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Acoustical characterization of the central mosque of Lisbon

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Summary
This paper presents the acoustical characterization of the Central Mosque of Lisbon. *In situ* measurements were done regarding Reverberation Time, RASTI and background noise associated with traffic. The analysis of the results is shown as a comparison with results in other mosques and Catholic churches, which have a similar volume.

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1. Central Mosque of Lisbon

1.1. Building characterization

The Lisbon Central Mosque (inaugurated in 1985) was designed by the architects António Braga and João Conceição and was possible due the help of many Islamic countries [1].
The mosque (Figures 1 and 2), located in Lisbon José Malhoa Avenue, is divided in three different parts with four floors and a basement. The Main and the Women prayer halls are located in the third and fourth floors (Figures 3 and 4).
In the Main prayer hall the walls and the pillars are finished with reflecting materials such as marble, tiles, bricks. Some walls and the ceiling are finished with painted plaster. In the centre of this hall is a dome and the floor area is covered with heavy carpets.
The long side wall of the hall (*Qibla*) is oriented towards Mecca. This wall includes a recess in its centre in the form of a wall niche (*Mihrab*) finished with reflecting materials (tiles) (Figure 4). The *Minbar* (Figure 4) is located in front of the *Mihrab* and is an elevated floor where the *Iman* preaches and delivers the Friday sermon, the *Khutba*.
The windows have small openings which permit the passage of outside noise [2].
The mosque does not have either air conditioning or mechanical ventilation. The sound reinforcement systems (SRS) are constituted by four loudspeakers in the corner of the hall, eight smaller loudspeakers in the dome and four loudspeakers located in the top of each central corner (the two loudspeakers localized in back of the hall were not working during the *in situ* measurements). All the loudspeakers were directed to the Main prayer hall, none of them were targeted to the Women prayer hall (at an upper mezzanine level).

Figure 1 – Central Mosque of Lisbon: Minaret (centre), dome of Main prayer hall (left) and dome of library (right).

Figure 2 – Central Mosque of Lisbon (Façade).

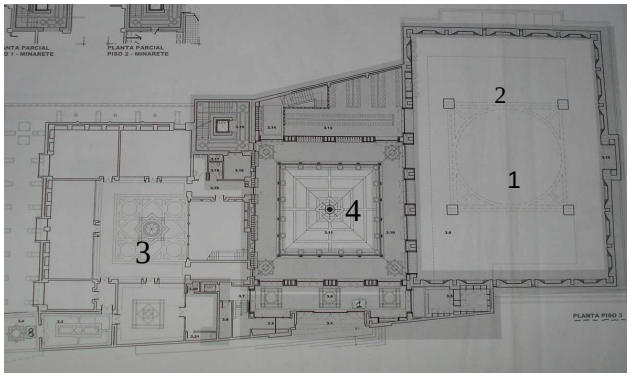

Figure 3 – Floor plan of Lisbon Mosque: 1-Main Prayer Hall (3rd floor); 2- Women Prayer Hall (4th floor); 3-Library; 4- Courtyard. Total area = 2760 m^2; 3rd floor area = 1393 m^2; 4th floor area = 1053 m^2; Volume (prayer halls) = 6040 m^3; maximum height = 15.4 m; capacity ≈ 950 people (≈ 750 men; 200 women).

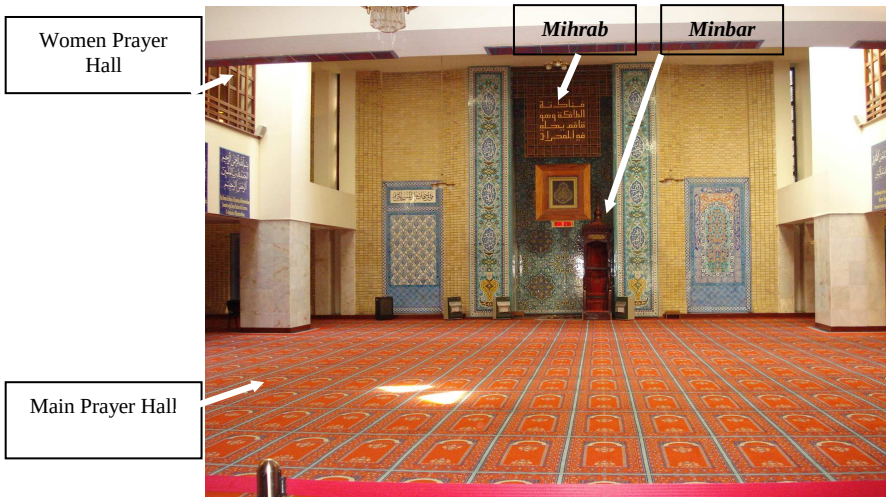

Figure 4 – Main and Women player halls in the Central Mosque of Lisbon.

