Premises for Effective Teaching and Learning : State of the Art, New Outcomes and Perspectives of Classroom Acoustics

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Many booklets and standards have already been published on classroom acoustics in several countries, based on studies that were completed up to ten years ago and which were mainly focused on the speech intelligibility of pupils under noisy conditions. In the last decade many studies began to consider the complex speech communication scenario in classrooms, where acoustic requirements are needed for both teachers and pupils. The voice monitoring of teachers has revealed challenging conditions for speaking because of bad acoustics, with consequences on vocal health. Research has underlined the importance of voice support from the room, which has led us to reconsider the optimal reverberation time in classrooms, whose tendency is towards higher values than those for listening. On the other hand, it has been proven that a high reverberation increases the listening effort and decreases reading abilities. Thus, the question of the optimal reverberation time for speaking and listening arises, as well as the need to optimize the design of classrooms to support the voice and control the sound tail. The perceived reverberation is closely related to the perceived acoustical quality, which is recognized as the most important environmental aspect in classrooms. Reverberation also amplifies the noise produced by pupils themselves and affects their well-being. To cope with this, a new device has been introduced to inform pupils on the need to lower their voices and respect others. A summary of the state of the art of classroom acoustics is given in this lecture, together with the new findings on the effects of bad acoustics on pupils' learning and well-being and on teachers' vocal behaviour. A new paradigm on speech communication is needed in classrooms that should involve both teaching and learning. Further work is required to investigate the factors that underpin this complex communication scenario.

1. INTRODUCTION

The effect of classroom acoustics has consequences on learning of students, mostly at the lower grades of education, for which it is mandatory to guarantee speech comprehension in classrooms, and on teachers and teaching, for which it is mandatory to reduce teachers' vocal effort and load.

The studies by J. Bradley, M. Hodgson, and B. Shield and J. Dockrell in the field of classroom acoustics have inspired me and pushed me into this field of research that can be recognized as one of the thorniest in the architectural acoustics ambit. A solution to problems that occur in a classroom occupied by young children helps to cope with problems in other environments occupied by adults where the same acoustic tasks are accomplished. For example, new speech intelligibility indexes are proposed for classrooms and they are maximized acting on layouts and furniture, as well as on the most performant and innovative sound insulation envelopes. It is mandatory to monitor the vocal effort given the vocal load of the teachers and new indexes that are proposed to preserve their vocal health. New devices are proposed to lower anthropic noise which encourage occupants' behavioural changes. Particular attention must be paid to children with hearing impairments and with special needs, that more frequently are included in regular classrooms with other children. Open plan classrooms have been recently proposed that are at the base of innovative teaching and that are challenging from the acoustical point of view.

A survey on the physical conditions of school facilities in the USA declared 28 per cent of all schools across the USA to be unsatisfactorily noisy. High ambient noise conditions characterize these premises, with measured A-weighted sound pressure levels on the order of 73 dB.[1] The Italian government has recently carried out a census of all Italian schools of different levels (pre-schools, primary schools, lower and upper secondary schools) in order to determine whether or not they needed to be improved.[2] Globally, more than 42,000 buildings, (of which 33,800 are active), distributed across all Italian Regions, have been examined, of which 55% of were built before 1976. Less than 10% of schools have acoustical protection against outdoor noise (such as improved acoustical insulation windows, noise barriers or other) and the Speech Transmission Index, calculated with negligible activity noise inside the classroom (the only noise coming from the façade), in unoccupied classrooms is poor in 31% of cases with "normal" vocal effort of the teacher, according to the classification given by the standard IEC 60268-16.[3]

Since the 80's many studies have been conducted aiming at identifying the classroom acoustic criteria that best enhance students' education. While some authors performed their study on carrying out acoustical surveys on the students' perception of their classroom acoustic environment to which they correlated objective parameters, others extended their research to the effects of classroom acoustics on students' performance. Some studies provided measured data on the acoustical quality of classrooms, a certain number of studies investigated the effects of classroom acoustics on speech intelligibility and few of them also analyzed the listening effort.

Bradley[3] and Sato and Bradley,[5] and Hodgson et al.[6] investigated the best acoustical conditions in small classrooms for speech intelligibility. Bistafa and Bradley[7–9] and Hodgson et al.[10–12] analyzed the acoustic field in classrooms of different sizes and proposed analytical, numerical, and empirical models that can be applied for simulation of classroom acoustics. Kennedy et al.[13] evaluated the perception of the listening environment by university students. Shield and Dockrell[14–20] did surveys on noise outside and inside the classrooms and administered questionnaires to children of different ages in order to detect their subjective impression and correlation with academic performances. Prodi et al. investigated the listening efficiency and the listening effort.[21–24]

The influence of classroom acoustics on students' performance was first investigated through the administration of standardized tests for the evaluation of children attainments in English, mathematics, and science,,[14] and then by the assessment of sentence comprehension,[25] math and language outcomes,[26] reading skills,[53] changes in attention level[27] and comprehension performance.[28]

According to teachers' perspective, three billion people are the working population in the world and teachers are the 2% (Europe: 2.1%; USA: 2%), i.e., 60M. In the world, 6M of teachers suffer of vocal pathologies and 1M only in Europe. Teachers vibrate their vocal folds 25% of the time that they teach,,[29] as opposed to 12% of time when they do not teach[30] and suffer from voice disorders twice as much as other professional groups. Teachers with documented voice disorders are up to 33%[31] and those with perceived ones are up to 50%.[32] Voice disorders, which are caused by incorrect use of voice or poor acoustics in the environment where the voice is used, are still not recognized as an occupational disease.

