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APPLICATION OF AURALIZATIONS TO EVALUATE THE INFLUENCE OF REVERBERATION AND BACKGROUND NOISE ON INTELLIGIBILITY AND LISTENING DIFFICULTY OF A CLASSROOM

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This article describes a subjective procedure based on auralizations to assess the influence of reverberation and background noise on intelligibility and listening difficulty. The auralizations were created by means of Binaural Impulse Responses (BIR) measurements and numerical simulation based on Geometrical Acoustics (GA) in order to evaluate a classroom of the University of San Buenaventura Medellin. The acoustical parameters of the classroom were characterized according to the standard ISO 3382-2008. Different acoustical conditions for the classroom were assessed taking into account the combination of two situations of reverberation time and two conditions of background noise. These acoustical conditions were defined according to the existing reverberation time and background noise of the classroom and a theoretical situation based on a hypothetical acoustic treatment, in which the acoustical parameters were estimated taking into consideration local and international standards. A subjective test was applied by means of auralizations using five logatome lists and considering all the acoustical conditions. The auralizations were reproduced in a recording studio applying a 3D binaural system based on Optimal Source Distribution (OPSODIS). The results showed that the intelligibility is affected to a greater extent by the reverberation rather than the background noise. The listening difficulty results suggest an influence of both acoustic variables, although a more significant impact is observed by the presence of background noise.

Keywords: Intelligibility, listening difficulty, auralization, reverberation.

1. Introduction

This study describes a subjective procedure based on auralizations for the evaluation of intelligibility and listening difficulty, given by the modification of the parameters of reverberation time and background noise levels and was part of a PhD research [1]. The results obtained for a subjective evaluation of intelligibility and listening difficulty in auralizations of a classroom in the University of San Buenaventura in Medellín, Colombia are presented. The acoustics indicators to assess the classroom were the reverberation time and background noise level. An acoustic treatment design was proposed in order to meet the background noise criteria established in [2] and the reverberation time recommended by building Bulletin 93. Then, numerical implementations including the acoustic treatment by means of Geometrical Acoustics (GA) were carried out.

With the purpose of including the ambient noise in the auralizations created, a simple approach was proposed. The next step was to subjectively evaluate the existing and future acoustical conditions of the classroom. Intelligibility (INT) and listening difficulty (LDFF) were assessed in both situations, determining the influence of background noise level and reverberation time. The results suggest that the intelligibility is affected to a greater extent by the reverberation rather than the background noise.

The listening difficulty results show an influence of both acoustic variables, although a more significant impact is observed by the presence of background noise. The inclusion of binaural recorded background noise in auralizations was successful, however it was not possible to include synthesized binaural noise.

2. Acoustic indicators to assess a classroom

A well-designed classroom takes into account acoustic parameters such as ambient noise, reverberation time and sound insulation in order to facilitate student listening, thereby improving learning experience. According to [3], there is sufficient evidence of the negative impact of background noise and reverberation on scholastic performance and professor's health, to indicate the importance of these two acoustic parameters when assessing acoustic conditions in a classroom. The limit values recommended in terms of background noise levels, although there is a range between 30 and 50 dB(A) for maximum interior noise, most of the standards and recommendations set a value of 35 dB(A). Regarding reverberation time, most standards and recommendations state a maximum between 0.4 and 0.8 seconds in the octave bands of 500, 1k and 2k Hz, or the arithmetic mean in these bands, which is referred as the mid reverberation time (T_{mid}). In Colombia, the technical standard NTC 4595 of 2006 established acoustic criteria performance of classrooms, defining a maximum background noise level of 40-45 dB(A) and reverberation time between 0.9 and 1.0 seconds.

The indicator used to characterize the interior background noise level of the classroom was the equivalent continuous sound pressure level weighted "A", which was measured according to the ISO standard 1996:2003 over thirty minutes. Even though, most international standards recommend an interior maximum background noise level of 35 dB(A), these are directly related to classrooms in schools, since children are especially sensitive to adverse acoustic conditions. Hence, it is expected that adult students have less difficulty in understanding a spoken message in the same acoustic conditions. Taking the last into account, in this research the background noise criteria was established according to [2], in which a maximum background noise level of 45 dB(A) was defined for a voice level of 60 dB(A) at one-meter distance.

