ARCHIVES OF ACOUSTICS
36, 4, 741–759 (2011)
DOI: 10.2478/v10168-011-0050-8

Analysis of Acoustical Characteristics and Some Recommendations for Different Educational Rooms

Valentín Gómez ESCOBAR, Juan Miguel Barrigón MORILLAS

University of Extremadura
Department of Applied Physics, Polytechnic School
Avda. de la Universidad s/n, 10003 Cáceres, Spain
e-mail: {valentin, barrigon}@unex.es

(*received March 18, 2011; accepted September 28, 2011*)

Acoustic parameters were analysed in nine auditoria and multi-purpose conference rooms in the University of Extremadura. Parameters related to the reverberation time, background noise, and intelligibility (both physical measurements of different parameters [Definition (D-50) and STI] and speech tests used to study the subjective response of listeners) were studied. The measurements were compared with some recommendations from the literature and, considering that speech was the main use of the studied rooms, with the intelligibility results. Some different recommendations for reverberation times taken from the literature were analysed. The intelligibility results obtained from the measurements were also compared with the intelligibility results that were determined by the speech tests.

Keywords: room acoustics, intelligibility, reverberation time, educational rooms.

1. Introduction

Although budget and æsthetic design are usually the main concerns in construction of buildings, there are other aspects that are sometimes not considered; for example, whether a room is acoustically adequate for its supposed use. Consequently, once a building is completed, it is not unusual to determine that rooms in which the acoustics are important do not meet basic acoustic standards. Indeed, although acoustic considerations may be taken into account in the most representative rooms, they are sometimes neglected in more common rooms.

Typical buildings in which insufficient attention has been given to the acoustic design are those devoted to teaching, such as lecture halls and auditoria of schools and universities. Recently, many works have studied acoustics of rooms in educational buildings, particularly in classrooms (Hodgson, 1999; Knecht *et al.*, 2002; Hodgson, Nosal, 2002; Bradley, Sato, 2008; Astolfi, Pellerey, 2008; Augustyńska *et al.*, 2010).

Many parameters have been suggested to assess the acoustical quality of rooms (Beranek, 1996; Bistafa, Bradley, 2000; Anhert, Tennhardt, 2008), and they can be divided in different groups including energy parameters [such as Sound Strength (G) or Clarity (C-80; C-50)], decay time parameters [such as the Reverberation Time (RT) or the Early Decay Time (EDT)], intelligibility parameters [such as the Speech Transmission Index (STI) or the Articulation Loss (AL_{cons})], and spatial parameters [such as the Interaural Cross Correlation Coefficient (IIAC) or the Lateral Fraction (LF)]. The high number of the proposed parameters and their corresponding recommendations substantially increases the difficulty of finding a room that conforms to all of the recommendations. Hence, only some of the parameters can be the focus of a given study. Various authors have published works that analyse the possibility of minimising the number of parameters or giving priority to some of them (Schroeder *et al.*, 1974; Beranek, 1996; Cerdá *et al.*, 2011).

In the present work, the acoustics of nine auditoria and conference rooms of the University of Extremadura is analysed. The purposes of this work are as follows:

- First, to obtain sufficient data regarding different parameters and characteristics of the rooms to have an impression of their acoustic qualities.
- Second, to compare the acoustical parameters measured using the recommendations. We analysed usefulness of different recommendations for achieving a maximum intelligibility in the rooms, as all of the studied rooms are mainly devoted to speech.

The chosen rooms covered a wide range of sizes and volumes (for this type of building), and there were some differences in shape. The measured parameters focused both on general acoustic parameters and on the acoustics related to verbal communication, as this is the most common use of these rooms. The general acoustic parameters measured were the reverberation time and background noise. The study of the conditions for verbal communication (i.e., adequate intelligibility) was performed by measuring the physical parameters of Definition (D-50), Speech Clarity (C-50), and Speech Transmission Index (STI), and also using speech tests to study the subjective response of listeners (Speech Intelligibility).

Section 2 is devoted to a brief description of the studied rooms. Section 3 describes the methods used including the acoustic parameters studied. Section 4 presents the results and discussion. Finally, Section 5 gives the principal conclusions of the study.

2. Brief description of the rooms studied

The University of Extremadura has campuses located in several cities in the region of Extremadura. It is a medium-sized university with fewer than 35,000 students. Of these, approximately 12,000 live in the Cáceres campus on the outskirts of the city. The campus comprises different buildings used for teaching more than thirty different degree courses. Apart from classrooms, each building has space devoted to general use (conferences, inaugurations, etc.). For the purpose of the present study, we arbitrarily divided these rooms on the basis of their volume into "auditoria" (volume greater than 1000 m^3; AU1–AU4) and – using a direct translation of the foregoing Latin term for the smaller multi-purpose conference rooms – "listening rooms" (volume less than 1000 m^3; LR1–LR5).

The rooms were in different buildings except for AU1 and LR2, which were in the same building of the Faculty of Law, and LR5 and AU3, which were in the building of the Faculty of Philosophy.

Tables 1 and 2 summarise some characteristics of the places studied. First, in Table 1, the dimensions l, b, and h are given assuming a "shoe box shape" (h represents the height, and l and b are the large and short dimensions of the floor, respectively), although this supposition is obviouslyly inexact for some of the rooms. In all the rooms except for LR2 the large dimension of the floor coincided with the direction of speaking (thus, the audience seats are perpendicular

Table 1. Size and other characteristics of the studied rooms.

Room	Volume [m^3]	l [m]	b [m]	h [m]	Floor	Sitting
AU1	2000	22.2	16.3	6.0	Small slope	275
AU2	1550	20.4	17.2	4.3	Stepped	340
AU3	1350	19.3	10.9	6.3	Horizontal	230
AU4	1300	19.1	19	4.8	Stepped	320
LR1	815	16.2	14.5	3.5	Small slope	260
LR2	710	17.3	10.8	4.4	Stepped	160
LR3	420	15.5	9.2	3.0	Horizontal	125
LR4	400	17.9	7.8	3.0	Horizontal	110
LR5	190	8.4	5.2	4.3	Stepped	25

Table 2. Percentage of surfaces occupied by different materials in the rooms studied. 'Porous materials' include curtains, fitted carpets, and, in one of the studied rooms, cork; seats are not included into this term. 'Audience' refers to the surface occupied by the seats.

