

Research Paper

Acoustic study of an auditorium by the determination of reverberation time and speech transmission index

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Abstract

The quality of the communication between teachers and students and ultimately, of classroom education itself, is closely linked to the acoustic quality of the auditorium. This acoustic quality can be characterized based on the reverberation time (RT), speech transmission index (STI) and the sound insulation. In this context, an acoustic study was conducted in an auditorium located in the Higher Institute of Technological Studies (ISET) of Sfax, south of Tunisia. The investigation used acoustic measurement methods to assess the acoustic quality of the nave and the results were compared with the standards ISO 3382-1 and ISO 3382-2. The results of this work were obtained by measuring the RT values and the sound insulation of auditorium façades. In addition to these parameters obtained by measurements, STI was obtained through the computer simulation (utilizing ODEON ver. 4.2, assuming the occupied case). The results showed that the measured and calculated values were consistent with those proposed by the standards for speech auditoria ($RT_{500Hz} = 0.98$ s, $D_{50} > 50\%$ and $STI > 0.45$), and are in line with the speech intelligibility requirements.

Keywords: Acoustic quality, Auditorium, Reverberation time (RT), Sound insulation, Speech transmission index (STI).

1. INTRODUCTION

An auditorium must provide a place where speech can be clearly understood. This means a good auditorium will have a good intelligibility rating. The set of minimum acoustic requirements that are met by a working auditorium starts with the direct sound from the speaker being loud enough, that means it replicates conversational sound levels. The background noise in the hall has to be fairly quiet. The hall acoustics should be fairly free from echoes and other types of late reflections. And finally, the hall acoustic is not very reverberant at all.

Acoustic quality is defined as the degree to which the totality of the individual requirements made on an auditory event is met. It comprises three different kinds of influencing variables: physical, psychoacoustic and psychological. This acoustic quality can be characterized based on the reverberation time, speech transmission index, sound insulation, and the noise levels inside and outside the auditorium [1-4]. High noise levels in the classroom impair oral communication, causing students to become tired sooner more often, and this premature fatigue tends to have

a negative effect on their cognitive skills [5].

Several recent studies have produced a considerable body of work related to the acoustic quality of auditorium [6-12]. For example Knight and Evans [13] reported, examining some auditoriums built in 1961, that the main acoustic defect that was complained by many users of the spaces was the speech intelligibility of students is particularly poor. Hodgson [14] found that the effect of a renovation depends on a complex relationship between changes in reverberation and changes in signal-to-noise level difference, as affected by sound absorption and source outputs. It can be said that architectural acoustics in general and auditorium acoustics in particular, seek two main objectives [15,16]:

- The first one is inside the room: to provide a good acoustical environment, which is known as sound absorption and propagation.
- The second one is between the room and its surroundings: which is known as sound isolation.

In the present study, the auditorium in the Higher Institute of Technological Studies (ISET) of Sfax, was the object of an in situ acoustic survey and computer simulation to evaluate its acoustic quality with regard to speech intelligibility. The collection of data and computer simulations followed the recommendations of the international standards. The field measurements provided, among other data, information about the reverberation

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time (RT) and speech clarity (Definition, D50) while the computer simulations served to evaluate the Speech Transmission Index (STI). The results were then compared with reference values suggested by the standards and by other researchers [17-19] in order to characterize the space.

2. AUDITORIUM DESCRIPTION

The auditorium studied is a building with a modern architectural style built in the 1980s. Made of concrete, it covers an area of about 246 m² with a volume of 735 m³. One of the most conspicuous characteristics of this building is the triangular shape of its longitudinal section. The height of the ceiling relative to the floor is 3.20 m above the entrance and 2.80 m at its opposite side (Fig. 1).

