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Revista Argentina de Ciencia y Tecnología

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Can coupling effects between outdoor noise and standing waves affect intelligibility in a classroom?

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ABSTRACT

Background noise level and reverberation time are the standard parameters used to evaluate speech understanding in a classroom. This space can be excited by an outdoor source of noise even when it has an acoustic treatment. The room geometry, usually rectangular, creates differences in the signal-to-noise ratio S/N between all listening positions due to eigenmodes. In the present study, 5 listening positions are used in a standard size classroom excited by a virtual source of pink noise. This source is placed in a corner to represent an external noise source. Using the matrix sentence method developed by Hochmuth et al. [Int. J. of Audiology, 51, 536–544 (2012)], 300 sentences from a virtual speaker are used as the signal source located at the opposite corner. In the reference point at the center of the room speech source is adjusted to a LAeq of 65 dBA. Noise source is adjusted to reach a A-weighted S/N (S/N(A)) of approximately -3 dB at this point. The level difference among the positions is less than 3.2 dB considering the S/N(A) but can reach more than 8 dB considering the S/N. Both sources are recorded simultaneously with a dummy head in all positions. A subjective test is then performed with headphones to evaluate intelligibility in these listening points. Room acoustic parameters for intelligibility, D50, STI, S/N and S/N(A), are compared with the subjective test results. Results show that speech recognition is different between all points but no correlation can be found with the objective parameters. In this context, intelligibility is not being affected by room eigenmodes.

KEY WORDS

Speech intelligibility, classroom, eigenmodes, subjective test.

INTRODUCTION

Effects of noise on intelligibility in classrooms have been studied for more than 40 years. In 2003, Shield and Dockrell made an extensive review on the effect of noise on children at school [1]. All the previous studies concluded that noise highly affects children performances at school. Some more recent works showed the effect of noise on comprehension and recognition memory in children [2-5]. Although they are less susceptible to poor acoustic conditions, learning task and comprehension of adults are also disturbed in a noisy environment [6,7]. Bradley insisted over the importance of several intelligibility parameters that can be obtained through measurements or numerical simulation according to the room impulse response and the signal-to-noise ratio (S/N) [7,8]. Then, Yang and Bradley showed that the main parameter for a good intelligibility, in a subject with normal hearing, is the A-weighted speech-noise level difference, S/N(A) [9]. The excess of background noise and a high reverberation time not only affect intelligibility, but they are also main factors in the quality and effectiveness of learning of students in classrooms [10,11]. It is nowadays generally accepted that appropriate acoustic conditions are necessary to facilitate learning. In fact, some countries consider the T30 and the S/N as acoustical criteria to be controlled to have good intelligibility [12,13].

Although many schools are built near noise sources, not all the countries have requirements and guidelines for it. Particularly in Argentina and other South American countries, many schools and universities are built close to sources of transportation noise. These external noise sources have a rich content of low frequencies [14,15] and can directly excite the eigenmodes of a classroom. Furthermore, some internal source of noise (projectors, fans, and computers) or other parts of the building (vibrations, air conditioning systems) can also increase the noise level in a classroom. In warmest days of the year, when the temperature can reach nearly 40°C, these internal noise sources are louder and the windows are open because not all the schools have an air conditioning system. Thus background noise has a stronger influence on classroom acoustics [16].

Advanced analytical models or numerical simulation can be used to more precisely describe low frequencies even if the room is not parallelepipedical [17,18]. The eigenmodes create variations of the sound pressure level among different listening positions in a small enclosure like a classroom. However, these positions are not always taken into account in room acoustic parameters determination, including intelligibility parameters [19]. The procedure only determines that the measurement positions shall be away from reflective surfaces. It is important to highlight that many students choose to sit close to the walls where the level of low frequencies is higher. Furthermore, they only consider a frequency range where room eigenmodes do not affect the sound pressure distribution in a standard size classroom. However, the presence of lower frequencies from an internal or external noise sources can create acoustic masking of speech information [20,21].

