Acoustical comfort in university lecture halls: simulating the dynamic role of occupancy

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Abstract

The acoustic comfort in teaching environments is generally determined through requirements concerning reverberation time, speech intelligibility and HVAC noise. The presence of students reduces the reverberation time but concurrently increases the background noise, that undermines the focus of students and the vocal effort of teachers. A double set of measures were acquired in two university lecture halls in unoccupied and occupied state to investigate the consequences of occupancy variations. Acoustic simulations allowed to assess the dynamic effects of the occupancy detecting the differences of speech intelligibility. Predicting the student activity may return reliable outcomes improving the quality of lessons.

Key Innovations

- Advanced monitoring of acoustic environments
- Combination of state-of-the-art simulation and machine learning outcomes
- Remarks on the actual background noise in lecture halls

Practical Implications

Consider the background noise due to the occupancy in speech intelligibility evaluation; test different levels of vocal effort to assess the acoustic comfort of teachers.

Introduction

The acoustics of teaching environments is a largely explored topic in scientific literature (Escobar and Morillas (2015), Hodgson (1999)). Several approaches have been developed aiming at the overall comfort conditions (Ricciardi and Buratti (2018)), both from the teacher's point of view - for a lower vocal effort (Visentin et al. (2018), Pelegrín-García et al. (2011), Bottalico and Astolfi (2012)) - and from the students' perspective - for a better speech intelligibility (Choi (2020)). Different predictive models have been proposed to grant the best acoustic conditions in this kind of rooms (Fratoni et al. (2019), Choi (2017)). Ray-tracing simulation methods were usually em-

ployed during these works (Astolfi et al. (2008), Reich and Bradley (1998), Hodgson and Wong (2009), Bistafa and Bradley (2000)).

The presence of the students in lecture halls significantly affects the quality of verbal communication Choi (2016), especially because they are the most sound absorbing element in reflective halls as the teaching environments. From a legal point of view, a recent overview of European regulations highlighted the different approaches to the reverberation requirements in classrooms (Pelegrín-García et al. (2014)). While in some cases the optimal values are stated in furnished and unoccupied condition, (Building Bulletin (1993)), in other cases the required values are considered in occupied state (DIN (2016), UNI (2018)).

The reverberation time is expressed in its classical and predictive form with the Sabine formula in each k-th octave band (125 Hz - 4000 Hz):

$$T_k = 0.16 \frac{V}{A_{\text{hall,k}} + A_{\text{people,k}} + A_{\text{air,k}}} \quad (s) \qquad (1)$$

where

- V is the volume of the hall, in m^3;
- $A_{\text{hall,k}} = \sum \alpha_i S_i$ is the equivalent absorption area of the hall in furnished and unoccupied state, in m^2 Sabine (α_i is the absorption coefficient of the i-th surface, S_i is the area of the i-th surface, in m^2),
- $A_{\text{people,k}} = d N A_{\text{1pers,k}}$ is the equivalent absorption area due to the occupancy, in m^2 Sabine (where d is the percentage of occupancy considered, N is the maximum seating capacity, $A_{\text{1pers,k}}$ is the equivalent absorption area of a single person, in m^2 Sabine),
- $A_{\text{air,k}} = 4 m_k V$ is the equivalent absorption area of the air (with m_k depending on the temperature and the relative humidity according to UNI EN ISO (1993)).

The speech transmission index (STI) quantifies the deterioration of a speech signal through a transmission channel, i.e. the room (BS EN (2011)). It is derived from the modulation transfer function $m(f_m)$,

that from a theoretical point of view is expressed in the k-th octave band as:

$$m_k(f_m) = \frac{1}{\sqrt{1 + \left(\frac{2\pi f_m T_k}{13.8}\right)^2}} \cdot \frac{1}{1 + 10^{(-\text{SNR}_k/10)}} \quad (2)$$