Reverberation time can affect the quality of speech communication in a room. The excess of reverberation generates a degradation of speech intelligibility, caused by a masking effect and an increase of background noise levels. In this research, the recommendation of the building Bulletin 93 was taken as a reference. This bulletin established a mid-reverberation time of less than 0.8 seconds, estimated as the arithmetic average of the octave bands of 500 Hz, 1 kHz and 2 kHz, for classrooms of no more than fifty people and without any furniture inside the room.

2.1 Speech intelligibility and STI

Speech intelligibility can be defined as the percentage of words or sentences that are correctly understood from a message by a group of listeners. In a room, intelligibility and listening difficulty parameters define the speech transmission quality, which is a function of the signal-to-noise ratio and the architectural acoustics; these two characteristics are related to reverberation time and background noise.

According to ISO standard 9921, STI has a strong direct relationship with intelligibility subjective classification ranges. Although in English language this measure has been extensively studied, little evidence can be found in the literature to verify STI values in comparison to subjective ranges in Spanish language. In [4] gave an example of this relationship in a subjective study applying a list of words with CVC logatoms of Latin American Spanish. The intelligibility classification of CVC (Consonant + Vowel + Consonant) logatoms obtained by [4], can be seen in Table 1.

Table 1: Intelligibility classification ranges for CVC testing according to ISO standard 9921. STI ranges corresponding to the correlations found by Sommerhoff for Spanish language. Adapted from [4].

	Excellent	**Good**	**Fair**	**Poor**	**Bad**
CVC	>81%	81% to 70%	70% to 53%	53% to 31%	<31%
STI (ISO)	>0.75	0.75 to 0.6	0.6 to 0.45	0.45 to 0.3	<0.3
STI (Noise)	>0.53	0.53 to 0.43	0.43 to 0.31	0.31 to 0.2	<0.2
STI (Reverberation)	>0.52	0.52 to 0.37	0.37 to 0.2	0.2 to 0.003	<0.003

3. Acoustic treatment design theory

This section describes the acoustic design proposal procedures applied to meet the assessment acoustic indicators of reverberation time and background noise. The theoretical basics took into account to estimate the sound pressure level due to a point source excitation in a room. The sound insulation fundamentals were reviewed in order to consider background noise in the acoustic design. The last point considered two main aspects: sound pressure field measurements and reverberation time estimation by means of theoretic Sabine model and numerical GA approach.

Once the acoustic diagnosis of the classroom was done, the respective calculations aiming to reduce reverberation time and background noise levels were carried out, in order to come closer to the acoustic criteria of background noise levels less than 45 dB(A) and T_{mid} less than 0.8 seconds. Regarding T_{60} criteria, it is important to note that different octave band values were assigned, having as a goal to obtain 1 second T_{60} for the octave bands of 125 and 250 Hz, and 0.8 seconds for the other octave bands. The reverberation times measured and simulated are shown in Fig. 1. For the reverberation time control, the first step after estimating the necessary absorption areas was to select from libraries materials having appropriate acoustic absorption coefficients to add in the room. The next step consisted in locating the materials chosen in the room, taking into account the room geometry and the corresponding absorption areas. The estimated reverberation times after the hypothetical acoustic treatment are shown in Fig. 2 (right).

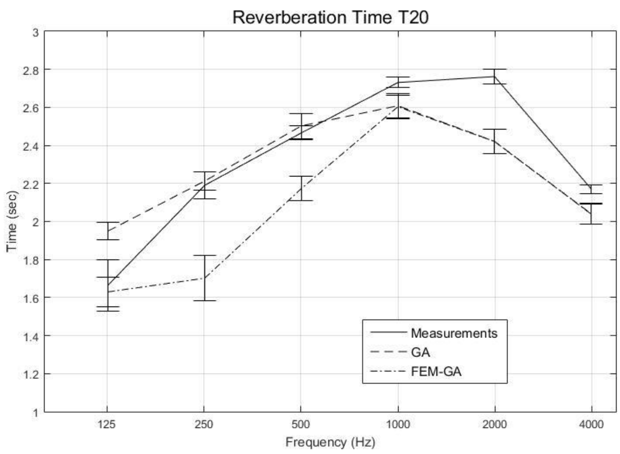

Figure 1: Spatially averaged T_{20} results of the Classroom obtained by measurements, GA simulations and the numerical approach combination of FEM-GA.

