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THE EFFECT OF CLASSROOM ACOUSTICS ON STUDENTS' LEARNING PROCESSES: SELECTION OF OBJECTIVE PARAMETERS AND PROVISION OF A MEASUREMENT PROTOCOL

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ABSTRACT

Despite it is well known that learning experience is affected by classroom acoustics, only a reduced number of studies in this area provides clear information on the acoustic quantities that most influence the academic achievements of students. In this study, the indexes with the greater effect on students' performance have been identified and these were therefore considered on the evaluation of acoustical quality in elementary classrooms through in-field measurements. Noise, room acoustics and intelligibility indices in occupied and unoccupied conditions of 29 first-grade classrooms belonging to 13 school buildings in Turin that differ in location and typology, were gathered in the study. Then, the relationships between objective parameters were assessed through statistical analysis in order to select the minimum number required to best characterize the acoustics of the classroom; furthermore parameter thresholds have been identified so the classrooms have been divided into two groups. In addition to that, new important considerations for the creation of a simplified protocol, that can be universally applied when performing acoustic measurements in classrooms so that comparisons across several environments can be performed, emerged.

1. INTRODUCTION

A listener is particularly challenged in the discrimination of useful sounds by long reverberation times and excessive noise. The control of these aspects is crucial especially in school premises where the learning process parallel to the cognitive development take place. In fact, children aged up to eight years are maximally influenced by the acoustic quality of the environment in which they are immersed for most of the time (i.e. their classrooms), as it affects both the speaking and the listening tasks [1–5].

National and international standards are not met by the majority of the classrooms in Italy, as they are settled in historical buildings characterized by vaulted ceilings and big volumes; even when they are settled in regular rectangular spaces the sound propagation could be not favorable for the learning activities as the acoustics has not been taken into consideration during the design and construction phases of the manufact. Furthermore, the approach of mixing and include students with different mother tongues and backgrounds, and with cognitive deficit too, in each classroom make it primary to develop strategies for the enhancement of speech intelligibility that account for different requirements and arrangements at the same time.

On one side, there are many scientific studies that have proven the negative effect of noise and reverberation on speech intelligibility and academic performance [6, 7]; on the other side only a small number of studies consider other parameters directly related to speech intelligibility as signal-to-noise ratio (S/N), early-to-late ratio (C), useful-to-detrimental ratio (U) and speech transmission index (STI) [7–9[10]]. If the majority of the studies present results in terms of noise levels and reverberation time, their acquisition procedures change from one reference to another. In Bradley [7] reverberation time is measured through a omnidirectional source and four receiver in occupied classroom condition while children in silence, while in Sato and Bradley [8] the source is directional and both occupied ad unoccupied conditions are accounted. Furthermore, in the former article reverberation time is given for the 1 kHz frequency, while in the latter it is given in the frequency range between 0.25-4 kHz for occupied condition and 0.5-2 kHz for unoccupied condition. A comparison across the literature reveals that (i) measurements procedures are not always completely described (i.e. the recording timing for the noise level measurements [7–10]; (ii) when information are available, a lack of details could exists (i.e. kind of activities carried out in classroom when measuring noise levels; in [7, 8; 11, 12] the height of the equipment is not indicated); (iii) the measurement procedures differ case by case (equipment elements and positions; measuring timing; condition and activity); (iv) the values of the specific parameters are returned in different ways case by case (frequency range, dB weighting, timing, statistical averages).

Hence, despite the large evidence of the link between classroom acoustics and students' performance, a longstanding lack of agreement on the preferred acoustical criteria for unconstrained speech accessibility and educational facilities still exists. In the same way, the absence of a univocal reference emerges, reporting how to carry out measurements in classrooms. So far, this work stems from the need of having comfortable teaching and learning environments and represents an attempt to identify the minimum number of parameters to best characterize the acoustics of the classroom, considering their recognized effect on learning too. Acoustical parameters along the main axis and in one or two positions offset to the axis of 29 primary school classrooms have been measured and statistical analyses have been carried out on the collected data. The analyses cover correlations between the obtained quantities as average values across positions or as single point values or values related to the whole classroom. Finally, the relationship between occupied and unoccupied setting have been investigated from the measurements.

2. MATERIALS AND METHODS

2.1 Schools and Classrooms

The present study involved 29 occupied classrooms belonging to 13 different schools located in the metropolitan area of Turin. The 29 classrooms differed in terms of construction time, location, geometry and orientation. Their volume ranged from 120 m^3 to 290 m^3 and their height from 3.0 m to 5.3 m.

