, at the height of 1.5 m from the floor, for the emission of exponential sine sweep signals. The sound level meter was located at 1.1 m from the floor in different positions over the pupils' seating area, representative of the first, the central and the last row of desks, respectively, then one listener position was chosen far from the source, at the rear of the classroom and offset to the axis, to account for the most disadvantaged conditions for speech intensity and directivity. For comparison purposes, the sound level meter was also collocated in a reference position whose configuration was kept unchanged in each classroom. The wooden clapper was activated in random positions inside the classroom.

The analyses carried out on the data acquired through the application of the measurement protocol revealed that reverberation time or speech clarity in the central point in occupied conditions can both be used as the most representative parameters to characterize classroom acoustics, at least under occupied conditions with the pupils silent, and with a lower background noise level than 56 dB(A). These results can be used to simplify the measurement protocol, whom measurement points can be reduced to a minimum number by measuring only the speech clarity in the central position of the classroom to satisfactory characterize the acoustic of the entire environment. Further simplifications concern the occupational condition of the classroom, since the measurement procedures can acquire ease and speed by measure T20 in unoccupied conditions from which the other related parameters can be estimated.

Objective 3: to identify the fundamental parameters for classroom acoustic characterization.

In **Chapter 3** and **Chapter 4**, correlation and regression analyses have been carried out on the collected data in order to identify the fundamental parameters for classroom acoustic characterization.

Based on the background noise level during silent and group activities, reverberation times, speech clarity, useful-to-detrimental ratio and speech levels measured in 29 primary school classrooms in Turin, Italy, statistical analyses have been carried out and they revealed that most of the parameters are significantly correlated. The fundamental parameters for classroom acoustic characterization resulted to be reverberation time or speech clarity in the central point in occupied conditions since from them it is possible to estimate the useful-to-detrimental ratio. The noise level in silent conditions, the slope per double distance of the speech level, and the speech level at 1 m from the source have not emerged as primary parameters to characterize classroom acoustics. Furthermore, reverberation time in unoccupied condition resulted to be significantly correlated with the speech clarity and useful-to-detrimental ratio parameters, so to measure reverberation time in unoccupied conditions is sufficient to estimate the other related parameters.

Objective 4: to provide thresholds to classify classrooms as compliant or non-compliant with the standard according to moderate or severe requirements.

In **Chapter 3**, new thresholds for classroom acoustic parameters, which discriminate the acoustic quality of primary school classrooms between compliant and non-compliant, are proposed on the basis of two different groupings, one that considers moderate classroom acoustic requirements and the other that considers severe ones.

The new thresholds for moderate requirements are 0.8 s and 0.9 s for the reverberation time under occupied and unoccupied conditions, respectively; 67 dB(A) for the noise level during group activities; 3 dB for speech clarity, when considered both as a spatial average and as a single value in the central position; 1 dB for the useful-to-detrimental ratio, when considered both as a spatial average and as a single value in the central position. The thresholds for severe requirements are 0.6 s and 0.9 s for the reverberation time in occupied and unoccupied conditions, respectively; 5 dB for speech clarity, when considered both as a spatial average and as a single value in the central position.

Moderate limits are intended for older pupils and for refurbishment, whereas severe limits are intended for younger pupils and in the case of new schools. These latter limits should be even more severe when children with special hearing and communication needs are included in mainstream classrooms. Both limits also support the teacher’s voice in the classrooms.

Objective 5: to investigate the association between objectively measured and subjectively perceived classroom acoustic conditions in the category of pupils.

In **Chapter 4**, the effect of classroom acoustics on noise disturbance and well-being was investigated through the association between the results of acoustical measures and the responses to questionnaires of pupils aged 6 to 7 years.

The findings of the study suggest that long reverberation times, i.e. higher than 0.8 s, which are associated with poor classroom acoustics as they generate higher noise levels and degraded speech intelligibility, bring pupils to a reduced perception of having fun and being happy with themselves. Furthermore, poor classroom acoustics is also related to an increased perception of noise intensity and disturbance, particularly in the case of traffic noise and noise from adjacent school environments. Finally, happy pupils reported a higher perception of noise disturbance in classrooms non-compliant with the standard, whereas unhappy pupils only reported complaints in classrooms characterized by such acoustics with respect to the perception of pleasances with himself or herself and of fitting in at school.

Objective 6: to obtain predictions for the evaluation of binaural speech intelligibility in noise, so that it can be used for design purpose.

In **Chapter 5**, a binaural speech intelligibility model (BSIM) is investigated for speech intelligibility predictions in a real classroom considering the effect of talker-to-listener distance and binaural unmasking due to the spatial separation of noise and speech source.