Sato and Bradley[5] and Durup et al.[33] found an increase in the teachers' voice level during active lessons at a rate of about 0.7 dB per 1 dB of increase in the noise level. Hunter and Titze[34] monitored the vocal activity of 57 teachers continuously for two weeks in occupational and non-occupational settings. In the occupational setting, the average of the most occurring voice intensity level was found to be 2.5 dB louder than the non-occupational level, and the average value of the mode of the fundamental frequency was 10 Hz higher compared to the non-occupational setting. The work by M. Hodgson[10, 11, 35] in the ambit of teachers voices were mainly focused to find algorithms for the estimation of the speech sound pressure levels in classrooms and to its propagation in different room acoustical conditions. According to his research dated 2003, teachers' voice problems should have been the object of future studies.[36] Thanks to his suggestion, progress has been made so far on the topics of vocal effort and vocal load, vocal fatigue and health, influence of noise and reverberation on vocal output and vocal comfort, for teachers of different grades of education. All this thanks to voice monitoring.

Long-term voice monitoring is recommended to prevent vocal fatigue and health issues that are related to vocal effort and load. Particularly, voice monitoring is aimed to warn the talker against at-risk situations, to highlight existing or incoming problems to the vocal apparatus, and to select suitable spaces for the vocal activity. Voice monitoring should be done without the influence of background noise and for this reason contact microphones which estimates vocal parameters from the skin vibration at the speaker's neck are recommended.[37] These devices should be qualified in terms of uncertainty of the measured quantities.[37–39]

This paper resumes the research outcomes that the author found during 15 years of working in the field of classroom acoustics, both from pupils' and teachers' perspective, and published in more than 30 peer-reviewed articles. Beyond the state of the art that constituted her background at the beginning of the research path, she deepened the topic of optimal reverberation time in small classrooms for both pupils and teachers, of the overall comfort, of the acoustical quality and well-being. The author also contributed to the development of a speech intelligibility test for the Italian language comparable across 17 languages, investigated on neurological basis the effect of bad acoustics on reading, developed and validated a new device for voice monitoring that allows investigation of the vocal behaviour of teachers, tried to establish some guidelines on acoustical design of classrooms, and developed a device based on a lighting feedback that encourages the self-control of one's own voice emission. Part of this work has been already published in memory of Murray Hodgson.[36]

In the future, the author's research goal is finding the relationships between speech emission and perception in complex and realistic auditory scenes, i.e., on understanding more about the involuntary adaptation of speech to classroom acoustics including the perception of students' understanding.

2. PUPILS' PERSPECTIVE ON CLASSROOM ACOUSTICS

2.1. Good and Bad Classroom Acoustics: What Does It Mean?

By a systematic and widespread literature review the indexes with the proven effect on students' performance have been identified and these were considered on the evaluation of acoustical quality in elementary classrooms through in-field measurements.[40] Noise, room acoustics and intelligibility indices located in 29 occupied first-grade classrooms belonging to 13 school buildings in Turin differing in location and typology, have been measured. The classrooms involved are representative of the typical acoustical quality available in most Italian schools, with reverberation times under occupied conditions ranging from 0.5 to 1.4 s. Cluster analysis allows splitting the classrooms in two groups, namely Bad and Good acoustics (BA and GA, respectively), and to identify the threshold values of the acoustical parameters for the two groups. The threshold between the groups have been identified by halving the sum between the 25th and the 75th percentile of the worse (higher) and better (lower) group data, respectively; in the case of reverberation time (RT), and halving the sum between the 75th and the 25th percentile of the worse (lower) and better (higher) group data, respectively; and, in the case of the speech intelligibility indexes Clarity (C50) and Useful-to-detrimental ratio (U50). In such a way classrooms with RT in occupied conditions higher than 0.8 s has been included in the BA group,

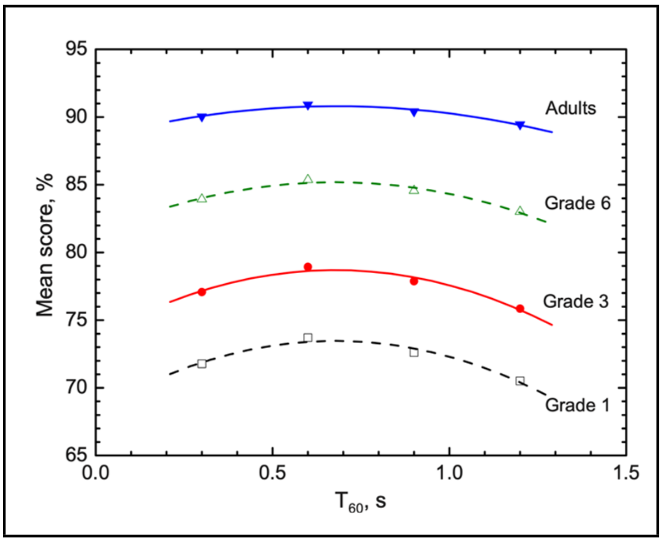

Figure 1. Smoothed speech intelligibility scores plotted vs RT60 values for the results of experiment with conditions having varied signal S/N values for grades 1, 3 and 6 and for adults. The curved lines are second order polynomial regression lines to the data. This figure is taken from Yang and Bradley.[42] © 2009 Acoustical Society of America.

which also corresponds to classrooms with an average of C50 lower than 3 dB and with an average of U50 lower than 0.9 dB.

