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A basic protocol for the acoustic characterization of small and medium-sized classrooms / Astolfi, A.; Minelli, G.; Puglisi, G. E.. - In: THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA. - ISSN 0001-4966. - ELETTRONICO. - 152:3(2022), pp. 1646-1659. [10.1121/10.0013504]

Availability:
This version is available at: 11583/2971969 since: 2022-10-02T06:16:05Z

Publisher:
ACOUSTICAL SOC AMER AMER INST PHYSICS

Published
DOI:10.1121/10.0013504

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12 October 2024

JASA ARTICLE

A basic protocol for the acoustic characterization of small and medium-sized classrooms

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ABSTRACT:
To promote a fast and effective characterization of the sound environment in small and medium-sized classrooms, a basic measurement protocol, based on a minimum number of parameters and positions, is provided. Measurements were taken in 29 occupied classrooms belonging to 13 primary schools in Turin, Italy, that differ in location and typology. The background noise level was acquired during silent and group activities, and the reverberation time, speech clarity, useful-to-detrimental ratio and speech level, were acquired along the main axis of each classroom and in one or two offset positions. To reduce the number of measured parameters that can be used to fully characterize classroom acoustics, data were divided into two groups on the basis of a cutoff value of maximum occupied reverberation time in the case of moderate and severe requirements. Given the strong correlation among the quantities, thresholds were identified for the other acoustical parameters, and their accuracy and precision were tested to assess their ability to classify the acoustic quality as compliant or non-compliant. Results suggest that more convenient parameters, like clarity in the central position of the classroom, can be used instead of reverberation time to classify classroom acoustics. © *2022 Acoustical Society of America.*
https://doi.org/10.1121/10.0013504

(Received 18 February 2022; revised 21 July 2022; accepted 25 July 2022; published online 13 September 2022)

[Editor: Shiu Keung Tang] Pages: 1646–1659

I. INTRODUCTION

What are the optimal acoustic conditions for speech communication and learning in classrooms? The scope of the present work has been to identify the basic parameters and their optimal values necessary to quickly and effectively characterize the acoustic quality of parallelepipedal shaped school classrooms with small and 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 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 we used in Astolfi *et al.* (2019)[1] has been enlarged in this work, although we have used the same protocol.

The importance of this work is grounded in the evidence that classroom acoustics affect both students and teachers for most of the time during their everyday life. 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,[2,3] since the classroom sound environment plays a crucial role in the learning process and the cognitive development of young children.[4] In these terms, the acoustic quality of classrooms affects the students' performance, as has already been underlined in many studies.[5–15] As far as the teachers are concerned, i.e., from the speakers' perspective, it is mandatory to reduce their vocal effort and load to prevent voice disorders and to preserve vocal health.[16–19] Indeed, dysphonic voice has a significant and negative effect on both speech intelligibility and listening easiness mainly in noise conditions and high reverberated environments.[20] Classroom acoustics also have effects on the occupants' well-being and in particular on feelings of joy[1] and comfort or discomfort,[21,22] on aggression levels,[23] and on personal relationships.[24]

A. Optimal values for classroom acoustics

1. Reverberation

There is still a lack of agreement on the optimal reverberation time (RT) since various target values have been proposed. In the following, apart from where it is otherwise specified, the RT 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 with higher acoustical quality. According to Picard and Bradley (2001),[25] a shorter RT leads to a greater toleration to background noise, and values of between 0.4 and 0.5 s are thus preferable. In a

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recent review by Minelli *et al.* (2022),[26] a RT of 0.6 s was found to guarantee a better learning performance for 5–11 year old students, and this RT was found to increase to 0.7 s for students over 12 years old. Yang and Bradley (2009)[27] suggested an acceptable RT for students aged 6–11 and adults of 0.3–0.9 s, with the ideal values being around 0.7 s. Moreover, Hodgson and Nosal (2002)[28] proposed RTs 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 0.4–0.8 s to be adequate, not only to maximize speech intelligibility but also to minimize vocal effort. Puglisi *et al.* (2017)[16] found the optimal RT for speech in primary school classrooms to be equal to about 0.7 s, while Bottalico and Astolfi (2012)[29] suggest a range of between 0.75 and 0.85 s. Pelegrín-García *et al.* (2014)[30] found it to be in the range of 0.5–0.6 s, while Calosso *et al.* (2017)[31] 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 to 0.9 s, even though well within the range of measured classroom conditions in many studies,[32] is greater than the upper limit of most standards and recommendations,[32,33] including the influential ANSI S12.6:2010,[34] and the associated ASA publications,[35,36] which recommend a RT in unoccupied conditions of 0.6 s. In the UK, Building Bulletin 93 (BB93:2015)[37] established a maximum mid-frequency unoccupied RT 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.[19] For comparison purposes, the unoccupied values should be reduced by about 10% to obtain occupied values,[1] 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 RT was 0.5 s, as recommended in the ANSI S12.6:2010 standard[34] and in BB93:2015,[37] 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,[38,39] 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 and 0.8 s in the case of primary school classrooms and for refurbished rooms or older students, respectively. A RT of 0.6, from 0.250 to 4 kHz, in occupied conditions, is also optimal according to the DIN 18041:2016[39] and UNI 11532–2:2020 standards,[38] assuming a room volume of about 210 m^3 (average volume of the 29 classrooms in Table I), for rooms dedicated to communication with the simultaneous presence of several people speaking in the classroom, as is the case during primary school lessons.