1.2. Measurements

1.2.1. Introduction

The *in situ* measurements were carried out in March 2010 in the unoccupied prayer halls with *Brüel & Kjaer* equipments: hand-held analyzer 2260, sound calibrator 4231, ½" microphone 4189, sound source 4224 and RASTI meter 3361. The analyses were done in both the Main and Women prayers halls because, due religious reasons, the women must perform prayers in separated halls [3].

1.2.2. Reverberation time

The reverberation time (RT) was measured for 1/1 octave frequency bands between 125 and 4k Hz in the two prayer halls (Table I). In the Main prayer hall six different points were selected in half of the room because it is symmetric. In the Women prayer hall the measurements were made only in one of the two similar rooms, in three different positions. The RT average at mid-frequencies (500-1k Hz) for the Main prayer hall was 2.8 s and in the Women hall was 2.6 s. The difference between these two values can be explained due to the greater volume of the Main prayer hall when compared with the Women hall. However, it is important to underline that these spaces are separated merely by open wooden slats (Figure 4).

The RT values are lower at high frequencies (Table I) due to the heavy carpet in the floor and the huge volume of air.

The level of dispersion of RT values in each frequency band (Table I) is very low due to the certain standardization of values in the different position in the Main prayer room. In the Women Hall there is a larger dispersion of values at the lower frequencies. However, in the others frequencies the dispersion is insignificant (Table I).

The RT values are influenced by the reflecting materials covering all the interior surfaces, the central dome and the overall large volume.

Some authors recommend for this kind of space the same ideal RT values advised for rooms where the speech intelligibility is important (about 1 s). Other authors made some curves with ideal RT values in function of volume for mosques. For a volume of 6040 m^3 (Mosque of Lisbon) Orfali and Kayili [4, 5] recommend a RT of 2.0 s.

The measured RT values in the Mosque of Lisbon are higher than the usually recommended ones, but the values obtained in the Women prayer Hall are closer to those ideals.

Table I – Average values of Reverberation Time (RT) in both prayer halls.

Prayer Hall	RT (s)	Frequency Band (Hz)					
		125	250	500	1k	2k	4k
Main (Men)	$RT_{average}$	2.3	2.5	2.9	2.7	1.9	1.5
	St. deviation	0.14	0.07	0.08	0.11	0.11	0.14
Women	$RT_{average}$	2.1	2,3	2.7	2.5	1.5	1.1
	St. deviation	0.21	0.21	0.04	0.05	0.06	0.06

1.2.3. RASTI

For the RASTI measurements the sound source was placed 2.65 m from the *Mihrab*. Nine positions on the Main prayer hall and three points in the Women hall were selected. In each point three lectures were done and then averaged. The measurements were done with and without the use of the Sound Reinforcement Systems (SRS) (Table II).

Without the SRS, for the Main prayer hall an average RASTI of 0.48 was obtained (*fair* level of speech intelligibility) while in the Women prayer hall was 0.38 (*poor* level of speech intelligibility).

In the Main prayer hall positions 1 and 2, located in front of the sound source, present a *good* level of speech intelligibility (Table II).

It appears, as one move away from the sound source that the speech intelligibility tends to decrease. However, position 3, situated in the first row in the front corner of the prayer hall, presents lower speech intelligibility than in position 4 in front of the sound source in the second row of measurements.

At the same row of measurements it was verified that as one move away to the corner of the room the speech intelligibility decreases and this reduction varies less at the positions located in the back of room.

In the Women prayer hall there are lower differences among the positions than in the Main prayer hall. This situation can be explained due to the bigger distance between sound source and the evaluated positions, and being smaller the relative distance among positions.

With the SRS being operated, the Main prayer hall obtained an average RASTI of 0.47, slightly lower than in the previous situation (SRS off), while in the Women prayer hall the average RASTI become 0.44, closer to the *fair* speech intelligibility level.

Table II presents the variations of RASTI values in the different positions at both prayer halls. In the Main prayer hall, positions 3 and 9 have the highest levels of RASTI because they are located closer to the loudspeakers situated in the corner of the hall. In relation to the previous situation (SRS off), the speech intelligibility level in the positions in front of the RASTI sound source decreased. At the other points in the room a slight loss of speech intelligibility is seen in the middle of the hall and a small improvement at the positions in the back room.