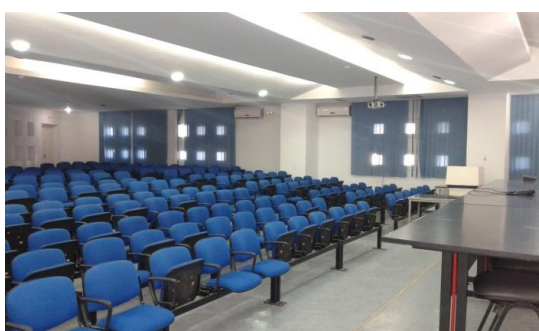


Fig. 1 Internal view of the auditorium

The floor is a trapezoidal shape whose large base measuring 18.40 m and the small base measuring 8.80 m. The height of the trapezoid is 18.00 m.

The auditorium floor contains three rows of velvet armchair with space to seat about 250 people. According to the acoustical references, a good sight line helps effectively in the good acoustical perception where the ability of reading lips helps in achieving part of speech intelligibility; this requires a minimum slope of 7° [20]. Stepped rows of velvet armchair have been utilized with slopes from 1°95' (first row) to 2°54' (last row). Thus, the slopes of the different floors are not compatible with the requirements for good sight lines.

The floor consists of a flexible carpet and the concrete ceiling has skylights for zenithal lighting. The auditorium's austere decoration is limited to stained glass windows that provide natural lighting during the daytime (Fig. 2).

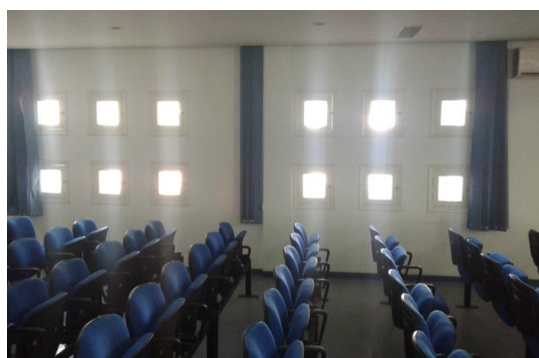


Fig. 2 Stained glass windows providing natural lighting during the daytime

3. EXPERIMENTAL STUDY

3.1. Evaluation of the Reverberation Time (RT)

The RT is the most important criterion affecting the acoustic quality of any auditorium. In fact, the room with best acoustical design is the one that insures the ears undistorted reception for the speech sounds [21].

The RT is determined for the frequency ranges normally used in room acoustics, in octave bands ranging from 125 Hz to 4000 Hz. The RT of a room can then be expressed by a single value, using the arithmetic mean of the bands of 500 Hz and 1000 Hz [22,23].

According to the ISO 3382-1 [24] and ISO 3382-2 [25], the RT can be measured by the interrupted noise method and by the integrated impulse response method. Measuring the RT by the interrupted noise method, as described in this chapter, consists of exciting the room with a pseudo-random pink noise and calculating the RT from the room's response to this excitation, The RT can be calculated using the following equation:

$$T = 0,161 \frac{V}{A} \quad (1)$$

where V is the room's volume in cubic meters; A is the total sound absorption of the room in Sabines given by the expression below:

$$A = \alpha_1 \cdot A_1 + \alpha_2 \cdot A_2 + \dots \dots \dots \alpha_n \cdot A_n = \sum_{i=1}^n \alpha_i A_i \quad (2)$$

where A_n is the area of a surface of the room; and α_n is the sound absorption coefficient of the materials that make up the room.

The reverberation time is strongly influenced by the absorption coefficients of the surfaces as suggested in the illustration, but it also depends upon the volume of the room as shown in the Sabine formula. You won't get a long reverberation time with a small room.

The characterization of the surfaces according to their coefficients of sound absorption and diffusion generally leads to major imprecision in these calculations. Table 1 lists the finishing materials used in the interior of the auditorium.

3.2. Deutlichkeit or definition (D₅₀)

As a channel-based measure for reverberation, the "Definition" D₅₀ ("Deutlichkeit") [26] is used for explaining certain effects in the accuracy curves in the sequel. It is defined as the ratio of the energy of the direct sound plus early reflections arriving within the first 50 ms and the energy of the complete RIR, i.e.,

The D₅₀ parameter is calculated separately for each frequency band from 125 Hz to 4000 Hz. The value obtained from the average of the bands at 500 and 1000 Hz shows a good correlation with the corresponding subjective sensation [27]. It is defined as:

$$D_{50}(\%) = \frac{\int_0^{0.05s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \quad (3)$$

where p is the sound pressure level and p²(t) is the quadratic response of the sound pulse.