The requirements are even stricter when children with special hearing and communication needs are included in mainstream classrooms.[40] In this case, other issues, apart from optimal values, should be included to control the low-frequency RT as well as for the use of face masks as a regular habit as a result of the ongoing COVID-19 pandemic.[41]

2. Noise

Ambient noise in classrooms is more annoying than reverberation and leads to a greater impairment of speech recognition when it is very high.[25] 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)[42] found that pupils aged from 7 to 11 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),[43] are considered. However, according to a recent review by Minelli *et al.* (2022)[26] 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, which is almost the same 34 dB(A) value that Picard and Bradley (2001)[25] proposed in the former review for the same age group in empty rooms or with silent occupants.

3. Speech intelligibility

As far as speech intelligibility is concerned, according to Formula (3) in Bradley (1986),[44] the recommended clarity for speech sounds, C50,[45] should be greater than 2 ± 1 and 4 ± 1 dB at mid frequencies for small classrooms with RTs of 0.8 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)[46] 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 signal-to-noise ratio (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 *et al.* (1999),[46] U50 values higher than 4 dB ensure a speech intelligibility that is almost equal to 100%.

B. 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.

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

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

TABLE I. 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

(ii) the details of the measurement procedures, e.g., the recording time for the noise level measurement,[39,44,47,48] the activities carried out in the classroom during measurements,[44,47] and the height or precise position of the equipment,[38,44,47,49] 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, and 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.[25] Moreover, the adopted measurement procedures are all time-demanding, although most of the parameters are closely correlated.[1,44]

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 (C) and non-compliant (NC) classroom acoustics in primary schools?

To answer these questions, we measured acoustical parameters in 29 primary school classrooms in Turin, Italy, according to a well-thought-out protocol. We carried out correlations and regression analyses on the collected data, and we then divided the classrooms into two consistent groups based on their compliance with an arbitrary occupied RT 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

https://doi.org/10.1121/10.0013504

parameters, which can be used alternatively to qualify classroom acoustics as C or NC 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 classrooms.

II. METHODOLOGY

A. Schools and classrooms

Table I 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.[50]

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 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 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 I shows the number of pupils in each classroom, and this number refers to those that were present during the measurements.

B. Characterization of the classroom acoustics

We performed the acoustic measurements in 1 day in each school in the last 2 months of the school year, over 3 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 RT 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.

1. Measurements, setup, and equipment

Details of the measurements, setup, and equipment can be found in Astolfi *et al.* (2019),[1] but for the sake of clarity, a brief description is reported hereafter and summarized in Fig. 1 and Table II. In particular, the schemes of the measurement positions for the different parameters are shown in Fig. 1 and were all applied for a full classroom acoustic characterization.

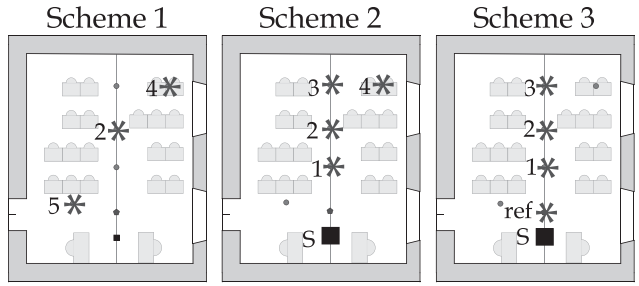

FIG. 1. Schemes of the measurement setup applied for a full classroom acoustic characterization with the positions of the sound level meter (SLM) (∗) and of the sound source (S) (■).