where f_m is the modulation frequency, in Hz, T_k is the reverberation time, in s, SNR_k is the signal-to-noise ratio, in dB. Therefore two factors affect the intelligibility: the characteristics of the room (the reverberation time T_k) and the signal-to-noise ratio (SNR_k). The latter is the difference between the sound pressurel level received at the listener position (SL) and the background noise, that in case of occupied state is mostly the student activity (SA) due to higher sound pressure levels compared to the HVAC systems. The speech signal is deteriorated by high reverberation time values and by low SNR values at the receiver location. Equation 1 shows that the presence of the students ($A_{\text{people,k}}$) causes the decrease of the reverberation time, returning a better acoustic condition for teaching environments. On the other hand, Equation 2 shows that the human noise, i.e. the so-called student activity, increases the overall background noise, leading to lower SNR values and thus worse teaching conditions.

The student activity is defined as the noise due to the students during lectures (Hodgson et al. (1999)). The dynamic properties of such noise makes it different from the HVAC mechanical noise and difficult to be measured or quantified. Since there is no standard measurement procedure, scholars assessed the student activity by means of sound level meters and employing various approaches. Some analyses are based on the equivalent and percentile levels (Shield et al. (2015); Bottalico and Astolfi (2012)), others exploited machine learning algorithms (Hodgson et al. (1999); Peng et al. (2018); Choi (2020); Sato and Bradley (2012); D'Orazio et al. (2020); Wang et al. (2020)).

The dynamic behaviour of noise sources can affect the acoustic comfort and the effectiveness of learning processes. High levels of background noise reduce the focus of the students and increase the vocal effort of the teachers. Indeed, the student activity is connected with the Lombard effect, i.e. the psychoacoustic consequence of raising voice in presence of high background noise levels (Lombard (1911)). It is basically caused by the need of speakers to hear themselves. Therefore, the noise sources occuring in lecture halls are linked each other. For instance, the noise due to HVAC systems causes a raise of the overall sound pressure level of students chatting among each other. As a consequence, the teacher gains his/her vocal effort as well. This chain of effects increases the noise within the lecture hall causing acoustic discomfort to speakers and listeners (Whitlock and Dodd (2006)).

Method

The motivation behind the present work is the importance of accurately considering the acoustic role of occupancy in teaching environments. The two lecture halls assessed in this study belong to the University of Bologna (Italy): the first room (A) has a volume of around 900 m^3 and an amphiteatre shape; the second room (B) has a volume of 850 m^3 and a shoe-box shape (see Figure 1). It is important to point out that both the lecture halls may be considered as "large" according to the framework of European regulations (Pelegrín-García et al. (2014)). About the maximum seating capacity in the halls, the first hall hosts up to 200 people while the second hall up to 160 people.

In a previous study a method to predict the intelligibility criteria by means of the spatial distribution of energy parameters was investigated (Fratoni et al. (2019)). In the present study, distinct kinds of measurements were carried out, in empty and occupied state. On the basis of the first set of measures the 3D virtual models have been calibrated basing on the acquired intelligibility criteria. In the second campaign of measurements sound pressure levels (SPLs) were recorded during a whole day of university lessons, along with every occupancy variation. The main data concerning the geometry, the volume, the occupancy, the main acoustic criteria, and the measured student activity are provided in Tables 1 and 2.

The acoustics of the halls was then simulated with different percentages of occupancy and with the corresponding background noise actually measured *in situ* to better evaluate the required vocal effort of the teacher for a suitable intelligibility.