Table 1 The absorption coefficients of the materials used in the auditorium

Materials	Frequency (Hz)					
	125	250	500	1000	2000	4000
Lime cement plaster	0.02	0.02	0.03	0.04	0.05	0.05
Single paned glass, 3mm	0.08	0.04	0.03	0.03	0.02	0.02
Solid wooden door	0.14	0.10	0.06	0.08	0.10	0.10
Carpet floor	0.05	0.10	0.25	0.40	0.60	0.70
Velvet armchair	0.15	0.20	0.30	0.40	0.50	0.60
Audience on velvet armchair	0.20	0.36	0.45	0.50	0.50	0.46

3.3. The speech transmission index (STI)

The speech transmission index, STI, has proven to be a valuable tool for such an objective assessment. The STI methods can be used to compare speech transmission quality at various listening positions and under various conditions within the same listening space. In particular it is useful for assessing the effect of changes in acoustic properties, including effects produced by the presence of an audience, changes in room surface properties or changes in a sound system. The methods are also able to predict the absolute rating of speech transmission quality with respect to intelligibility when comparing different listening spaces under similar conditions or assessing a speech communication channel.

The basis for the STI index is that the intelligibility of speech is largely based on the slow amplitude modulation of a sound that acts as a carrier. In the STI-method, the carrier is stationary gaussian noise divided into seven octave bands ranging from 125 Hz to 8 kHz. The width of each band is one-half octave. Each of the bands is modulated with one of 14 modulation frequencies. The modulation frequencies are selected in one-third octave steps from 0.63 Hz to 12.5 Hz, which gives a total of 98 combinations.

The STI method may be modified in different ways to reduce the time needed for the measurement. If the impulse response can be regarded as a well-behaved room-response with an exponential decaying envelope, characterized by reverberation time, the modulation transfer function at frequency F may be calculated directly from the value of the reverberation time T and the effective signal-to-noise ratio S/N (in dB). A simplified formula, not taking the effects of masking and the threshold of hearing into consideration, gives the

following relationship:

$$m(F) = \frac{1}{\sqrt{1 + \left(2\pi F \frac{T}{13,8}\right)^2}} \cdot \frac{1}{1 + 10^{(-S/N)/10}} \quad (4)$$

where m(F) is the modulation reduction factor; S/N is the effective signal-to-noise ratio (dB); F is the modulation frequency (Hz) and T is the reverberation time of the room.

The effective signal-to-noise ratio S/N is determined by using the following relation:

$$\left(\frac{S}{N}\right) = 10 \log\left(\frac{m}{1-m}\right) \quad (5)$$

The S/N above is in parenthesis to indicate that it is the apparent S/N and not the true S/N in the room.

The (S/N) must be limited to a 30 dB range so any value greater than 15 dB is set equal to 15 dB and any value less than -15 dB is set equal to -15 dB.

When we have 14 values for each octave band, we just add them up and divide by 14 to obtain 7 mean (S/N) values, one for each octave band. The STI value is given as follows:

$$STI = \frac{\left(\frac{S}{N}\right) + 15}{30} \quad (6)$$

Table 2 STI-value and speech intelligibility assessment according to IEC 60268-16

STI value	Speech Intelligibility Assessment
STI ≥ 0.75	Excellent
0.6 ≤ STI < 0.75	Good
0.45 ≤ STI < 0.60	Fair
0.30 ≤ STI < 0.45	Poor
STI < 0.3	Bad

3.4. Measurements of reverberation time

The measurements were taken using the following equipment (Fig. 1):

- A Brüel & Kjaer 4296 omnidirectional sound source: a set of 12 loudspeakers set up in a dodecahedron with a flat response for a frequency range of 100 Hz to 16 kHz, connected to a Lab.Gruppen Lab 300 power amplifier.
- A Brüel & Kjaer 4188 omnidirectional microphone with the manufacturer's original filters and polarization,
- A Brüel & Kjaer 2238 sound level meter: provide high precision measurements by installing software modules making the instrument into a dedicated solution to measurement tasks in environmental, occupational and industrial application areas,
- DIRAC 3.1 signal generation and decay curve recording software installed in a 1.4 MHz processor notebook.
- RME Fireface 800 firewire audio interface circuit board, to connect the equipment to the notebook.
- Tripods for setting up the sound source, sound meter and tapeline.