The measurement equipment consisted of a TalkBox acoustic stimulus generator (NTi Audio, Schaan, Liechtenstein), which, according to the datasheet provided by the manufacturing company,[51] presents a standardized voice-like acoustical signal emission of the human voice,[52] and of a calibrated-class-1 SLM (model XL2 by Nti Audio, Schaan, Liechtenstein). The TalkBox was placed at the position typically occupied by the teacher during lessons, i.e., 1 m from the blackboard wall at a height of 1.5 m from the floor. The SLM was located at least 1 m from any surface and at a height of 1.1 m from the floor, in different positions over the pupils' seating area, which were selected case by case to acquire acoustic stimuli for the extraction of several parameters.

Receivers 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., receivers 4 and 5, were then added. Receivers 1, 2, and 3 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.

Off-axis receiver 4 represents 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 receiver 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,[53] and facade reflections further reduce this gap. Furthermore, as it will be reported in Sec. III A, receivers 3 and 4 are positioned at more than 5 times the critical distance in all the considered classrooms and do not benefit from the direct sound to a large extent. However, when a human talker[53] and the TalkBox[51] directivity patterns are compared, we detect differences lower than 1 dB up to the octave band center frequencies of 4 kHz and of ∼6 dB at 8 kHz, for the same azimuth angle of 30° on the horizontal plane.

Receiver 5, which is closer to the source, in correspondence to the first row of pupils, at a wider azimuth angle

TABLE II. Characteristics of the source stimuli, acquisition intervals, parameters, and considered reference or standard for the measurement of the different parameters related to the schemes shown in Fig. 1. In case of scheme 3, no references or standards have been followed for the measured parameters; thus, n.a. (not available) has been entered in the correspondent cells.

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 min in each position		15 s for each position				20 s for each position	
Parameter, averaging, symbol							
Single value for each classroom		Single value for each classroom Frequency average (0.25–2 kHz)	(0.5–1 kHz)	(0.5–1 kHz)	(0.5–1 kHz)	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.* (2015) (Ref. 57)		DIN 18041:2016 (Ref. 39), ISO 3382-2:2009 (Ref. 49)	ISO 3382-2:2009 (Ref. 49), Puglisi *et al.*(2017) (Ref. 16)	ISO 3382-1:2009 (Ref. 58)	Bradley (1986) (Ref. 44); Bradley *et al.* (1999) (Ref. 46)	n.a.	n.a.

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° in the first row of pupils. The drop in value measured in this condition, due to speaker's directivity, is −0.6 dBA, with maximum differences of ∼−1 dB in the octave bands that are the most important for speech intelligibility, i.e., from 0.5 to 4 kHz.[52,54] These slight differences in the speaker's level, due to directivity, can be 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 setup.

Receivers 1, 2, 3, 4, and 5 differed slightly from classroom to classroom, depending on the size of the rooms. The distance from the source was between 2.2 and 3.1 m, between 3.4 and 5.6 m, between 5.9 and 7.1 m, and between 4.2 and 7.5 m, for receivers 1, 2, 3, and 4, respectively. Receiver 5 was only used for the measurement of background noise, and its distance from the source was about 2.2 m. 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 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 RT in unoccupied conditions.[16] 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 omnidirectional sound source for higher frequencies than 0.5 kHz,[55] and the compatibility of a RT 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,[56] the use of the two procedures should not have implied any significant differences, except for the lowest frequency range, from 0.125 to 0.5 kHz. However, an *ad hoc* comparison, performed in a small unoccupied university classroom, revealed quite a good match between the two measurement procedures, with differences lower than 5% for the octave bands from 0.125 to 8 kHz.

Table II shows the characteristics of the source stimuli, the acquisition intervals, the acoustical parameters, and the references and/or standards considered for the measurements. The parameters that were measured are T20, which is the RT when children are in a classroom; $T20_{_e}$, which refers to the

empty conditions; L_{N_sil}, which is the noise acquired when the students are silent; and L_{N_gr}, which is the noise acquired while the students are performing group activities. Moreover, the speech level was recorded at 1 m from the source, L_{S_ref}, and then in positions from 1 to 4 for the calculation of U50, and in positions from 1 to 3 along the main axis, for the calculation of its slope per double distance, mL_S;[1,59] speech clarity and the useful-to-detrimental ratio refer to the mean distributions in the classroom and are labeled with the subscript "M," e.g., $C50_{_M}$ and $U50_{_M}$, or refer to single values in the center of the classroom, i.e., position 2, and are labeled with the subscript "ctr," e.g., $C50_{_ctr}$ and $U50_{_ctr}$. The useful-to-detrimental ratio, U50 (dB), is defined as 10 time the logarithmic ratio of the early-arriving speech energy and the sum of the later-arriving speech energy and the ambient noise. It has been calculated according to Bradley *et al.* (1999)[46] from the measured C50, averaged over the four octaves from 500 Hz to 4 kHz, and from the A-weighted SNR.