Two conditions, i.e., before and after an acoustic correction intervention, respectively, were compared and it was found the acoustic quality was better after the acoustical treatment of the room. This outcome emerged from the results of the measured monoaural parameters and from the predictions of speech intelligibility. In particular, before the intervention of acoustic correction, the parameters reverberation time and speech clarity did not comply with the reference standard and testified a degradation of speech intelligibility, as found in many studies. The degradation of speech intelligibility parallel to the increase of reverberation was confirmed by the predicted speech recognition thresholds, that presented values higher by about 11 dB SNR on averaged before the acoustic correction intervention. The speech intelligibility also degraded when the noise source was spatially co-located to the listener’s head, since the listeners could benefit less from binaural cues compared to a configuration with the noise source spatially separated.

6.2. Future perspectives

This Ph.D. thesis is not supposed to be the ending point of the research on classrooms acoustics. The experiments and analyses that were conducted so far allowed for the obtainment of interesting findings that constitute a step forward in the existing knowledge on the processes of teaching and learning in school environments, however several aspects still deserve a deeper insight.

6.2.1. Towards new requirements for classroom acoustic design

The work presented in **Chapter 3** has adopted a counter-current approach, since it has tried to highlight that different classroom acoustics requirements can be adopted. In fact, it is not always necessary to adopt too restrictive room acoustics requirements, and this is now evident from many research studies, from both the pupils' and the teachers' points of view. Furthermore, this work has drawn attention to the concepts of admittable tolerance, accuracy in prediction and uncertainty in the measurement results, and it has stressed the greater importance of increasing the speech signal-to-noise ratio than precisely pursuing the room acoustics requirements. The evidence should be further proved through studies that focus on the difference in the learning outcomes by adopting less severe room acoustic requirements and higher signal-to-noise ratios. Moreover, the approach should be holistic and consider the needs of both pupils and teachers. These less severe requirements can help teachers to suffer less from vocal illnesses and can make interventions on existing classrooms less expensive and affordable for everyone. Through such an approach and with the essential protocol, many classrooms could be renovated, since the main problems are for existing classrooms and not for new buildings, which, unfortunately, are in the minority. The acoustic refurbishment can be adopted together with the energetic refurbishment to a great extent thanks to the European incentives for energy saving. In order to enrich the database and reach more definite conclusions, the use of data from other Countries in Europe, based on the essential protocol proposed, would be desirable. The abovementioned arguments and the new conclusions drawn from any further analysis should be included in a new European standard on classroom acoustics.

6.2.2. Towards an inclusive policy

In **Chapter 2** and **Chapter 4**, the data from more susceptible groups of people were collected but then excluded for analyses. **Chapter 5** investigates binaural speech intelligibility for normal-hearing listeners, neglecting more disadvantaged subjects. Future studies should account for the presence of these more vulnerable groups of people, such hearing-impaired, children with learning disabilities and non-native speakers, since it is crucial to provide them with optimal acoustics in their frequently attended environments, such as school classrooms, to support speech communication in their daily life. Indeed, a high degree of speech intelligibility and a favorable environment for speech production increase social

inclusion as they underpin an effective information transmission in the challenging communication processes. The finding of such studies could cover the needs of these vulnerable groups of learners that more and more often are included in regular classrooms together with mother-tongue and normal-hearing pupils where optimal acoustic quality is not always guaranteed. A multidisciplinary project involving acoustic engineering, audiology and psychology is investigating new strategies to guarantee proper communication in frequently-attended environments, among which there are schools. The project sees the collaboration between several Italian Universities with the cluster of Excellence Hearing4all of the Carl von Ossietsky Universität of Oldenburg (Germany) and aims at developing an innovative, ecological audio-video rendering platform to go beyond the current audiological clinical practice. Based on this platform, advanced testing protocols especially designed for vulnerable groups of children with hearing impairment are developed, accurately representing everyday listening situations through the use of ecologically valid auditory and visual scenes. These scenes are created with recordings, simulations and renders, and reproduced through a Higher-Order Ambisonics. Among the many final benefits, these new means will support acousticians to develop and provide tools for the acoustical design of frequently attended environments, oriented to warrant an optimal communication also for more vulnerable subjects. These will promote a step forward in the available knowledge by surpassing the actual standards and updating their requirements.