As stated above, no studies on intelligibility have been considering the standing waves in a small enclosure like a classroom. Therefore, this work aims to investigate if intelligibility is affected by the eigenmodes of a room excited by an external noise source. Both speech and noise sources were reproduced from loudspeakers and binaurally recorded with a dummy head at typical listening positions in a classroom. Then a speech intelligibility test using phonetically balanced sentences was conducted. Some intelligibility parameters and S/N were analyzed and compared with the subjective test results.

METHODOLOGY

Noise and speech sources

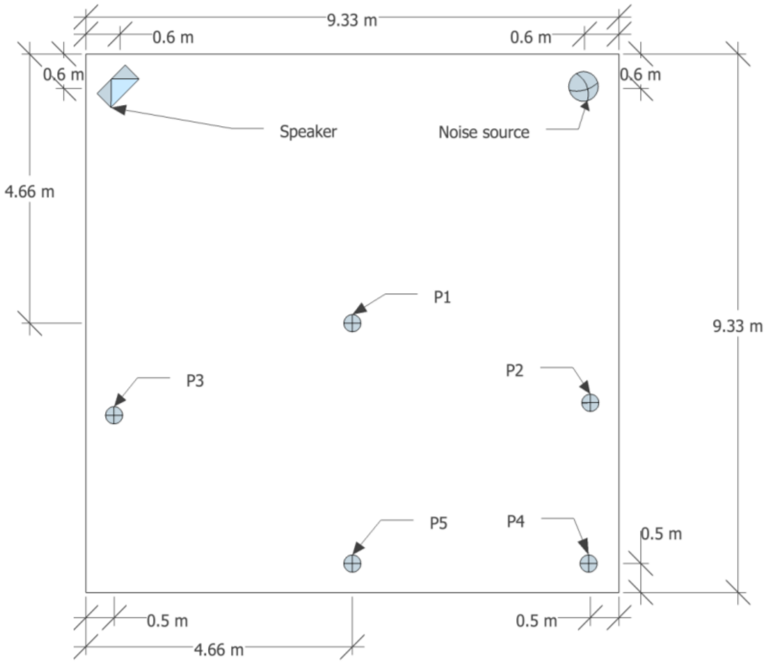
The effect of eigenmodes excited by an external source of noise was evaluated under a simulated acoustic condition. Figure 1 shows the source and listening positions. A pink noise was reproduced from an omnidirectional loudspeaker placed in a corner of a room in order to excite all the room eigenmodes. It simulates an external noise coupled with other internal sources of noise. A speech signal was reproduced from a directional loudspeaker in the opposite corner representing a sitting teacher. Each source and each listening point are located respectively at 1.2 m and 1 m above the floor. Reference position P1 is chosen at the centre of the room where the standing waves effect is expected to be lower. P2 and P3 are located in front of the speech and the noise sources, respectively. These positions are at the same distance from P1. P4 and P5 are located in a corner and at the middle of rear wall. All the positions except P1 are 0.5 m away from a wall. The main objective of this study is to evaluate if there are differences in speech recognition between all the listening points.

As the speech source, sentences were selected rather than isolated words in order to simulate a real classroom condition. These sentences come from the Spanish Matrix Sentence Test for assessing speech reception thresholds (SRT) in noise [22]. This method has been selected to create a balanced number of syllables within sentences and to match the Spanish specific phoneme distribution. The SRT is defined as the signal-to-noise ratio corresponding to 50% of intelligibility. Previous works on speech intelligibility showed that the SRT for normal hearing subjects is between -10 and -5 dB [23].

The speech and noise signal levels were then adjusted to a S/N(A) of approximately -3 dB at reference point P1. In all the other points it is expected a worst S/N(A).

The impulse responses for the omnidirectional source at the noise source position were measured at each receiver position, and the room acoustic parameters T_{30}, STI and D_{50} were evaluated. As explained above, the standard [19] does not take into account some receiver positions of interest for this study. Four of five positions do not fulfil the minimum distance to reflective planes.