Measurements

The first typology of measurements is intended to return the main objective criteria concerning the acoustics and the speech intelligibility in the halls. The second nature of measurements is intended to detect the effect of the human noise caused by the presence of the students. While the former represents a standard procedure to qualify and characterize the acoustics of a room with an objective method, the latter is still an ongoing research field that could allow to investigate further variables affecting the verbal communication during the lessons. The first campaign of measurements was carried out in furnished and unoccupied condition, in compliance with the state-of-the-art procedure (EN ISO (2008), UNI (2018), DIN (2016)), using a dodecahedron as omnidirectional sound source, a microphone as monoaural receiver, and the exponential sine sweep technique. Two sound sources locations and a grid of receivers points were used to investigate the spatial distribution of the acoustic features in both the halls, as it can be seen in Figure 1. The main criteria acquired are provided in Table 1 in terms of reverberation time (T_{30}) and speech transmission index (STI).
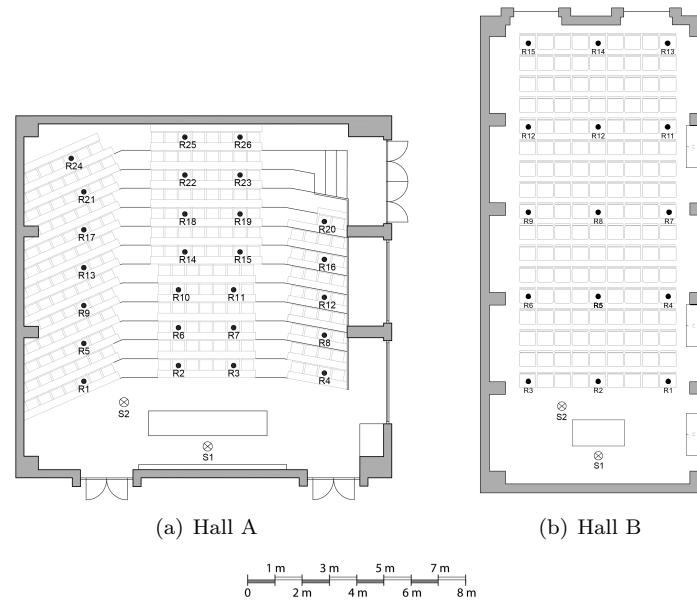
(a) Hall A (b) Hall B

1 m	3 m	5 m	7 m
0	2 m	4 m	6 m	8 m

Figure 1: Sound sources' locations (S1, S2) and the spatial grid of microphone receivers (R1, R2, ..., RN) employed during the first measurements campaign in furnished and unoccupied condition.

Table 1: Main features of the lecture halls under study. The total volume (V), the shape, the maximum seating capacity (N), and the students area (S) are reported. The main room and intelligibility criteria measured in unoccupied condition are also provided: the reverberation time (T_{30}) at mid frequencies and the speech transmission index (STI) (EN ISO (2008); BS EN (2011); UNI (2018); DIN (2016)).

Hall	V (m^3)	Shape	N	S (m^2)	T_{30} (s)	STI
A	900	Amphiteatre	200	100	1.34	0.48
B	850	Shoe-box	160	80	1.88	0.44

Table 2: Occupied condition: main results from measurements carried out during a whole day of lessons. For each lesson, the percentage of people compared to the maximum seating capacity, the measured A-weighted values of student activity, the temperature and the relative humidity are shown. Values are averaged over the two sound level meters employed in the measurements performed during lessons.

Hall	Lesson	Occupancy (%)	Student activity (s.d.) dB(A)	Temperature (s.d.) °C	Relative humidity (s.d.) (%)
A	1	125	48.4 (0.3)	24.1 (1.9)	56.6 (3.0)
	2	80	50.3 (1.5)	25.3 (0.3)	52.1 (1.8)
	3	60	61.0 (0.6)	26.1 (0.7)	51.7 (3.2)
	4	75	55.3 (0.1)	23.8 (0.6)	48.3 (1.7)
	5	100	53.4 (0.0)	26.5 (0.7)	50.3 (2.8)
B	1	65	53.0 (2.0)	23.2 (0.7)	46.2 (1.4)
	2	50	50.6 (1.2)	24.2 (0.6)	47.7 (3.4)
	3	105	57.7 (1.0)	24.6 (0.4)	47.6 (3.4)
	4	105	51.1 (2.4)	25.7 (0.6)	51.5 (2.9)

