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Acoustic comfort in high-school classrooms for students and teachers

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Abstract

This work focuses on the evaluation of acoustical quality in high-school classrooms through in-field measurements and self-reports. Two school buildings that differ in location and typology, were considered. In-field measurements included sound insulation, room acoustics and intelligibility indices in unoccupied and simulated occupied conditions. Teacher's vocal load was monitored over several working days through the Voice Care device and was related to the correspondent background noise and room acoustics. Teachers subjective perception investigated noise disturbance, vocal effort and status after each monitoring. The receiver operating curve was implemented to assess agreement between in-field measurements and self-reports for teachers. The association between objective parameters was assessed with linear regression analysis.

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Keywords: classroom acoustics, long-term monitoring, vocal load, acoustical quality, subjective surveys.

1. Introduction

This work is part of the Green School Project, a cooperation between Politecnico di Torino and the Province of Torino. It has the aim of developing methods and tools to easily transform existing school buildings in *green schools*, offering healthy and comfortable environments for students and teachers accordingly to environmental,

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economic and social sustainability criteria. The Project aims at promoting the evaluation of existing buildings through procedures of quality rating. Among many aspects of interest for sustainability improvement in schools, acoustic comfort plays a primary role for students learning ability [1-3] and teachers health [4,5]. Recently, research in the acoustic field was focused on listening quality and on noise effects in learning environments [6,7]. A good acoustic environment is primarily achieved by the minimization of the contributions of noise from external (e.g. traffic) and from internal (e.g. HVAC systems, chatting) sources. In addition, good communication is ensured when room acoustics and intelligibility parameters are in the acceptable ranges for teaching and learning purposes [8-12].

A methodology for acoustic comfort assessment in schools is here proposed, that consists in objective in-field measurements and teachers subjective impression evaluations, aiming to design a protocol that can easily be applied to extended campaigns in schools. To achieve a complete acoustic evaluation of school environments, sound insulation of partitions, room acoustics and speech intelligibility in classrooms, noise in occupied environments, voice monitoring of teachers, were considered. In-field measurements were performed in unoccupied and simulated occupied classroom conditions. Agreement between the measurements and self-reports of teachers, assessed using a survey, was investigated through the Receiver Operating Characteristic (ROC) curve [13]. Teacher's vocal load was monitored over several working days with the Voice Care device. The analysis included mean and mode sound pressure level estimated at one meter from the teacher's mouth (SPL_{1m}, dB), mean and mode fundamental frequency (F_0, Hz), phonation time percentage ($D_{t\%}$, %). Background noise (L_{A90}, dB) was measured repeatedly for time intervals of 15 minutes during the teacher's voice monitoring, and related to the teaching activities and subjects.

2. Case studies

School A - A. Avogadro, Torino. Built in early 1800, this school building is located in the city center, close to high traffic arteries. Its structure was built using reinforced concrete in accordance with the typical technologies of the early XIX century. The building is composed by an older part of five floors and a more recent portion distributed over three floors. The façades are made of bricks and double-glazed windows. Learning environments differ in volumes, ranging between 210 m^3 and 380 m^3 for classrooms and between 400 m^3 to 1200 m^3 for laboratories, and also in acoustical treatment (some classrooms have absorptive false ceilings).

School B - J.C.Maxwell, Nichelino. This school building dates back to the second half of 1900 and is placed in a suburban area of Torino called Nichelino, nearby low traffic arteries. The building consists in a semi-basement floor, a mezzanine floor and two upper floors that host classrooms, which are all characterized by acoustical treatment on the false ceilings. The structure of this building is made of reinforced concrete, prefabricated elements and double-glazed windows. Internal spaces are separated by light weight plasterboard walls and wooden doors with no particular insulation properties. Classrooms are in the range of volumes from 170 m^3 to 330 m^3.

Figure 1. A. Avogadro (school A, left) and J.C. Maxwell (school B, right) Institutes: external views

3. In-field measurement methodology

3.1. Classroom acoustics parameters

- *Sound insulation*: measurements were carried out in compliance with the Italian standard UNI EN ISO 10052 [14]. In-field measurements regarded the *standardized noise level difference value of façade* ($D_{2m,nT,w}$, dB); the *minimum weighted standardized level difference* ($D_{nT,w}$, dB) for partitions between adjacent classrooms, overlapped classrooms and between classroom and corridor; the *maximum weighted standardized impact sound* *pressure level* (L'_{nT}, dB). Measurements were taken inside classrooms in many source-receiver positions using a class-1 sound level meter as receiver (model XL2 by NTi Audio), a sound source generating pink noise for airborne sound insulation, and a generator of simulated walking for impact sound insulation.