Figure 1: Sources and listening positions (classroom of 2.5 m high).



Sourse: Own elaboration.

A Dynaudio BM6A was used to reproduce the speech signals although the directivity index differs from that of a person. At the reference point P1, the speech level was adjusted to an equivalent sound pressure level LAeq of 65 dBA with a Class 1 sound level meter. A list of 20 sentences form the sentence matrix was used to adjust and measure the LAeq. Then, the noise signal was also reproduced to reach a S/N(A) of approximately -3 dB at this position. These sentences are recorded and used for the level adjustment of the subjective test.

In total 300 sentences from the matrix have been carefully selected to avoid too similar sentences. They have been previously recorded in a recording studio by a male speaker and adjusted to have a maximum level difference of 6 dB across subsequent words as explained in [22].

All the sentences were then recorded with a dummy head at each listening position. The dummy head were oriented toward the front wall, not the speech source. While recording, the source of noise was emitting the constant background pink noise to recreate artificially the outdoor noise.

Subjective test

The test was conducted in a quiet place. The background noise level in the test room was controlled to be 20 dB lower than the signal played through the headphones in each octave band from 63 to 4000 Hz. This frequency range is considered as the range of interest for the study due to the sources characteristics. The stimuli were presented through Audio Technica ATH-D40fs headphones. The level of the speech signal (the list of 20 sentences explained in Section 2.1) was adjusted at both ears by using a dummy head to reach the previously measured LAeq. This corresponds to the situation of the classroom measurements.

The test was performed with a GUI interface and self-conducted. Each subject listened to 10 sentences for each position in a random sequence. Thus it consists of 50 sentences randomly extracted from the 300 sentences recorded at each listening position. The subject could reproduce and listen to each sentence only once. The subjects were asked to write down the sentences they listened to.

The first 20 sentences (4 for each point) were just used as a training session and were not included for the later analysis. This is necessary to obtain reliable and reproducible results [22]. The last 30 sentences were used for the analysis. The test duration was approximately 15 min.

OBJECTIVE PARAMETERS AT LISTENING POSITIONS

Background noise and speech source levels

Table 1 shows the results of the sound pressure level measurement at each point for each source measured separately. The level difference among the positions is less than 3.2 dB considering the S/N(A) but can reach more than 8 dB considering the S/N.

Figure 2 shows the differences between both sources in Z-weighted octave bands for P1 and P5. Since P5 was closer to a wall than P1 the quantity of eigenmodes was higher in this position. It can create more acoustic masking of speech even if the frequency range is not exactly the same as the speech signal.

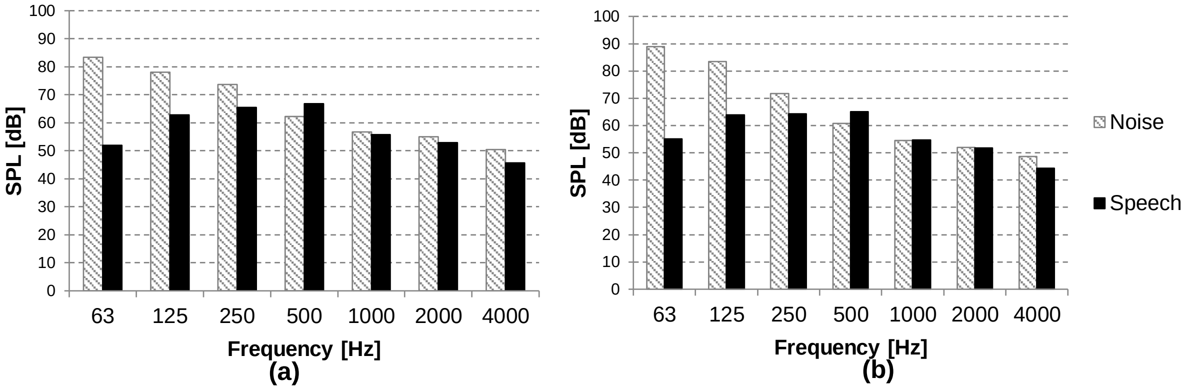
Table 1: Sound pressure Levels and S/N measured at each point.