As far as optimum RT is concerned, it is worthy to cite the conclusions of the study by Bradley et al.,[41] who state that the effect of room acoustics characteristics is much less important than the effect of signal-to-noise ratios (S/N) in reaching high speech intelligibility in rooms. This usually implies that it is most important to reduce ambient noise levels so that acceptable speech-to-noise ratios are achieved, i.e., > 15 dB, then achieving precisely the "correct" reverberation time and especially if an adequate S/N is not first achieved. Furthermore, as advised by Yang and Bradley[42] for the conditions usually encountered in real classrooms, where the dominant sources of interfering sounds are the nearby children, that is mostly the direct sound from their speech which interferes with the useful speech signal from the teacher. Acceptable reverberation times can be described as the range from about 0.3 to 0.9 s, with a preferred value around 0.7 s (Fig. 1). This is the condition in which noise level remains constant and speech level, increase with the increase in the reverberation time.

Almost the same results were achieved by Hodgson and Nosal,[6] who demonstrated with analytical formulas that when noise is incorporated in a more physically realistic manner, that is e.g., when the dominant sources of interfering sounds are the nearby children, nonzero reverberation times in the range of 0.1 s to several seconds, are found to be optimal. An ideal approach to the acoustical design of classrooms would be to first reduce all noise levels at the source and then design the reverberation time of the room to optimize the provision of added reflected sound to enhance speech levels. They suggest that design criteria should not specify maximum reverberation times. They should specify a range of acceptable values. Too little reflected sound is potentially expensive and can lead to serious voice problems. However, Bradley[3] and Picard and Bradley[1] indicate that a smaller RT between 0.4 and 0.5 s is preferable because more background noise can be tolerated with these lower RT values.

The target C50 and U50 values obtained by Astolfi et al.[40] from the cluster analysis agree with those obtained by Bradley,[3] who recommends C50 greater than 3 dB at mid frequencies for small classrooms with reverberation time of 0.8 s, and 1 kHz U50 optimum of 1.0 dB for very good speech intelligibility.

As a result of data measured in many classrooms, considerations for a simple measurement protocol should be applied for classroom acoustic characterization to be drawn so that more effective comparisons can be done. Focusing on small rooms with reverberation time between 0.5 and 1 s, in the view of a protocol to be applied at the verification phase with an occupied condition, a measurement is needed at least at C50 in the middle of the room with a small source which has the directivity pattern of the human head, placed at the teacher's desk.[40] All the other parameters, such as reverberation time and U50, both at the central point or average between different positions of the room, are strictly related to C50.

2.2. Overall Comfort, Acoustical Quality and Well-Being

Based on a subjective survey carried out on 51 secondary-school classrooms and questionnaires administered to 1006 students, it was found that students consider acoustical and visual quality in the classroom as the environmental aspects that more than others influence their school performance. Furthermore, they attribute more relevance to acoustical quality in the overall environmental quality judgment. Acoustical quality is positively related to speech comprehension and negatively related to perceived reverberation,[43] and classrooms with high reverberation are also affected by the feeling of disturbance from traffic noise and from noise in the school,[44] since reverberation amplifies noise.

Overall, students are more disturbed by intermittent than constant noise,[43] as also found by Dockrell and Shield,[17] and the most important consequences of the poor acoustics in the classrooms is decreased concentration followed by decreased teacher and student voice perceptions.[43]

Classroom acoustical quality also affects well-being of the students. The finding of a study carried out with 330 pupils aged from 6 to 7 years is that a long reverberation time, which is associated with poor classroom acoustics as it generates higher noise levels and degraded speech intelligibility, brings pupils to a reduced perception of having fun and being happy with themselves. Different is the perception of bad acoustics between happy and unhappy pupils. Particularly, happy pupils report a higher perception of noise disturbance under poor acoustics, whereas unhappy pupils report complaints in poor acoustics with respect to the perception of satisfaction with himself or herself and of fitting in at school.[44]

2.3. Speech Intelligibility

Speech intelligibility is defined as the percentage of a message understood correctly.[3] Speech intelligibility with different reverberation times and types of noise has been obtained using diagnostic rhyme tests on 983 pupils nominally from 7 to 10 years old, and these scores have been correlated with the parameter Speech Transmission Index (STI).[3] The grade 2

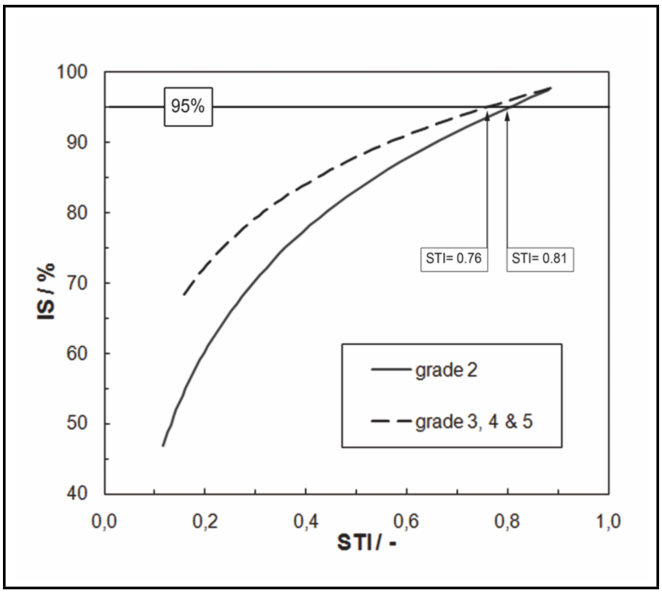

Figure 2. Regression curves of the plotted Intelligibility Score (IS) versus STI for grade 2 and grades 3, 4 and 5 together, considering all the classes and all the noises, and the near-ideal STI value conditions corresponding to an IS of 95% correct scores. This figure is taken from Astolfi et al.[45] © 2012 Acoustical Society of America.