- *Reverberation Time* (T_{30}, s): measurement carried out in compliance with UNI EN ISO 3382 [15] standard applying the integrated impulse response method. The software DIRAC was used for the signal processing. The results, measured in two source and four microphone positions, were combined as a whole to give spatial averaged values. Frequency averaging and standard compliancy was done following the German standard DIN 18041 [8]. A "clapper", a pair of wooden boards hinged to generate impulsive signals, was used in school A; a sweep signal was used in school B that was generated by the B&K type 4128 Head and Torso Simulator (HaTS). Measurements were performed in unoccupied and occupied (simulated with polyester fiber panels) classroom conditions.
- *Clarity* (C_{50}, dB): measurements were taken according to the UNI EN ISO 3382, using a B&K type 4128 HaTS placed at the teacher's desk as source, and a class-1 sound level meter in the centre of the room, as receiver.
- *Speech Transmission Index* (STI): measurements were taken according to the international standard IEC 60628-16 [16], in central position inside the classroom, using the B&K type 4128 HaTS placed at the teacher's desk.
- *Voice Support and Room Gain* (ST_V and G_{RG}, dB): these parameters defined in [12] were obtained measuring the impulse response (IR) from the mouth to the ears of the B&K 4128 HaTS. Results were averaged for two source positions inside each classroom, being the HaTS placed at a height of 1.5 m and at least 1 m from every surface.
- *Background Noise* (L_{A90}, dB): a class-1 sound level meter (model XL2 by NTi Audio) was placed at 1.2 m from the ground, at least 1 m far from all surfaces. Measurements were carried out in empty room with closed windows and door.

3.2. Vocal load monitoring

- *Vocal monitoring*: the Voice Care device [17] was used to acquire teachers vocal parameters *sound pressure level* (SPL, dB), *fundamental frequency* (F_0, Hz) and *phonation time percentage* ($D_{t\%}$, %). It consists in a data-logger connected to an electret condenser microphone (ECM MIAE38 by Midland) placed at the speaker's jugular notch with a surgical band. The vocal monitorings were composed by three samples: entire monitoring (EM), pre-monitoring (PM), and plenary lesson (PL). The EM lasted 4 hours, representing a complete working day. The PM was taken at the beginning of the working day, when the teachers were asked to speak at a comfortable and conversational pitch for about 5 minutes, one meter far from a seated listener. The PLs were extracted from each EM and analyzed separately. A total of 37 teachers (6 male, mean age 49, and 27 female, mean age 53) were monitored for 2 to 3 days in both the schools. For SPL estimation, each talker was asked to perform a calibration in a quiet room of the school before and after every monitoring, repeating the vowel */a/* at increasing intensity levels [18]. During each monitored lesson, teachers were asked to fill in a form to indicate the activity performed by choosing between 4 categories (plenary, individual work, group work, watching/listening). Furthermore, they were asked to rate three main aspects related to vocal fatigue and noise at the end of each working day, aiming to evaluate: (question 1) the vocal status at the end of the working day, (question 2) change in voice intensity with respect to an ideal situation with no noise at the beginning of the day, (question 3) the degree of noise in the classroom compared to a condition of empty room and school at the beginning of the day.
- *Background Noise* (L_{A90}, dB): a class-1 sound level meter (model XL2 by NTi Audio) was placed at 1.2 m from the ground, close to the teacher's desk at a minimum distance of 1 m from all surfaces. Measurements were performed for 2 to 3 times during each lesson for a time interval of 15 minutes.

4. Results

Table 1 shows measured acoustic parameters in unoccupied and in simulated occupied classroom conditions. School A and school B performances in terms of compliance or not compliance with optimal values are reported.

The vocal parameters mean sound pressure level at 1 m from the talker's mouth, $SPL_{mean,1m}$, mean fundamental frequency, $F_{0,mean}$, and phonation time percentage, $D_{t\%}$ along different days of monitoring were measured and averaged per each teacher. Some monitorings have not been taken into account because of the failure of the validation of the calibration session [18]. Some teachers moved to classrooms with different room acoustics along the days, therefore results are shown which refer to averages of different amounts of teachers/monitorings. Table 2 shows the obtained values of vocal parameters under different reverberation times and volumes. They refer to plenary lessons, which resulted to be the most frequent activity, being monitored for the 80% of the total time.

Table 1. Measured classroom acoustics and insulation parameters, in occupied (occ.) and unoccupied (unocc.) conditions. Standard deviation is reported in brackets when frequency averaging and repeated measurements were taken (NA = not available). Values in bold indicate the parameters that respect the acceptable values/ranges proposed in the references.