Room	Wood	Porous material	Audience	Rest
AU1	13.2	5.2	12.0	69.6
AU2	5.0	0.3	16.1	78.5
AU3	6.0	6.6	19.9	67.5
AU4	0.5	17.9	19.9	61.7
LR1	11.9	8.1	17.0	63.0
LR2	6.3	0.0	9.5	84.1
LR3	7.4	8.3	11.1	73.1
LR4	8.6	32.4	13.9	45.1
LR5	1.7	0.0	7.7	90.6

to the large dimension in these rooms). The dimensions of the rooms, assuming a shoe box shape, show a relationship between them that is quite unlike to what is recommended in the blob diagram of Bolt (1946). Table 2 presents some information about the surfaces occupied by different materials in the rooms. For simplicity, the materials were divided into four different groups: wood, porous material, audience, and the rest (generally, with small absorption coefficients).

Although the construction materials differed, all the rooms had seats of similar characteristics – medium-to-high upholstered. Thus, even though no people were present when the studies were performed, the effect of an audience on the acoustics is not very noticeable in rooms with this type of seating because the difference in absorption is small (Beranek, 1996).

3. Methods

3.1. Measurement points

In each room, several measurement points were chosen in the audience plane following the ISO 3382 recommendations (ISO 3382, 2001). The source was positioned at least in two different places. The number of measured points ranged from 24 to 60 depending on the room, except for LR5 in which only 13 points were measured due to its small size. The total number of measurement points was greater than 350.

The different acoustical parameters were determined at all the measurement points. A microphone was placed at a height of 1.2 m (ISO 3382, 2001) at the points corresponding to a seated person. At the points corresponding to a standing person (less than 10% of the total number of points), the height of the microphone was changed to 1.5 m.

3.2. Acoustical parameters

The acoustic parameters studied were divided into three groups:

a) *Parameters related to the reverberation time*. This group consisted of the reverberation time (RT), bass ratio (BR), and brightness (Br). The reverberation time was determined by the interrupt method as T20 using pink noise. At each point, the value of the reverberation time was determined in third-of-an-octave bands from 100 Hz to 5000 Hz as the mean of three measurements and then, for each band, the mean of the values for all the points was taken to be the average reverberation time of the room for that band. Points at the shortest distance of one metre from the source were excluded from the calculation of this average as being unrepresentative of the placement of the audience. The parameters BR and Br were obtained from the average reverberation time (by octaves) and were used to check whether the form of dependence of the reverberation time on the frequency was similar to the recommendations at low and high frequencies, respectively. They were calculated using the following standard expressions:

$$\mathrm{BR} = \frac{\mathrm{RT}(125\ \mathrm{Hz}) + \mathrm{RT}(250\ \mathrm{Hz})}{\mathrm{RT}(500\ \mathrm{Hz}) + \mathrm{RT}(1000\ \mathrm{Hz})}, \tag{1}$$

$$\mathrm{Br} = \frac{\mathrm{RT}(2000\ \mathrm{Hz}) + \mathrm{RT}(4000\ \mathrm{Hz})}{\mathrm{RT}(500\ \mathrm{Hz}) + \mathrm{RT}(1000\ \mathrm{Hz})}. \tag{2}$$

b) *Background noise*. This was measured in the middle of the room with the measurement time of five minutes. From the measured third-of-octave band values, the octave band values were first calculated, and then the Noise Rating (NR) value associated with the room's background (ISO R-1996).

c) *Intelligibility parameters*. As mentioned in Introduction, intelligibility was determined both from measuring physical parameters [Speech Transmission Index (STI) (Hougast, Steeneken, 1973), Speech Clarity (C-50) (Anhert, Schmidt, 1980), and Definition (D-50) (Thiele, 1953)] and by means of speech tests for studying the subjective response of listeners (Speech Intelligibility).

These speech tests were performed *in situ* using one syllable logatomes. For this purpose, sequences of 100 nonsense syllables were used by at least five different speakers (except for LR5 in which there were only two speakers) and different listeners (at least 15 persons). The nonsense syllables were chosen according to the proposal of researcher of Spanish idioms (Vela *et al.*, 1995) and the order of the emission of these syllables was different in each sequence. After each sequence, each listener changed his/her position. For the analysis of Speech Intelligibility a preliminary statistical analysis was performed, and listeners whose average values of the percentage of correct logatomes presented differences with an overall medium value greater than twice the typical standard deviation were discarded. The statistical analysis was then repeated with the rest of the listeners. The number of tests for the different rooms ranged from 75 to 315.

3.3. Equipment

The reverberation time was measured with a Brüel and Kjær 2260 Type 0 analyser. Background noise and intelligibility parameters were measured with a Type 1 "Symphony System" from 01dB using the manufacturer's dBBati software that was provided with the system. In both cases, a Brüel and Kjær 2726 amplifier and Brüel and Kjær 4296 omni-directional power source were used. The sound pressure level at 1 m from the source was 70 dB in the intelligibility parameter determinations and approximately 100 dB in the reverberation time measurements.

Before and after the measurements both analyser systems were calibrated using a Brüel and Kjær 4231 calibrator.

4. Results and discussion

First, a global vision of the acoustic parameters studied is shown to help the reader visualise the acoustics of the room. Second, reverberation times are compared with some recommendations. Finally, intelligibility measurements are analysed considering the influence of the reverberation time on the STI value, and conclusions about the suitability of the studied reverberation time recommendations are drawn.

4.1. Parameters related to the acoustical situation of the rooms

a) Parameters related to the reverberation time

This grouping includes the reverberation time of the rooms and some parameters obtained from it. Table 3 presents the mean reverberation time (RT) by octaves, the average RT, RT_{mid} (the mean of RT for the octave bands of 500 Hz and 1000 Hz), BR, and Br for each room studied.

Table 3. Acoustic parameters related to the reverberation time, background noise, and intelligibility in different rooms.

	Frequency [Hz]	Studied room								
		AU1	AU2	AU3	AU4	LR1	LR2	LR3	LR4	LR5
RT [s]	125	1.70	1.17	0.95	0.77	0.91	1.36	0.82	1.07	1.03
	250	1.23	1.15	1.16	0.65	0.74	1.28	0.74	0.80	1.07
	500	1.19	1.22	1.32	0.59	0.71	1.31	0.78	0.70	1.16
	1000	1.36	1.37	1.47	0.65	0.74	1.49	0.78	0.68	1.16
	2000	1.35	1.42	1.44	0.69	0.74	1.52	0.77	0.65	1.16
	4000	1.21	1.24	1.15	0.60	0.68	1.26	0.69	0.58	1.08
Average RT [s]		1.34	1.26	1.25	0.66	0.75	1.37	0.76	0.75	1.11
RT_{mid} [s]		1.27	1.30	1.39	0.62	0.73	1.40	0.78	0.69	1.16
BR		1.15	0.89	0.76	1.14	1.14	0.94	1.00	1.35	0.91
Br		1.01	1.03	0.93	1.04	0.98	0.99	0.93	0.89	0.96
NR value		35	40	25	25	45	25	45	45	35
STI		0.60	0.61	0.62	0.76	0.71	0.58	0.71	0.71	0.65
Intelligibility		Good	Good	Good	Excellent	Good	Fair	Good	Good	Good
Correct logatomes [%]		73	73	85	81	79	85	84	74	83
C-50 Average [dB]		−0.11	0.71	−0.34	5.26	3.15	−1.30	3.44	3.53	1.40
Critical radius [m]		2.6	2.1	1.9	3.7	2.2	1.5	1.5	1.6	0.8
Volume [m^3]		2000	1550	1350	1300	815	710	420	400	190