C. Statistical analysis

The statistical analysis was carried out with SPSS (IBM Statistics 20, IBM, Armonk, NY). Since the distribution of the database resulted as 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[60] 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. In this way, the classroom acoustics were classified as C or 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.

Once the classrooms were subdivided between the two groups based on the T20 thresholds and once the acoustical parameters that significantly differ between the groups were detected with the MWU test, we resorted to the receiver operating characteristic (ROC) approach for these parameters. First, the area under the curve (AUC) of each of these acoustical parameters was inspected to assess its overall summary accuracy to classify cases between the groups of classrooms C or NC with the threshold. AUC ranges from 0.5 to 1.0: an AUC greater than 0.6, 0.7, 0.8, and 0.9 reflects a poor, fair, good, and excellent ability of the parameter to separate those classrooms compliant with the thresholds from those that do not comply, respectively. Second, the analysis of the ROC curves allowed for the identification of the most suitable threshold value for the acoustical parameters, based on the minimum squared distance (MSqD) 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.[61] Third, 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.[62] To perform these analyses, the values of the parameters were indicated as follows:

- True positive (TP), when the classification was C based on T20 and the value of the specific parameter was correctly identified in the C group based on its threshold;
- true negative (TN), when the classification was NC based on T20 and the value of the specific parameter was correctly identified in the NC group based on its threshold;
- false positive (FP), when the classification was C based on T20 and the value of the specific parameter was identified in the NC group based on its threshold;
- false negative (FN), when the classification was NC based on T20 and the value of the specific parameter was identified in the C group based on its threshold.

Accuracy, $(TP + TN)/(TP + FP + TN + FN)$, is the percentage of positive and negative predictions that were correct and responded to the following question: "How many classrooms have been correctly labeled out of all the 29 classrooms?" Precision, $TP/(TP + FP)$, 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?"

III. RESULTS

A. Measurement results

Table III shows the results of the acoustic measurements in the primary school classrooms, while Table IV 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.[63] T20 ranges from 0.5 to 1.4 s, $C50_{_M}$ ranges from -2.2 to 7.6 dB, and $U50_{_M}$ ranges from -2.2 to 6.5 dB. The RT for classroom A2 under unoccupied condition $T20_{_e}$ is lower than T20 under occupied conditions. This result is due to the shape and inclination of the vaulted ceiling. These architectural features determined longer RTs for medium frequencies between 0.5 and 1 kHz, along the main axis of the occupied classrooms as a result of increased reflections due to focalization.

In occupied classrooms, the critical radius, approximately calculated as $rc = \sqrt{0.0032\,V/T}$ (with V representing the room's volume and T its RT),[64] which denotes the distance from the source at which the reverberant field has the same intensity as the direct field, is between 0.7 and 1.1 m. According to Houtgast *et al.* (1980),[65] speech intelligibility remains constant and depends only on the reverberant field if the distance exceeds 5 times the critical radius. In

TABLE III. The acoustic parameters measured for each classroom. Standard deviations are indicated in parentheses, when available; n.a. stands for not available, as in the case of measurements that went wrong. 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 thresholds in Table VIII, 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. FP is intended when the classification was C based on T20 grouping (a) and (b) and the value of the specific parameter was identified in the NC group. FN is intended when the classification was NC and the value of the specific parameter was identified in the C group.

	Acoustical parameters										Group	
ID	T20 (s)	$T20_{_e}$ (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)	$T20 \leq 0.8$ s (a)	$T20 \leq 0.6$ s (b)
A1	0.9 (0.02)	***0.9*** (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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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)	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.	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)	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)	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)	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)	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)	49.6	76.7	62.3	−1.9	2.3 (1.1)	2.4	0.5 (0.7)	**0.7**	NC	NC

each classroom, we checked that the distance of the receivers 3 and 4 was 5 times the critical radius; thus, for the receivers farthest from the source, the reverberant field predominates over the direct field.

TABLE IV. Descriptive statistics of the acoustical parameters for all the classrooms. Standard deviations are indicated in parentheses. 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
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

We also checked that the Schroeder frequency of each classroom was always lower than the lowest frequency of the lowest octave band averaged for each acoustical parameter. The Schroeder frequency for the investigated classrooms ranges from 123 to 159 Hz, and the lowest bound of the 250 Hz octave band is higher than these values.