pupils (i.e., from 7 to 8 years old) understand about 10% less words in the lowest STI range than older pupils of grades 3,4 and 5, whereas speech intelligibility of 97% was achieved by all the grades with a STI of 0.9 (Fig. 2). Traffic noise results the most interfering noise on speech intelligibility compared to babble noise, fan-coil noise, and impact noise from tapping machine.[21]

During these tests, it frequently happens that over a certain level of success of the transmission channel most of the subjective answers are crowded on the 100% value of speech intelligibility, and the same happens for bad conditions of the transmission channel, where the scores plummet down to 0%. Subjective rating of the "listening easiness score" (LES) is based on a five-point discrete scale, ranging from 0 to 100%: the lowest corresponds to "extremely difficult", 25% to "difficult", 50% to "fairly easy", 75% to "easy" and 100% to "definitely easy". LES provides an alternative approach to speech intelligibility. Both "speech intelligibility" (expressed as intelligibility score, i.e., IS) and "listening easiness" are inherently bound and their data distributions usually exhibit a significant accumulation of scores in the upper and lower parts. The truncation procedure has been hence addressed with a method based on the normal probability plot which enables identification of simple mathematical models relating to STI (Eq. (1) and (2)), as well as the related uncertainties that does not exceed 4%:[46]

$$\mathrm{IS} = 73\,\mathrm{STI} + 55; \qquad (1)$$

$$\mathrm{LES} = 78\,\mathrm{STI} + 38. \qquad (2)$$

High speech intelligibility is obtained by lowering the noise, particularly from the outdoors, and applying sound absorbing and diffusing materials on the walls. The optimal layout for acoustical panels on the classroom surfaces results from recent research based on acoustical simulation performed with the software ODEON 15.[47] It advises the application of absorptive materials on the ceiling or around the borders, creating a reflective middle area, and on the upper part of one of the lateral walls and on the rear wall. Configurations with diffusers do not generally bring significant improvements.

These guidelines are particularly recommended currently because the use of face masks to contrast the COVID 19 pandemic further reduces speech intelligibility in classrooms. The effects of wearing face masks on classroom communication has been carried out in auralized university classrooms where speech stimuli were presented in the presence of speech-shaped noise with a signal-to-noise ratio of 3 dB under two different reverberation times of 0.4 s and 3.1 s. It has been found that the use of fabric masks yields a significantly greater reduction in speech intelligibility compared to surgical and N95 masks.[48] Therefore, surgical masks or N95 masks are recommended in teaching environments.

2.3.1. Speech Intelligibility Tests for the Italian Language

Speech intelligibility tests in the Italian language usually applied in research or in clinics are rather limited in accuracy due to the small number of test items and to the variability in intelligibility across the test items. To overcome this weakness an Italian matrix sentence test for the assessment of speech intelligibility in noise has been developed for normal adults and children.[49] The test consists of a 50-word base matrix (10 names, 10 verbs, 10 numerals, 10 adjectives, and 10 nouns, e.g., "Andrea eats many useful chairs") and from the matrix semantically unpredictable sentences of a fixed grammatical structure are randomly generated. With a standard deviation of the speech reception threshold (SRT50%), i.e., the signal-to-noise ratio (in dB) to yield a fixed level of speech intelligibility that is 50% in this case, across the test lists of 0.2 dB and a test–retest reliability of 0.6 dB, the ITAMatrix test can be considered accurate and reliable. The matrix-type sentence test has been developed in a comparable way for at least 17 languages[50] and can be used as an accurate tool for multilingual studies. A simplified version of the test consisting of three-word speech phrases instead of five-word sentences has been recently validated.[51] High test–retest reliabilities of 1.0 and 1.1 dB for the SRT80% were obtained for the adults and children, respectively. This makes the test suitable for accurate and reliable speech-recognition measurements.

2.4. Learning

The need of tuning into speech in noisy and reverberant classrooms is a challenge for good speech communication and literacy development at school. Every time pupils learn they try to understand and decode a voice message from the teacher. Thus, they try to tune into speech and to tune out competing sounds. When considering the literacy development of children, the cognitive effort demanded under noisy conditions has proven to be very high. According to the recently formalized "rise-time theory",[52] impairments in the phonological processing that are related to difficulties in recognizing the speech sound structure, particularly its amplitude modulation, may turn into the appearance of potential reading disorders. The role of optimal acoustics in terms of noise and reverberation control in the learning environments is therefore crucial, as it contributes to prevent the amplitude modulation of the speech signal produced by a teacher that is then effectively received by a pupil.

On the basis of results on the influence of classroom acoustics on the reading speed of 94 Italian second-graders (i.e. 7 years old), where one-to-one measurements on the reading abilities have been performed (e. g., words and text reading speed), it has been found that Speech Clarity C50 is significantly correlated with many reading tasks, while no significant correlations were found with reverberation time.[53] In conclusion, reading development can be compromised if children are exposed to inadequate acoustics, especially those with poor neural processing in speech discrimination.

The possibility to compensate for bad classroom acoustics with sound field amplification systems (SFAS) in first to fourth-grade primary school students with and without language disorders is investigated in classrooms with different acoustics.[54] One hundred forty-five monolingual primary school pupils were included in the study, divided in two groups: 1) pupils with typical language development (TD) ($n = 145$); and, 2) pupils with developmental language disorders ($n = 72$). The goal was to check the prelexical level of the speech recognition process, to find whether SFAS benefits the first stage of speech perception. The results of monosyllabic nonsense words perception tests presented by an examiner, where the task involved segmenting phonemes, generating an appropriate sound-letter output representation, and writing the letters in a specific order showed that first-grade students benefit from sound field amplification regardless of classrooms acoustics, and irrespective of the level of language development. The positive effect of SFAS is not so evident in pupils of higher grades because of their more advanced development in the processing of auditory information and skills of sound perception, discriminating and encoding.[55] However, classroom acoustics impacts the effect of SFAS for children older than first graders, that is sound field amplification increases speech perception and decreases the number of errors in the reproduction of monosyllabic nonsense words in classrooms with short reverberation time but decreases speech perception in classrooms with longer reverberation time. This result underlines as SFAS devices should "not be routinely employed" and establishing classrooms' acoustic parameters is necessary before installing an amplification system.