A comparison of the reverberation time values with some of the recommendations is shown below. With respect to the form in which the reverberation time depends on the frequency, this can be analysed using the BR and Br values. Considering the same recommendations as those given for music for the reverberation time shape of the studied rooms, it is generally supposed that reverberation times should be longer at low frequencies than at mid frequencies, and then either remain constant or decline gradually towards higher frequencies. These considerations imply that the BR values should be close to or slightly greater than unity (typically between 1.0 and 1.2), and the Br values should be close to or slightly below unity (typically between 0.8 and 1.0). Table 3 shows that, in four of the rooms studied (AU1, AU4, LR1 and LR3), the BR values fell within the suggested interval; in the rest of the rooms they were above or below the recommended levels. All of the Br values were close to the recommended levels.

b) Background noise levels

With respect to the NR values, the rooms studied fell into two groups. One comprised rooms with low NR values; these were AU3, AU4, and LR2 with an NR value of 25. The other comprised rooms with NR values that were clearly high enough to be sure that the background noise was excessive; these were AU2, LR1, LR3, and LR4 with NR values of 40 for the former and 45 for the rest. AU1 and LR5 presented an NR value of 35 in a more moderate situation. Action could perhaps be taken in the middle group to reduce the background levels, in particular, by improving the sound-proofing of the entrance door of these rooms, which was in nearly all the cases inadequate for noise reduction.

c) Intelligibility parameters

As noted in Methods section, the intelligibility of the rooms was determined on the one side by means of physical measurements of Definition (D-50), Speech Clarity (C-50), and STI, and on the other side through subjective trials with listeners. As the use of the studied rooms is mainly for oral communication, intelligibility parameters can be considered the most important; therefore, they are useful for studying the suitability of the preliminary recommendations.

First the results were studied in each room, then an average value was obtained for each room, afterwards all the average values were analysed together. For Speech Clarity (C-50), the average value (C-50av) was calculated according to the proposed octave weightings (Marshall, 1994). While calculating the average values, values at the 1 m point were excluded because this distance is not representative of the situation of the audience. These average values are shown in Table 3 together with the corresponding assessment of intelligibility (obtained from the STI value). In this table, the average percentage of correct logatomes is also presented.

A similar tendency was observed when comparing the results of the measured parameters (STI, D50, and C-50av). This behaviour was observed individually for each room and also for the average values of these parameters, which showed a clear linear relationship between STI and both Definition and Speech Clarity (Fig. 1), and is presented by the following linear regressions:

$$\text{D-50 [\%]} = -37.9 + 146.0 \cdot \text{STI},$$

$$\text{C-50av [dB]} = -21.0 + 34.5 \cdot \text{STI},$$

with coefficients of determination (r^2) of 0.99 and 0.98, respectively.

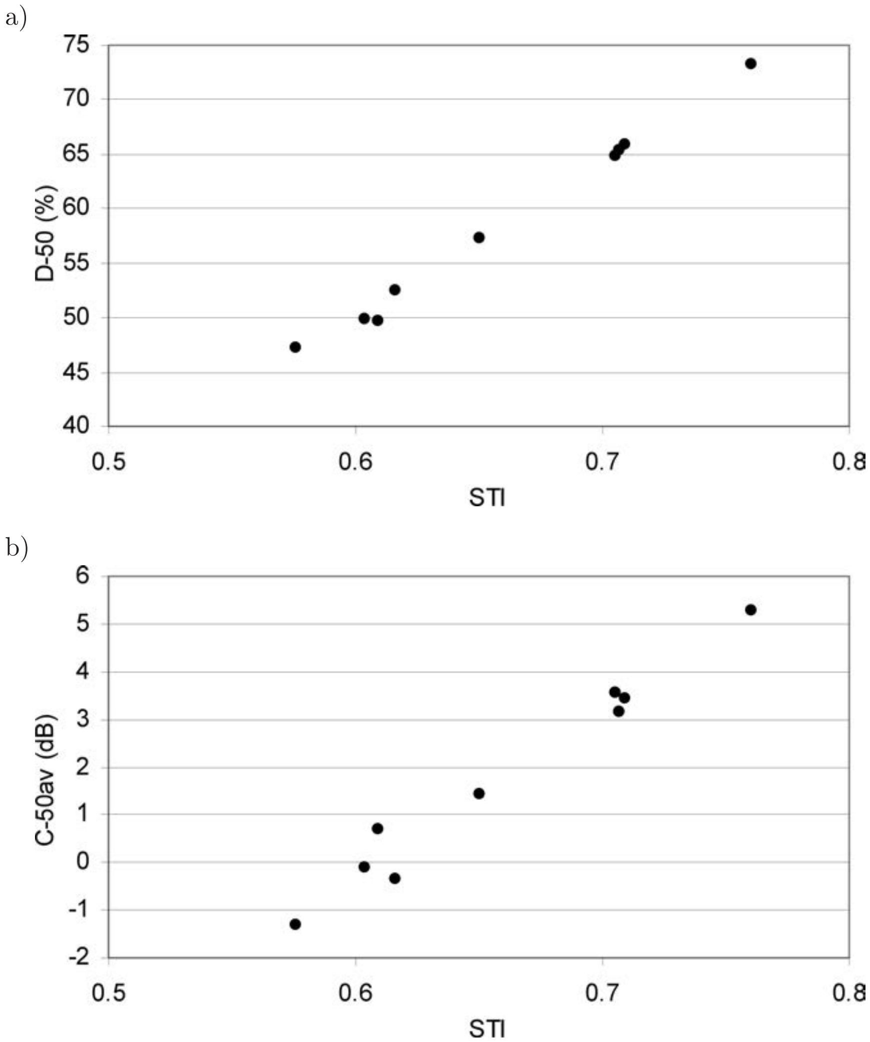


Fig. 1. Relationships between STI mean values and the other measured physical intelligibility parameters: a) Definition (D-50), b) Average Speech Clarity (C-50av).

The fitting parameters and coefficients of determination obtained individually in each room are shown in Table 4.