3.5. Assessment of the speech transmission index (STI)

The STI was simulated using Odeon 9.0 software [29]. This software uses the hybrid method to obtain the acoustic parameters. Rindel [30] claims that hybrid methods combine the best characteristics of the image source and ray tracing methods. A comparison of several computer simulation methods indicated that programs that use the hybrid method produce the best results.

The STI simulations were performed according to the IEC 60268-16 [28] standard. To obtain acoustic parameters through simulations required first making a three-dimensional drawing of the room. Suitable calculation parameters were then inserted (such as the length of the impulse response), the characteristics of the finish surfaces (absorption and scattering coefficients) and

the specifications of the sound source and receiver. For the source, the IEC 60268-16 standard establishes that it should be of the point wise directional type, in order to simulate the characteristics of the human mouth. The noise generated by the source should simulate both the timbre and volume of the human voice.

The three-dimensional models were calibrated based on a comparison of the values of measured and simulated RT. The values of sound pressure level in octave band frequency measured inside the auditorium were then inserted in the calibrated model, and the loudspeaker and microphone positions were defined. The spacing between the points was 5 m. The microphone was positioned in the seating area at a relative height of 1.2 m from the floor, reproducing the condition of a seated audience. The measuring point positions are shown in Fig. 3.

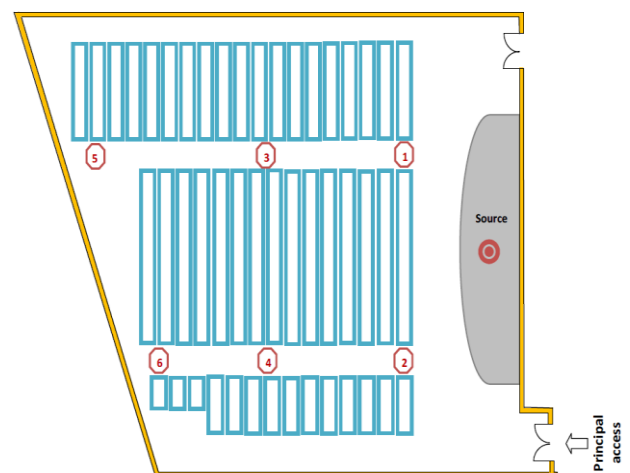


Fig. 3 The measuring point positions in the auditorium

4. RESULTS AND DISCUSSION

Table 3 gives the results of the RT measurements for the six octave bands from 125 Hz to 4000 Hz taken at the six points in the auditorium.

Table 3 RT in seconds in octave bands of the auditorium

Measured point	Frequency (Hz)					
	125	250	500	1000	2000	4000
P1	1.10	0.83	0.99	1.08	1.16	1.12
P2	1.06	0.96	0.95	0.97	1.11	1.10
P3	1.81	0.96	0.98	0.98	1.13	1.15
P4	1.51	0.95	0.98	1.02	1.08	1.15
P5	1.54	0.98	0.99	1.02	1.19	0.99
P6	1.40	0.98	0.98	0.95	1.18	1.05
Mean value	1.40	0.96	0.97	1.00	1.14	1.09

In order to obtain a value for the room as a whole, a spatial average between the points was calculated for each octave band. It is noted that the auditorium presented a fairly uniform response in the 125 Hz, 1000 Hz, 2000 Hz and 4000 Hz bands and low RT values in the 250 Hz and 500 Hz bands. The behavior of these frequencies can be explained by the low values of coefficients sound

absorption properties of the materials in these octave bands [31,32]. In fact, like any acoustic measurement, reverberation time is also frequency dependent. The simple reason is that each material absorbs sound of different frequencies in different efficiencies. For smaller spaces, standard recommends to make reverberation time independent of frequency, which means it is better to have

rather uniform reverberation time throughout the frequency range. However, it is generally considered acceptable in large volumes to have some increase in reverberation towards the low frequencies.