Regarding the background noise criteria, the variation of background noise level given by the changes of reverberation time was estimated. Taking into account these values and the background noise levels measured, a new internal background noise level was estimated for each octave band. Then the areas of acoustic materials to be added were calculated, according to its corresponding octave band absorption coefficients and the geometry of the classroom. The A-weighted background noise level measured and estimated after the acoustic treatment were 48.5 and 43.6 dBA respectively. The differences between noise levels measured and estimated after the hypothetic acoustic treatment can be seen in Fig. 2 (left).

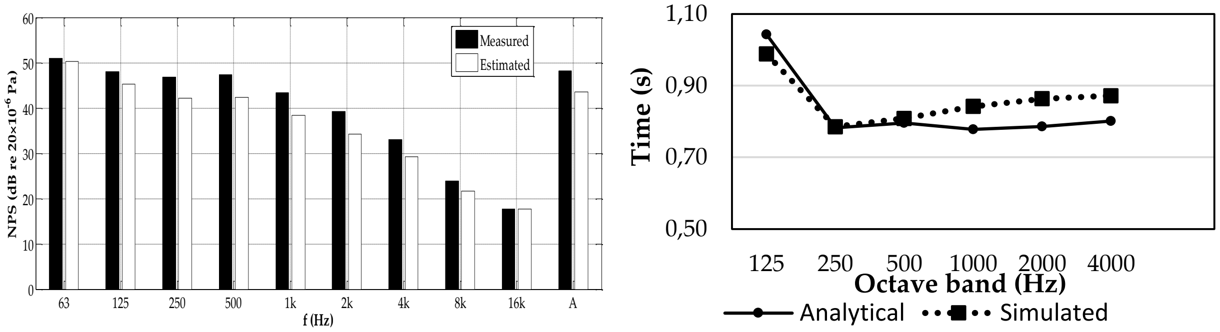

Figure 2: Background noise levels measured (black) and estimated (white) after the application of the hypothetical acoustic treatment (Left). Classroom Reverberation times estimated by means of Sabine model and GA numerical method, after considering the designed acoustic treatment (Right).

4. GA simulations including the acoustic treatment

The creation of the GA model with the projected acoustic treatment considered the theoretical methods and the same absorption coefficients above mentioned. Scattering coefficients were assigned according to the dimensions of the elements presented in the model; leaving a default coefficient of 0.1 in all the frequency bands for big surfaces, as it is recommended by software User´s manual. The GA model including the acoustic treatment and the T_{60} obtained by means of GA simulations can be seen in Fig. 2 (right). The measurements results were used to estimate the Sabines per octave band required to achieve the desired reverberation times. The next step consisted in calculating the area of acoustic materials to be added, according to its corresponding octave band absorption coefficients and the geometry of the classroom. The materials selected were fiberglass of 4 inches thick protected by a decorative veil and a membrane resonator composed of a 4 mm plywood sheet, with a 7.5 cm cavity and 25 mm of mineral wool on the partition. In order to place the acoustic material on room walls, three hypothetic panels (A, B and C) were designed. Panels A and B corresponded to the fiberglass supported in a 5 cm width frame, with the same thickness of the absorbent material and the following dimensions for panel A, 1 m x 2.16 m and 0.7 m x 2.16 m for panel B. Panel C was given by the membrane resonator with dimensions of 1m x 2.16m. The classroom with the acoustic treatment designed can be seen in Fig. 3.

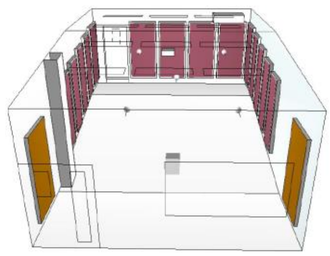

Figure 3: GA model of the classroom including the hypothetic acoustic treatment, simulated in software CATT-Acoustic.

Table 2: Listening difficulty scale adapted from Sato´s (2005).