Table 4. Results of the coefficient of determination (r^2) of the linear relationship between STI and the percentage of correct logatomes for the studied rooms. Significance is indicated by [** = highly significant ($p \leq 0.01$); * = significant ($p \leq 0.05$)].

	Studied room								
	AU1	AU2	AU3	AU4	LR1	LR2	LR3	LR4	LR5
Number of logatome tests	274	125	302	207	315	109	159	277	78
Number of points	43	20	58	43	47	22	31	45	13
Slope (a) (STI-logatome)	58.0	66.8	35.3	29.2	32.2	36.1	67.4	94.4	35.2
Origin (b) (STI-logatome)	38.5	32.4	58.9	61.8	62.2	64.2	26.0	12.0	59.8
Correlation coef. (r) (STI-logatome)	0.55**	0.64**	0.28*	0.25	0.47**	0.71**	0.36*	0.62**	0.29
r^2 (STI-logatome)	0.30	0.41	0.08	0.06	0.22	0.50	0.13	0.39	0.09
Slope (a) (STI-D50)	194.9	194.2	200.3	138.4	163.6	186.4	156.6	212.2	214.7
Origin (b) (STI-D50)	−67.9	−68.5	−71.2	−32.2	−50.3	−60.3	−45.2	−85.3	−82.2
Correlation coef. (r) (STI-D50)	0.96**	0.97**	0.95**	0.87**	0.77**	0.99**	0.94**	0.96**	0.97**
r^2 (STI-D50)	0.92	0.95	0.90	0.76	0.59	0.98	0.88	0.93	0.94
Number of points	51	10	38	54	47	22	31	54	13
Slope (a) (C-50av-STI)	44.8	36.2	42.0	56.5	48.0	41.4	45.2	51.9	53.6
Origin (b) (C-50av-STI)	−27.1	−22.0	−25.9	−36.6	−30.6	−25.1	−28.7	−33.0	−33.5
Correlation coef. (r) (C-50av-STI)	0.96**	0.97**	0.95**	0.94**	0.95**	0.98**	0.96**	0.92**	0.93**
r^2 (C-50av-STI)	0.93	0.95	0.91	0.88	0.90	0.96	0.92	0.84	0.86

Due to this similarity, only STI values were used for the analysis of the room acoustics and for the study of the relationship between the physical measurements of intelligibility and other parameters.

Because the average STI values were above 0.55 for all of the rooms, the intelligibility could in all cases be considered as at least acceptable; in 7 of the 9 studied rooms, the intelligibility could be considered as good, and in one of the rooms it was excellent (AU4). This room is one of the largest rooms, and, as it was mentioned above, had a high absorption, which caused the reverberation time to be shorter than in the other rooms.

As expected, the intelligibility results for the individual rooms showed that the parameters depend on distance from the source. Figures 2a and 2b show the behaviour observed for the STI and intelligibility test of one of the rooms (AU1) by way of illustration.

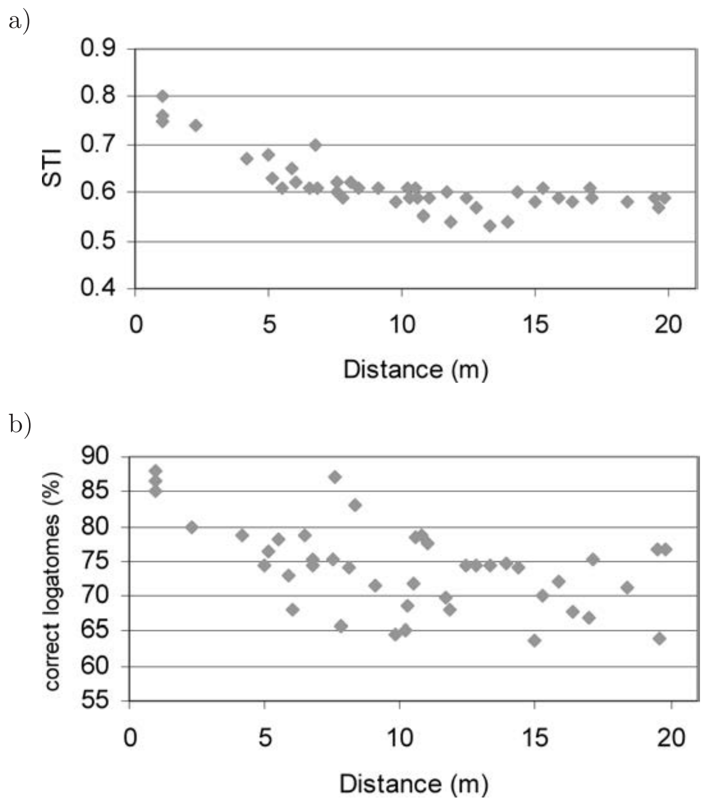
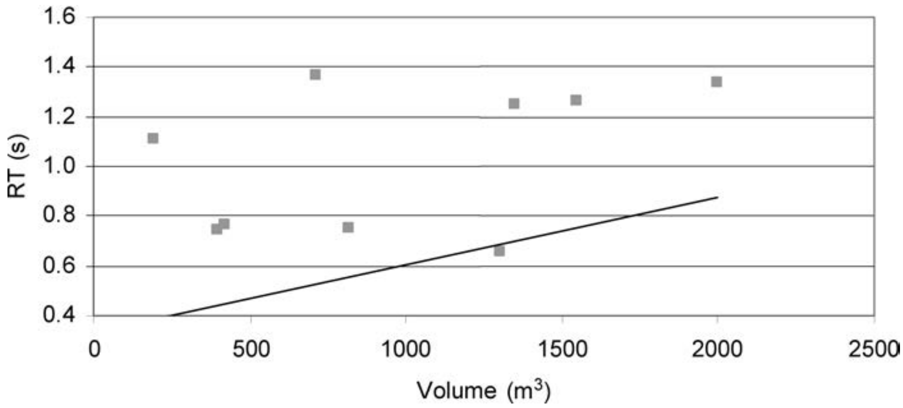


Fig. 2. Intelligibility parameters: a) variation of STI with distance for one of the rooms studied (AU1), b) variation of the percentage of correct logatomes with distance for the same room.

4.2. Comparison of measured reverberation times with some recommendations

There are several optimal reverberation times ($RT_{optimal}$) equations proposed in the literature for rooms. We considered four, although they might not have specifically been proposed for the type of rooms studied here. For university classrooms, Hodgson (2004) proposed the influence of the volume of the room (V) in the form: $RT_{optimal} = 0.04 \cdot V^{0.4}$. This optimal reverberation time and the measured average RT values are shown in Fig. 3a. As it can be seen, except for one room (AU4), there were clear differences between the measured RT values and Hodgson's proposal. While this would appear to indicate that the acoustics of the studied rooms are unsuitable, we must consider that the rooms studied are not university classrooms (although the smaller rooms LR1–LR5 are similar in size to several university classrooms); therefore, it is necessary to consider other recommended values.