Position	Source	Leq [dBA]	Leq [dB]	S/N (A) [dB]	S/N [dB]
1	Noise	67.8	84.7	-2.8	-11.8
	Speech	65.0	72.9		
2	Noise	69.3	86.4	-6	-16.8
	Speech	63.3	69.6		

3	Noise	68.9	90.1	-3.9	-18.7
	Speech	65.0	71.4		
4	Noise	68.5	91.4	-4.7	-20.0
	Speech	63.8	71.4		
5	Noise	69.4	90.1	-5.8	-20.1
	Speech	63.6	70.0		

Source: Own elaboration.

Figure 2: Speech and noise levels at P1 (a) and P5 (b).

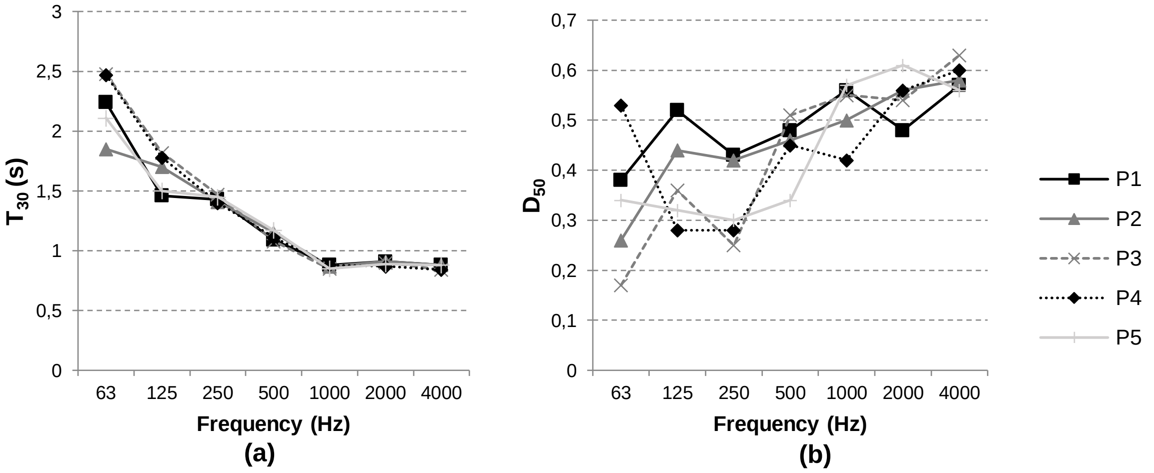


Source: Own elaboration.

Room acoustic parameters

Figure 3 shows the results of T_{30} and D_{50} at each position. Only the values for the left channel are represented because the values for the right channel showed similar results. T_{30} in this classroom is too long considering the ANSI recommendations [12] but do not differ between each point. No conclusion can be drawn for D_{50} due to the variations among the positions and frequency bands.

Figure 3: T30 (a) and D50 (b) at each position (Left channel).



Source: Own elaboration.

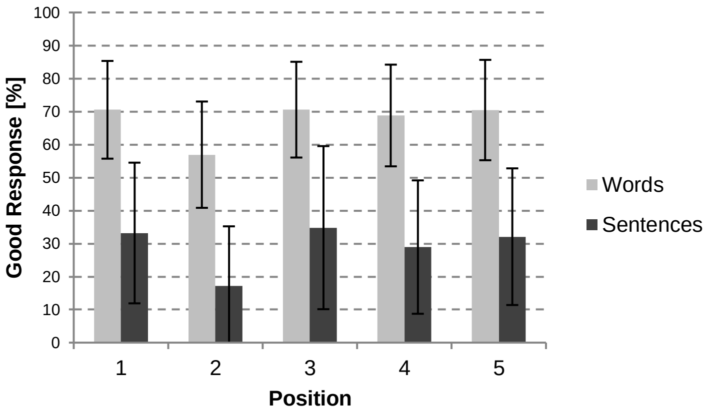
Measurements of STI gave logical results according to the long reverberation time. In this room the intelligibility is quite poor giving a value of 0.60 (s.d.: ± 0.01) at all listening positions. This STI measurement was done without the noise source since S/N without weighting was close to 15 dB at all positions. The STI with the noise source would give worse results; in all cases clearly below the recommendations.