2.2 Acoustic Measurements

Measurements were carried out with a calibrated NTi XL2 sound level meter, a NTi Audio TalkBox source and a clapperboard. Figure 1 shows the standard measurement setup used in each classroom. Measurements have been performed for two source positions (S1 and S2). A fixed reference position, REF, that has placed at 1 m from the source mouth, at the same height, was common across all the classrooms, then a maximum of 6 microphone positions were selected case-by-case.

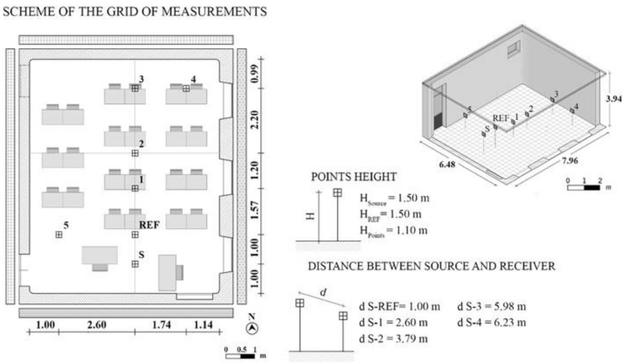

Figure 1. Measurement setup in a typical classroom.

Room impulse responses were acquired from exponential sine sweep signals emitted by the TalkBox and recorded by the SLM in positions REF, 1, 2, 3, and 6.

Reverberation time (T20, s) was averaged in the range 0.25–2 kHz and speech clarity (C50, dB) in the range 0.5–1 kHz. An optimal occupied T20 was set between 0.5 and 0.8 s, according to a number of recent studies [3, 13–16]. An optimal value of C50 should be greater than around 3 dB, as given in [7].

Reverberation time was also measured under empty classroom conditions ($T20_{\_e}$), without the presence of pupils and teachers. According to [12], a wooden clapper, i.e. two wooden boards hinged together, was used as described in [3]. Reverberation time values in unoccupied classroom were averaged between 0.5-1 kHz according to [11].

Background noise level (L_N, dBA) was considered in terms of indoor A-weighted equivalent sound pressure level. 3-min acquisition measurements [17] were carried out with children in silence, L_{N_sil}, and with the children performing group activities, L_{N_gr}. According to [6, 18] the L_{N_sil} recommended value must be less than or equal to 35 dBA.

For the measurement of the speech signal (L_S, dBA) the TalkBox was positioned in S and emitted a voice signal to 60 dBA at 1 m in anechoic conditions. The speech signals were acquired in positions REF, 1, 2, 3, and 4.

The ratio of useful to detrimental energy (U50, dB) was obtained for each position in the range of 0.5-1kHz and, as given in [19], an optimal value should be greater than 1 dB.

Overall, the acoustic parameters that are distance dependent (i.e., C50, L_S, and U50) were measured point by point and then processed to have single values. In particular, C50 and U50 values were averaged to have a spatial mean (C50_M, U50_M). As underlined in [5] in the case of C50, such a value was found to be not so different from the central value, i.e., the value measured at position 2 in Figure 1, (C50_ctr, U50_ctr). Furthermore, L_S values were associated to obtain their slope per double distance (mL_S) [1].

2.3 Statistical Analysis

The statistical analysis was carried out with SPSS (IBM Statistics 20, IBM, Armonk, NY, United States).

Before starting any analysis, Cook's distance was used in regression analysis between the reverberation time in occupied condition (T20) and each variable, i.e. acoustic parameter, to find influential outliers. This method allowed to identify the points (classrooms) that did show anomalous tendencies based on the expected relationship with reverberation time (T20), so these cases have been considered outliers and thus canceled from the database. For every parameter, observations with a Cook's distance of more than 3 times the mean was considered an outlier and less than 15% of the data was deleted. Table 1 reports the dataset complete of every measured value, while in Table 2 are shown the descriptive statistics once the outliers were eliminated from the original dataset. All the subsequent analyses were conducted on the basis of the sample without outliers.

Once checked the normality of the distribution for each acoustic parameter, their relationships were investigated through the nonparametric and non-linear correlation estimator Spearman's rho [20]. Correlations with a significant coefficient minor than 0.01 are reported in Table 3; they have been further analyzed through linear regression techniques. This allowed to inspect the relationship identified as significant and to quantify it through equations, like it is shown in Figure 2.