Figure 3b shows a comparison of the results for the 500 Hz octave with the two recommendations of Knudsen and Harris for this octave (Knudsen, Harris, 1988); one is for "auditoria" and another is for "other rooms where speech is the a)



b)

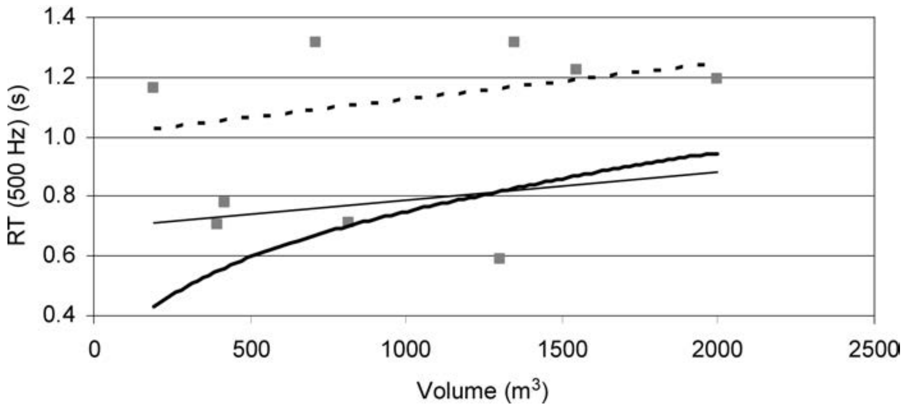


Fig. 3. Comparison between the experimentally measured and proposed optimal reverberation times: a) average experimental RT (points) and optimal value according to Hodgson (2004) (line), b) experimental 500 Hz octave value (points); optimal value proposed by Knudsen, Harris (1988) for auditoria (dashed line) and non-auditoria speech-use rooms (thin solid line); and optimal values proposed by Conturie (1955) for theatres and conference rooms (thick solid line).

main sound source". The curve of the optimal value proposed by Conturie for this octave band for theatres and conference rooms is also plotted (Conturie, 1955). It can be seen that, except for LR2 and LR5, the results for the "listening rooms" were similar to the recommendations of both Conturie and Knudsen and Harris for "other rooms where speech is the main sound source". For three of the "auditoria" (all except AU4), the reverberation times were higher than in the two foregoing recommendations and closer to those of Knudsen and Harris for "auditoria." Overall, the absorption in the two "listening rooms" LR2 and LR5 was notable in being lower than the value corresponding to their categories; they are the two "listening rooms" with the lowest percentage of surfaces of absorbing materials (wood, audience, and other porous materials) (see Table 2).

The absorption of AU4 was notably higher than the value corresponding to its category; this is also corroborated by the surface of the materials of the different "auditoria" (see Table 2).

The measured and recommended reverberation times are further discussed below following the analysis of the intelligibility results.

4.3. Analysis of intelligibility parameters

As mentioned previously, STI was chosen to be representative of the three measured physical parameters [Definition (D-50), Speech Clarity (C-50) and STI].

In the first analysis, the possible relationship between STI and the percentage of correct logatomes (%) was analysed for each room. The resulting coefficients of determination (r^2) of the observed linear relationship among these variables are presented in Table 4. As it can be seen, in seven of the nine rooms, a relationship considered to be significant ($p \leq 0.05$) was found, and the relationship was highly significant ($p \leq 0.01$) in five of them. As an example, Fig. 4a shows the results and the linear relationship for one of the rooms (AU1).

To minimise the effect of the variability introduced by listeners and speakers in the analysis of the data, the results of each room were grouped as is sometimes done in studies where the objective variables and subjective ones are compared (Miedema, Vos, 1999; Klæboe *et al.*, 2004). First, they were grouped as a function of the location of the measurement point with respect to the critical distance (d_c) of the room. In this way, the results in points located between 0 meters and d_c were averaged. This was also done for data between d_c and $2d_c$, $2d_c$ and $3d_c$, and so on. Next, they were grouped as a function of the STI value with a step of 0.02. For each group of data, the average of the STI values and the average of the correct logatome percentages were calculated; the results of the relationships between these average values are shown in Table 5 and illustrated in Figs. 4b and 4c for the AU1 room. As expected, when grouping the data, the variability was reduced. Therefore, the coefficient of determination (r^2) of the results (and, thus, the variability of the STI explained by the results of the logatome tests) increased considerably (more than 50% in five of the rooms for the d_c grouping and in seven of the rooms for the STI grouping). In any case, according to our results, the STI value appeared to be a good indicator of the Speech Intelligibility.

Looking at the STI values, the reverberation times, and the recommendations for reverberation time, we observed that the four highest values of STI were obtained for the rooms whose reverberation times for the 500 Hz octave band were closest to the recommended value of Conturie (Conturie, 1955) or Knudsen and Harris (Knudsen, Harris, 1988) for rooms in which speech is the major sound source [see Fig. 3b]. Therefore, given the medium intelligibility results, we can conclude that these two recommendations for the optimal reverberation time are better suited to this type of room than the other two that we considered, i.e., the Hodgson recommendation for university classrooms (Hodgson, 2004) and

a) b) c)