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) suggested in Minelli *et al.* (2022)[26] for a better learning performance. 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.[42]

B. Correlations between the acoustical parameters

Table V shows the two-tailed significant correlations between the acoustical parameters measured in the classrooms, which corroborate the outcomes that had already

https://doi.org/10.1121/10.0013504

TABLE V. Correlation matrix of the acoustical parameters measured in the classrooms. Spearman correlation coefficients with two asterisks 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		0.865**					−0.934**	−0.892**	−0.823**	−0.802**
$T20_{_e}$					0.586**		−0.905**	−0.804**	−0.809**	−0.730**
L_{N_sil}									−0.489**	
L_{N_gr}										
L_{S_ref}										
mL_S										
$C50_{_M}$								0.934**	0.861**	0.807**
$C50_{_ctr}$									0.777**	0.829**
$U50_{_M}$										0.945**
$U50_{_ctr}$										

been found in Astolfi *et al.* (2019).[1] First, a strong negative relationship can be observed between the RT under occupied conditions, T20, and the C50 and U50 speech intelligibility indexes, an outcome that 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),[44] where it is indicated that many of the early/late ratio values can be predicted from the measured RTs 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 possibility 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 is needed to represent the behavior of the whole classroom, in terms of speech intelligibility, as already shown by Puglisi *et al.* (2018).[6]

Figure 2 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 RT increases from 0.5 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 RT values, while the contribution of the environmental reflections increases the level of the signal emitted by the source for higher RTs.

It is possible to assume, from the graphs in Fig. 2 and the correlations in Table V, 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 could be preferred in comparison to T20 and U50 because of its faster measurement procedure, which 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 Fig. 2, which suggests that only the empty condition needs to be considered for an experimental survey.

C. C and NC classrooms

To categorize certain classrooms as belonging to an acceptable or non-acceptable ranking, i.e., C or NC, they were subdivided into two groups twice, i.e., assuming arbitrary T20 cutoff 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 cases.

The T20 cutoff value of 0.8 s for grouping (a) was chosen as being representative of moderate requirements for classroom acoustics since (i) it is toward the upper range of admittable RTs in comfortable classrooms used for learning;[27,28] (ii) it is the optimal value advised in the case of the refurbishment of primary school classrooms, and it is recommended for older pupils;[37] and (iii) it also minimizes the vocal effort for teachers.[29,31]

On the other hand, for grouping (b), a T20 value equal to 0.6 s is the cutoff 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[39] and the UNI 11532-2:2020 standards,[38] and (ii) there is evidence that 0.6 s is the optimal value to guarantee a better learning performance for primary school students.[26]

Tables VI and VII report the descriptive statistics for compliance and non-compliance classrooms for cases (a) and (b), respectively, together with the information if the two

