Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms

Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms

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A subjective survey on perceived environmental quality has been carried out on 51 secondary-school classrooms, some of which have been acoustically renovated, and acoustical measurements were carried out in eight of the 51 classrooms, these eight being representative of the different types of classrooms that are the subject of the survey. A questionnaire, which included items on overall quality and its single aspects such as acoustical, thermal, indoor air and visual quality, has been administered to 1006 students. The students perceived that acoustical and visual quality had the most influence on their school performance and, with the same dissatisfaction for acoustical, thermal and indoor air quality, they attributed more relevance, in the overall quality judgment, to the acoustical condition. Acoustical quality was correlated to speech comprehension, which was correlated to the speech transmission index, even though the index does not reflect all the aspects by which speech comprehension can be influenced. Acoustical satisfaction was lower in nonrenovated classrooms, and one of the most important consequences of poor acoustics was a decrease in concentration. The stronger correlation between average noise disturbance scores and $L_{\mathrm{A\,max}}$ levels, more than L_{Aeq} and L_{A90}, showed that students were more disturbed by intermittent than constant noise. [DOI: 10.1121/1.2816563]

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I. INTRODUCTION

The environmental quality of a building is its suitability to provide health and comfort for occupants. It includes four main aspects: acoustical, thermal, indoor air and visual quality. The beneficiaries of good environmental conditions in classrooms are the teachers and learners and, as a first consequence, this will lead to an increase in school performance of the students and in productivity of teachers. This paper focuses on the subjective and objective evaluation of the acoustical quality in secondary-school classrooms, and on the subjective evaluation of the other environmental aspects and their influence on the overall quality. The main purposes are: (1) to assess acoustical quality by means of questionnaires and in-field measurements and to discuss the results of changes due to acoustical renovation; (2) to correlate subjective and measured data to identify the correspondence between the perception scales and the main acoustical factors; (3) to investigate the main factors that also affect the thermal, visual and indoor air quality and which environmental aspect is most correlated to overall environmental quality perception.

Only a few studies have dealt with how users perceive acoustical quality during typical classroom use. Speech intelligibility tests and measurements have been performed in classrooms of different grades.[1–3] Hétu *et al.*[4] carried out a study on the effect of noise and reverberation in primary and high-school classrooms, based on questionnaires and measurements. Dockrell and Shield[5] administered questionnaires to primary-school children in order to assess their ability to discriminate in different listening conditions and found relationships between the children's perceptions of awareness and annoyance and objective measures of noise. Hagen *et al.*[6] used questionnaires to evaluate whether adding sound-absorption and/or sound-field amplification systems in classrooms would improve the acoustic comfort for primary-school children, and investigated educational possibilities to improve the listening abilities during lessons. Kennedy *et al.*[7] administered questionnaires to university students to investigate the factors that influence the perceived listening quality. In their work, a measure of perceived classroom-listening quality during typical classroom use, called PLE (perception of listening ease), was identified by means of a response analysis, and correlations among PLE and items regarding classrooms environment, courses, teachers, and individual factors were analyzed.

II. OBJECTIVE ASSESSMENT OF THE ACOUSTICAL ENVIRONMENT

Bad acoustic conditions in classrooms decrease the quality of speech communication, reducing the school performance of students and causing the teachers to suffer from fatigue. According to the ISO 9921:2003 standard,[8] the quality of speech communication can be expressed in terms of speech intelligibility, which is quantified as the percentage of a message that is understood correctly. Speech intelligibility at a listener's position in a classroom depends on the speech-

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TABLE I. Main characteristics of the eight classroom types.

	S1	M1	M2a/M2b	M3	M4	L1	L2	EL1
Location	courtyard	courtyard	street/square	street	street	street	street	street
Floor	first	ground	first	first	first	second	first	ground
No. of classrooms for each type	3	7	5/7	3	1	6	1	7
Sound absorption intervention	partial	full	absent	partial	full	full	partial	full
No. of students in the classroom during measurements (apart from teacher's vocal effort and background noise)	14	18	11/n.c.	16	16	13	15	18
Percentage of students present in the classroom during measurements (apart from teacher's vocal effort and background noise) compared to the full occupancy	70%	86%	65%/n.c.	75%	70%	55%	63%	72%
No. of administered questionnaires	36	120	61/89	59	19	126	17	149
Ceiling treatment	no	yes	no	no	yes	yes	no	yes
Acoustic reflector	no	yes	no	no	no	yes	no	yes
Vaulted ceiling	yes	no	yes	yes	yes	no	yes	yes
Floor area (m^2)	40.0	62.1	42.0	50.3	51.8	78.0	70.0	73.9
Mean height (m)	4.3	3.1	4.5	3.9	3.9	3.2	4.2	6.3
V (m^3)	160.0	189.4	190.0	201.2	207.2	250.4	296.0	465.8

signal-to-noise-ratio and the reverberation and can be predicted by the speech transmission index, STI,[9,10] which varies from 0 to 1. STI combines the two above-mentioned factors in a single quantity and is related to a five-point intelligibility scale:[8,10] "Bad" for STI values lower than 0.30, "Poor" between 0.30 and 0.45, "Fair" between 0.45 and 0.60, "Good" between 0.60 and 0.75, and "Excellent" for STI values higher than 0.75. In situations of a relaxed type of communication, such as during lectures, a "Good" level of intelligibility is recommended, considering a "Normal" vocal effort.[8] Vocal effort refers to the exertion of the speaker. It is quantified by the A-weighted speech level at a distance of 1 m in front of the speaker's mouth and subjectively as Very Loud, Loud, Raised, Normal and Relaxed. Free-field normal vocal efforts are given by Pavlovic[11] and Byrne *et al.*,[12] while typical vocal efforts in classrooms are reported by Houtgast,[1] Sato and Bradley[13] and Picard and Bradley.[14]

Speech intelligibility in a noisy environment with low reverberation, as in the case of a small occupied secondary-school classroom (e.g., 300 m^3), can also be approximately investigated with the reverberation time and A-weighted speech-signal-to-noise ratio, SNR_A.[2] According to Picard and Bradley,[14] the optimal values of the mid-frequency reverberation time and the minimum value of the SNR_A for 12 + years old students, in occupied classrooms, are estimated to be 0.5 s and 15 dB, respectively. As far as the noise level is concerned, an upper level of 33 dB(A) is indicated as the *ideal* condition, restricted to more vulnerable groups, which can rise to 40 dB(A) for an *acceptable* condition, to be used for more general purposes. Research on the effects of noise and poor acoustics in schools[15] has recently led many countries to write or revise a series of guidelines on classroom acoustics. For example, the S12.60 ANSI standard[16] and the UK Building Bulletin 93,[17] in unoccupied classrooms, require a maximum ambient noise level of 35 dB(A), $L_{\mathrm{Aeq,1\ h}}$ and $L_{\mathrm{Aeq,30\ min}}$, respectively, plus a maximum reverberation time, quoted in terms of the average in the 500 Hz, 1 kHz and 2 kHz octave bands, of 0.6 and 0.8 s, respectively.