The second campaign of measurements was intended to obtain sound pressure levels related to the student activity (D'Orazio et al. (2020)). Therefore, it was performed in occupied state by recording an entire day of lessons in each hall. The equipment employed in this kind of measurements is made up of two sound level meters placed in the students area. A-weighted equivalent levels has been recorded every 100 milliseconds to better detect the background noise during the pauses of the speech. The location of the sound level
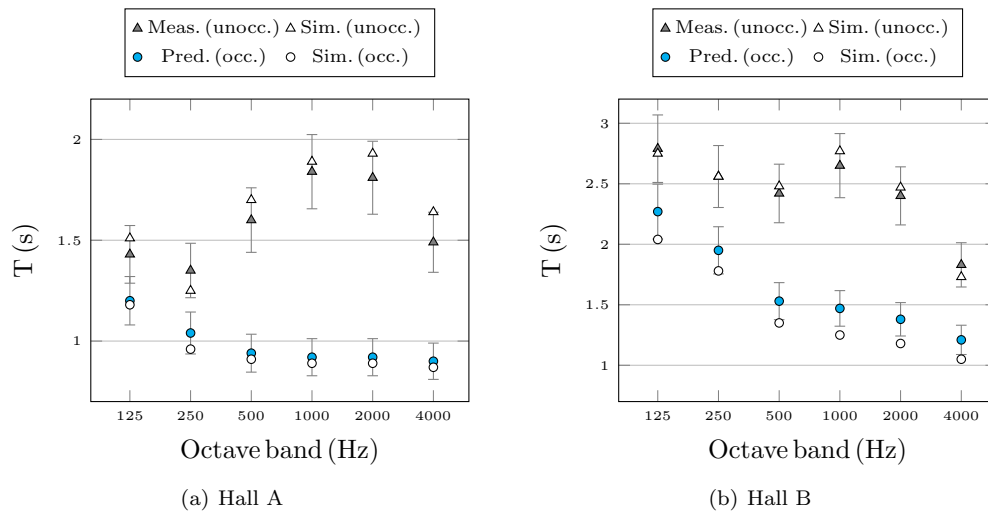
(a) Hall A

(b) Hall B

Figure 2: Reverberation time values: measured and calibrated values are referred to the unoccupied state; predicted and simulated values are referred to the occupied state. T values are averaged over all the source-receivers pairs and reported for each octave band. The error bars are referred to twice the Just Noticeable Difference (JND) EN ISO (2008), according to Vorländer (2013).

meter was selected in the middle of the lecture halls, at least 1 m far from surfaces to avoid strong reflections by the nearest surfaces. The height was set at 1.2 m above the floor, similar to the ear of a seated person. The lessons have been attended by an operator among the students. Pauses between and within lessons and unforeseen peaks have been cut in the post-processing phase.

Acoustic simulation

In the present study the acoustic simulations were used to investigate the different consequences of the occupancy on the speech intelligibility. First of all, the 3D models of the lecture halls were built with precise rules of modeling approximation using a commercial CAD software. The acoustic simulation method selected for the present work employs ray-tracing algorithms (Christensen (2011)), which are particularly suited to simulate the acoustics of large environments as those ones under study (Vorländer (2007), Savioja and Svensson (2015)). The virtual models of the halls were calibrated based on the outcomes of the first campaign of measurements aforementioned. According to geometrical acoustics (GA) techniques, the models were tuned adjusting the material properties assigned to the surfaces within reliable ranges recommended in available datasets (Cox and d'Antonio (2016)). All the remaining details of the calibration process are described in Fratoni et al. (2019).

Once having tuned the models according to the acoustic features in unoccupied state, the possibility to simulate the percentages of occupancy recorded during the second kind of measurements were exploited. With reference to Equation 1, the values of $A_{1pers,k}$ referred to the absorption area of one person seated on wooden chairs were taken from specific

datasets provided in the standards DIN (2016) and UNI (2018). It was chosen to simulate the presence of the students related to 80% and 50% of the maximum seating capacity, respectively, of hall A and hall B, setting 50 dB as the corresponding level of student activity.