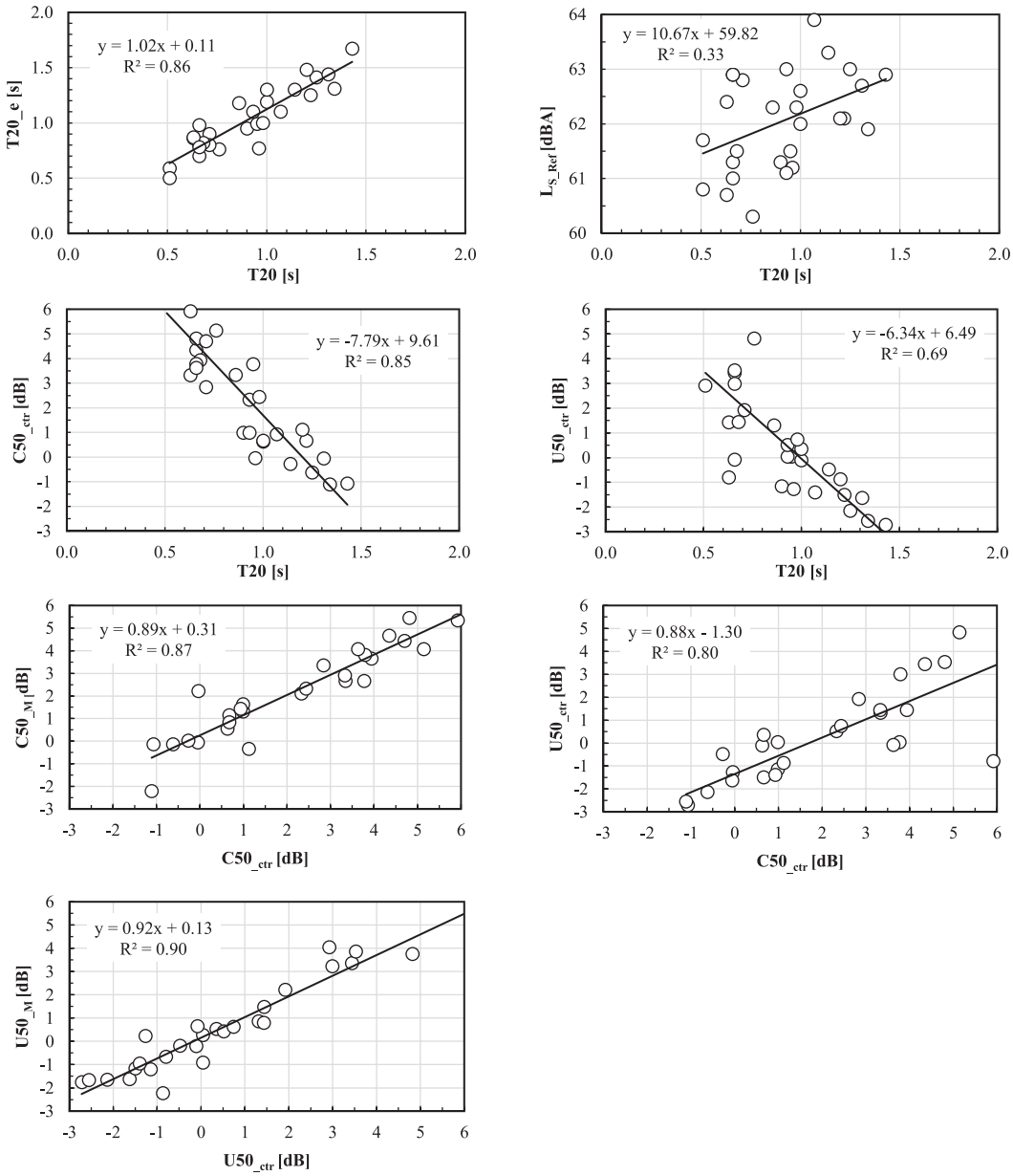

FIG. 2. Regression lines of the significant correlations shown in Table V. The determination of R^2 coefficient confirms the close relationship between the parameters in most of the considered cases.

groups differ significantly. The boxplots are included as supplementary material.[66] As can be seen from Table VI, 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 MWU are greater than 0.05. Table VII 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.

Table VIII 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.

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. From the thresholds identified through the MSqD from the ROC curve, classrooms with T20 and $T20_{_e}$ equal to or lower than 0.8 and 0.9 s, respectively, and with L_{N_gr} equal to or lower than 67 dB(A), are labeled as C. C are also labeled classrooms with $C50_{_M}$ and $C50_{_ctr}$ equal to or higher than 3 dB and with $U50_{_M}$ and $U50_{_ctr}$ equal to or a higher than 1 dB. On the contrary, they are labeled as NC. 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 VI.

About grouping (b), the AUC values derived from the ROC analysis are generally lower compared to grouping (a). Greater values of AUC are shown for $C50_{_M}$ and $C50_{_ctr}$

https://doi.org/10.1121/10.0013504

TABLE VI. Descriptive statistics of the acoustical parameters with a subdivision into compliance (C) and non-compliance (NC), based on a T20 lower than or equal to 0.8 s, according to grouping (a). Standard deviations are indicated in parentheses. The percentiles were calculated using Tukey's hinges. The *p*-values that were obtained with the MWU are also shown, and the ones lower than 0.05 are reported in bold. In the case of T20, the *p*-value is not available (n.a.) because the test has not been performed as the grouping was based on this parameter.

		Average	25th percentile	50th percentile	75th percentile	*p*-value
T20 (s)	C	0.6 (0.1)	0.6	0.7	0.7	n.a
	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	
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	**0.00**
	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	

TABLE VII. Descriptive statistics of the acoustical parameters with a subdivision into compliance (C) and non-compliance (NC), based on a T20 lower than or equal to 0.6 s, according to grouping (b). Standard deviations are indicated in parentheses. The percentiles were calculated using Tukey's hinges. The *p*-values that were obtained with the MWU are also shown, and the ones lower than 0.05 are reported in bold. In the case of T20, the *p*-value is not available (n.a.) because the test has not been performed as the grouping was based on this parameter.

		Average	25th percentile	50th percentile	75th percentile	*p*-value
T20 (s)	C	0.6 (0.1)	0.5	0.6	0.6	n.a.
	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	**0.03**
	NC	1.1 (0.3)	0.8	1.1	1.3	
L_{N_sil} (dBA)	C	49.2 (6.8)	44.6	50.6	53.9	0.87
	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	0.28
	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	0.12
	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	0.58
	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	**0.01**
	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	**0.01**
	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	0.09
	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	0.12
	NC	0.2 (2.0)	−1.4	−0.1	1.4	

that have an excellent ability to separate the classrooms that comply with the threshold from those that do not comply, followed by the $T20_{_e}$ that can do the same in a good way. From the thresholds identified with the MSqD from the ROC curve, classrooms with $T20_{_e}$ equal to or lower than 0.9 s and with $C50_{_M}$ and $C50_{_ctr}$ equal to or higher than 5 and 6 dB, respectively, are labeled as C. 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, as shown in Table VI.