Then, after standardizing the variables, classrooms have been divided in two groups through a 2-means cluster analysis. Its attempt was double: in one hand the objective was to classify the cases based on their acoustic quality considering all the selected parameters; in the other hand the cluster analysis pointed to obtain thresholds for each parameter. On the basis of the obtained threshold a specific classroom could easily being attributed to the group of good or bad acoustics. Table 1 shows the belonging of the cases to the group of good or bad acoustics, while table 4 returns the values of the thresholds. The significance of the differences between the mean values of the acoustic parameters in good and bad classroom acoustics was assessed with the Mann–Whitney U Test (MWU), used for two groups of independent observations. As shown in Table 4, there was no significant difference for three of the parameters, in fact thresholds are not available. This outcome resulted unexpected for the parameter mL_S in particular, so it has been further investigated through regression analysis, showed in Figure 3.

3. RESULTS

Table 1 shows the measured values of the acoustic parameters for each individual classroom, while Table 2 returns the results in terms of mean value for each parameter.

ID	T20 [s]	T20_e [s]	L_{N_sil} [dB]	L_{N_gr} [dB]	L_{s_Ref} [dB]	mL_S [dB/dd]	C50_M [dB]	C50_ctr [dB]	U50_M [dB]	U50_ctr [dB]
A1	0.9 (0.1)	0.9 (0.1)	51.7		61.3	-1.9	1.3 (1.2)	1.0	-1.2 (1)	-1.1
A2	0.9 (0.2)	**0.8 (0.1)**	49.0	64.7	61.2	-2.4	2.2 (1.8)	0.0	0.2 (1.1)	-1.3
D1	1.2 (0.1)	1.4 (0.1)	51.2	68.0	63.0	-1.8	0 (0.9)	-0.6	-1.5 (1)	-2.1
D2	1.3 (0.2)	1.4 (0.1)	52.0		62.7	-2.1	-0.3 (1.1)	0.0	-1.8 (1.4)	-1.6
E1	1.2 (0.1)	1.3 (0.1)	54.0	66.6	62.1	-1.4	1.1 (0.9)	0.7	-1.2 (0.6)	-1.5
E2	1 (0.1)	1.0 (0.2)	54.3	73.7	61.5	-1.9	2.7 (1)	3.8	-0.9 (0.8)	0.0
F1	1.2 (0.1)	1.5 (0.1)	52.0	75.1	62.1	-1.7	-0.3 (1.8)	1.1	-2.2 (1.6)	-0.9
F2	1.4 (0.3)	1.7 (0.1)	52.0	73.8	62.9	-1.8	-0.1 (1.2)	-1.1	-1.8 (1.3)	-2.7
G1	0.9 (0.1	1.2 (0.1)	51.5	72.2	62.3	-2.1	2.6 (1)	3.3	0.9 (0.9)	**1.3**
I1	1.4 (0.1)	1.3 (0.1)	45.7	59.9	61.9	-1.6	-2.2 (0.2)	-2.2	-2.6 (0.2)	-2.6
I2	1.2 (0.4)	1.3 (0.1)	42.3	71.1	63.3	-2.3	0 (0.9)	-0.3	-0.2 (0.9)	-0.5
L1	1.0 (0.1)		47.9	67.4	61.1	-1.9	1.6 (1)	1.2	0.4 (1.1)	0.0
L2	1.1 (0.1)	1.2 (0.1)	46.0	71.6	62.0	-2.2	0.5 (2)	0.6	-0.2 (2.1)	-0.1
L3	1.0 (0.1)	1.3 (0.1)	43.0	81.3	62.6	-2.3	1.4 (1.7)	0.7	**1.1 (1.7)**	0.3
M1	0.9 (0.1)	1.1 (0.1)	52.0	81.9	63.0	-1.7	2.1 (1.3)	2.3	0.4 (0.9)	0.5
N1	1.3 (0.9)	1.1 (0.1)	54.3	76.1	63.9	-1.4	1.4 (0.7)	0.9	-1.0 (1)	-1.4
O1	1.0 (0.1)	1.1 (0.1)	49.6	76.7	62.3	-1.9	2.3 (1.1)	2.4	0.6 (1.2)	0.7
A3	**0.8 (0.1)**	**0.8 (0.1)**	38.4	61.8	60.3	-2.0	**4.1 (0.9)**	**5.1**	**3.8 (0.9)**	**4.8**
A4	0.7 (0.1)	**0.7 (0.1)**	47.1	69.2	61.3	-1.6	**4.7 (1.4)**	**4.4**	**3.4 (1.4)**	**3.4**
A5	0.7 (0.1)	**0.8 (0.1)**	46.3	78.4	61.0	-2.3	**5.4 (0.4)**	**4.8**	**3.9 (0.6)**	**3.5**
B1	**0.5 (0.1)**	**0.6 (0.1)**	49.3	66.3	60.8	-2.1	**7.6 (1.5)**	**7.3**	**4 (1.9)**	**2.9**
B2	**0.5 (0.1)**	**0.5 (0.1)**	39.9	66.3	61.7	-2.6	**7.0 (1)**	**8.1**	**6.5 (0.9)**	**7.3**
C1	**0.8 (0.1)**	0.9 (0.1)	49.3	62.2	62.8	-1.6	**3.3 (0.8)**	2.8	**2.2 (0.6)**	**1.9**
G2	**0.6 (0.1)**	0.9 (0.1)	51.9	65.3	60.7	-0.8	2.9 (0.9)	**3.5**	0.8 (0.7)	**1.4**
G3	0.7 (0.1)	0.8 (0.1)	52.5	63.5		0.0	**4.4 (0.3)**	**4.7**		
H1	**0.8 (0.2)**	0.8 (0.1)	51.6	71.9	61.5	-1.1	**3.6 (0.2)**	**3.8**	**1.5 (0.2)**	**1.4**
H2	**0.6 (0.1)**	0.9 (0.1)	55.9	68.1	62.4	-2.2	**5.3 (0.3)**	**5.4**	-0.8 (0.5)	-1.0
H3	**0.7 (0.1)**	1.0 (0.1)	45.5	63.9	62.9	-1.8	**3.8 (0.3)**	**3.8**	**3.2 (0.3)**	**3.0**
H4	**0.7 (0.1)**	0.8 (0.1)	53.1	65.5	62.9	-2.1	**4.1 (0.6)**	**3.5**	0.6 (0.6)	-0.1