0	No difficulty
1	Little difficulty
2	Moderate difficulty
3	Much difficulty

In order to add background noise a practical approach had to be proposed, taking into account that the same signal-to-noise ratio for each source-receiver combination had to be achieved for both acoustic conditions: existing and calculated. For a particular source-receiver combination, the background noise was calculated from the direct and reverberant sound pressure levels in the classroom. In order to do that, the first step consisted of estimating the acoustic power level of the source considering a typical spectrum and directivity factor of a male voice speaking at normal loudness.

5. Intelligibility and listening difficulty subjective test

To assess subjectively the present conditions of a classroom and the impact of implementing an acoustic treatment, a comparative exploratory study was conducted using auralizations and a sample of 40 people. The classroom acoustics was taken as an independent variable in two different situations (present and with acoustic treatment), and as dependent variables, intelligibility and listening difficulty were assessed. The first situation corresponded to the current acoustic conditions, characterized by BIR measurements, at five different receiver positions distributed inside the classroom. The second condition considered the same receiver positions in a numerical GA simulation, but this time an acoustic treatment has been included in the classroom. In order to evaluate the influence of background noise over the dependent variables, the study was carried out again; nonetheless, this time background noise was added to the auralizations.

In the intelligibility test, each participant was assigned one of the five receiver positions in the classroom, thus eight people evaluated each source-receiver combination. The auralizations corresponding to both conditions were reproduced in the recording studio, by means of binaural reproduction system OPSODIS. In the test form, the participant wrote the logatom they were able to understand. Intelligibility was assessed according to the percentage of correctly written words. Participants were asked to rate the listening difficulty of each word, according to Table 2.

6. Auralizations of the classroom

Four groups of auralizations were created in order to evaluate the influence of the acoustical conditions of background noise and reverberation times over the variables of intelligibility and listening difficulty. The first group of auralizations were considered as the reference ones, created by means of BIR measurements to have a characterization of the classroom with the existing acoustical conditions. The second group consisted of the auralizations of the classroom considering the acoustic treatment. These two groups were created including a background noise level of 48 dBA. The other two groups considered the same auralizations created in the first two groups but with a background noise level of 43.6 dB, included for both conditions.

The equipment for the measurement consisted of a two-way active loudspeaker JBL EON15 G2, a dummy head of reference Cortex MK2B from the manufacturer 01dB and the excitation signal was a Log Sine Sweep from 20Hz to 20kHz. The measurements were done without furniture or persons inside the room. In the sound generation stage, a male voice reading six lists of 40 phonetically balanced logatoms [4] was used to create the sound signals. The lists were recorded at the Recording studio of San Buenaventura University. The background noise was recorded on the centre position of the classroom, using a dummy head. For the inclusion of background noise, the OPSODIS as sound reproduction system was used [5].

7. Results

This section presents the results obtained by the application of the subjective tests assessing intelligibility and listening difficulty, all based on auralizations as well as the reverberation time *T20* obtained from measurements and numerical approaches. According to the test design, both parameters (INT and LDFF from now on), were evaluated with existing acoustical conditions (denoted PRE) and considering an acoustic treatment (symbolized by POS). The test was applied twice, including background noise (denoted NOI) in the second one. Figures 4 and 5 illustrate the spatially averaged estimates of INT and LDFF subjective assessments of the classroom. Tables 3 and 4 describe the correlation between each pair of data assessed for INT and LDFF, respectively. Finally, Fig. 6 illustrates the proportion of students assessing more than 50% of LDFF for all the situations considered.

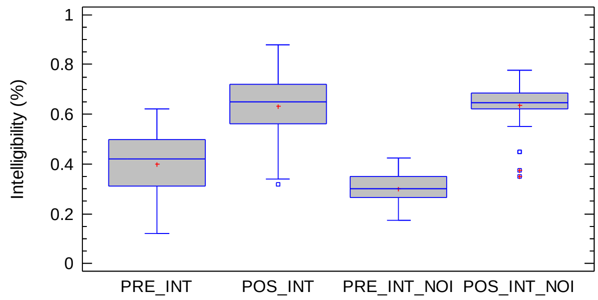

Figure 4: Spatial average estimates of Intelligibility subjective assessments of the classroom. The results for existing acoustical conditions and taking into account the hypothetical acoustic treatment denoted as PRE_INT and POS_INT, respectively. The results including background noise for both conditions symbolized as PRE_INT_NOI and POS_INT_NOI.