RESULTS OF THE SUBJECTIVE TEST

Forty-nine subjects participated in the subjective test. Only results from the students of high school or university were considered for the analysis. It corresponds to a total of forty subjects aged between 13 and 35 years old with a mean age of 24 years old. They informed that at least two years before the test they did an audiologic study and do not suffer any hearing loss. Results have been analysed considering two conditions: the amount of words recognized and the number of complete sentences identified. Figure 4 shows the results of good responses (GR) in each case. The standard deviation is higher for the sentence identification. This result was expected because the S/N is low and the attention of the subjects can fluctuate during the length of the test. Considering this fact, no subjects have been discarded for the analysis.

The normality of the obtained data was tested with the Kolmogorov-Smirnov's test ($p < 0.05$) for both sentences and words recognition. In all cases results are showing no significant deviation from normality.

Figure 4: Good response of words and sentences for each position.



Source: Own elaboration.

The correlation between objective parameters and subjective results were then analyzed. Table 2 shows that no correlation can be found, even with a significance level of 0.05. For T_{30} and D_{50} parameters a mean value have been calculated from values in each octave band from 63 to 4000 Hz.

Table 2: Correlation between objective parameters and subjective results.

	S/N	S/N(A)	T_{30}	D_{50}	GR Words	GR Sentences
S/N	1					
S/N(A)	0.642	1				
T_{30}	-0.363	0.373	1			
D_{50}	0.848	0.517	-0.415	1		
GR Words	-0.082	0.581	0.428	-0.119	1	
GR Sentences	0.032	0.683	0.486	-0.113	0.973**	1

** $p < 0.01$, * $p < 0.05$.

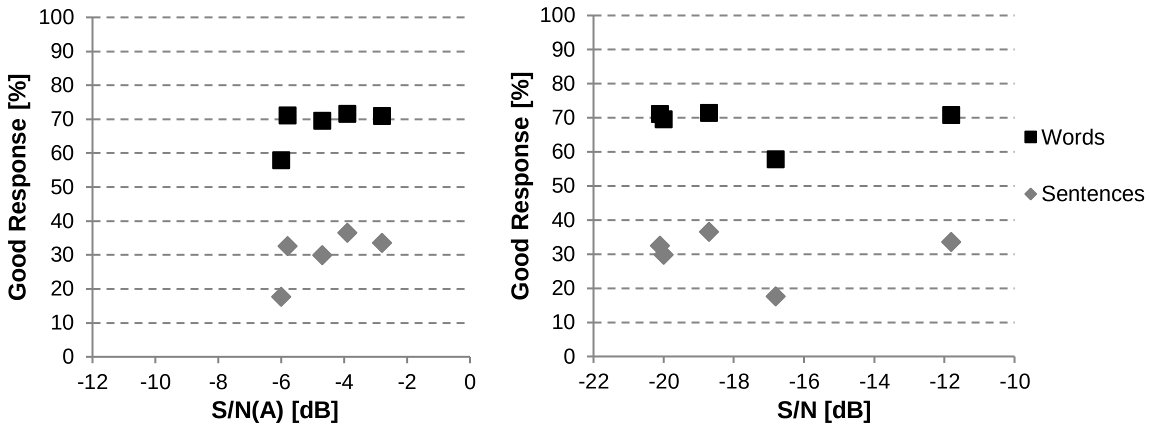
Source: Own elaboration.

DISCUSSION

The repetition of each sentence is not the same since their selection was done randomly and only forty subjects were evaluated. On average, each sentence of the 300 sentences has been listened only 4.5 times (s.d.: 3.4). However, the correlation between good responses of words and sentences is significantly high ($r = 0.983$, $p < 0.01$). It confirms that the Matrix Sentence Test is useful and that the effect of sentences is not significant.

