Applied Acoustics 96 (2015) 1–10

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Technical Note

Analysis of intelligibility and reverberation time recommendations in educational rooms

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ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 16 February 2015
Accepted 6 March 2015
Available online 23 March 2015

Keywords:
Room acoustics
Intelligibility
Reverberation time
Educational rooms

ABSTRACT

Acoustic parameters, including background-noise levels, reverberation time and intelligibility, were analyzed in 17 auditoria and multi-purpose conference rooms at the University of Extremadura. The study of intelligibility was performed by measuring the objective parameters and by using speech tests to study the subjective responses of listeners (speech intelligibility). Relationships between objective and subjective intelligibility parameters were studied, and the grouping of the experimental data was considered to reduce variability. It was concluded that the STI value is a good predictor of the intelligibility of rooms. Relationships between STI values with background-noise levels and reverberation time were also studied.

Different proposals of recommended reverberation time were analyzed, taking into consideration the STI values of the studied rooms. Improvements in the slopes of the recommended equations were suggested.

1. Introduction

In the design of architectural spaces, acoustics considerations should be one of several main elements to be considered. Depending on the final use of the room, room acoustics may have either greater or lesser importance, but in all cases, both must be taken into consideration.

Clear examples of architectural spaces in which both aspects should be taken into account are rooms dedicated to educational uses, such as classrooms, conference rooms, auditoriums, and so on. In these rooms, as verbal communication is the major path for knowledge transmission, suitable communication factors that ensure the successful transmission of the oral message are critical. Different acoustic parameters have been proposed for the assessment of speech intelligibility in rooms. A review of some of these parameters can be found in [1].

Paradoxically, it is not unusual to find educational rooms in which acoustics do not meet basic acoustic standards because of the failure to consider the principles of room acoustics in the design. This is relevant given the role of these spaces in the learning process. Thus, the absence of good acoustics can greatly influence the learning capacity of students. Because this is more relevant in the first years of education, several studies have been conducted to assess acoustic conditions in primary classrooms [2–5] and the effect of these acoustic conditions on student achievement [6,7]. However, the problem associated with acoustics in educational classrooms is also a drawback in secondary and university classrooms [8–11]. Thus, a common renovation of materials in these classrooms is necessary to achieve more appropriate acoustical conditions [11–12].

To achieve suitable acoustics in these particular types of buildings, several recommendations have been suggested. These recommendations include limiting the degree of background-noise levels and the reverberation time. Standards and reviews of these recommendations can be found in [13–15]. With respect to the optimum reverberation time recommendations, the recommendations in the aforementioned references are usually discrete, given as a fixed number that is independent of the volume of the room or as a fixed number for a range of volumes. On the other hand, other authors [12,16,17] have suggested recommendations of the reverberation time that are continuously dependent on room volume using various formulae.

In the present work, the acoustical performances of several university rooms were studied, and their reverberation times were compared with those proposed in the bibliography. For this comparison, we used the intelligibility of the rooms as a reference to form our conclusions. Intelligibility was characterized both by measuring objective parameters of definition (D-50) and of the speech transmission index (STI) and by using speech tests to study the subjective responses of listeners (speech intelligibility). In the present work, we justify the use of the speech transmission index

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http://dx.doi.org/10.1016/j.apacoust.2015.03.001
0003-682X/

Table 1
Size, percentage of surfaces occupied by the different materials and other characteristics of the studied rooms. 'Porous materials' includes curtains, fitted carpet and, in one of the studied rooms, cork; seats are not included in this term. 'Audience' refers to the surface occupied by the seats.

Room	Volume (m^3)	l (m)	b (m)	h (m)	Floor	Sitting	Wood	Porous material	Audience	Rest	Global average absorption coefficient	d_c (m)
AU1	2000	22.2	16.3	6.0	Small slope	275	13.2	5.2	12.0	69.6	0.21	2.44
AU2	1550	20.4	17.2	4.3	Stepped	340	5.0	0.3	16.1	78.5	0.20	2.12
AU3	1350	19.3	10.9	6.3	Horizontal	230	6.0	6.6	19.9	67.5	0.20	1.91
AU4	1300	19.5	19	3.5	Stepped	320	0.5	17.9	19.9	61.7	0.32	3.06
LR1	815	16.2	14.5	3.5	Small slope	260	11.9	8.1	17.0	63.0	0.27	2.19
LR2	710	17.3	10.8	4.4	Stepped	160	6.3	0.0	9.5	84.1	0.12	1.32
LR3	420	15.5	9.2	3.0	Horizontal	125	7.4	8.3	11.1	73.1	0.16	1.43
LR4	400	17.9	7.8	3.0	Horizontal	110	8.6	32.4	13.9	45.1	0.22	1.55
LR5	190	8.4	5.2	4.3	Stepped	25	1.7	0.0	7.7	90.6	0.09	0.76
CL1	840	17.0	14.0	3.5	Horizontal	200	17.6	0.0	0.0	82.4	0.07	1.12
CL2	800	16.6	13.8	3.5	Horizontal	200	35.5	0.0	0.0	64.5	0.07	1.06
CL3	790	17.6	14.9	3.0	Horizontal	200	10.2	0.0	0.0	89.8	0.07	1.03
CL4	610	13.5	13.2	3.8	Stepped	80	29.2	0.0	0.0	70.8	0.09	1.03
CL5	525	13.5	13.5	2.9	Horizontal	100	2.4	11.8	3.9	82.0	0.12	1.17
CL6	450	12.0	10.7	3.5	Horizontal	115	23.8	0.0	0.0	76.2	0.07	0.87
CL7	380	11.6	10.8	3.0	Horizontal	115	25.7	0.0	0.0	74.3	0.06	0.72
CL8	275	11.5	7.9	3.0	Horizontal	30	13.4	0.0	7.3	79.4	0.10	0.86