At the Women prayer hall the RASTI values present a smaller variation among the three positions, however, there is a slight improvement due to the loudspeakers located in the dome and in the top corners in the centre of the hall which permit a certain sound regularity in the centre space. The loss of speech intelligibility in the Main prayer hall can be explained due to the inappropriate location of the loudspeakers which increases the number of reflections causing more delayed reflections with a considerable intensity.

To conclude, there is no appropriate improvement in having the SRS on.

Table II – RASTI values measured in the Main and Women prayer halls, with and without the Sound Reinforcement System (SRS).

Prayer Hall	Positions	RASTI			
		Without SRS		With SRS	
		Position avg	Room avg	Position avg	Room avg
Main (Men)	1	0.71	0.48	0.48	0.47
	2	0.63		0.43	
	3	0.41		0.52	
	4	0.50		0.47	
	5	0.46		0.46	
	6	0.37		0.45	
	7	0.43		0.47	
	8	0.41		0.46	
	9	0.39		0.52	
Women	1	0.40	0.38	0.46	0.44
	2	0.37		0.42	
	3	0.36		0.44	

1.2.4. Sound pressure level of background noise

This mosque is located among noisy streets due to traffic and aircraft flyovers (every three minutes passes an airplane). For that reason, measurements were done during 15 minutes to stabilize the background noise present in the room, in two positions in each prayer hall. The sound pressure levels were analyzed between 63 and 16k Hz frequency bands (Table III).

The background noise in the two rooms was very similar because there are not sufficient heavy elements separating them. For the Main and the Women prayer halls, a sound pressure level of 59 dB and a sound pressure of 49 dB(A) were obtained (Table III).

Table III – Background sound levels and sound pressure levels measured in each point in Main and Women prayer halls due to traffic.

Frequency band (Hz)	Main hall		Women's hall	
	$L_{average}$ (dB)	L_A (dB)	$L_{average}$ (dB)	L_A (dB)
63	57.1	31.1	57.1	31.1
125	50.7	35.2	50.4	34.9
250	48.3	39.8	48.2	39.7
500	48.4	45.4	48.3	45.3
1k	44.0	44.0	43.8	43.8
2k	36.8	37.8	36.7	37.7
4k	26.7	27.7	26.6	27.6
8k	18.0	17.0	17.8	16.8
16k	12.7	5.7	12.7	5.7
∑	59.0	49.0	58.9	48.9

2. COMPARISON WITH OTHER MOSQUES AND CHURCHES WITH SIMILAR VOLUME

2.1. Comparison with other mosques

To evaluate the acoustic behaviour of the Mosque of Lisbon in relation to other mosques around the world, a comparison was done with values from a group of some mosques (Table IV) [6 to 12].

In relation to RT (500-1k H values, a regression function was traced out with the values obtained in the other mosques ($R^2 = 0.91$) (Figure 5a).

According to the volume of Lisbon mosque (6040 m^3) it presents a RT discrepancy of 0.9 s when compared to the predicted RT value obtained with that function (1.9 s). The mosque of Lisbon does not follow the trend of other mosques, having a higher estimated RT value (2.8 s) for this type of building.

For the parameters RASTI/STI (Table IV) there are two different situations: without and with the SRS being operated. For the first situation (without SRS) the average values obtained in the mosques around the world present a variation between 0.30 and 0.58, which means, that in these places the speech intelligibility varies between *poor* and *fair* intelligibility. The mosque of Lisbon presents an average RASTI of 0.48, higher than the average mosques (0.44).

When the SRS is operating, the majority of mosques have an average RASTI/STI better than without the use of SRS. However, there are some cases (TH 32, 27 and 48) like the Mosque of Lisbon whose sound system is not totally appropriated to the hall and decreases the level of speech intelligibility. The mosque of Lisbon has an average RASTI of 0.47, lower than the average for the other mosques (0.49). So according to this situation, the Central Mosque of Lisbon presents slightly better internal building characteristics than the majority of mosques for speech intelligibility and with an appropriate sound system could improve the intelligibility achieving values higher than the value obtained for the average mosque.

The mosque of Lisbon has a background noise level of 49 dB(A), higher than the other mosques (Figure 5b). On the other hand, the majority of these mosques present sound levels lower than 40 dB(A).

Table IV – Reverberation Time and RASTI values for some mosques around the world and Mosque Central of Lisbon.