2.5. Engagement of Occupants in Reducing Noise Level Thanks to Lighting Feedback

High noise levels that are mainly generated by occupants in densely occupied environments such as classrooms, cause annoyance, low performance, and effects on health and well-being. Recently, the research community is pushing on occupants' active engagement in reducing noise by changing their behaviour. In this context, a method based on a lighting feedback which notifies occupants of excessive anthropic noise levels, thus encouraging their proactive behaviour which brings to lowering their voices, changing the room for conversations or switching off noisy devices, has been validated.[56] At the base of this method there is SEM (Speech and Sound SEMaphore), i.e., a noise monitoring system with lighting feedback that alternates colours from green, yellow and red according to the change of noise levels.[57]

Validation has been carried out with 13 primary school classes over three scholastic years. A significant decrease of background noise levels during plenary lessons when the lighting feedback of SEM was switched on has been found for a total of 51% pairs of independent lessons (one with SEM and one without SEM). In particular, the activation of the lighting feedback led to an average decrease of about 3 dB on average. In the other pairs of independent lessons (49%), background noise levels increased or did not significantly decrease with the lighting feedback, determining no improvements. Several reasons may be hypothesised for this opposite behaviour, for example, the activities of the class required more interaction with the teacher or because the background noise was not extremely annoying to provoke a behavioural change or the engagement of teachers in motivating pupils to follow the lighting feedback was lower.

2.6. Acoustical Design

To achieve a good level of speech intelligibility, even in small classrooms, an accurate prediction of the reverberation time and speech level is necessary.[58] Several acoustic models exist, some of which have been specifically tested for classrooms. The diffuse field theory is commonly used to determine both the reverberation time (Sabine and Eyring formulas) and the reverberant sound level.[7,8,59] The Sabine and Eyring formulas give accurate results for mid-frequency reverberation time in small sized occupied classrooms with overall relative error of about 12%.[58] Barron and Lee's diffuse field theory[60] gives accurate predictions of reverberant sound level in classrooms with an error of 1.4 dB.[58]

Raytracing based codes, such as ODEON room acoustic software[61] are generally used for small empty classrooms[7,8] and generate model errors once the assumptions of GA are no longer met.[62] Therefore, in general, they are not able to provide a reliable prediction of room acoustic parameters outside a medium frequency range $0.5 - 2$ kHz. For a small sized untreated room, a trend for overestimating the actual reverberation time at 0.125 kHz, that is lower than the Schroeder frequency of the room, and underestimating at high frequencies above 2 kHz, is found as result of a round robin test across 5 geometrical acoustics (GA) software. Overall, over different room sizes, the differences between measurement and simulation are particularly high for the 125 Hz and 250 Hz octave bands, where the measured reverberation times are, on average, overestimated by 58% (125 Hz) and 35% (250 Hz). For the mid-frequency range, there is no systematic deviation, but the differences between simulation and measurement are around the just noticeable difference (JND) of 10%.[58] On the other side, it has been found that the simulation of a small rectangular room with an absorbing ceiling and low scattering is inaccurate both with energy-based GA simulation, i.e., ODEON, and with GA simulation which includes phase shifts on specular reflections to model the acoustics of the room below the Schroeder frequency.[63]

3. TEACHERS' VOICE MONITORING

In order to perform teachers' voice monitoring during teaching time, our research team at the Politecnico di Torino, in collaboration with S.C. ENT 2 U. of the University of Turin and PR.O.VOICE Ltd, start-up incubated in I3P of the Politecnico di Torino, designed two voice dosimeters based on the former Voice Care™ technology.[37,39] The light version, named, "Vocal Holter App", can be installed on a common smartphone, while the pro version, "Vocal Holter Med™" (VHM), is made up of a dedicated device which performs more extensive and personalized analysis useful to physicians and speech pathologists. Some measurement campaigns have been carried out in-field during the last seven years, with teachers of different grades who taught in schools with different acoustics.[29,64,65] Results are presented below on the vocal effort and load and on the effect of classroom acoustics (noise and reverberation) on the vocal behaviour of teachers. Subjective outcomes are also commented.

3.1. Vocal Holter Med

Vocal Holter Med consists in a data logger equipped with an encapsulated Electret Condenser Microphone (ECM), which is fixed at the jugular notch. The ECM acquires voltage levels that are generated by changes in acoustic pressure at the surface of the neck due to vocal-fold activity and it exhibits a low sensitivity to background noise.[39] A proper root mean square (rms) voltage threshold distinguishes voiced and unvoiced frames, which are subdivided into non overlapped intervals of 46 ms to effectively detect voiced and unvoiced portions of speech up to the phonemic segmental level. The device provides the voiced sound pressure levels (SPL) at a fixed distance from the speaker's mouth, after a calibration vs a reference microphone, which consists of estimating the best-fit regression function between the rms values of the signal obtained from the skin vibration and the SPL measured by the reference microphone (Fig. 3). Besides vocal intensity, that is related to effort, it also estimates vocal behaviour in terms of vocal load, vocal intonation, and health. Sound Pressure Level (SPL), phonation time percentage (D_t), Fundamental frequency (F_0) and Cepstral Peak Prominence Smoothed (CPPS), are the main parameters related to the four previous categories. CPPS is a measure considered to be one of the most promising predictors of dysphonia and its severity.[66] Vocal parameters are provided in the form of statistical metrics derived from the distributions of occurrences.