6.2.3. Towards new modelling tools

As previously stated, the approach to go beyond the actual classroom acoustic requirements and update them should be holistic and consider the needs of both pupils and teachers. The proposed guidelines should be based on innovative principles, referring not only to the typical application of absorbent surfaces to control reverberation and noise in frequently attended environment such as schools, but also to scattering surfaces that play a key role in supporting the speech level produced by a talker and in correcting acoustic defects. The best way to reach the optimal classroom acoustic requirements and signal-to-noise ratio is to consider them since the first design stages, so that a modelling tools to study several configurations combining absorptive and diffusive surfaces will be developed. In particular, the new tool will be able to model speech intelligibility under realistic noise and reverberation conditions. In such a way, different layouts for the design of optimal acoustics can be imagined and then used in the modelling tool to quantify changes in speech intelligibility based on the distribution of the surfaces in the classroom. The new configurations will be examined through scale and computer modelling.

6.2.4. Towards the gathering of data from subjects

In **Chapter 3** new moderate and severe requirements for classroom acoustics are given, while **Chapter 5** provides prevision of speech intelligibility based on which it is possible to formulate hypotheses for an adequate classroom acoustic design. The outcomes obtained in **Chapter 3** and **Chapter 5** derive from statistical analysis on measured objective acoustical parameters and from predictive models, respectively, that do not involve the collection of data from subjects. In order to consolidate and to verify the outcomes of the aforementioned chapters, future studies should include testing of subjects. Particularly, learning attainment tests, questionnaires on well-being and disturbance should be administrated to pupils inside classrooms with the aim to acquire objective and subjective data from subjects, that will be used to confirm or reshape the obtained outcomes. Only confirming the correspondence between the results of the subjects and those of the studies, the requirements and tools can be applied and implemented.

Appendix E
Definitions

All the parameters used and/or mentioned in the framework of this thesis are reported in this appendix, that gives their definition and mathematical formulation.

E.1.1. Temporal parameters

Reverberation Time

Reverberation time, RT, (s), is the duration required for the space-averaged sound energy density in an enclosure to decrease by 60 dB after the source emission has stopped (ISO 3382-1:2009).

Reverberation time can be obtained applying the integrated impulse response method, that is the method of obtaining decay curves by reverse-time integration of the square impulse response, i.e., Schroeder's integrated energy decay curve. RT can be evaluated on a smaller dynamic range than 60 dB and extrapolated to a decay time of 60 dB. Thus, if reverberation time is derived from the time at which the decay curve first reaches 5 dB and 25 dB below the initial level, it is labelled T20. If decay values of 5 dB to 35 dB below the initial level are used, it is labelled T30.

Early Decay Time

Early Decay Time, EDT, (s), is similarly obtained as RT from the slope of the integrated impulse response curves but it is determined from the initial 10 dB of the decay. In fact, as the Reverberation time, is extrapolated on Schroeder's integrated energy decay curve, considering a decay between 0 dB and -10 dB (ISO 3382-1:2009).

Usually, EDT is considered more subjectively important and related to perceived reverberance, while RT is related to the physical properties of the space under analysis.

E.1.2. Speech and background levels and their ratio

In the present work, speech levels and background noise levels were acquired as equivalent A-weighted continuous sound pressure levels at the receiver position.

Equivalent continuous sound pressure level

Equivalent continuous sound pressure levels are calculated as ten times the logarithm to the base 10 of the ratio of the square of the root-mean-square sound pressure over a stated time interval to the square of the reference sound pressure, the sound pressure being obtained with a standard frequency weighting (ISO 1996-1:2003).

$$L_{eq} = 10log_{10}\left[\frac{1}{T}\int_{T}\frac{p^2(t)}{p_0^2 dt}\right]$$

Where:

-$p(t)$ is the instantaneous sound pressure at the running time t;

-$p_0(t)$ is the reference sound pressure (equal to 20 μPa).

It is possible to obtain the A-weighted equivalent continuous sound pressure level (L_{Aeq}) if the sound pressure levels at each frequency are A-weighted.

Signal-to-noise ratio

Signal-to-noise ratio, SNR, (dB), is about the strength of the desired signal compared to the unwanted noise. When the signal and the noise measurements are already in dB form, it is possible to calculate SNR as simply subtracting the noise figure from the main signal.

E.1.3. Early-to-late energy parameters

Speech Clarity

Clarity, C_{te}, (dB), is the balance between early-and late-arriving energy (ISO 3382-1:2009). This could be calculated for either a 50 ms or an 80 ms early time limit, depending if the results are intended to relate to speech or music conditions, respectively, using the following equation:

$$C_{t_e} = 10lg \frac{\int_0^{t_e} p^2(t)dt}{\int_{t_e}^{\infty} p^2(t)dt}$$

where:

-C_{t_e} is the early-to-late index;

-t_e is the early time limit of either 50 ms or 80 ms

-$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point.

Definition

Definition, D_{50}, (-), is the early to total sound energy ratio and it is sometimes used for speech conditions (ISO 3382-1:2009). It is expressed by the following equation:

$$D_{50} = \frac{\int_0^{0.05} p^2(t)dt}{\int_0^{\infty} p^2(t)dt}$$

where:

-$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point.