III. CASE STUDY

The subject of the study is a 19th Century secondary school in a small town near Turin (Italy). It consists of two different buildings next to each other. The main building, a three story square-court building, contains 39 classrooms which face onto a quiet street or the internal courtyard. The classrooms differ in volume and shape, and were renovated or partially renovated with special acoustical design features. The second building is part of an old two-story building and contains 12 nonrenovated classrooms which face onto a quiet street or a large quiet square.

A subjective survey on perceived environmental quality was carried out on all 51 secondary-school classrooms, and acoustical measurements were carried out in eight of the 51 classrooms, these being representative of all the types of classrooms that were the subject of the survey. The main characteristics of the eight chosen types are shown in Table I. These can be divided into four groups in relation to volume: S1, M1, M2, M3, M4, L1, L2 and EL1 (where S stands for small, M for medium, L for large and EL for extra large). A full acoustical sound-absorption treatment was carried out in four of the eight classrooms (M1, M4, L1, EL1). It consisted of placing holed plaster-board panels filled with mineral wool on the ceiling, on the upper part of the lateral walls and on the back wall. An acoustic reflector was inserted into the flat absorbing ceilings in rooms M1 and L1 in order to increase the first reflections of speech sound to the rear part of the room. In the classroom with the highest ceiling (EL1) two large slightly convex rectangular panels were suspended at a height of 3 m from the floor, in order to reduce the useful volume. The three classrooms S1, M3 and L2 were only partially renovated. Sound absorption material was applied to the upper part of the back wall, and, in M3, also to the upper part of the lateral walls. M3 and M4 are identical and with the same sound absorbing treatment, with the exception of the vault, which in M3 was plastered and in M4 was completely covered with absorbing material. Only one classroom type, which is in the second building, M2, was not renovated at all. It was divided into two groups, M2a, looking onto a street, and M2b, facing onto a square. The external walls of the buildings are thick and made of masonry and the windows are double glazed, apart from M2 which have a single glass. The sound insulation intervention mainly concerned the walls between adjacent classrooms, while the sound insulation from the corridors was not optimized. The floors were covered with ceramic tiles without a floating floor. The classrooms did not have any speech-reinforcement or ventilation systems.

IV. MEASUREMENTS

The following quantities were obtained from the in-field measurements in each classroom type: the teacher's vocal effort and noise level during regular lessons; the reverberation time in unoccupied and occupied conditions; the speech level, the SNR_A and the STI for six positions in the occupied classrooms. The classrooms chosen for the measurements were representative of the eight selected types, but not all the types were used for all the analyses. As M4 was very similar to M3, it was excluded for the measurements of all the quantities, with the exception of reverberation time. As far as M2a and M2b are concerned, the reverberation time was the same, and no significant difference in noise level was perceived. For these reasons only M2a was considered. Apart from the teacher's vocal effort and noise level, the measurements were all carried out when the building was empty, in order to have low noise from inside the building, and only the classroom under measurement was occupied. It should be pointed out that the classrooms were not fully occupied, as they are during lectures, for this set of measurements. As reported in Table I, the percentages of occupation ranged from between 55% and 86%, compared to the average occupancy during regular class time obtained from the subjective survey data.

A. Measured and calculated quantities

1. Teacher's vocal effort ($L_{spA1\ m}$)

From three to five teachers were asked to speak without pausing during a regular lesson in each classroom type, first speaking directly to the students as they do during a lesson, without dealing with any particular topic, and then reading a text from a book (the same text for all the teachers). Both female and male teachers were tested; they were asked to stand facing the student-seating area. Equivalent continuous speech levels of the teacher's voice, based on 20–60 s recordings, were measured for each type of speech at 1 m in front of the teacher's mouth, obtaining the octave band levels ($L_{sp1\ m}$) and the overall A-weighted speech levels ($L_{spA1\ m}$). A total of 26 teachers were tested (20 females and six males), but only five of them agreed to perform both types of experiments. The mean difference of $L_{spA1\ m}$ values between the lectures and texts was 0.9 dB. Since lectures are more common during lessons only the lecture level was considered for these five teachers in the averaging with the speech levels of the other teachers, in order to obtain the average octave band and the average overall A-weighted speech levels for each classroom type. During the measurements it was checked that at 1 m teacher's voice level exceeded the noise level, in the same position, by more than 10 dB over the entire frequency range. The noise level, even when recorded immediately after the teacher's speech, was representative of the noise that occurred during the voice-level measurements, with quiet students, and there was no significant noise in the classrooms being tested.

2. Background-noise level (L)

This included noise from traffic and other external sources and noise due to student activity in the corridors or adjacent classrooms. It was based on a 3–6 min recording in the center of the room, in the occupied classrooms during regular lessons, immediately after the teachers had spoken. The students were asked to remain quiet and there was no significant noise in the classrooms being tested. The following quantities were obtained for each classroom type: the equivalent continuous octave band level, L_{eq}, the A-weighted equivalent continuous noise levels, L_{Aeq}, the A-weighted noise level that is exceeded by 90% of each sample period, L_{A90}, and the maximum A-weighted level, $L_{A\ max}$, where maximum levels quantify intermittent sounds.

3. Reverberation time in occupied and unoccupied conditions (RT_o and RT_u)

Octave band reverberation time measurements were carried out in both occupied (RT_o) and unoccupied (RT_u) conditions by means of the interrupted noise method using an omni-directional sound power source, with a pink noise test signal. The results from two source-receiver combinations gave a spatial average value for each classroom type as a whole. The RT_o was also obtained from the impulse response measurements using a sine-sweep signal generated by the 4128 Brüel & Kjær head and torso simulator placed in the same way as for the speech signal measurements, as described in Sec. IV A 4. The octave band classroom RT_o values were then obtained by averaging the results from one source and seven microphone positions distributed over the seating area. At medium and high frequencies the results from the two measurement techniques were coincident for all but two classrooms, where the small differences were due to the slightly different numbers of students present in the classrooms during the two sets of measurements. The results from the sweep technique were then used for the analyses.