According to previous results a high correlation between the subjective test results and the S/N(A) was expected. Figure 5 shows that even with differences between speech and noise levels (varying between -2.8 to -6 dBA or between -11.8 to -20.1 dB), the percentage of good responses of the subjective test do not change. In [22], it has been shown that for the open-set method (when subject must identify the words in an unlimited number of response alternative, method used in this work) the speech recognition should decrease when the S/N decrease (Figure 6). This tendency is not confirmed in the present study.

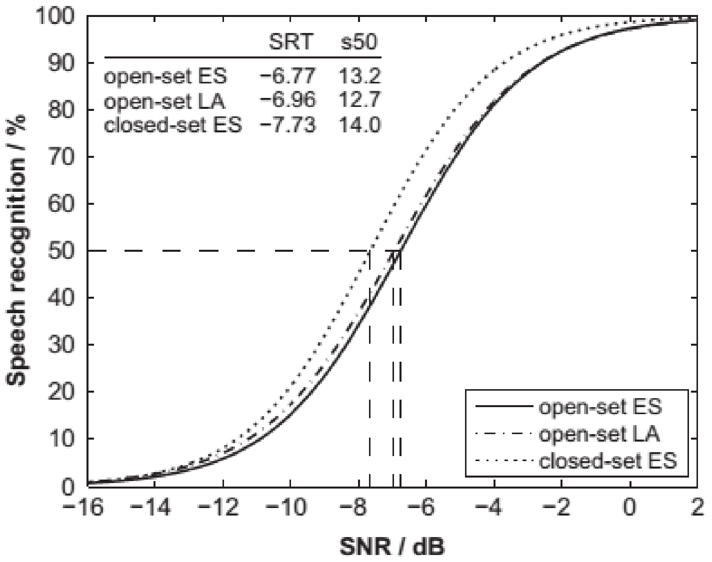
Figure 5: Relationship between subjective results and the S/N(A) (a) and S/N (b).



(a) (b)

Source: Own elaboration.

Figure 6: Speech recognition curves derived from the measurements at fixed S/N for Spanish (ES) and Latin-American (LA) subjects using open-set test format (solid and dash-dotted line, respectively) and Spanish subjects using closed-set test format (dotted line). The dashed lines indicate the SRT of each recognition curve. SRTs in dB S/R and slopes (s50) in %/dB are given.



Source: Hochmuth et al., 2012.

The effect of low frequencies on intelligibility is not verified in this condition but an ANOVA analysis shows that the effect of position is highly significant (F = 10.0; df = 1,4; p < 0.001).

The main difference in this study with the previous works is that binaural signals were used for the test. Previous studies showed that the effect of binaural hearing is important in speech intelligibility [24, 25]. The interaural time differences (ITD) and the interaural level differences (ILD) have clear effects on speech recognition in a noisy environment. The dummy head used for recordings was always oriented to the front wall of the room, not to the speech source. Differences in ITD and ILD are present in all listening positions but have not been analysed. Further analysis should be done on the objective parameters to find a correlation with the subjective results.

CONCLUSIONS

This research aimed to study if intelligibility is affected by the eigenmodes of a room excited by an external noise source. Signals from a source of noise and a speech source were recorded with a dummy head in five listening positions of a classroom. In total, 300 sentences were used for a speech recognition test. Results show in this case that the low frequencies do not affect speech understanding even if level difference among the positions can reach more than 8 dB considering the S/N due to a higher quantity of eigenmodes. However, some differences in speech recognition have been obtained due to the listening position. No correlations were found between the subjective test and the room acoustic parameters T_{30}, STI and D_{50}.

More subjects should be used to ensure the tendency that has been obtained in this work although the Matrix Sentence Test results being useful for this study.

Possible effects of binaural hearing have been pointed out but a further analysis is necessary to confirm this hypothesis.

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