Table VIII 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 III shows the values that do not comply with the threshold of the specific parameters, i.e., FP and 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 VIII, 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. 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

TABLE VIII. AUC, thresholds for the compliant group of classrooms (C), identified through the MSqD 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, while n.a. stands for "not available." Not available data are related to parameters that resulted with *p*-value higher than 0.05 in the MWU, as shown in Table VII.

Grouping		$T20_{_e}$ (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**	0.77	**1.00**	**0.98**	**0.95**	0.90
	Threshold for C classrooms	**≤0.9**	≤67	**≥3**	**≥3**	**≥1**	≥1
	Accuracy	**89% (25/28)**	74% (20/27)	**100% (29/29)**	**93% (27/29)**	**100% (28/28)**	86% (24/28)
	Precision	**92% (11/12)**	67% (8/12)	**100% (12/12)**	**100% (12/12)**	**100% (11/11)**	82% (9/11)
(b) T20 ≤ 0.6 s	AUC	0.85	n.a.	**0.91**	**0.92**	n.a.	n.a.
	Threshold for C classrooms	≤0.9		**≥5**	**≥6**		
	Accuracy	68% (19/28)		**93% (27/29)**	**100% (29/29)**		
	Precision	100% (4/4)		**75% (3/4)**	**100% (4/4)**		

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 acoustics 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 they remain around 70%, 80%, and 90%, respectively. 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. $C50_{_ctr}$ 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 $C50_{_ctr}$. 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. $T20_{_e}$ threshold can accurately subdivide the classrooms into the two groups 19 times out of 28 (68% accuracy), while its precision is 100%. $C50_{_M}$ threshold shows 93% accuracy and 75% precision.

Based on the accuracy and precision in discriminating compliance and non-compliance cases, Table VIII shows, in bold, the thresholds and the parameters that can be used alternatively to characterize classroom acoustics, according to the different performance required in the classroom, that is, moderate performance, as with grouping (a), or severe performance, as with grouping (b). T20, $T20_{_e}$, $C50_{_M}$, $C50_{_ctr}$, and $U50_{_M}$ are suitable for moderate requirements, while in the case of a severe requirement, T20, $C50_{_M}$, and $C50_{_ctr}$ are advised.

Table III shows the paucity of cases belonging to the C group for the 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 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 slightly higher RT values.

IV. DISCUSSION

A. Thresholds for C and NC classroom acoustics

Thresholds of acoustical parameters for C and NC classroom acoustics were established in the case of moderate and severe requirements. Consistent with Building Bulletin 93 (BB93:2015),[37] RT for moderate requirements fits well in the case of refurbishments and for secondary school students,[19] whereas severe limits are intended for younger pupils and in the case of new schools. Severe conditions are also supported by the DIN 18041:2016[39] and UNI 11532–2:2020 standards,[38] for about 200 m^3 rooms (see Sec. I A 1).

In the case of moderate acoustic requirements, classrooms need to ensure T20 equal to or lower than 0.8 s, $T20_{_e}$ equal to or lower than 0.9 s, or $C50_{_M}$ and $C50_{_ctr}$ equal to or higher than 3 dB. These classrooms should also implicitly guarantee $U50_{_M}$ and $U50_{_ctr}$ equal to or higher than 1 dB and L_{N_gr} equal to or lower than 67 dBA. The C50 and U50 target values for moderate requirements agree with those obtained by Bradley,[44,46] who recommended a C50 greater than 2 ± 1 dB at mid frequencies for small and medium-sized classrooms with a RT of 0.8 s and a 1 kHz U50 optimum of 1 dB to ensure very good speech intelligibility.

On the other hand, if severe acoustics are required for young pupils or to respect the standards for new schools, classrooms should guarantee T20 equal to or lower than 0.6 s or $C50_{_ctr}$ and $C50_{_M}$ equal to or higher than 6 and 5 dB, respectively. These classrooms should also implicitly guarantee $T20_{_e}$ equal to or lower than 0.9 s.

However, the thresholds investigated in this study are based on statistical analyses that depend on the collected data and on the imposed cutoff, and not on studies testing performance or subjective perception of pupils. This constitutes a limitation of the study, and further work should be done to validate these values with children's performance and perception.