Comparison among results can be made as the measures are also characterized in terms of uncertainty.[67,68] For the mean and equivalent speech SPL, devices such as VHM, exhibits an uncertainty of ≈ 3 dB, compared to an uncertainty of ≈ 2 dB in the case of headworn microphone. However, when a microphone in air is not suitable (e. g., high background noise or long-term voice monitoring), the advantage of using a contact microphone is not recommended despite its higher uncertainty.

In a comparison with other three commercial dosimeters, that are VocaLog2, VoxLog and APM3200, the VHM results showed it is one of the most accurate in the determination of the mean voice sound pressure level and of the mean fundamental frequency.[38] The mean vocal sound pressure level was captured most accurately by the Voice Care and the VoxLog while the APM3200 was the least accurate. The most accurate mean vocal fundamental frequency was estimated by the Voice Care and the APM3200, while the VoxLog was the least accurate.

3.2. Vocal Effort and Load

As a result of a large monitoring campaign with primary and secondary school teachers during plenary lessons, a speech level of 71 dB @1 m from the mouth has been found on average for both the categories,[64,65] i.e., a vocal effort between "Raised" and "Loud",[75] while a phonation time percentage from 26% to 29% and of about 40%, was obtained, respectively.[64,65]

A significant speech level increase of 5 dB was found in the afternoon compared to the morning.[64] Moreover, secondary school teachers who worked in bad classroom acoustics showed a 2 dB increase in the vocal effort and a 10% decrease in the voicing time percentage at the end of the school year compared to the beginning.[65]

3.3. Vocal Fatigue

Vocal fatigue in the case is considered as a negative vocal adaptation that occurs because of prolonged voice use in critical conditions.[70] In this context, a tendency to increase the voicing periods as the reverberation time increase was on average observed for university professors and schoolteachers, and more generally for speakers who are highly motivated to make themselves understood in an unfavorable speaking situation.[71] Particularly, a reverberation time higher than 0.9 s in classrooms implicate higher accumulations of voicing periods for teachers, thus suggesting that vocal fatigue is highly related to classroom reverberation time.[72]

3.4. Noise and Lombard Effect

The involuntary tendency of speakers to increase their voice level as the noise level increases, to improve intelligibility of the speech signal is called the Lombard effect.

Lombard effect with slopes between 0.4 and 0.7 dB/dB was found on average during plenary lessons in primary and secondary schools.[29,64,65] A longitudinal study carried out in secondary school classrooms showed this effect was not maintained at the end of the school year.[65] In both the school typologies, it was found to be an increase in the mean fundamental frequency with an increase in background noise at a rate of $1 - 3$ Hz/dB.

3.5. The Effect of Reverberation

The reverberation time that should be set in primary and secondary school classrooms to minimize the voice level should be in the range between 0.7 and 0.8 s, at mean frequencies.[29,64,65] An optimal reverberation time of 0.7 s over 250 Hz and 2 kHz was found by Puglisi et al.[64] for primary school teachers, that is the minimum value of the best fit quadratic regression curve of the speech sound pressure level (SPL) vs reverberation time in occupied classrooms (Fig. 4). This relation corroborates the results of the study by Bottalico and