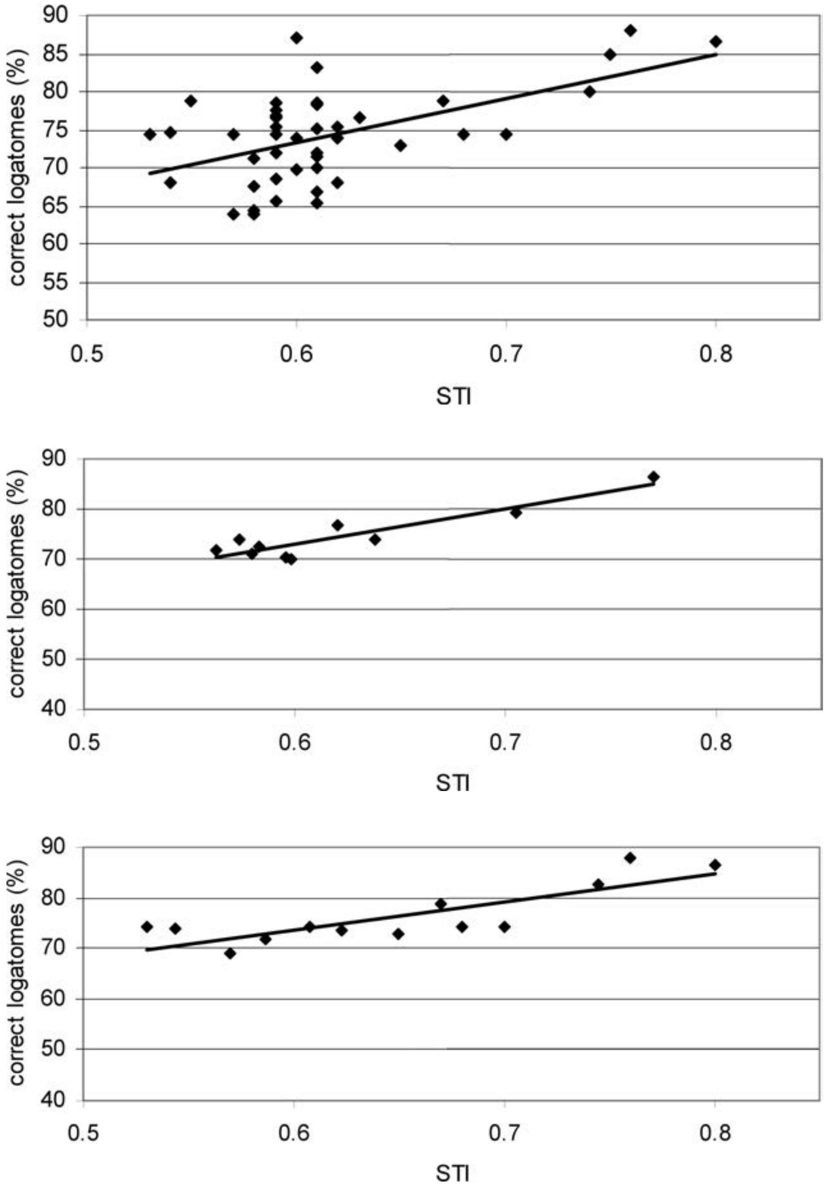


Fig. 4. a) Variation of the percentage of correct logatomes (%) as a function of the STI value for one of the rooms studied (AU1), b) the same as (a), but the results are grouped as a function of the location of the evaluation point with respect to the critical distance, c) the same as (a), but the results are grouped as a function of the STI values (in steps of 0.02).

the Knudsen and Harris recommendation for the 500 Hz octave band for auditoria. Nevertheless, the room with the highest STI was the only one in which the reverberation time coincided with the Hodgson recommended value.

Table 5. Results of the coefficient of determination (r^2) of the linear relationship between STI and the percentage of correct logatomes for the studied rooms when data is grouped as a function of the critical distance and as a function of the STI value. Significance is indicated by [** = highly significant ($p \leq 0.01$); * = significant ($p \leq 0.05$)].

	Studied room								
As a function of critical distance	**AU1**	**AU2**	**AU3**	**AU4**	**LR1**	**LR2**	**LR3**	**LR4**	**LR5**
data	10	9	12	8	9	8	9	14	7
Slope (a) (STI-logatome)	71.1	84.6	1.7	60.8	42.8	42.1	89.7	76.2	60.6
Origin (b) (STI-logatome)	30.3	20.0	81.6	37.2	54.6	60.2	12.3	25.7	43.2
Correlation coef. (r) (STI-logatome)	0.92**	0.89**	0.02	0.67	0.83**	0.87**	0.80**	0.60*	0.66
r^2 (STI-logatome)	0.85	0.80	0.00	0.44	0.69	0.76	0.64	0.36	0.43
Slope (a) (STI-D50)	191.6	189.3	216.3	134.7	172.3	184.2	152.7	215.0	224.7
Origin (b) (STI-D50)	−66.0	−65.2	−81.3	−29.0	−56.8	−58.9	−50.6	−87.0	−88.7
Correlation coef. (r) (STI-D50)	0.99**	0.99**	0.97**	0.96**	0.97**	1.00**	0.98**	0.98**	0.98**
r^2 (STI-D50)	0.98	0.97	0.94	0.92	0.94	0.99	0.96	0.97	0.97
As a function of STI (0.02 intervals)	**AU1**	**AU2**	**AU3**	**AU4**	**LR1**	**LR2**	**LR3**	**LR4**	**LR5**
data	13	9	10	12	9	8	8	11	5
Slope (a) (STI-logatome)	56.3	58.1	22.6	35.7	35.1	36.6	65.6	80.0	55.7
Origin (b) (STI-logatome)	39.8	38.9	69.3	57.9	60.5	63.6	28.6	21.4	46.3
Correlation coef. (r) (STI-logatome)	0.83**	0.68*	0.55	0.79**	0.78*	0.95**	0.84**	0.80**	0.84
r^2 (STI-logatome)	0.68	0.46	0.31	0.62	0.60	0.90	0.70	0.63	0.70
Slope (a) (STI-D50)	198.3	188.0	183.9	134.7	155.7	186.2	151.8	214.6	221.6
Origin (b) (STI-D50)	−69.9	−64.6	−59.9	−30.2	−42.2	−60.1	−41.8	−87.7	−86.6
Correlation coef. (r) (STI-D50)	0.98**	1.00**	0.99**	0.94**	0.95**	1.00**	0.99**	0.99**	1.00**
r^2 (STI-D50)	0.96	0.99	0.97	0.88	0.91	0.99	0.98	0.97	0.99

To study the suitability of the equations for the recommended reverberation time, the average STI was compared with the relative deviation of the reverberation time with respect to the recommended value [(RT measured − RT recommended)/RT recommended ratio]. The results of this comparison showed that significant relationships were not found either for the Conturie recommendation or for the Hodgson recommendation for university classrooms. Nevertheless, a highly significant correlation [$p \leq 0.01$] was found for the Knudsen and Harris recommendation for rooms in which speech is the major sound source (Knudsen, Harris, 1988). The relationship found was

$$STI = 0.701 - 0.1496[(RT_{\text{measured}} - RT_{\text{recommended}})/RT_{\text{recommended}}],$$

with a coefficient of determination (r^2) of 0.79. This relationship is shown in Fig. 5a. The coefficient of determination indicates that about 80% of the vari-