4. Spatial distribution of the average speech level (L_{spA})

A 4128 type Brüel & Kjær head and torso simulator was used as a speech source to obtain a spatial distribution of the speech signal in the occupied classrooms. The source, emitting a test signal shaped like a male spectrum,[10] was calibrated in an anechoic chamber, where an output level of 68 dB(A) was set at a distance of 1 m in front of the mouth. It was located at the teacher's position and oriented towards the student-seating area. The receiver positions were placed 1 m from the source's mouth, at mouth height, and at six other representative students' seats uniformly distributed

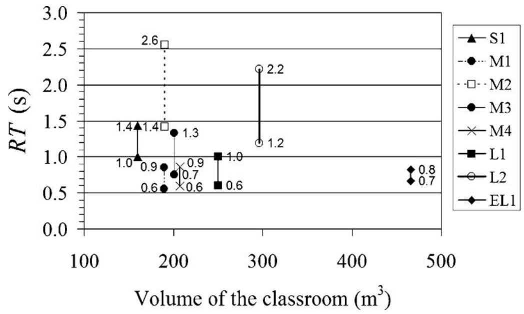

FIG. 1. Single number frequency averaging between 500 Hz, 1 kHz and 2 kHz, for reverberation times as a function of the room volume in unoccupied (upper value) and occupied (lower value) classrooms.

over the seating area, at seated ear height. It was checked that the source level at the measurement locations exceeded the noise level by at least 10 dB, over the entire frequency range, so as to minimize the influence of noise. In order to obtain the speech level distribution throughout the classroom, the source level reductions, with respect to the level measured at 1 m in front of the source's mouth, were determined in octave bands for each microphone position and the same reductions were applied to the 1 m average octave band speech levels for each classroom type. The overall A-weighted speech levels (L_{spA}) in the various positions in each classroom type were then obtained from the octave band values.

5. A-weighted speech-signal to noise ratio (SNR_A) and speech transmission index (STI)

The $\mathrm{SNR_A}$ were obtained as the L_{spA} minus the level of noise, at each of the six representative positions used to assess the spatial distribution of the speech signal. The noise was measured in occupied condition, with no student-activity noise, at the center of the room (L_{Aeq}).

The STI was obtained from the octave band filtered squared impulse response and the average speech-signal-to-noise ratio.[9,10] AURORA 4.1 was used for the analyses. The impulse response measurements were obtained from a sine sweep signal generated by the head and torso simulator placed in the same manner as for the speech level measurements. The STI values for the six student positions in each classroom were calculated for the occupied condition with the contribution of noise measured during lessons.

B. Results

1. Reverberation time

In Fig. 1 the average reverberation times at 500 Hz, 1 kHz and 2 kHz of the eight chosen classrooms are presented versus classroom volumes, for unoccupied and occupied conditions. A shorter RT_u in M1, M4, L1 and EL1, for which a full sound-absorption treatment was carried out, can be observed. Among these, only EL1 satisfies the UK regulations[17] requirements, but none satisfies the ANSI requirements.[16] In order to check the reverberation time in fully occupied conditions, corrected RT_o values were calculated applying the Sabine formula, in which the total acoustic absorptions, obtained from measured occupied reverberation time, were increased by an amount equal to the average absorption per student[18] multiplied by the difference in the numbers of students for full and partial occupancy. After the correction the average RT_o reduced from 0.55 to 0.53 s in M1, from 0.59 to 0.54 s in M4 and from 0.64 to 0.56 s in L1, thus approaching the 0.50 s limit required by Picard and Bradley.[14] In the other classrooms, most of them with poor or inexistent acoustical treatment, the corrected values were 0.68 s in M3, 0.67 s in EL1, 0.85 s in S1, 1.01 s in L2, and 1.13 s in M2. All the values are higher than 0.50 s, confirming that acoustical treatment is necessary also in small occupied classrooms.

2. Teachers' vocal effort and background noise level

The measurements were made for each classroom type, with the exception of M2b and M4 (because they were very similar to the M2a and M3 classrooms, respectively). Table II shows the teachers' vocal efforts measured for each teacher in the classroom types with the indication of the teacher's gender and the type of speech (text or lecture), the average values for each classroom type, and the corresponding free-field values based on the averages, $L_{\mathrm{spA1\ m,free\ field}}$. The free-field values were calculated applying Barron and Lee's theory.[19]

The average value of the in-field data shown in Table II was 65.3 dBA (standard deviation=3.9 dB), almost all the

TABLE II. Individual teachers' vocal efforts, $L_{\mathrm{spA1\ m}}$, measured in seven occupied classroom types with the indication of the teacher's gender (f/m) and the type of speech (t=text/l=lecture), average values for each classroom type and corresponding free-field values based on the averages, $L_{\mathrm{spA1\ m,free\ field}}$. Measured background noise level L_{Aeq} and L_{A90}.

	Vocal effort												Noise	
	$L_{\mathrm{spA1\ m}}$ dB(A)													
Classroom	Individual teachers' values										Average (st.dev.)	$L_{\mathrm{spA1\ m,free\ field}}$ dB(A)	$L_{\mathrm{A,eq}}$ dB(A)	L_{A90} dB(A)
S1	68.5	(f,l)	63.9	(f,t)	70.7	(f,t)					67.7 (3.5)	63.1	38.6	33.8
M1	69.0	(f,t)	62.4	(m,l)	68.1	(f,t)	67.2	(f,l)			66.7 (2.9)	64.0	35.2	28.9
M2a	69.8	(f,l)	68.0	(m,l)	65.8	(f,t)	67.2	(f,t)			67.7 (1.7)	62.5	44.3	39.0
M3	59.3	(f,t)	64.1	(m,l)	63.2	(m,l)					62.2 (2.5)	59.0	41.2	31.4
L1	60.4	(f,t)	69.1	(f,t)	71.3	(f,l)	58.2	(f,t)	63.2	(f,l)	64.5 (5.6)	61.5	38.4	28.7
L2	64.2	(m,t)	58.6	(f,t)	60.5	(f,t)					61.1 (2.9)	57.6	37.9	32.1
EL1	70.1	(f,l)	68.8	(f,l)	63.2	(f,t)	64.2	(f,t)			66.6 (3.4)	65.1	32.6	28.2