B. Optimal RT in classrooms and priorities for classroom acoustics

Yang and Bradley (2009)[27] stated that acceptable RTs in classrooms during lessons should vary between 0.3 and 0.9 s, while Hodgson and Nosal (2002)[28] demonstrated that when the dominant sources of interfering sounds are nearby children, nonzero RTs should be in the range of 0.1 s to several seconds. To corroborate this, Bradley *et al.* (1999)[46] found that room acoustics are less important than the SNR to have good speech intelligibility in classrooms. This usually implies that guaranteeing high SNRs, i.e., SNR > 15 dB, is more important than guaranteeing an optimal RT, especially if an adequate SNR is not guaranteed first. Furthermore, Astolfi and Pellerey (2008)[21] found that anthropic noise is the main source of disturbance in classrooms. Thus, 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 behavioral engagement strategies where, e.g., a visual feedback is provided to the occupants when anthropic noise levels exceed certain limits, to promote the lowering of the voice level or the interruption of the conversation.[67–69] Second, the teachers' voice should be supported toward the end of the room with early reflections, which can be achieved as a result of an optimized classroom layout.[70,71]

In summary, according to the above findings, the design criteria should not specify the maximum allowable RT in a classroom, but rather a range of acceptable values, which should vary between 0.6 and 0.8 s. This range also ensures

advantageous conditions for speech production.[16,31] Moreover, classroom design should maximize early reflections toward the back of the room with the aim of increasing speech clarity and speech level, and it should promote specific devices or strategies to reduce anthropic noise.[72]

C. C50 as representative parameter to characterize classroom acoustics

This work suggests that speech clarity C50 can replace RT to classify classroom acoustics as C or NC. Clarity in the central position, $C50_{_ctr}$, and averaged across measurement positions, $C50_{_M}$, can both be used to characterize classroom acoustics under occupied conditions and with a background noise level lower than 56 dB(A). $C50_{_ctr}$ and $C50_{_M}$ equal to or higher than 6 and 5 dB, respectively, are advised for severe requirements. This is an important result supported by other studies. $C50_{_ctr}$ was found to be significantly correlated with reading speed for second graders, while no significant correlations were found with RT, by Puglisi *et al.* (2018).[6] Arvidsson *et al.* (2021)[73] found that the perceived speech quality in a room with different acoustic treatment is correlated to $C50_{_M}$ and that to obtain satisfactory sound quality, $C50_{_M} > 8$ dB is required at mid frequencies. It was also seen that $C50_{_M}$ more than other parameters affected the perception, with a minimum difference of 2 dB needed to recognize different room acoustic settings.[74]

V. 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 and medium-sized environments was provided and applied in 29 classrooms. Statistical analyses have been carried out to detect the main correlations among acoustical parameters and to search their thresholds for identifying classrooms as C or NC. The survey allowed us to answer the research questions listed in the Introduction of the present article, 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. RT, T20, and speech clarity in the central point, $C50_{_ctr}$, or averaged across measurement positions, $C50_{_M}$, can all 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), which 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 to 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 (at 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?

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 RT was measured in both occupied and unoccupied conditions, and the resulting times were 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 this work, it is possible to state that it is sufficient to measure $T20_{_e}$, i.e., in unoccupied conditions, and, if the threshold is respected, have a guarantee that the thresholds are respected also when the classroom is occupied.

D. What are the thresholds for C and NC classroom acoustics in primary schools?

New thresholds for classroom acoustic parameters, which discriminate the acoustic quality of primary school classrooms between C and NC, are here proposed on the basis of two different groupings, one for moderate and one for severe classroom acoustic requirements. The thresholds for moderate requirements are as follows:

- 0.8 s and 0.9 s for the RT 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 as follows:

- 0.6 s and 0.9 s for the RT in occupied and unoccupied conditions, respectively,
- 5 dB for speech clarity, when considered as a spatial average, and 6 dB, when considered as a single value in the central position.

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 and in the case of new buildings. Moderate requirements should be considered to make

interventions on existing classrooms more affordable and to help teachers suffer less from vocal disorders.

ACKNOWLEDGMENTS

This work has been accomplished thanks to the funding of Fondazione Cassa di Risparmio di Torino (CRT) within the "Io Ascolto 2" (RF = 2016.1101), "Io Ascolto 3" (RF = 2017.1229), and "Io Ascolto 4" projects. Thanks are due to Professor Franco Pellerey of the Politecnico di Torino for his support in the statistical analysis and to the teachers, the school administrations, and the children involved in the present study.

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