Fig. 4 shows the RT at the frequency of 500 Hz as a

function of the room's volume. The normalized reference value for room that has a volume of 750 m³ is 1.00 s. The building under study has a volume of 735 m³ and, as can be seen in Table 3, the mean RT at 500 Hz is 0.98 s.

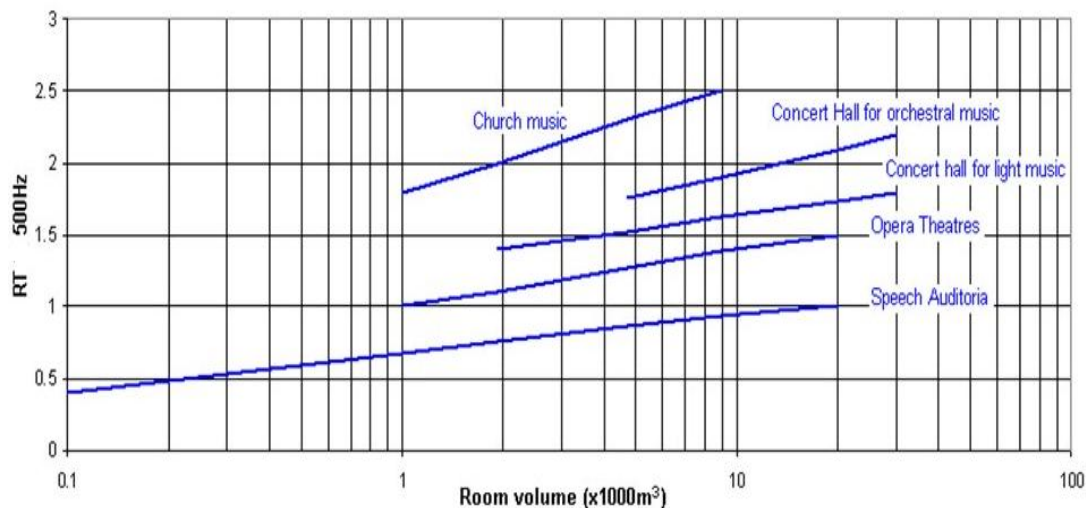


Fig. 4 RT values at the frequency of 500 Hz as a function of room volume

A lower reverberation favors speech intelligibility [33,34]. The answer is very application specific. A long reverberation time makes a space acoustically “live” and may suit spaces for music. On the other hand, shorter reverberation times enhance the speech intelligibility in a room and are better suited to spaces for speech. A very low reverberation time however can be unbearable, imagine talking in an anechoic chamber. However, these conditions do not suffice to characterize a room as adequate for speech. The analysis of the

results obtained for D₅₀ and STI allied to the RT results complements this diagnosis. The results for the parameter definition (D₅₀), as a function of frequency, for each receiver point are shown in Table 4. As can be seen, the Definition values varied considerably from one position to another. The variation in these values can be explained by the change in the pattern of reflections resulting from the geometric characteristics of the room and the relative position between the sound source and the receiver.

Table 4 Definition (D₅₀) values measured in octave bands of the auditorium

Measured point	Frequency (Hz)					
	125	250	500	1000	2000	4000
P1	61	79	73	62	48	59
P2	54	73	72	57	45	56
P3	52	32	49	38	31	33
P4	51	41	51	35	30	29
P5	66	57	58	49	37	40
P6	69	51	50	50	42	46
Mean value %	59	55	66	57	47	51

By theoretical definition, (D₅₀) is evaluated in the four octave frequency (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) and should have values above 50% for good speech intelligibility [35]. According to the results presented in Table 4, we note that the points P3 and P4 presented the lowest D₅₀ values. These results do not seem consistent since the distance between the source and the receiver is low. The measured D₅₀ data demonstrated acoustic conditions compatible with good speech clarity. These results are the consequence of the low reverberation and the reflection pattern of the sloping ceiling in this auditorium. The ISO 3382-1 standard indicates for

auditorium as typical values of D₅₀, in the average frequencies of 500Hz and 1000Hz, values between 30% and 70%. It is noted that D₅₀ values measured (range from 47% to 66%) are within the range of values recommended by the standard.