	Index	Reference	Optimal or typical range/value	School A				School B	
				210 m^3	280 m^3	320 m^3	380 m^3	170 m^3	210 m^3
Classroom acoustics	$T30_{0.125\text{-}2kHz,unocc}$ [s]	DIN 18041 [8]	Volume dependent	2.1 (0.21)	**0.9** (0.04)	2.2 (0.08)	2.0 (0.02)	**0.7** (0.06)	**0.5** (0.04)
	$T30_{0.125\text{-}2kHz,occ}$ [s]	DIN 18041 [8]	Volume dependent	1.1 (0.13)	**0.7** (0.14)	1.2 (0.15)	1.6 (0.22)	**0.5** (0.04)	**0.5** (0.1)
	$C50_{0.5\text{-}1kHz,occ}$ [dB]	UNI 11367	≥ 0	**0.8** (0.6)	**8.5** (1.18)	-2.2 (0.13)	(NA)	**5.7** (0.77)	**6.1** (0.51)
	$ST_{V,0.5\text{-}2kHz,occ}$ [dB]	Pelegrìn-Garcìa [12]	$-14 < ST_V < -9$	**-9.26** (0.87)	**-13.3** (1.02)	**-10.1** (1.03)	(NA)	**-11.8** (0.75)	**-13.5** (NA)
Intelligibility	$STI_{,occ}$ [-]	ISO 9921	> 0.5	**0.53** (NA)	**0.82** (NA)	**0.57** (NA)	(NA)	**0.7** (NA)	(NA)
Sound insulation	$D_{2m,nT,w}$ [dB]	DPCM 5/12/97	≥ 48	26				26	
	$L'_{n,w}$ [dB]	DPCM 5/12/97	≤ 58	65				59	
	$D_{nT,w}$ [dB] adjacent classrooms	UNI 11367	≥ 45	44				34	
	$D_{nT,w}$ [dB] classroom/corridor	UNI 11367	≥ 27	**31**				26	
	$D_{nT,w}$ [dB] overlapped classrooms	UNI 11367	≥ 50	49				**52**	

Table 2. Background noise level and voice parameters (mean sound pressure level SPL and fundamental frequency F0, phonation time percentage Dt%) as averages for all monitorings, referring to plenary lessons with standard deviation reported in brackets (NA = not available). Results are shown for homogeneous groups depending on the volume and reverberation time (T30,0.125-2kHz,occ) of occupied classrooms.

	V [m^3]	$T_{30,0.125\text{-}2kHz,occ}$ [s]	N teachers M	N teachers F	N monitorings M	N monitorings F	$SPL_{mean,1m}$ [dB]	$F_{0,mean}$ [Hz] M	$F_{0,mean}$ [Hz] F	$D_{t\%}$ [%]	$L_{A90,mean}$ [dB]
School A	210	1.1	1	1	2	1	69 (3)	143 (16)	198 (NA)	69.9 (5)*	49.4 (1)
	280	0.7	2	10	3	15	65 (6)	126 (5)	218 (40)	48.3 (8)	48.4 (4)
	320	1.2	1	5	2	7	72 (6)	161 (NA)	235 (30)	43.9 (8)	48.9 (1)
	380	1.6	-	4	-	5	73 (4)	(NA)	245 (5)	53,0 (8)	52.1 (3)
School B	170	0.5	2	4	5	9	69 (5)	161 (15)	203 (20)	33.8 (10)	46.5 (4)
	210	0.5	-	5	-	10	68 (4)	(NA)	245 (17)	43.6 (7)	49.1 (4)

* Anomalous average value that includes a computer science lesson, which was characterized by long monologues of the teachers.

4.1. Statistical analysis of data

The SPSS 21 software (IBM - NY, USA) was used for the statistical analysis. Since not important differences in the day-by-day were found, the acquired data of each monitored activity were averaged per each teacher. Associations between objectively measured parameters of voice (SPL, F_0, $D_{t\%}$) and acoustic-related factors (L_{A90}, T_{30}) were assessed by linear regression analysis. Agreement between in-field measurements and self-reports was explored by the ROC curves. The three main subjective aspects were rated by placing a cross on a 10 cm continuous line. Agreement between the three answers and the objective parameters was assessed as follows: the scores of question 1 were related with SPL_{1m} (mean and mode), F_0 (mean and mode) and $D_{t\%}$. The scores of question 2 were related with L_{A90}. The scores of question 3 were related with the difference between PM and EM on SPL_{1m} (mean and mode), F_0 (mean and mode) and $D_{t\%}$. Table 3 shows the results of the univariate analysis between indoor acoustic conditions and objectively measured voice parameters. Table 4 shows the results on the agreement assessment by means of ROC analysis between objectively measured voice parameters and self-reports (cut-off value of 75%). An AUC of 0.5 or lower reflects a complete absence of any agreement, an AUC of 1 presents a perfect agreement, and an AUC of 0.8 is considered a little agreement.