vocal efforts were above 60 dB(A), and half of the values fell above 66 dB(A). No significant differences were observed between males and females, while the average value for the text reading, 64.2 dBA (s.d.=4.1), was about 3 dB lower than those for the lecture, that is 67.0 dBA (s.d=3.2). As far as the free-field value is concerned a mean value, referred to the same sample, of 62.0 dBA (s.d.=4.0) denotes a vocal effort of between "Normal" (60 dBA) and "Raised" (66 dBA), according to the ISO 9921:2003 standard.[8] For a free-field "Normal" vocal effort Pavlovic[11] and Byrne *et al.*[12] reported 63.0 and 58.0 dB, respectively, which, minus 2.5 dB for conversion to an A-weighted value,[14] gives 60.5 dB(A) and 55.5 dB(A), respectively. Houtgast[1] found a $L_{\text{spA1 m,free field}}$ of 57.0 dB(A) in a 200 m^3 occupied classroom with students exposed to traffic noise. Picard and Bradley[14] indicate 60.1 dB(A) at 2 m from the teacher's mouth, as a mean value over a large set of data from kindergarten to university. If this value were to be measured in an average classroom of 300 m^3, with a reverberation time of 0.7 s, a $L_{\text{spA1 m,free field}}$ of 60.5 dB(A) would be obtained using Barron and Lee's theory.[19] Sato and Bradley[13] found a $L_{\text{spA1 m,free field}}$ of 68.8 dB(A) in noisy primary schools. The present result of 62.0 dB(A) is slightly higher than the literature data, apart from that by Sato and Bradley, but it should be considered that most of the previously indicated vocal efforts were calculated values or obtained from measurements in controlled fields.

Table II shows also the comparison between the vocal efforts of the teachers and the noise levels L_{Aeq} and L_{A90}. Most of the L_{Aeq} values were lower than the *acceptable* target of 40 dB(A) as indicated by Picard and Bradley,[14] but only one is lower than the *ideal* target of 33 dB(A). The L_{A90} noise levels were lower for fully renovated classrooms (M1, L1 and EL1) than for partially and nonrenovated ones, and most of them were lower than 33 dB(A). All the classrooms look onto a quiet street or square, except S1 and M1, which look onto a courtyard, but no marked differences were observed between the two types of classrooms in this respect, which means that the noise comes mainly from inside the building. In a comparison with literature data, all measured in urban area with quiet students, Shield and Dockrell[20] found an average L_{Aeq} of 56.3 dB(A) in primary schools, Houtgast[1] of 47.4 dB(A) (s.d.=3.1) with 8–15-year-old students and Bradley[2] of 41.9 dB(A) (s.d.=2.1) with 12–13-year-old students. The L_{Aeq} values in Table II are similar to those reported by Hétu *et al.*[4] which in empty classrooms in occupied buildings located far from traffic arteries measured 37.2 and 37.8 dB(A).

3. Speech intelligibility

Figure 2 shows the mean SNR_A and STI values and the min-max range bars for each occupied classroom type, with the exception of M2b and M4 (see Sec. IV B 2). These measures were obtained for six positions uniformly distributed over the seating area, and then averaged. The SNR_A values varied from 15.4 to 27.0 dB(A), but no marked differences were observed between nonrenovated and renovated classrooms. High values of SNR_A were found in the classrooms,

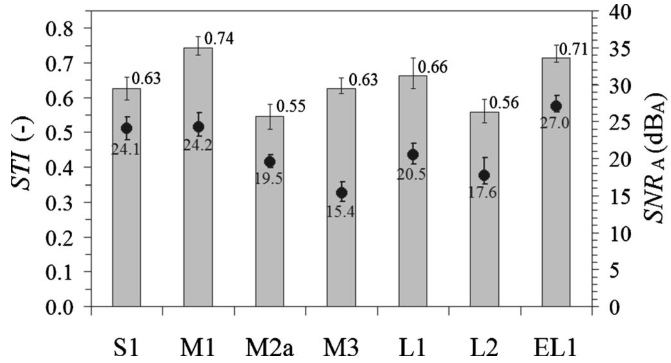

FIG. 2. Mean STI (gray blocks) and SNR_A (black circles) values and min-max range bars for seven of the eight classroom types.

which signifies that the teachers tend to compensate for noise with a greater vocal effort in order to ensure better student-speech comprehension. In the non- or poorly renovated classrooms, M2a and L2, the STI values were 0.55 and 0.56, respectively, 0.63 in both of the partially renovated S1 and M3, and 0.74, 0.66 and 0.71, respectively, in the fully renovated M1, L1 and EL1.

All the SNR_A values are higher than the optimal target of 15 dB(A), while, due to high reverberation, the STI values in M2a and L2 do not meet the minimum criterion of 0.60. The STI values were also mathematically derived following the lines of statistical room acoustics, according to the overall nonfrequency-specific approach reported in Houtgast *et al.*[9] After the satisfactory correspondence between the measured and calculated STI values had been checked for the partial occupancy, the new values for the fully occupied condition were obtained. Even though this method only provides approximations, no relevant differences were observed between the original and corrected values, confirming what has been stated previously.

V. SUBJECTIVE SURVEY

A subjective survey on perceived environmental quality has been carried out on the 51 classrooms by means of questionnaires. The main objectives were to investigate the relevance of the four environmental aspects in the overall environmental quality perception and to analyze the factors that affect the acoustical quality in secondary-school classrooms. All statistical analyses were carried out with the support of the SPSS® package. Subjective data related to acoustical quality were also correlated with the objective values, as described in Sec. VI.

A. Questionnaire

The questionnaire was drawn up following a methodology based on specific literature.[21] Experts in thermo-fluid dynamics and lighting have contributed to acquire all the relevant components of subjective perception concerning each environmental aspect. It was validated after numerous pilot tests with individual classes of different ages with the aim to test the readability and comprehension of the text and the ease of administration. The final version, which is available from the authors, contained 55 questions in six sections:

TABLE III. Influence of the four different environmental aspects on the students' school performance: mean scores of the answers and t-test significances for the differences of the mean scores between the renovated and nonrenovated classrooms. The five-point scales range from "very little" (1) to "very much" (5).