Mosque				Vol. (m^3)	RT(s) 500-1k Hz	RASTI-STI avg	
Name			#			No SRS	With SRS
King Abddullah, Amman [6]			1	34000	2.0	-	0.70
State of Kuwait [7]			2	150000	6.9	0.30	0.38
Istambul [8]	Suleymanie		3	115000	5.8	-	-
	Selymie		4	79300	5.4	-	-
	Sokullu		5	5700	2.3	-	-
	S.Sergius-Bacchus		6	14900	3.4	-	-
Saudi Arabia [9]	A	TH16	7	633	2.0	0.40	0.48
		TH32				0.48	0.45
		DM242				0.43	0.43
		TH27				0.46	0.45
	B	TH48	8	1288	1.3	0.58	0.56
		DM16				0.45	0.51
		DM260				0.45	0.54
		KH45				0.44	0.45
		KH17				0.47	0.54
	C	KH03	9	1821	1.1	0.50	0.53
		TH42				0.42	0.44
		KH12				0.47	0.48
		DH14				0.40	0.51
	D	DM125	10	2203	1.7	0.51	0.57
		KH59				0.49	0.58
		TH06				0.37	0.48
		DM06				0.41	0.51
	E	DH03	11	6142	2.1	0.38	0.45
		TH13				0.47	0.49
		TH01				0.38	-
	F	DM43	12	23390	2.6	0.35	0.37
Models [10]	Rectangle		13	1659	1.6	0.50	-
	Square					0.53	-
Atlanta, USA [11]			14	6370	1.5	-	-
Darussholah, Indonesia [12]			-	-	-	0.50	-
Lisbon [1]			15	6040	2.8	0.48	0.47

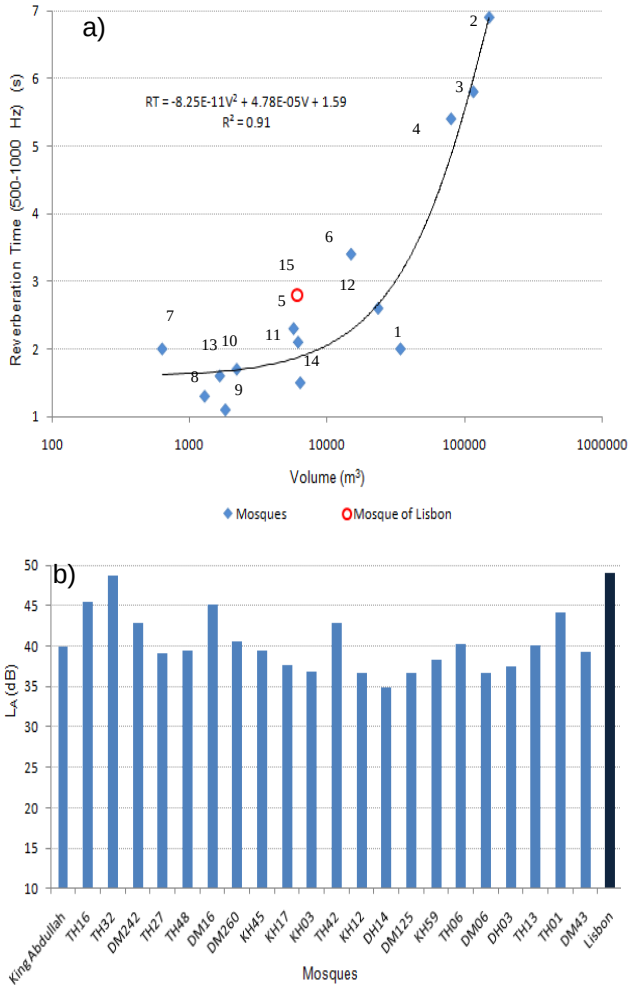

Figure 5 – Comparison among world mosques: a) RT values in function of Volume with their regression function (R^2 = 0.91); b) Interior background noise levels.

However, all the mosques have background noise levels higher than the recommended.
The mosque of Lisbon presents a worst acoustical behaviour than in average the other mosques around the world with similar volume, in the analyzed aspects.

2.2. Comparison with churches having similar volume

The Portuguese Catholic churches with similar volume than the Lisbon Mosque, present an average value of RT higher than that mosque (Table V and Figure 6) [13].
With the group of churches analyzed a regression function was found (R^2 = 0.31). For the volume of the Central Mosque of Lisbon (6040 m^3) a RT of 3.9 s was expected, higher than the value measured in the mosque (2.8 s). This situation agrees with the acoustics goals, because the mosque is used only for speech while in the Catholic churches it is preferable to have a little higher RT values because of music and songs/hymns.