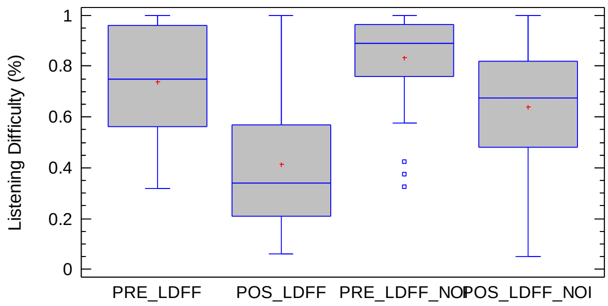

Figure 5: Spatial average estimates of Listening Difficulty subjective assessment of the classroom. The results for existing acoustical conditions and taking into account the hypothetic acoustic treatment denoted as PRE_LDFF and POS_ LDFF, respectively. The results including background noise for both conditions symbolized as PRE_ LDFF _NOI and POS_ LDFF _NOI.

Table 3: Pearson correlation coefficient between each pair of Intelligibility tests results, the number of pairs of data values used to compute each coefficient and the P-value testing the statistical significance of the estimated correlations.

	PRE_INT	**POS_INT**	**PRE_INT_NOI**	**POS_INT_NOI**
PRE_INT		7.44 E-01	1.05 E-01	-2.83 E-01
		(40)	(40)	(40)
		5.00 E-06	5.21 E-01	7.70 E-02
POS_INT	7.44,E-01		-2.47 E-01	-5.18 E-01
	(40)		(40)	(40)
	3.00 E-07		1.25 E-01	6.00 E-04
PRE_INT_NOI	1.05 E-01	-2.47 E-01		5.22 E-01
	(40)	(40)		(40)
	5.21 E-01	1.25 E-01		6.00 E-04
POS_INT_NOI	-2.83 E-01	-5.18 E-01	5.22 E-01	
	(40)	(40)	(40)	
	7.70 E-02	6.00 E-04	6.00 E-04	

Table 4: Pearson correlation coefficient between each pair of Listening Difficulty tests results. the number of pairs of data values used to compute each coefficient and the P-value testing the statistical significance of the estimated correlations

	PRE_INT	**POS_INT**	**PRE_INT_NOI**	**POS_INT_NOI**
PRE_INT		6.92 E-01	1.75 E-01	1.16 E-01
		(40)	(40)	(40)
		5.00 E-06	2.81 E-01	4.75 E-01
POS_INT	6.92 E-01		1.50 E-01	9.63 E-02
	(40)		(40)	(40)
	7.00 E-07		3.57 E-01	5.54 E-01
PRE_INT_NOI	1.75 E-01	1.50 E-01		8.07 E-01
	(40)	(40)		(40)
	2.81 E-01	3.57 E-01		4.00 E+06
POS_INT_NOI	1.16 E-01	9.63 E-02	8.07 E-01	
	(40)	(40)	(40)	
	4.75 E-01	5.54 E-01	1.00 E-06	

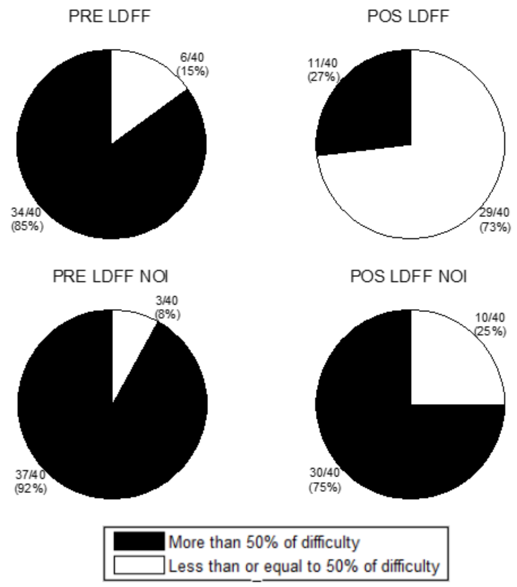

Figure 6: Listening difficulty test results. showing the proportion of students assessing more than 50% of difficulty for all conditions.