	Mean scores attributed to the influence of each aspect on the students' school performance (1–5 scale)				
	Renovated classrooms (702 ind.)		Non-renovated classrooms (150 ind.)		
Environmental quality aspect	Mean	95% confidence interval	Mean	95% confidence interval	t test for the difference of the means (p value)
Acoustical	**3.47**	[3.38, 3.56]	**3.32**	[3.13, 3.51]	0.16
Thermal	**3.08**	[2.99, 3.18]	**3.13**	[2.92, 3.34]	0.70
Indoor air	**2.92**	[2.83, 3.02]	**3.00**	[2.80, 3.20]	0.50
Visual	**3.59**	[3.50, 3.68]	**3.35**	[3.12, 3.57]	0.05

the first two sections were on general information and overall environmental quality, while the last four sections were on acoustical, thermal, indoor air and visual quality. Most of the answers referred to a 5-point scale, in which each step was labeled from 1 to 5, and the extremes with semantic descriptors.

The general information section was related, among others, to the influence of the four environmental aspects on students' school performances. The overall quality section consisted of one single question on the satisfaction of all the environmental aspects together.

The acoustical quality section covered: intensity and disturbance to lessons due to the average noise in the classroom; intensity, disturbance and frequency of occurrence from some different noise sources in the classroom; reverberation of the teachers' and students' voices; how well students comprehend the spoken words by the teacher; perceived vocal effort of the teacher; frequency of a list of consequences caused by bad classroom acoustics; satisfaction with the classroom acoustics. Only the students who attended the school before the renovation were asked to indicate the degree of improvement or deterioration with respect to the previous condition.

The thermal quality section, according to EN ISO 10551:2001 standard,[22] basically concerned: perception of the thermal environment on a symmetrical 7-point two-pole scale (from "very cold" to "very hot"), frequency of annoyance due to sun rays through the window, frequency of drafts, satisfaction with the thermal conditions. The indoor air quality section covered: frequency of perception of the air as dry, frequency of perception of the classroom as dirty or dusty, frequency of opening the windows, intensity of odors, satisfaction with the indoor air quality. The section on visual quality covered: quantity of light (natural+artificial) over the desks and on the blackboard, annoyance due to glare from windows, lighting and from the overall brightness of the room, frequency of using artificial lighting systems, satisfaction with the lighting conditions.

Questionnaires were filled in during one day of February, about one year after the acoustical treatment in the classrooms had been carried out, so that the students had passed a sufficiently long period of time in the renovated classrooms to make subjective assessments. The students were asked to answer with reference to the winter period, when the typical weather was cold and sunny, with a daily average external temperature of 3.0 °C. In order to obtain coherent and realistic answers, the questionnaire was explained to the students before they filled it in.

B. Sample

The questionnaires were administered to 1006 students in 51 classes. Those containing missing answers, referring to subjects with hearing or visual problems and by non native Italian speakers, were disregarded from the full sample. After this, an analysis of the consistency of the answers was developed by means of the Kolmogorov-Smirnov normality test and using Mahalanobis and Cook distances. A final sample of 852 questionnaires was used for the subjective analyses. The students had an average age of 16.1, with a majority of females (88.5%, as this type of school is predominantly attended by females), and 99.9% were Italian. A reduced sample of 676 students, corresponding to the 40 representative classrooms of the eight chosen types, were also used for the correlation between the subjective and objective acoustical data.

C. Relevance of the single aspects in the overall environmental quality assessment

The relevance of each single aspect of the perceived quality (acoustical, thermal, indoor air and visual) to the overall environmental quality assessment was investigated from the final sample, subdividing the answers between renovated (702) and nonrenovated classrooms (150).

Four questions on the supposed influence of the four aspects on students' school performance, on a five-point scale from "very little" to "very much," were included in the survey. The mean scores the students attributed to the influence of each aspect are shown in Table III. Almost the same importance was awarded to the four aspects by the two groups of students, with a prevalence of influence of visual quality and acoustical quality, followed by thermal and indoor air quality. Apart from visual quality, there are no significant differences between the mean values for the renovated and nonrenovated classrooms.

The correlations of the different aspects with the overall satisfaction scores are shown in Table IV. In the renovated classrooms, the overall satisfaction was more closely corre-

TABLE IV. Correlation of the overall environmental quality satisfaction with the satisfaction of each of the four environmental aspects.

	Correlation with overall environmental quality satisfaction (Pearson's coefficient)	
Environmental quality aspect	Renovated classrooms (702 ind.)	Nonrenovated classrooms (150 ind.)
Acoustical	0.39	0.50
Thermal	0.50	0.28
Indoor air	0.32	0.31
Visual	0.29	0.25

lated to thermal satisfaction, while in the nonrenovated ones, the highest correlation is to acoustical satisfaction (significant with a p value equal to 0.00).

Table V reports the mean scores, the 95% confidence intervals and t-test significances of the mean differences, for the overall and for each environmental aspect in the acoustically renovated and nonrenovated classrooms. The five-point scales range from "very dissatisfied" to "very satisfied." In the renovated classrooms, the students perceived a fair level of satisfaction for acoustical and visual quality, with very similar scores, and lower values for thermal and indoor air quality. Lower values of satisfaction, for all the aspects, were reported in the nonrenovated classrooms, where the only significantly higher aspect than the others was the visual quality. In particular, it can be seen that the mean satisfaction score for acoustical quality increased from 2.21 to 3.48 after renovation. Even the overall quality satisfaction increased, from 2.17 to 3.09, but less than for the acoustical quality aspect, probably because the visual satisfaction (whose influence on the overall judgment in the students' school performances is more relevant, e.g. Table III) remains almost constant.

Some considerations can be made from a comparison of Tables IV and V. In the renovated classrooms, where a fair satisfaction level of acoustical quality was achieved, the overall quality satisfaction closely depended on the thermal quality, one of the aspects the students were less satisfied with. In the nonrenovated ones, where the acoustical quality was poor, this is the aspect that was mainly correlated to the almost negative overall quality judgment. With a parity of dissatisfaction concerning the acoustical, thermal and indoor air quality conditions, it seems that students attribute more relevance, in the overall quality judgment, to the acoustical condition, an aspect they considered more important for their school performance.