The quality of speech can be judged also from the values and spatial distribution of STI map calculated by ODEON in the room. As can be concluded from Fig. 5, two main zones can be identified; the first contains “Fair” STI. This zone is close and concentrated around the main sound source. The second zone contains “Good” STI; it is formed by small areas located at the corners of the room

where there are slight increase in the values of STI due to the reflections of the side and back walls.

Fig. 5 also shows that the average value of the measured STI is about 0.57 (“Fair” on the STI rating

scale, but near to the lower limit of the “Good” zone). In fact, the simulated STI results for the six receiver positions fall within the range of values for satisfactory speech intelligibility.

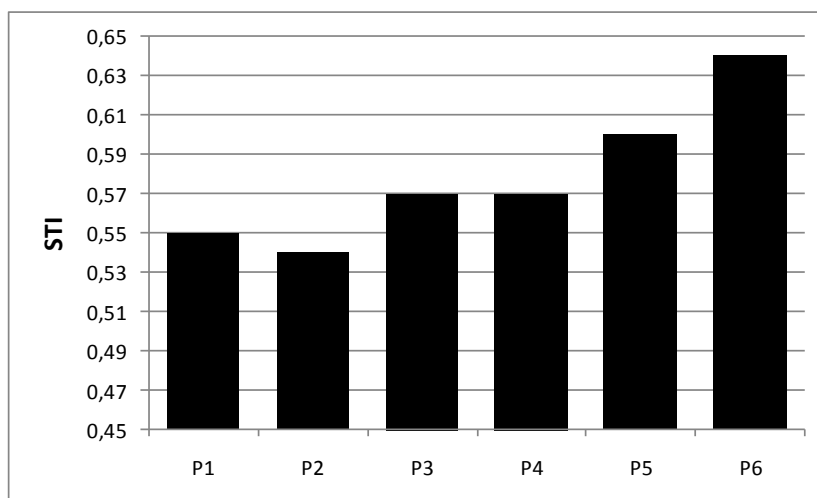


Fig. 5 Speech Transmission Index of the auditorium

5. CONCLUSION

The present paper has presented results of an acoustic study conducted in an auditorium located in the Higher Institute of Technological Studies (ISET) of Sfax, south of Tunisia. The investigation used acoustic measurement methods to assess the acoustic quality of the nave and the results were compared with the standards ISO 3382-1 and ISO 3382-2. The following conclusions have been drawn from the investigation:

1. The auditorium presented a fairly uniform response in the 125 Hz, 1000 Hz, 2000 Hz and 4000 Hz bands and low RT values in the 250 Hz and 500 Hz bands.
2. The mean RT at 500 Hz was 0.98 s. This value is lower than that proposed by the standard for the acoustic treatment of enclosed spaces.
3. The results for D_{50} in all the measured positions are within the range of values recommended by the standard ISO 3382-1.
4. The measured D_{50} data demonstrated acoustic conditions compatible with good speech clarity.
5. The Speech Transmission Index (STI) produced results exceeding 0.45 for most of the seating area. These results reflect speech intelligibility that is at least satisfactory, according to the recommendation of the IEC 60268-16 standard.

NOMENCLATURE

RT	Reverberation Time, s
V	Volume of the room, m^3
A	Area of a surface of the room, m^2
F	Modulation frequency, Hz
P	Sound pressure level, dB
D_{50}	Deutlichkeit or Definition (%)

GREEK SYMBOLS

α Sound absorption coefficient of the material

NOTATIONS

m	Modulation reduction factor
STI	Speech Transmission Index
S/N	Effective Signal-to-Noise ratio

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