Table 1. Acoustic parameters. L_{S_REF} is the signal measured at the reference point.

Parameter	Average	25th Percentile	50th Percentile	75th Percentile
T20 [s]	0.9 (0.3)	0.7	0.9	1.2
T20_e [s]	1.0 (0.3)	0.8	1.0	1.2
L_{N_sil} [dB]	50.3 (3.2)	47.7	51.5	52.1
L_{N_gr} [dB]	70.1 (5.7)	65.4	68.6	74.1
Ls_Ref [dB]	62 (0.9)	61.3	62.1	62.8
mL_s [dB/dd]	-1.9 (0.3)	-2.1	-1.9	-1.7
C50_M [dB]	2.4 (2.2)	0.8	2.3	4.1
C50_ctr [dB]	2.1 (2.1)	0.5	2.4	3.8
U50_M [dB]	0.5 (2.0)	-1.2	0.4	1.7
U50_ctr [dB]	0.4 (2.0)	-1.3	0.0	1.6

Table 2. Descriptive statistics excluding the outliers from the original dataset. Standard deviations are indicated in parentheses. Percentiles were calculated using Tukey's hinges.

Table 3 shows that the majority of the acoustic parameters are very well related to U50. A very tight connection is shown between central and mean values of the quantities C50 and U50; U50_ctr is also well related to C50_ctr . Figure 2 shows both the regressions. Finally, the parameters L_{S_REF} is positively related to T20_e.

	T20	T20_e	L_{S_ref}	C50_M	C50_ctr	U50_M	U50_ctr
T20		**.842****		**-.950****	**-.864****	**-.837****	**-.836****
T20_e			**.604****	**-.865****	**-.701****	**-.724****	**-.657****
C50_M					**.920****	**.886****	**.849****
C50_ctr						**.811****	**.906****
U50_M							**.939****

Table 3. Correlation matrix of the acoustic parameters. Spearman correlation coefficients with p-value less than 0.01 are shown.