D. Results for the acoustical environment

1. Intensity, disturbance and frequency of occurrence of different noise sources

The mean values and standard deviations of the classroom mean values (used instead of the mean value of the total number of answers because of the differences in number of students in the classes) of the intensity, disturbance and frequency of occurrence of different noise sources in the classrooms, are shown in Fig. 3. The 5-point scales were from "very low" to "very high." The highest mean values were attributed to "Students talking in the classroom" (STC), with mean scores of more than 3 on the scale, while lower mean scores of about 2.2 were attributed to "Students moving in the classroom" (SMC). As far as the high mean scores of about 2.6 assigned to "Students talking and moving in the corridor" (STMCO) are concerned, the reason is the low sound insulation of the doors, while the absence of floating floors was probably the reason for the scores (about 2.0) assigned to "Students moving or shuffling in the neighboring classrooms" (SMNC). Sometimes open windows could have been the cause of the mean scores of about 2.1 and 1.8 for "Traffic" (TR) and "Other noise outside the building" (ONOB), respectively, while the lowest mean scores of about 1.6 and 1.3 were assigned to "Students talking in the neighboring classrooms" (STNC) and "Other noise inside the

TABLE V. Satisfaction scores for the overall environmental quality and the four environmental aspects on 1–5 discrete scales from "very dissatisfied" (1) to "very satisfied" (5): mean scores of the answers and t-test significances for the differences of the mean scores between the renovated and nonrenovated classrooms.

	Renovated classrooms (702 ind.)		Nonrenovated classrooms (150 ind.)		
Environmental quality aspect	Mean	Confidence interval	Mean	Confidence interval	t test for the difference of the means (p value)
Overall quality satisfaction	**3.09**	[3.04, 3.15]	**2.17**	[2.06, 2.28]	0.00
Acoustical quality satisfaction	**3.48**	[3.42, 3.55]	**2.21**	[2.08, 2.33]	0.00
Thermal quality satisfaction	**2.81**	[2.73, 2.88]	**1.95**	[1.80, 2.09]	0.00
Indoor air quality satisfaction	**2.55**	[2.49, 2.61]	**2.17**	[2.04, 2.31]	0.00
Visual quality satisfaction	**3.31**	[3.25, 3.39]	**2.87**	[2.73, 3.00]	0.00

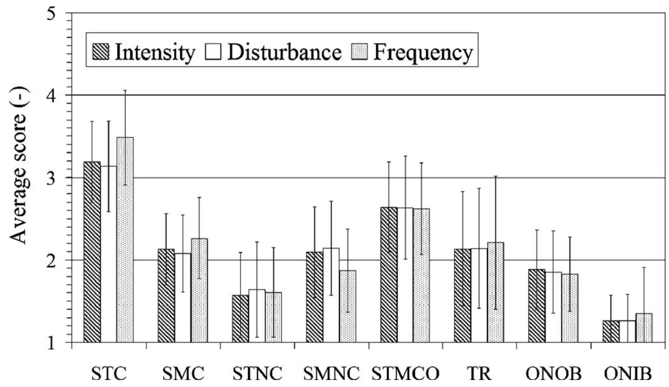

FIG. 3. Mean values and standard deviation of the mean classroom values of intensity, disturbance and frequency of occurrence of different noise sources in the classrooms. The five-point scale is bounded by the words "very low" (1) and "very high" (5). The following abbreviations are used for the noise sources: STC for "Students talking in the classroom," SMC for "Students moving or shuffling in the classroom," STNC for "Students talking in the neighboring classrooms," SMNC for "Students moving or shuffling in the neighboring classrooms," STMCO for "Students talking and moving in the corridor," TR for "Traffic," ONOB for "Other noise outside the building," and ONIB for "Other noise inside the building."

building" (ONIB), respectively. Different results are shown between the mean answer scores of the renovated and nonrenovated classrooms. For example, the mean disturbance scores for most sources in M3 are slightly higher than those in M4 (p value of t test lower than 0.10), with the exception of STNC, SMNC and ONIB. These results can be explained by considering that a higher reverberation time in M3 can amplify the noise inside the classrooms and make it seem more disturbing. The exceptions could be due to the fact that they are distant sources from outside the classroom, and hence more difficult to distinguish. On the other hand, when the occupied reverberation time is almost the same, as for S1 and M1, the mean scores are more similar (the difference is rejected with a p value higher than 0.40 for all the sources with the exception of STC and ONOB).

A correlation and a factorial analysis were performed, and they showed that the intensity, disturbance and frequency of each noise source are closely correlated. Exactly eight factors were singled out from the factorial analysis, each one corresponding to one of the above-mentioned noise sources. For this reason, in subsequent sections, when carrying out the data analyses, the scores attributed to these questions were replaced by the scores of these eight resulting factors.

2. Acoustical quality satisfaction

Noticeable differences between renovated and nonrenovated classrooms on the perception of some acoustical factors were observed. For the renovated classrooms the mean scores and 95% confidence intervals of speech comprehension (on a 5-point scale from "very badly" to "very well"), teachers' vocal effort (5-point scale from "very low" to "very raised") and voice reverberation (5-point scale from "very dry" to "very reverberant") are 3.88 [3.81, 3.95], 2.86 [2.81, 2.92] and 2.06 [1.99, 2.12], respectively, while for the nonrenovated ones the same mean scores are 3.07 [2.90, 3.23], 3.43 [3.31, 3.54] and 3.69 [3.52, 3.87]. In all the three cases the t tests strongly reject (with p values lower than 0.01) the hypothesis of no differences between the perceptions of the two groups. One of the questions on the acoustic environment, which was only answered by those students who were in the renovated rooms, was about the improvement in classroom acoustics after renovation. The arithmetic mean of these answers is 4.17, with a standard deviation equal to 0.93 on a 1 ("much worse") to 5 ("much better") discrete scale, thus it can be stated that the improvements after renovation were noticed by the students.

Table VI shows the most significant part of the correlation matrix for acoustic answers related to the renovated and nonrenovated classrooms. An arbitrary limit of the correlation coefficient $|r| \geq 0.25$ was chosen and only the coefficients with $p \leq 0.01$ are shown. Some correlations are only present for the nonrenovated classrooms with poor acoustic conditions. From the analysis, it seems that the poorer the acoustics, the more the acoustical quality satisfaction is af-

TABLE VI. Correlation matrix between the acoustic answers for the renovated classrooms (RC) and for the nonrenovated ones (NRC). An arbitrary limit of the correlation coefficient $|r| \geq 0.25$ was chosen and only the coefficients with $p \leq 0.01$ are shown.