8. Discussion

Figure 4 clearly illustrate a significant improvement of intelligibility when the subjective assessment includes the designed acoustic treatment. According to the rating scale of ISO 9921. when the scenario without background noise is considered. the spatially averaged intelligibility with existing conditions is assessed as poor (40%); in contrast with the results obtained when the acoustic treatment is considered. which is evaluated as fair (63%). When the background noise is included in the auralizations. similar results are perceived between current and hypothetic acoustical conditions. scoring once again as poor (30%) and fair (64%) respectively; although a more significant difference is given by the numerical implementation of the acoustic treatment. which improves in this case by 10% more the intelligibility assessment. Table 3 shows an analysis of correlation coefficients between each pair of variables to quantify the strength of their linear relationship. The underlined number is the p-value. which below 0.05 indicates. with a confidence level of 95.0%. a statistically significant non-zero correlation. Considering this. it is possible to distinguish an acceptable positive correlation between PRE_INT and POS_INT variables. having a Pearson correlation value of 0.7438. A linear regression analysis gives a coefficient of determination of 0.5532. in order to explain the variability of the intelligibility in the classroom given by the change of the reverberation times. taking into account the existing conditions and the virtual implementation of an acoustic treatment.

In terms of listening difficulty. Fig. 5 shows the positive effect of the implementation of a virtual acoustic treatment for both situations. Without background noise. the Listening Difficulty is reduced from a spatially averaged of 74% to 41%. which gives an improvement of 33%. In the second scenario. the addition of background noise increases the Listening Difficulty to 83% when existing acoustical conditions are considered. In this case. a spatially averaged of 64% is obtained with the acoustic treatment. having a less significant decrease of 19%. It is possible to see by looking at the statistical indicators variation. how the dispersion increases when the hypothetical treatment is considered no matter the presence of background noise. The last ideas suggest that both acoustic dependent variables affect the listening difficulty; although. when the proportion of student´s rating in all conditions is more than 50% of difficulty as illustrated (see Fig. 6). it is possible to distinguish that the presence of background noise along with the reverberation have a significant influence on this dependent variable. In this aspect. it is important to note that all the receiver positions analysed are in the reverberant field of the room. which means that the signal-to-noise ratio is dependent of background noise levels and the corresponding reverberant field contribution. Considering this. the signal-to-noise ratio estimates for both scenarios provide similar results of about ±1dB at each source-receiver combination. which indicates that background noise presents a similar behaviour with existing and hypothetical acoustic conditions. The analysis of correlation coefficients between each pair of Listening Difficulty test results can be seen in Table 4. In this case. a positive significant statistical correlation is distinguished between PRE_LDFF_NOI and POS_LDFF_NOI variables. with a Pearson correlation value of 0.8069. A linear regression analysis gives a coefficient of determination of 0.651. which is a statistical measure indicating how well the variability of the listening difficulty in the classroom. might be explained by the change of the reverberation times in the presence of background noise. considering existing conditions and the virtual implementation of an acoustic treatment.

9. Conclusions

A simple approach to incorporate binaural background noise to auralizations applying binaural technology for reproduction was evidenced. In this sense. it was possible to include and control the sound level reproduction of binaural recorded background noise. It is important to bear in mind that this approach not allow to include synthesized binaural noise.

Intelligibility was more affected by reverberation time than background noise level. Taking into consideration the rating scale of ISO 9921. the intelligibility was assessed as poor with existing acoustic conditions and fair. when the acoustic treatment was considered. no matter whether background noise was included or not in the auralizations. On the other hand, the listening difficulty assessment results suggested the influence of both acoustic variables. although. a more significant impact was given by the presence of background noise. since a high percentage average was obtained even with the hypothetical acoustic condition having a short reverberation time.

It was demonstrated that an acceptable positive correlation between existing conditions and the virtual implementation of an acoustic treatment. In the first case. the variability of the intelligibility in the classroom given by the change of the reverberation times could be explained by a linear regression. when background noise is not included in the auralizations. In the second case. the variability of the listening difficulty in the presence of background noise might be explained by a linear regression. having the reverberation time as an independent variable. These ideas indicate that there is a potential in order to study the variability of intelligibility and listening difficulty. given by the modification of acoustic variables. by means of statistical models based on subjective assessment results of virtual sound environments.

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