Table 3. Linear regression analysis coefficients (β) with standard error (SE) for objective parameters of voice and environmental acoustic conditions association. Values in bold have significant association (p-value < 0.05).

		$F_{0,mean}$ [Hz]		$F_{0,mode}$ [Hz]		$D_{t\%}$ [%]	
	Variable	β	SE	β	SE	β	SE
EM	L_{A90} [dB]	3.64	2.28	3.71	0.54	**1.01**	0.37
PL	L_{A90} [dB]	4.44	2.24	**5.13**	2.40	0.96	0.61
Difference between EM and PM	L_{A90} [dB]	**2.87**	0.88	**3.09**	1.17	0.42	0.53
	$T30_{0.125\text{-}2kHz,unocc}$ [s]	17.13	8.48	**25.56**	11.90	3.70	6.62

Table 4. Mean values of measured parameters and area under curve (AUC) coefficients for self-reports (questions on vocal status, background noise and vocal effort perception) and objectively measured parameters are reported for entire monitorings and plenary lectures. Standard deviation (SD) and standard error (SE) of values are in brackets.

			Self-report of voice complaints			
			EM		PL	
	Parameter		Mean (SD)	AUC (SE)	Mean (SD)	AUC (SE)
Q.1 – vocal status Correlations between objective voice parameters and self-reported voice complaints	Phonation time percentage		34.8 (7.8)	0.69 (0.14)	46.0 (10.6)	0.46 (0.16)
	Mean fundamental frequency (Hz)	M	145 (20)	0.53 (0.13)	146 (19)	0.46 (0.13)
		F	227 (23)		225 (32)	
	Modal fundamental frequency (Hz)	M	133 (25)	0.49 (0.13)	134 (17)	0.41 (0.14)
		F	219 (29)		213 (38)	
	Mean sound pressure level (dB)		67.2 (5.0)	0.68 (0.14)	68.0 (5.0)	0.72 (0.11)
	Modal sound pressure level (dB)		68.9 (5.5)	0.63 (0.15)	69.3 (5.7)	0.67 (0.14)
Q.2 – noise Correlations between measured background noise level and self-reported noise conditions			EM			
			Mean (SD)		AUC (SE)	
	Background noise level, L_{A90} (dB)		48.3 (3.8)		0.59 (0.14)	
	Reverberation Time (s)		0.8 (0.4)		0.55 (0.13)	
Q.3 – vocal effort Correlations between the difference of voice in EM and PM and self-reported vocal effort			EM - PM			
			Mean (SD)		AUC (SE)	
	Phonation time percentage		-8.05 (13.9)		0.42 (0.14)	
	Mean fundamental frequency (Hz)	M	34 (12)		0.69 (0.13)	
		F	45 (19)			
	Modal fundamental frequency (Hz)	M	32 (19)		0.71 (0.13)	
		F	42 (27)			
	Mean sound pressure level (dB)		7.2 (4.1)		0.65 (0.13)	
	Modal sound pressure level (dB)		8.5 (5.6)		0.64 (0.13)	

5. Conclusions

- Room acoustics complied with regulations in school B. Sound insulation is acceptable in school A for $D_{nT,w}$ between classroom and corridor, and in school B for $D_{nT,w}$ between overlapped classrooms. Acoustical renewal would thus be needed to guarantee acoustical comfort for optimal teaching and learning environments.
- Based on [11], the mean vocal effort of teachers can be classified between "raised" and "loud", which might generate light or severe dysphonia [19].
- The background noise level was associated with fundamental frequency in the case of plenary lesson and with phonation time percentage in the case of entire monitoring. Both background noise level and reverberation time

were associated with the difference between entire monitoring and pre-monitoring. One explanation for this relationship might be the strong correlation (Pearson´s correlation coefficient = 0.92) between average values of reverberation time and background noise level. This finding agrees with previous studies on voice production in occupational- compared with non-occupational-settings [20,21].

- Objective parameters of voice had no to little discriminatory value to identify teachers with self-reported voice complaints neither self-reported vocal effort. This finding is in concordance with previous studies that reported weak association between voice parameters and self-reported voice disorders [22,23]. Objective measures of noise showed fair discrimination to identify teachers who reported high noise conditions. This finding is in concordance with [24], which reported no differences in mean values of background noise levels and reverberation time between teachers who reported uncomfortable acoustic conditions and those who reported them as comfortable.

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