	Acoustical quality satisfaction (AQS)		Speech comprehension (SC)		Teachers' vocal effort (TVE)		Voice reverberation (VR)		Noise intensity (NI)		Noise disturbance (ND)	
	RC	NRC	RC	NRC	RC	NRC	RC	NRC	RC	NRC	RC	NRC
AQS	1.00	1.00										
SC	0.42	0.56	1.00	1.00								
TVE		−0.32		−0.28	1.00	1.00						
VR	−0.32	−0.48	−0.27	−0.39			1.00	1.00				
NI									1.00	1.00		
ND		−0.41		−0.26		0.25		0.26	0.49	0.36	1.00	1.00
Students talking in the classroom									0.37	0.27	0.47	0.29
Students talking in the neighboring classrooms												0.30
Students moving or shuffling in the neighburing classrooms												0.25

fected by the factors that are not optimized. Speech comprehension is affected by voice reverberation, teachers' vocal effort and noise disturbance in the classrooms with poor acoustics, but only by voice reverberation in the classrooms with better acoustics. Acoustical quality satisfaction is affected by speech comprehension, voice reverberation, teachers' vocal effort and noise disturbance in the classrooms with poor acoustics, but only by speech comprehension and voice reverberation in the classrooms with better acoustics.

Generally, a good correlation exists between noise disturbance and noise intensity, and both of them are well correlated to students talking in the classroom. In the nonrenovated classrooms, poor sound insulation also determines close correlations between noise disturbance and students talking in the neighboring classrooms and students moving or shuffling in the neighboring classrooms. These correlations are only with noise disturbance and not with noise intensity, probably because the noise from these other sources is not very intense but it is very annoying. The above results agree with Kennedy *et al.*,[7] who, in university classrooms, found students talking in the classroom as the factor that is most commonly reported as interfering with the listening environment, followed by intermittent noises in the building but outside the classroom, while constant noise within or outside the building was less likely to be reported as interfering.

3. Consequences caused by poor acoustics

The students were asked to indicate the frequency of a list of perceived consequences caused by poor classroom acoustics on a five-point scale from "never" to "very often." Only the mean values for the students who were not satisfied about the overall classroom acoustics (i.e., the 165 students that marked 1 and 2 on the correspondent satisfaction scale) have been analyzed. The most important consequences of the poor acoustics in the classrooms are "Decrease in concentration" (mean=3.5, s.d=1.2), "Decrease in teacher voice perception" (mean=3.2, s.d=1.1) and "Decrease in students questions perception" (mean=3.1, s.d.=1.2). The most commonly reported adverse consequence of a poor listening environment according to Kennedy *et al.*[7] was failure to hear questions asked by other students in the class followed by concentration broken, which coincides with the present results.

E. Results of the thermal, indoor air and luminous environments

Correlation analyses based on the answers of the full sample, concerning the thermal, indoor air and luminous environments, were performed. These correlations show that, as far as the thermal conditions are concerned, the dissatisfaction is associated with the high temperature and the drafts, that students feel when they open the windows for ventilation and cooling during breaks. External screens on the windows and ventilation systems should be applied. Ventilation is also necessary for indoor air quality since students associate dissatisfaction with the high intensity of odors. As for visual quality, the students associate dissatisfaction with the brightness of the windows and lighting. Blinds or curtains should be mounted on the windows, slightly darker paint should be used on the walls and the lighting system should be correctly designed. Once again, the satisfaction of the thermal and visual conditions depends on the factors for which the students feel discomfort, which are not optimized in the building. Most of the classrooms in fact have windows without screens and are exposed to direct solar radiation, which causes high temperatures inside the classrooms and too much brightness from the windows.

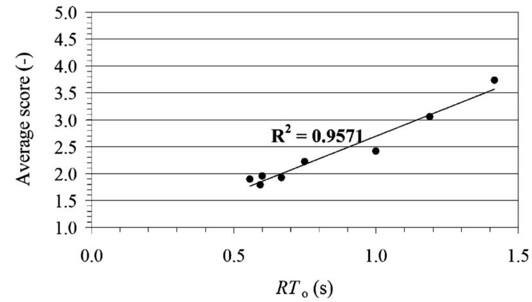

FIG. 4. Average scores for voice reverberation versus measured values of reverberation time (single number frequency averaged between 500 Hz, 1 kHz and 2 kHz) in occupied classrooms, and best-fit regression line. The five-point scale is bounded by the words "very dry" (1) and "very reverberant" (5).

VI. RELATIONSHIPS BETWEEN THE OBJECTIVE AND SUBJECTIVE DATA

A. Voice reverberation

Figure 4 plots the RT_o against the average scores for voice reverberation in the eight classroom types. The good correlation ($R^2=0.957$) was maintained when the reverberation times were corrected for full occupancy. It seems that students are aware of the different reverberant conditions in the classrooms, and are able to classify the sensations in a judgment scale, even though a larger amount of data would be necessary to confirm this statement.

B. Noise disturbance and intensity

Figure 5 shows the averages of the noise disturbance

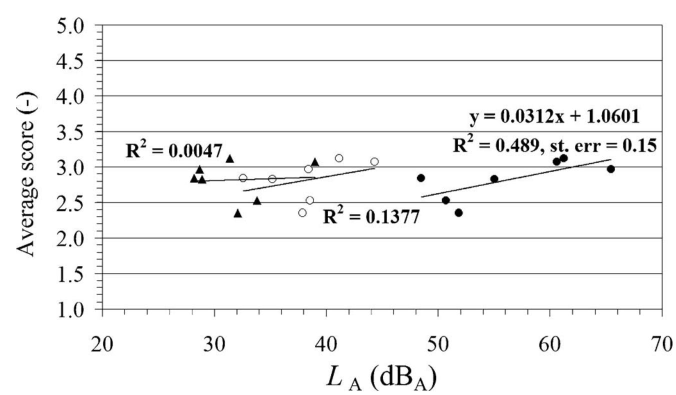

FIG. 5. Average noise disturbance scores versus measured values of L_{Aeq} (white circles), L_{A90} (solid triangles) and $L_{A\,max}$ (solid circles) and best-fit regression lines. The five-point scale is bounded by the words "very low" (1) and "very high" (5).

scores for each classroom type versus the corresponding measured values of L_{Aeq}, L_{A90} and $L_{A\,max}$, and the best-fit lines. Results are given for seven of the eight classroom types, as types M2b and M4 were excluded from the in field measurements (see Sec. IV B 2). A slight correlation exists between the mean subjective scores and the $L_{A\,max}$ (related to single-event noise, measured inside the classrooms), with an R^2 of 0.489 (p value for incorrelation test, $r=0$, is equal to 0.08): noise disturbance scores increase with an increase in the maximum A-weighted sound-pressure levels. Similar results for noise intensity have been observed, where, again, a good correlation is present between the subjective scores and $L_{A\,max}$, with an R^2 coefficient of 0.531 (p value for the incorrelation test equal to 0.06). It should be pointed out that these correlations are only significant when classroom average scores, instead of the answers of the single students, are considered. However, they seem to reveal that a stronger relationship exists between either noise disturbance or intensity and $L_{A\,max}$, more than L_{Aeq} and L_{A90}, so showing that students seem to be more disturbed by intermittent loud noises than by constant noise. This has also been proven in recent research by Dockrell and Shield,[5] who found that for young children (6–11-year olds) external $L_{A\,max}$ levels play a significant role in reported annoyance (caused mainly by trains, motorbikes, lorries and sirens), whereas external L_{A90} and L_{A99} levels play a significant role in determining whether or not children hear sound sources.