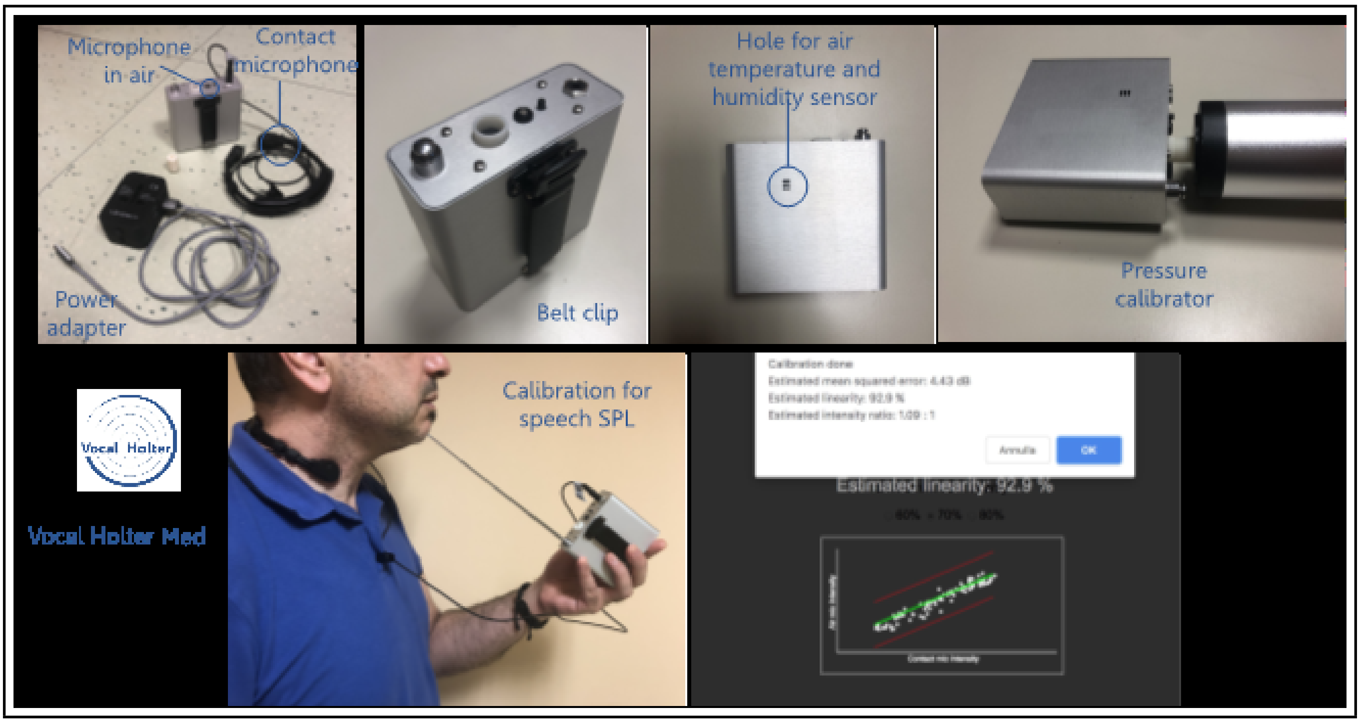

Figure 3. Vocal Holter Med and its calibration procedure for speech SPL.

Astolfi[29] in which the same quadratic curve was found for a monitored sample of other 40 primary school teachers. They found that the minimum of the quadratic relation corresponds to a reverberation time of 0.8 s. Again, Calosso et al.[65] found that the speech level is related to the average value of reverberation time between 250 Hz and 2 kHz in occupied secondary classrooms through a quadratic regression curve, both at the beginning and at the end of the school year, with the minimum values of these regression curves which correspond to 0.83 and 0.77 s for the two stages, respectively (Fig. 4). Teachers raise their voice with both lower and higher reverberation time. In the case of lower reverberation time teachers rise their voice due to the lack of voice support from the room, while in the case of higher reverberation time it is supposed that they rise their voice due to the amplified background noise. A tendency of background noise level to increase with increasing reverberation time was in fact observed at a rate of 13 dB/s.[14] The minimum speech level that was measured on average in the case of optimal reverberation time was $\approx$ 65 dB SPL_{mean} @1 m from the teacher's mouth, which corresponds to a "normal" vocal effort.[65]

On the other side, based on theoretical and empirical models, a lower reverberation time range between 0.45 and 0.60 s is recommended by Pelegrín-García et al.[73] to preserve speech intelligibility and vocal comfort in fully occupied classrooms with volume below 210 m^3 and with less than 40 students.

Regarding the effect on voice level of reverberation only, on the basis of laboratory studies in a semi-anechoic and reverberant rooms, speakers described a map while they were wearing the voice dosimeter VHM (former Voice Care™), which is based on a contact-sensor fixed at the base of the neck (see paragraph 3.1). It was found that a significant increase of about 2 dB in mean, equivalent and mode speech level in semi-anechoic compared to a reverberant room, thus, highlighting an increased vocal intensity in dead rooms compared to live rooms.[74]

Another study revealed that under simulated acoustic environments, talkers lowered their voice intensity linearly with the Voice Support, which represents the degree of amplification offered by the room to the voice of a speaker, at his own ears. The slope of this relationship, called the room effect, of -0.24 dB/dB, was significant only in the case of noise levels of $\approx$ 60 dB.[75] This could be seen as an opposite result compared to the previous finding obtained in-field, but it should be noted that in a laboratory a speech shaped noise has been used for the experiments, which is a stationary noise sequence whose spectrum follows the long-term average speech spectrum, and not a real speech noise that can be found in real classrooms. Further investigations on this aspect should be done in the future.

3.6. Vocal Health

On the basis of a study that investigated the voice quality measures used to discriminate different types of organic dysphonia from sustained [a:] vowels or [a:] vowels excerpted from speech, detected with microphone in the air in a quiet environment, the mean of the cepstral peak prominence smoothed (CPPS) distribution and the 95th percentile of the sample entropy (SampEn) distribution showed better performance.[76] It also understood that when using CPPS or SampEn there is an advantage of using the measures' distributions rather than their average values. Overall, it has been recognized that CPPS parameters obtained from distribution of occurrences obtained from both microphones in the air and contact microphones have a strong to good discrimination power related to an unhealthy voice.[66]

A rest period of a few seconds may produce some vocal fatigue recovery, but in the case of subjects with organic voice disorders periods shorter than 3.16 seconds may not have an observable effect.[77] Subjects with organic voice disorders ac-