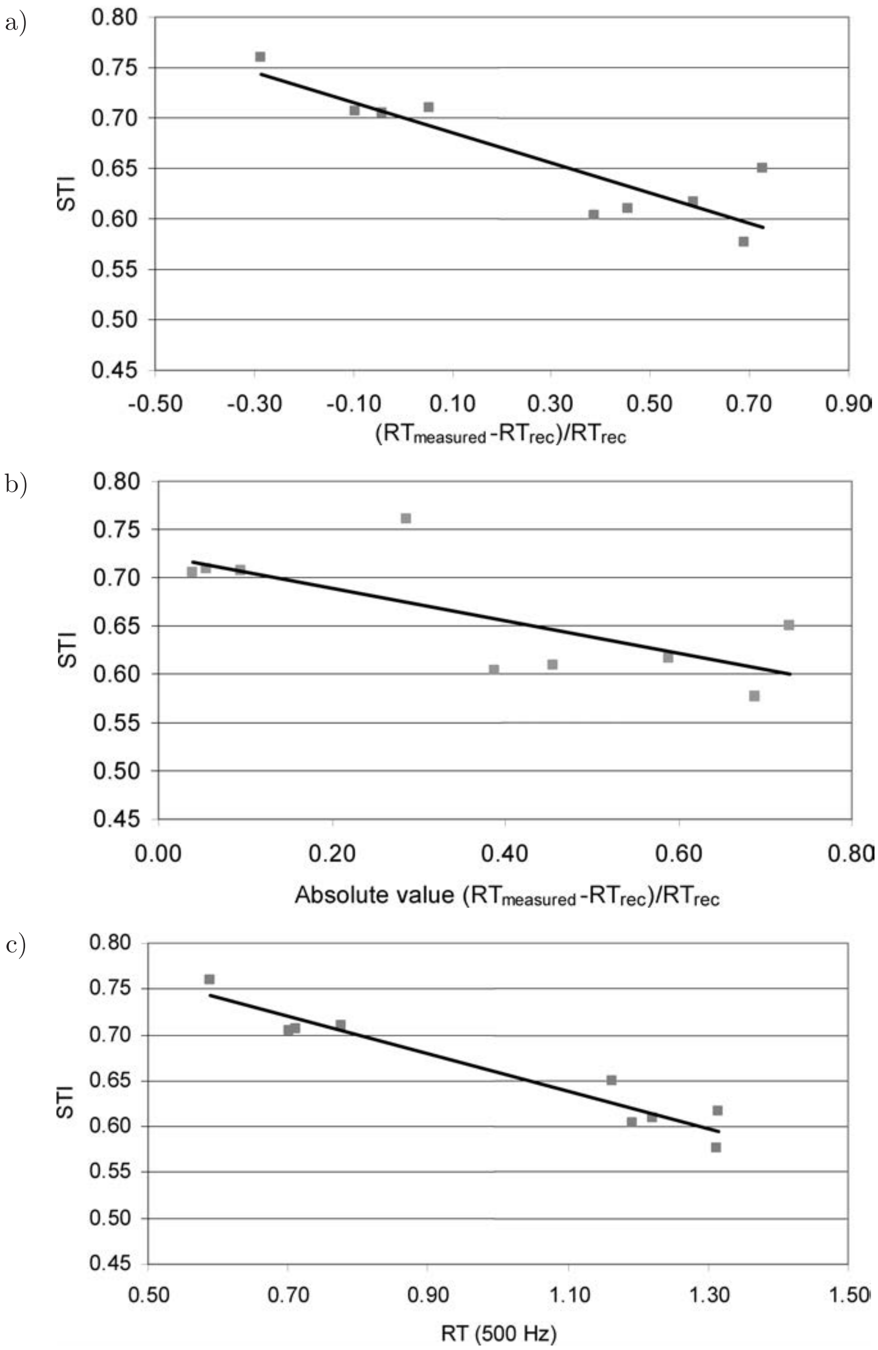


Fig. 5. a) Variation of the STI with the normalised difference among the measured reverberation time and the recommended reverberation time of Knudsen and Harris for the rooms, b) variation of the STI with the absolute value of the normalised difference mentioned in (a), c) relationship between the average STI and RT (500 Hz) for the eight rooms studied.

ability of the STI value was explained by the normalised difference among the measured reverberation time and the recommended reverberation time of Knudsen and Harris for rooms in which speech is the major sound source. When the absolute value of the mentioned relative deviation was considered (Fig. 5b) the results were worse, although the relationship found [$r^2 = 0.52$] was significant [$p \leq 0.05$]. These results indicate that downward deviations from the mentioned recommended value of the reverberation time imply improvement of intelligibility and, thus, in the STI value. As deduced from the above mentioned relationship, values of STI over 0.701 were only achieved with measured reverberation times under the recommended, and an STI maximum would be obtained for zero reverberation time. These statements are corroborated when analysing the relationships between STI and the reverberation times. These relationships were highly significant [$p \leq 0.01$] for $\mathrm{RT}_{\mathrm{mid}}$, the average RT, and RT (500 Hz). The linear regressions found were as follows:

$$\mathrm{STI} = 0.853 - 0.186 \cdot \mathrm{RT}_{\mathrm{mid}}, \qquad (r^2 = 0.93),$$

$$\mathrm{STI} = 0.877 - 0.211 \cdot \mathrm{RT}_{\mathrm{average}}, \qquad (r^2 = 0.96),$$

$$\mathrm{STI} = 0.862 - 0.202 \cdot \mathrm{RT}\ (500\ \mathrm{Hz}), \qquad (r^2 = 0.93).$$

As an example, Fig. 5c shows the behaviour found for the 500 Hz reverberation time value (a frequency that is commonly used to study the acoustic quality of rooms).

From these relationships, we can deduce again that the maximum STI value can only be obtained when the reverberation time is zero meaning that, for the zero value, intelligibility can be considered as "excellent" in the three relationships. The zero value of the optimum reverberation time was previously suggested by other authors (Nabelek, Pickett, 1974; Finitzo–Hieber, Tillman, 1983) as analysed by Hogdson and Nosal (2002), although other authors showed that Speech Intelligibility was not the highest for this value of the reverberation time (Bistafa, Bradley, 2000).

It is important to note that the above relationships were similar to those obtained if the "auditoria" and "listening rooms" were analysed separately. Thus, as an example, the relationships for the 500 Hz reverberation time value for "auditoria" and "listening rooms" were, respectively,

$$\mathrm{STI} = 0.887 - 0.222 \cdot \mathrm{RT}\ (500\ \mathrm{Hz}), \qquad (r^2 = 0.95),$$

$$\mathrm{STI} = 0.851 - 0.194 \cdot \mathrm{RT}\ (500\ \mathrm{Hz}), \qquad (r^2 = 0.91).$$

Finally, with respect to the BR and Br values, no statistically significant relationships were found between these parameters and the STI value. Although a higher STI value was obtained in one of the rooms with a lower NR value, taking into consideration the rest of the results no statistically significant relationship was found between both variables.