(STI) to predict the subjective intelligibility scale (SIS) of the Spanish language. The use of the STI as the reference parameter is justified, as this parameter is related to both the noise-to-signal ratio and the reverberation time-to-signal ratio, both of which have a major influence on the intelligibility in rooms [1,8]. For this study, 17 educational rooms at the University of Extremadura (Spain) are chosen. These rooms all have a wide volume range (190–2000 m^3), a wide reverberation time range (unoccupied values from 0.65 to 2.55 s at 1 kHz) and different intelligibility conditions (average STI values from 0.47 to 0.76).

The selected rooms also have important differences in their design and use. Some are used solely as classrooms, while others are used also or only for other purposes such as conferences, institutional functions, defense of thesis works, and so on. With respect to the latter set of rooms, some were initially designed for a specific purpose, such as conferences, while others were initially designed as classrooms and later adapted for a secondary purpose. Among the major differences between the classrooms and the other rooms are the characteristics of the audience materials. For example, in classrooms, the audience seats are made of wood, while in the other rooms, the audience seats are medium-to-high upholstered.

With respect to an analysis of the results, due to the differences in the use of the studied rooms, five different recommendations for optimal reverberation time are considered. The first four recommendations are dependent on room volume: the classical optimal value proposed by Conturie [16] for theatres and conference rooms; the recommendations of Knudsen and Harris for auditoria and for rooms where speech is the main sound source [17]; and the recommendations of Hodgson specifically for university classrooms [12]. The last of the recommendations is independent of room volume (for rooms under 566 m^3), that is, the fixed value of 0.6 s as recommended by ANSI [15].

The main objectives of this work are summarized as follows:

- To study and compare the acoustical performance of several university rooms based on different recommendations.
- To identify possible relationships among intelligibility measurements, both subjective and objective, among intelligibility parameters and among other parameters.
- To analyze different reverberation time recommendation equations with the intent to improve them, if possible.

Section 2 describes the methods used, including a brief description of the places and the acoustic parameters studied. Section 3 presents a discussion of the results. Finally, Section 4 provides the principal conclusions of the study.

2. Methods

2.1. Brief description of the rooms studied

For the purpose of the present study, we divide the 17 studied rooms into two groups: classrooms (eight rooms; CL1–CL8) are those rooms that are used only as classrooms and the rest of rooms, which are those used only or additionally for other purposes, such as conferences, and institutional functions. The latter group of rooms are also arbitrarily divided on the basis of volume into auditoria (volume greater than 1000 m^3; AU1–AU4) and – using a direct translation of the Latin term for smaller multi-purpose conference rooms – listening rooms (volume less than 1000 m^3; LR1–LR5).

Table 1 summarizes some of the characteristics of the places studied. First, the dimensions l, b and h (l and b are the large and short dimensions of the floor, respectively, and h represents the height) are given assuming a rectangular shape, although this supposition is clearly inaccurate with respect to some of the rooms. In all of the rooms, except LR2 and CL5, the large dimension of the floor coincided with the direction of speaking (thus, the rows of audience seats are perpendicular to the larger dimension in all of the rooms). The dimensions of the rooms, assuming a rectangular shape, show a relationship that is quite unlike what is recommended in the blob diagram of Bolt [18]; indeed only one of the studied rooms (LR5) has dimensions that fit the recommendations. Table 1 also presents information about the different materials that make-up the surfaces in the rooms. For simplicity, the materials are divided into four groups [wood, porous, audience and rest (generally, with small absorption coefficients)].

In classrooms, because the audience seats are made of wood, the presence of people in the rooms can alter the grade of adsorption of the room significantly. In the other rooms, where the audience seats are medium-to-high upholstered, the effect of an audience on the acoustics is not significantly noticeable because the difference in absorption is minimal [19].

2.2. Sampling points and measurement

In each room, several sampling points are chosen in the audience plane following the ISO 3382 recommendations [20]. The