Results

The first set of results concerns the acoustic measurements performed during the lessons in occupied condition. The A-weighted equivalent levels L_{eq} were extracted from the recordings and their occurrences were analysed via different methods (for more details see D'Orazio et al. (2020)). In the present work, the outcomes of the Gaussian mixture model (GMM) were considered, as they seem more reliable and accurate. The probability density functions of L_{eq} values' occurences were analysed for each lesson attended. Since occurrences curves presented two peaks, they were fitted as a mixture of two Gaussian curves, corresponding to two distinct contributions. In each listener position the Gaussian curve with higher values of sound pressure level may be associated to the speech level of the teacher. The Gaussian curve with lower values of sound pressure level may be associated to the student activity. The mean values of the student activity level are reported in Table 2 for each lesson attended in the two lecture halls (values were averaged over the two sound level meters employed).

The second set of outcomes is provided in Figure 2 in terms of reverberation time in octave bands. Measured and calibrated values are provided in unoccupied state, while predicted values according to Equation 1 and simulated values through GA techniques are provided in occupied conditions. Since the rever-

(a) Unocc. - Vocal effort: N
(b) Unocc. - Vocal effort: R
(c) Unocc. - Vocal effort: L

(d) Occ. - Vocal effort: N
(e) Occ. - Vocal effort: R
(f) Occ. - Vocal effort: L

(g) Unocc. - Vocal effort: N
(h) Unocc. - Vocal effort: R
(i) Unocc. - Vocal effort: L

(j) Occ. - Vocal effort: N
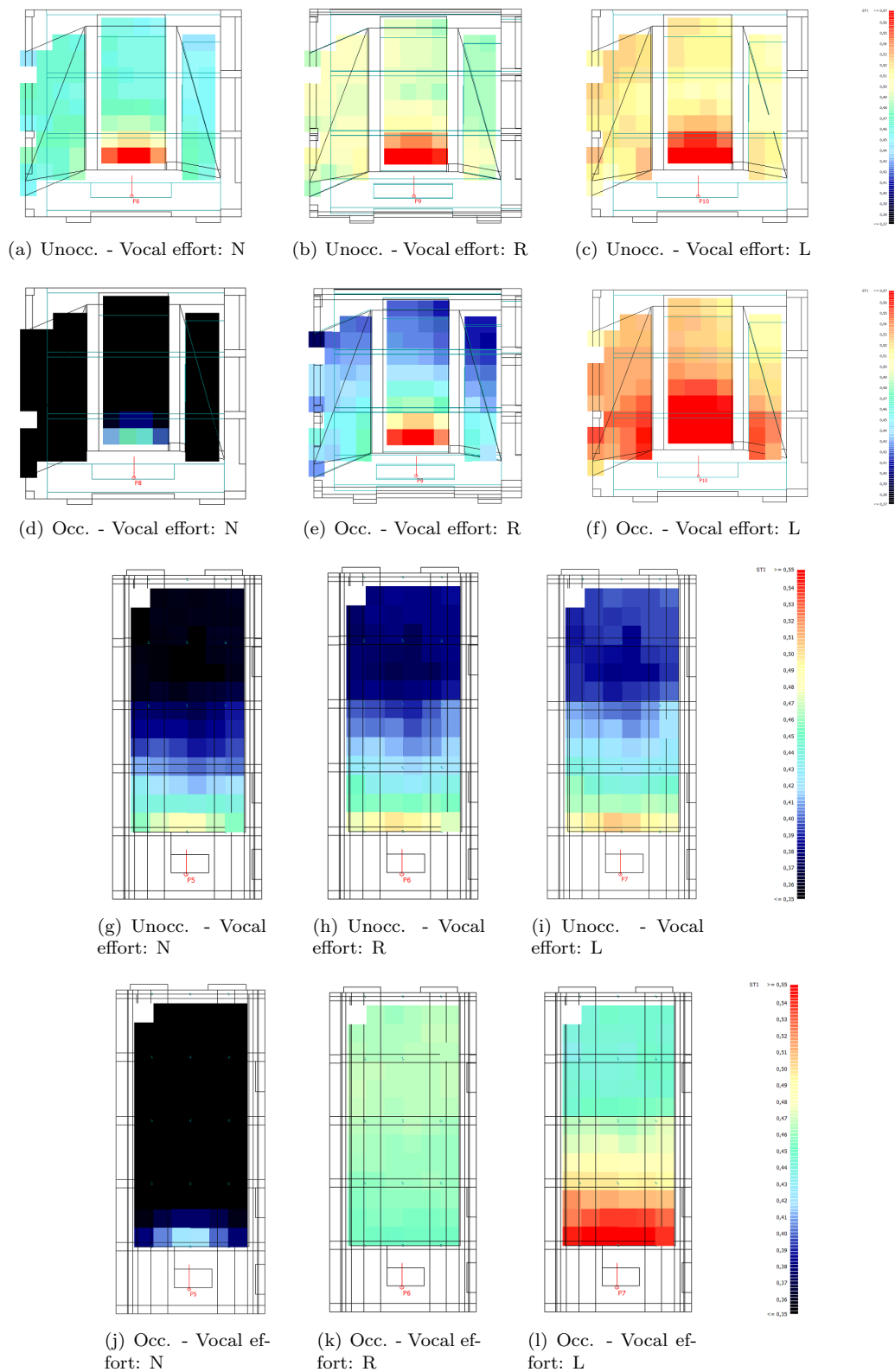(k) Occ. - Vocal effort: R
(l) Occ. - Vocal effort: L