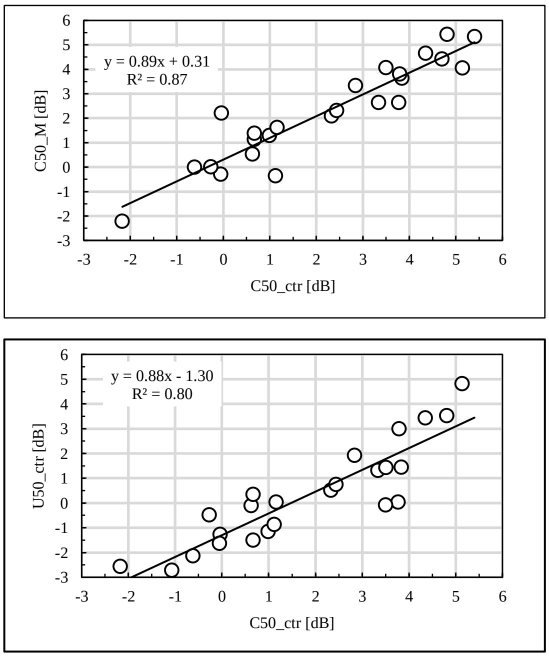

Figure 2. Linear regression between C50 values in terms of spatial mean values (C50_M) and single values measured in the center of the room (C50_ctr). The second image shows the strong relationship between U50 and C50.

In Table 1, cases from A1 to O1 belong to the group of bad acoustics (BA), while cases from A3 to H4 were attributed to the group of good acoustics (GA). The subdivision was determinate considering all the selected parameters and confirmed the results already obtained in [21], where the criteria for the division was based on the T20 value of each classroom, respectively over or under 0.8 s. In GA, optimal values are shown for speech intelligibility parameters C50 and U50, strictly related to reverberation time. The values of L_{N_gr} decrease in GA, but L_{N_sil} remains unchanged. The same passes with mL_S and L_{S_REF}: no significant difference emerged for these parameters comparing BA and GA.

		Average	25th Percentile	50th Percentile	75th Percentile	Threshold
T20 [s]	BA	1.1 (0.19)	1.0	1.1	1.2	0.8
	GA	0.7 (0.09)	0.6	0.7	0.7	
$T20_{\_e}$ [s]	BA	1.2 (0.21)	1.0	1.2	1.3	0.9
	GA	0.8 (0.13)	0.7	0.8	0.9	
L_{N_sil} [dB]	BA	50.4 (3.28)	48.4	51.6	52.0	n.a.
	GA	50.2 (3.32)	47.1	50.5	52.5	
L_{N_gr} [dB]	BA	72.9 (5.18)	68.0	73.0	76.1	68
	GA	66.9 (4.65)	63.7	65.9	68.6	
Ls_Ref [dB]	BA	62.2 (0.71)	61.8	62.3	62.8	n.a.
	GA	61.7 (0.95)	60.9	61.5	62.6	
mL_s [dB/dd]	BA	-1.9 (0.3)	-2.1	-1.9	-1.7	n.a.
	GA	-1.9 (0.38)	-2.1	-2.0	-1.6	
C50_M [dB]	BA	1 (1.38)	0.0	1.3	2.2	3.0
	GA	4.6 (1.09)	3.8	4.3	5.3	
C50_ctr [dB]	BA	0.8 (1.58)	-0.2	0.7	1.7	2.6
	GA	4.2 (0.82)	3.5	4.1	4.8	
U50_M [dB]	BA	-0.6 (1.13)	-1.5	-0.9	0.4	0.9
	GA	2.6 (1.34)	1.5	3.2	3.8	
U50_ctr [dB]	BA	-0.8 (1.18)	-1.5	-0.9	0.0	0.7
	GA	2.5 (1.46)	1.4	2.9	3.4	

Table 4. Descriptive statistics of the acoustical parameters considering the division in BA and GA. Standard deviations are indicated in parentheses, while n.a. is for “not available”. Percentiles were calculated using Tukey’s hinges.

Since the propagation of the signal level would have been expected to behave differently in the two acoustic conditions (in particular it would have been expected that in free field the signal level (L_S) near the source would be higher than the one in the center and at the bottom, while in the reverberant field L_S would have more or less the same level in all positions due to the reverberation), the study of mL_S was deepened through regressions. Figure 3 shows that the slope of the signal level does not differ in BA and GA: in fact, in both conditions, doubling the distance from the source, the L_S decreases around 2 dB. Furthermore, since this reduction should be of 3 dB by the laws of the diffuse reverberant field, the predicted values of L_S at the bottom of the classroom result underestimated related to the measured ones. In the diffuse reverberant field the first reflections seem to have a greater influence than the later ones; the significant difference in BA and GA found in this study for the parameter C50 confirms this too.