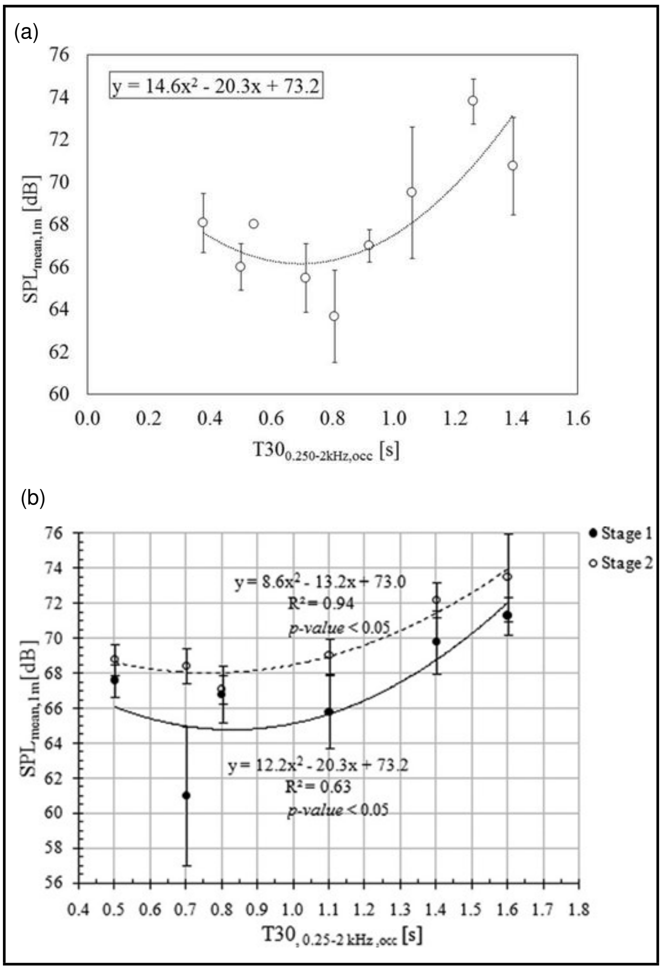

Figure 4. Best-fit quadratic regression curve between the voice levels of the teachers ($SPL_{mean,1m}$) and the reverberation times in the classroom in occupied conditions ($T30_{0.250\text{-}2kHz,occ}$). (a) Primary school teachers as described in Puglisi et al.[64] (b) Secondary school teachers at the beginning (Stage 1) and at the end (Stage 2) of the school year, as described in Calosso et al.[65] © Acoustical Society of America.

cumulate higher silence accumulation values in intervals between 0.1 and 3.15 seconds than other subjects, as well as voicing accumulations between 0.17 and 3.15 seconds. The time dose is higher as well. Regarding silence periods higher than 3.16 seconds, subjects with structural voice disorders showed lower silence accumulations than subjects without such disorders. In this case, lower silence accumulations could indicate an inadequate redistribution of fluids in the vocal fold tissue. It is feasible that this result may indicate an inadequate recovery time, which could lead to pathology. On the other side, teachers with structural voice disorders accumulated longer voicing periods than teachers without such disorders. Vocal abuse is generally regarded to be the main cause of vocal fold nodules. Hence, the vocal behaviour of persons with long phonation times could be considered a risk factor in vocal abuse.

3.7. Subjective Outcomes

On average, the vocal comfort for speakers is found to be more closely related to noise annoyance than to room reverberance.[75] The Decay time at the ears is one of the acoustic parameters most related to the perceived sensation of vocal comfort, which is defined as the average of the subjective impression related to different aspects of the use of the voice in different acoustic environments.[78] It results in the parameter that is mainly associated with the self-reporting assessment of noise condition.[45] It is the decay time that is derived from an impulse response measured from the mouth to the ears of a talker. Particularly, a recommended decay time at the ears of 0.49 s and a range between 0.29 and 0.53 s minimize the vocal effort and maximize the vocal comfort of primary school teachers.[64,78]

As far as the speaker's behaviour, a cohort study performed with 27 primary school teachers during one work week, shows that fewer complained about self-reported voice conditions are reported by teachers with a higher standard deviation in conversational speech sound pressure level (SPL). This finding suggests that teachers who register a higher variability in their vocal SPL can control their vocal volume to improve their communication.[79]

4. FUTURE WORK ON CLASSROOM ACOUSTICS

Thanks to the research that has been accomplished so far, many important results have been drawn in the ambit of classroom acoustics which are based on the improvement of speech communication. Different activities are supported by good classroom acoustics: students clearly understand the teacher's speech, but they also efficiently communicate with their classmates or with the teacher herself, teachers voices are supported in its propagation inside the classroom so that excessive vocal fatigue or voice disorders are prevented. Classroom acoustics (i.e., the control of room acoustics and noise), speech intelligibility together with learning and well-being, and speech production, are strictly related and the acoustic model that are at the basis of these relationships, has not been yet fully discovered (Fig. 5).

Speech production depends on classroom acoustics, and the same is true for speech intelligibility, but it is unclear if speech production can improve speech intelligibility, learning and well-being. For example, a proper speaking style can be the key factor to ensure effective speech communication. This is an uncovered aspect that deserves investigation in future works. Other aspects that can be explored in the future are the effect on learning on the interaction between the different aspects of environmental quality, i.e., acoustic, lighting, thermal and indoor air quality factors. The neural mechanisms that are at the basis of learning when immersed in an acoustic field should also be investigated because poor classroom acoustics have not only been a negative influence on the occupants' performance, but it brings physiological and psychological implications too, with an effect on occupants' health and well-being.[80]

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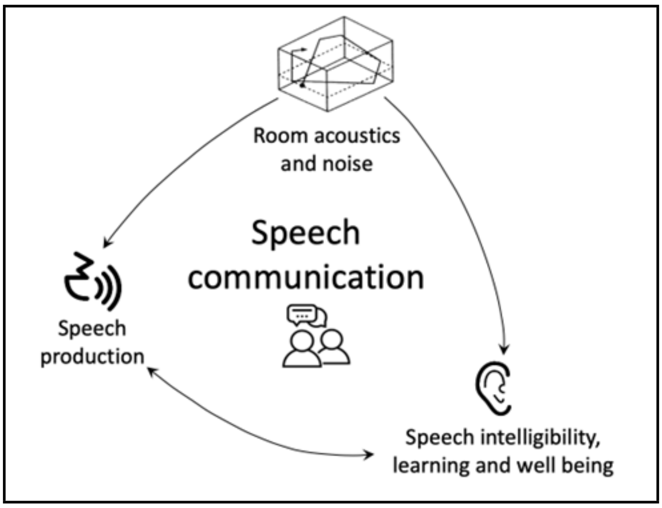

Figure 5. Relationships between factors at the base of speech communication in classrooms.

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