Figure 3: Simulated STI values in unoccupied and occupied condition with different level of vocal effort by the speaker: normal (N), raised (R), loud (L) (UNI EN ISO (2004)).
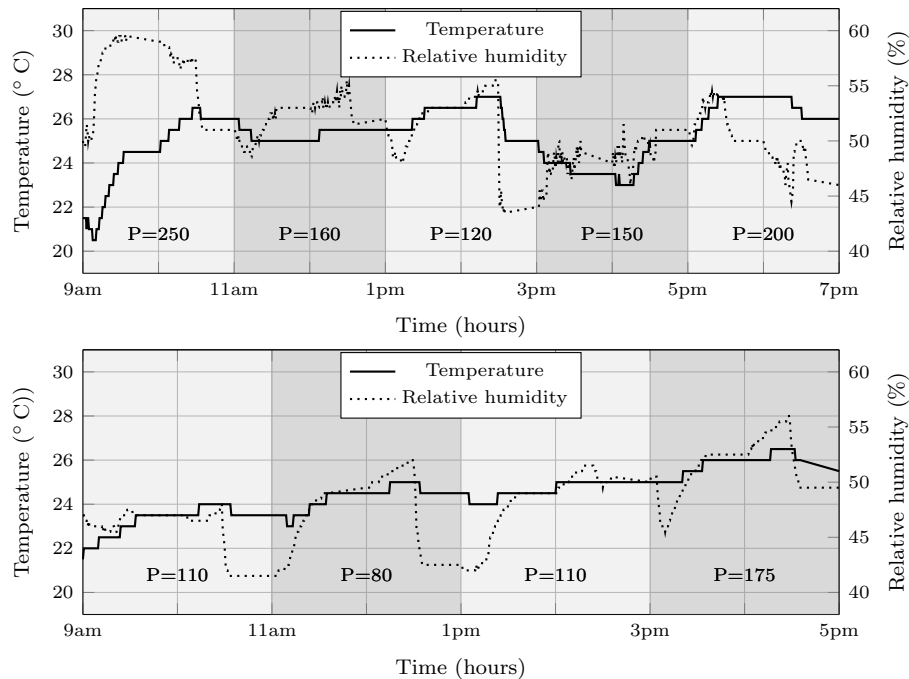
Figure 4: Measured values of temperature and relative humidity during lessons activity in halls A and B. The "P" values indicate the mean number of people present during lessons, corresponding to the percentages of occupancy reported in Table 2.

beration time is a quite uniform criterion throughout the space, the mean values are provided by averaging the results over all the receiver points. In general, results show a good agreement between predicted formulas and simulated values in occupied state in terms of trend versus frequency (see Figure 2). In detail, in lecture hall A the outcomes are particularly accurate because all the differences between simulated and predicted values are within the just noticeable difference (EN ISO (2008)). Conversely, in lecture hall B the simulations seem to slightly overestimate the role of the occupants on the reverberation time. This is probably due to phenomena like the edge diffraction caused by the seats, that are computed by the geometrical acoustic simulation and neglected by the predictive formulas.