C. Speech comprehension

The STI and SNR_A were considered as the predictors of speech comprehension scores. These measures were obtained for six positions in each of the six chosen occupied classroom types. No measurements were carried out in rooms M2b or M4 (see Sec. IV B 2); room L2 was also excluded because of fewer subjective data (only one classroom was surveyed for this type, instead of a minimum of three for the others). The student seating area of each classroom was divided into six approximately equal areas around each measurement point, counting at least four student positions, in order to correlate the measurements to the speech comprehension scores. The average speech comprehension score for each of these groups was obtained by averaging the answers of all the student around the same measurement position for all the classrooms of the same type. Figure 6 shows the average speech comprehension scores versus measured STI. A slight relationship ($R^2=0.342$) can be observed: STI values close to 0.80, which qualifies as excellent intelligibility, can be associated with higher average speech comprehension scores (4.5 on a 1–5 scale), while STI values of about 0.50, corresponding to fair intelligibility, can be associated with the medium score (point 3 of the scale). The same good correlations are maintained when the reverberation times are corrected for full occupancy. A similar analysis with SNR_A showed no correlation with the subjective scores ($R^2=0.072$). Teachers tend to compensate for noise with higher vocal efforts, guaranteeing high values of SNR_A in all the classrooms, but, even with these high SNR_A levels, the students are aware of the detrimental effect of reverberation,

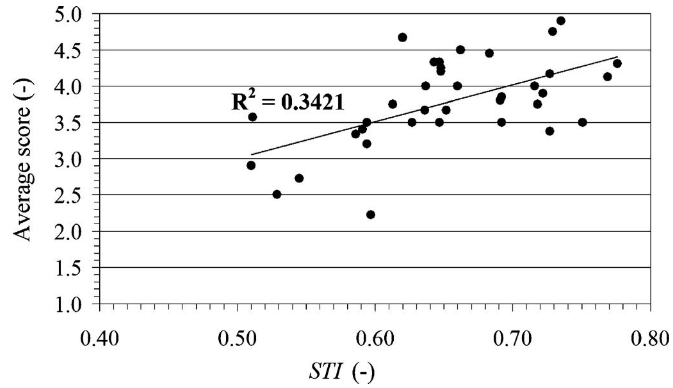

FIG. 6. Average speech comprehension scores for each point in the six chosen classroom types (S1, M1, M2a, M3, L1, EL1) versus STI values and best-fit linear regression function. The five-point scale is bounded by the words "very badly" (1) and "very well" (5).

which is well represented by the better association of the speech comprehension scores with the STI values. These representations are only an attempt to correlate the assessment of speech communication with the measured parameters. A correlation exists between the STI values and the speech comprehension scores in the classrooms, but it is not the same as the correlation between the STI and speech intelligibility, which is obtained with speech intelligibility tests.[2,3,8] In a speech comprehension score there is a speech intelligibility contribution, but also the contribution of other factors that have not been investigated in the survey. Kennedy *et al.*[7] found that other environmental aspects, personal factors, course material and teachers' characteristics were at least as important as STI values in predicting the perception of listening ease (PLE) score in university classrooms. Volberg *et al.*[23] found that, when evaluating the quality of speech communication, the listeners take into account speech intelligibility, but also the effort to understand what the speaker says, how difficult the task is, how annoying the environment and how absorbing other parallel activities are. Hagen *et al.*[6] reported a significant improvement in the subjective evaluation after acoustical interventions were made in classrooms, but not sufficient for successful listening at school. They indicated an improvement of the listening climate due to the correct behavior of the teacher which comprehend loudness of voice, articulation, listening mode, not shouting.

VII. CONCLUSIONS

A subjective survey on perceived environmental quality has been carried out on 51 secondary-school classrooms, some of which have been acoustically renovated, and acoustical measurements were carried out in eight of the 51 classrooms, these eight being representative of the different types of classrooms that are the subject of the survey.

Concerning acoustical measurements, it was confirmed that sound-absorption treatments are necessary also in small occupied classrooms in order to obtain optimal reverberation times, and that the noise levels in the classrooms of the school, far from high traffic arteries with quiet students inside the classrooms, are generally lower than the *acceptable* target of 40 dBA L_{Aeq}.[14] The noise comes mainly from inside the building and the average free-field vocal effort is between "Normal" and "Raised." It should be pointed out that other studies are necessary to better investigate factors that can influence the teacher's vocal effort.

Concerning the subjective survey, the students awarded a prevalence of influence of visual and acoustical quality on school performances, and with a parity of dissatisfaction in the acoustical, thermal and indoor air quality conditions, it seems that they attributed more relevance in the overall quality judgment, to the acoustical satisfaction. The subjective evaluations of intensity, disturbance and frequency of each noise source are closely correlated, and the highest perceived noisy source are the students talking in the classroom. Acoustical satisfaction was lower in nonrenovated classrooms, and one of the most important consequences of poor acoustics was the decrease in concentration.

From the correlations between objective and subjective data, a stronger relation has been noticed between both noise disturbance and intensity average scores and $L_{A\,max}$ levels, more than L_{Aeq} and L_{A90}, so showing that students seemed to be more disturbed by intermittent loud noises than by constant noise. Teachers compensated for noise guaranteeing SNR_A values higher than the optimal target of 15 dB(A) in all the classrooms while in nonrenovated ones STI values do not meet the minimum criterion of 0.60. Even with these high SNR_A, the students were aware of the detrimental effect of reverberation, which is well represented by the better association of the speech comprehension scores with the STI values. It should be pointed out that in speech comprehension there is a valuable speech-intelligibility contribution but also the contribution of other factors of the listening environment, considered in recent literature, that can strongly improve speech comprehension, and that can be investigated in future studies.

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