Useful-to-detrimental ratio

Useful-to-detrimental ratio, U50, (dB), is defined as the logarithmic ratio of the useful to the detrimental sound, being useful just the early-arriving speech energy and detrimental the sum of the late-arriving speech energy and the ambient noise given by both noise and reverberation (Bradley *et al*., 1999). In the present study (see Chapter 3) it was obtained through the following formula:

$$U_{50} = 10log\left\{\frac{10^{\frac{C_{50}}{10}}}{1+\left[\left(10^{\frac{C_{50}}{10}}+1\right)\cdot\left(10^{\frac{L_N-L_S}{10}}\right)\right]}\right\}$$

where:

-C_{50} is the speech clarity index in the early time limit of 50 ms;

-L_S is the speech level emitted by the sound source and recorded at the measurement point;

-L_N is the background noise level while pupils in silence recorded at the measurement point;

E.1.4. Sound energy parameters

Sound Strength

Sound Strength, G, (dB), is the logarithmic ratio of the sound energy (squared and integrated sound pressure) of the measured impulse response to that of the response measured in a free field at a distance of 10 m from a calibrated omnidirectional sound source (ISO 3382-1:2009), as expressed in the following equations:

$$G = 10lg\frac{\int_0^\infty p^2(t)dt}{\int_{t_e}^\infty p_{10}^2(t)dt} = L_{pE} - L_{pE,10}$$

in which

$$L_{pE} = 10\text{lg}\left[\frac{1}{T_0}\int_0^\infty \frac{p^2(t)dt}{p_0^2}\right]$$

and

$$L_{pE,10} = 10\text{lg}\left[\frac{1}{T_0}\int_0^\infty \frac{p_{10}^2(t)dt}{p_0^2}\right]$$

where:

-$p(t)$ is the instantaneous sound pressure of the impulse response measured at the measurement point;

-$p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 m in a free field;

-L_{pE} (dB) is the sound pressure exposure level of $p(t)$;

-$L_{pE,10}$ (dB) is the sound pressure exposure level of $p_{10}(t)$.

In the above equations, t = 0 corresponds to the start of the direct sound, and ∞ should correspond to a time that is greater than or equal to the point at which the decay curve has decreased by 30 dB.

G requires a calibration procedure for the sound power of the source (see Chapter 3, Appendix C). In the present work, the calibration file consisted in the impulse response recorded at the reference position, i.e., the receiver position at 1

m from the TalkBox sound source described in Chapter 3, of classroom A1. The impulse response was muted in its late component, so that only the first 50 ms of the sound pressure exposure level were considered and the measurement condition was assimilated to that of anechoic room.

In addition to G values obtained from the complete impulse responses, G_{50} values for the initial 50 ms of the impulse responses and G_{late} values for the remaining part of the impulse responses were also determined.

E.1.5. Speech intelligibility

Speech Intelligibility

Rating of the proportion of speech that is understood (BS EN IEC 60268-16: 2020).

Speech Transmission Index

Speech Transmission Index, STI, (-), is an objective method for prediction and measurement of speech intelligibility (BS EN IEC 60268-16: 2020). The measurement with a complete signal test (full STI) considers 7 pink noise signals, one for each centre frequency band from 125 Hz to 8 kHz. These are elaborated with 14 frequencies of modulation, with interval of one third of octave band from 0.63 Hz to 12.5 Hz: thus, 98 test signals are obtained, of 10 s each one. The level of each octave band corresponds to the spectrum of the long term continuous speech.

As the measurement of the STI con complete signal test in most of the time impracticable, faster measuring methods have been developed (e.g. the STIPA or STITEL), or the measurement can be realized with indirect method. This latter, which could be applied only with linear transmission systems, and without time-variance, preview the measurement of the IR, in absence of noise, and of Signal-to-Noise Ratio, SNR.

Speech Reception Thresholds

Speech reception threshold, SRT, (dB SNR), is the presentation level, or Signal-to-Noise-Ratio, that is necessary for a listener to recognize a speech material correctly for a specified percent of the administration time, that is usually 50% (Nilsson et al., 1993).

Spatial release from masking

Spatial release from masking, SRM, (dB SNR), is defined as the difference between the speech recognition threshold (SRT) obtained in a co-located condition, i.e., the case in which a target and a masker are positioned on the same axis of the listeners' head thus either at 0° or 180°, and the SRT obtained in a spatially separated condition, i.e., the case in which either the target or the masker sources or both are positioned on a different axis with respect to the listener's head (Westerman and Buchholz, 2015).