5. Conclusions

Some conclusions can be made on the basis of the present study. With regard to the reverberation time, all the rooms studied showed similar behaviour except AU2, LR2, and LR5 whose reverberation times were shorter (the first) and longer (the last two) than expected from the tendency of the value of RT in the rest of the rooms studied. These differences can be explained by analysing the materials of the rooms.

The room with the highest STI value was the only one whose reverberation time coincided with the Hodgson recommendation. Nevertheless, taking into consideration all the data and looking for a good intelligibility, the recommendation of Knudsen and Harris for rooms other than auditoria in which speech is the main sound source appeared to be better than the other recommendations studied. Nevertheless, if STI values close to unity are desired, reverberation times under the recommended levels are necessary. Therefore, we can conclude that the shape of the recommendation values is the best but must be displaced to achieve a better intelligibility.

When the intelligibility results were analysed individually for each room, all of the mentioned intelligibility parameters depended on the distance to the source and were less homogeneous in the case of the subjective tests with listeners (the percentage of correct logatomes). The variability introduced by listeners and speakers was reduced by grouping the results for the rooms considering the critical distance and the STI values. The results were better for the STI grouped results.

The average intelligibility results of the rooms studied were clearly related to the reverberation time values [highly significant ($p \leq 0.01$)] relationships of the STI with $\mathrm{RT}_{\mathrm{mid}}$, the average RT, and RT (500 Hz)]. In addition, the results indicated that downward deviations from the recommended values of the reverberation time implied an improvement in intelligibility and, thus, in the STI value, achieving a maximum value for a hypothetical zero value of the reverberation time. In addition, a highly significant relationship was found between STI and Definition (D-50) and between STI and the average value of the Speech Clarity (C-50av).

No statistically significant relationships were found among the intelligibility results and the other parameters studied such as BR, Br, and the NR value.

Acknowledgments

The authors wish to thank everyone who helped in performing the measurements and developing the intelligibility tests.

References

1. Augustyńska D., Kaczmarska A., Mikulski W., Radosz J. (2010), *Assessment of teachers' exposure to noise in selected primary schools*, Archives of Acoustics, **35**, 4, 521–542.

2. Anhert W., Schmidt W. (1980), *Akustik in Kulturbauten*, Institut für Kulturbauten, Berlin.

3. Anhert W., Tennhardt H.-P. (2008), *Acoustics for Auditoriums and Concert Halls*, [in:] Handbook for Sound Engineers, Glen M. Ballou [Ed.], Focal Press, Boston.

4. Astolfi A., Pellerey F. (2008), *Subjective and objective assessment of acoustical and overall environmental quality in secondary school classrooms*, Journal of the Acoustical Society of America, **123**, 163–173.

5. Beranek L.L. (1996), *Concert and Opera Halls: How They Sound?*, Acoustical Society of America, New York.

6. Bistafa S.R., Bradley J.S. (2000), *Reverberation time and maximum background-noise level for classrooms from a comparative study of speech intelligibility metrics*, Journal of the Acoustical Society of America, **107**, 861–875.

7. Bradley J.S., Sato H. (2008), *The intelligibility of speech in elementary school classrooms*, Journal of the Acoustical Society of America, **123**, 2078–2086.

8. Bolt R.H. (1946), *Note on the Normal Frequency Statistics in Rectangular Rooms*, Journal of the Acoustical Society of America, **18**, 130–133.

9. Cerdá S., Giménez A., Romero J., Cibrián R. (2011), *A Factor Analysis Approach to Determining a Small Number of Parameters for Characterising Halls*, Acta Acustica united with Acustica, **97**, 441–452.

10. Conturie L. (1955), *L'acoustique dans les bâtiments. Théorie et applications*, Editions Eyrolles, Paris.

11. Finitzo–Hieber T., Tillman T.W. (1983), *Room acoustic effects on monosyllabic word discrimination ability for normal and hearing-impaired children*, Journal of Speech, Language, and Hearing Research, **21**, 440–458.

12. Hodgson M.R. (1999), *Experimental investigation of the acoustical characteristics of university classrooms*, Journal of the Acoustical Society of America, **106**, 1810–1819.

13. Hodgson M.R. (2004), *Case-study evaluations of the acoustical design of renovated university classrooms*, Applied Acoustics, **65**, 69–89.

14. Hodgson M.R., Nosal E.-M. (2002), *Effect of noise and occupancy on optimum reverberation times for speech communication in classrooms*, Journal of the Acoustical Society of America, **111**, 931–939.

15. Hougast T., Steeneken H.J.M. (1973), *The modulation transfer function in room acoustics as a predictor of Speech Intelligibility*, Acustica, **28**, 66–73.

16. ISO 3382: 2001. Acoustics. Measurement of the reverberation time of rooms with reference to other acoustical parameters. International Organization for Standardization, Geneva, Switzerland.

17. ISO R-1996. Acoustics. Description and measurement of environmental noise. International Organization for Standardization, Geneva, Switzerland.

18. Klæboe R., Amundsen A.H., Fyhri A., Solberg S. (2004), *Road traffic noise – the relationship between noise exposure and noise annoyance in Norway*, Applied Acoustics, **65**, 893–912.

19. Knecht H.A., Nelson P.B., Whitelaw G.M., Feth L.L. (2002), *Background noise levels and reverberation times in unoccupied classrooms: predictions and measurements*, American Journal of Audiology, **11**, 65–71.

20. Knudsen V.O., Harris C.M. (1988), *Acoustical design in architecture*, Acoustical Society of America, New York.

21. Marshall L.G. (1994), *Acoustics measurement program for evaluating auditoriums based on the early/late sound energy ratio*, Journal of the Acoustical Society of America, **96**, 2251–2261.

22. Miedema H.M.E., Vos H. (1999), *Demographic and attitudinal factors that modify annoyance from transportation noise*, Journal of the Acoustical Society of America, **105**, 3336–3344.

23. Nabelek A.K., Pickett J.M. (1974), *Monaural and binaural speech perception through hearing aids under noise and reverberation time with normal and hearing-impaired listeners*, Journal of Speech, Language, and Hearing Research, **7**, 724–739.

24. Schroeder M.R., Gottlob D., Siebrasse K.F. (1974), *Comparative study of European concert halls: correlation of subjective preference with geometric and acoustic parameters*, Journal of the Acoustical Society of America, **56**, 1195–1201.

25. Thiele R. (1953), *Richtungsverteilung und Zeitfolge der Schallrückwürfe in Räumen*, Acustica, **3**, 291–302.

26. Vela A., Arana M., García A. (1995), *Revisión de pruebas subjetivas de inteligibilidad mediante la emisión de logatomos*, Proceedings of Tecniacústica 1995, La Coruña, Spain.