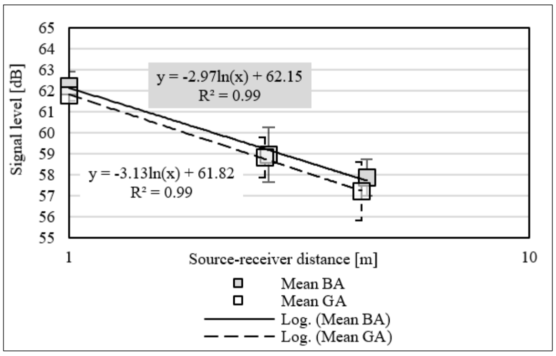

Figure 3. Regression lines of the propagation of the measured signal level L_S in BA and GA classrooms. The regressions are obtained considering the mean values of BA and GA cases in position Ref, 1 and 2; point 3 was not included in order to exclude the effect of the back wall on the signal propagation.

Further analysis are need to better characterize the influence of the early and the late reflections in this kind of environments.

4. CONCLUSIONS

The purpose of the present work was to provide a useful protocol for acoustics measurements in classrooms where speech plays a key role. Measurements involve selected parameters and are performed systematically: repeating the same scheme make it possible to create a database of comparable values and to do further analyses.

The present study involved 539 6-years students of 13 primary schools in Turin. Half of the classrooms were characterized by an insufficient sound quality compared to the optimal reference values. The intelligibility is good in classrooms with good acoustics, while it is mainly insufficient in the other classrooms. For both good and bad acoustics environments were recorded values of noise level beyond the limit, both in silence and during group activities.

Correlations found in [8] and [21] were confirmed. In particular, the acoustic parameters that are distance-dependent (i.e. C50, L_S and U50) were measured point by point and then processed to have single values, useful for an effective comparison across classes. Spatial mean and Slope per double distance parameters were obtained to evaluate the sound distribution’s uniformity and the effects caused by the distance from the source position. Not such a clear tendency emerged for the slope of the speech signal, mL_S: the expected values closer to zero in the case of a more uniform (or diffuse) acoustic field did not appear. On the contrary, the comparison between the spatial mean of C50_M and U50_M with their single values in the central position, C50_ctr and U50_ctr, confirmed that a single measurement in the center of the environment is indicative of the entire intelligibility of the environment.

Then, the clustering of the classrooms in bad and good acoustics reflected that of [21]; hence considering all the parameters for conducting the division held to an equivalent result of considering just the reverberation time (even if in this study there were 9 more cases).

Furthermore, in [21] the subjective aspect of wellbeing was measured by the happiness scale and was better in GA, so it is assumed that the subdivision of the classes into BA and GA reflect a subjective perception also in this study.

Based on the BA and GA clusters, thresholds of parameters were provided for the attribution of each case to one group or another. In this way the references given by literature are outdated and new values are proposed. L_{N_sil}, mL_S and L_{S_ref} were excluded from the threshold's identification as their means did not resulted significantly different in BA and GA.

Focusing the analyses on the BA and GA clustering, in small rooms a reverberation between 0.5 and 1 s makes no difference in terms of L_{S_ref} and L_{N_sil}, so in the view of the measurement protocol, they have not to be measured; also U50 resulted not necessary for the acoustic characterization since it is calculated from C50. On the contrary, it is fundamental to measure the reverberation time, in occupied or unoccupied condition, and the C50 parameter. Doubts remain about mL_S behavior in BA or GA.

More case studies are needed in order to deeper examine the early and late reflections in such environments, i.e. classes smaller than or equal to 250 m^3, and to consolidate the new statistics emerged during this work. In particular, special focus will cover spatial mean of C50 and U50 and Slope per double distance of Ls parameters, in order to evaluate the sound distribution uniformity and the effects caused by the distance from the source position.

Lastly, it is really important to carry on this work to promote the use of the intelligibility parameters as design parameters.

5. AKNOWLEDGEMENTS

This work is part of a cooperation between the Applied Acoustic group of Politecnico di Torino, the University of Turin and the National Institute of Metrological Research.

The authors thank the teachers and school administrations who made this work possible and all the children who participated in the survey.

This work was funded by the Fondazione CRT of Turin (Italy) in the framework of "Io Ascolto 2", "Io Ascolto 3" and "Io Ascolto 4" projects.

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