The third group of results concerns the computation of STI values through GA techniques. Distinct values of background noise were set during the simulations depending on the occupancy conditions: 40 dB (HVAC systems) in unoccupied state and 50 dB in occupied state (corresponding to 80% of maximum capacity in hall A and 50% of maximum capacity in hall B in Table 2). Three levels of vocal effort were set for the sound source corresponding to the A-weighted sound pressure level of a speaker at 1 m in front of the mouth (UNI EN ISO (2004)): 60 dB (normal), 66 dB (raised), and 72 dB (loud). While the background noise may be considered quite even throughout the space, the received speech level at the listener - without any support from the public address system - spatially decreases, as measured and assessed in a

previous work (Fratoni et al. (2019)). Therefore, the SNR values are expected to decrease moving away from the speaker, as the speech intelligiblity. The aim is to explore the vocal effort needed to achieve a certain quality of speech intelligibility throughout the students area. Figure 3 shows the results of the different combinations simulated in each lecture hall, in unoccupied and occupied state.

Discussions

In teaching environments, lessons are generally attended by a quite constant number of students, meaning that the effects of the occupancy on the acoustics may be considered as stationary. It is true in case of primary and secondary lessons, when the occupancy is expected to be quite constant during the day. In university lecture halls the issue of the occupancy is related to the strong variations of the number of students during the day. Other parameters vary with the occupancy, i.e. the temperature and the relative humidity, and for this reason these quantities have been systematically measured - every minute - during the student activity measurements (see Figure 4). With reference to Table 2 and Figure 4, the second lessons in the two lecture halls considered have been simulated. Therefore, the simulation results provided in Figure 3 are referred to those number of occupants: 160 people in hall A and 80 people in hall B, corresponding, respectively, to the 80% and the 50% of each maximum seating capacity. It should be noted that in university lessons, even a situation with an occupancy higher than the maximum seating capacity

may occur (see Table 2). Together with the corresponding absorption coefficient and the background noise set equal to the student activity actually measured, also the temperature and the relative humidity were set during the acoustic simulations. Even though it still remains difficult to estimate the effects of temperature and relative humidity variations on the intelligibility, the influence of those variables on the overall comfort - and probably on the distraction and the chatting of the students - is well known.

Concerning the STI maps in Figure 3, among the three levels of vocal effort the level corresponding to "normal" is the less reliable situation because it has been proved that there is a sort of adaptation of the teacher's voice with the increase of background noise (Lombard (1911), D'Orazio et al. (2020)). Nevertheless, the comparison among the spatial distribution of STI values is intended to show that the common simulated situation would require a "loud" level of vocal effort to grant a good speech intelligibility in the hall (STI > 0.55).

Indeed, all these remarks are reliable as long as any support from a public address system is omitted. Actually, in situation like those ones assessed in this study, i.e. lecture halls with large seating capacity, a PA system turns to be necessary to preserve the health and the voice of the teacher and to grant the maximum speech intelligibility allowed by the acoustics of the hall.

Conclusion

The role of the occupancy has been explored by means of geometrical acoustic simulations in large university lecture halls. Machine learning results previously obtained from measurements of student activity were used as input data to evaluate the effective background noise in occupied state, higher than the measured one in unoccupied condition. A more accurate estimation of the speech intelligibility and the actual vocal effort required by the teacher may be obtained depending on the occupancy variations during the lessons. Future developments of the present work could involve a predictive model to estimate the student activity level given a certain percentage of occupancy.

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