Table V – RT (500-1k Hz) and RASTI (without SRS being operated) average values, for the Mosque of Lisbon compared with Portuguese Catholic churches with similar Volume [13].

Church		V (m^3)	H_{max} (m)	RT(s) 500-1k Hz	RASTI avg
Name	#				
Clérigos, Porto	1	5130	20.0	3.4	0.39
Sta Clara, V. Conde	-	5394	13.8	-	0.44
Matriz Golegã	2	5563	13.7	3.6	0.39
Matriz Caminha	3	5899	14.4	2.9	0.42
Salvador, Penafiel	4	6028	16.8	2.9	0.39
S. João Baptista, Porto	-	6048	16.7	-	0.42
S.João Baptista, Moura	5	6300	13.4	6.6	0.32
Bustêlo, Penafiel	6	6476	16.1	4.1	0.36
St. Sacramento, Porto	7	6816	15.5	5.0	0.33
Azurara, V. Conde	-	7212	15.0	-	0.41
Mosque, Lisbon	O	6040	15.4	2.8	0.47

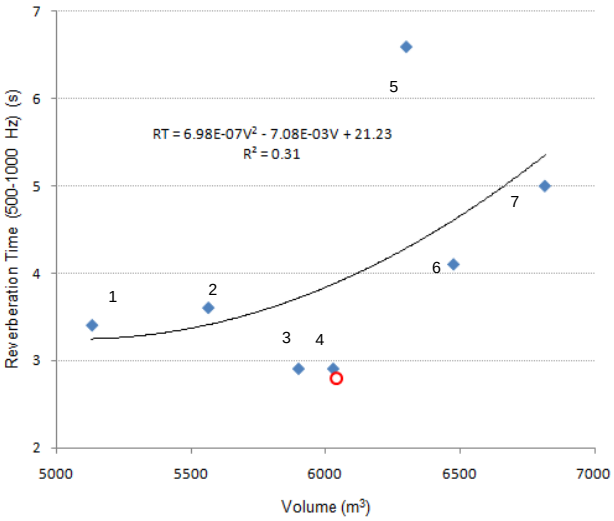

Figure 6 – RT (500-1k Hz) in function of Volume for Portuguese Catholic churches with volumes between 5100 and 7300 m^3 and their regression function (R^2 = 0.31).

The mosque of Lisbon presents an average RASTI (without SRS) of 0.48, higher than the verified in Catholic churches with similar volume (0.39) (Table V and Figure 7). This reveals a better speech intelligibility level in mosques than in Catholic churches (with similar Volume).

To conclude, the mosque of Lisbon presents a better acoustical behaviour than Catholic churches with similar volume, being therefore more appropriate for speech.

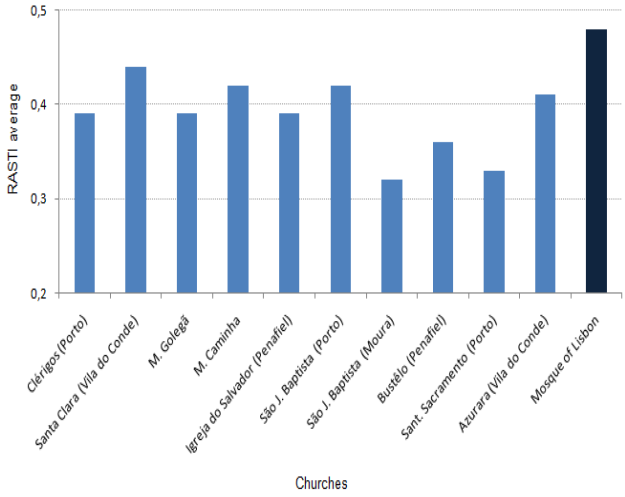

Figure 7 – RASTI average values (without SRS) in the Mosque of Lisbon and in the Portuguese Catholic churches with similar volume.

3. Conclusions

The Central Mosque of Lisbon presents an average RT (500-1k Hz) of 2.8 s, a little higher when compared with the value recommended by some authors (≈ 2 s).

For the RASTI two situations were tested: Without and With the SRS being operated. For the first situation the speech intelligibility level was classified as *Fair* (avg. 0.48) in the Main prayer hall while in the Women hall the level was *poor* (avg. 0.38). When the SRS was operating, the RASTI average decreased to 0.47 and in the Women hall that value increased to 0.44 closer to a *Fair* classification. So, the SRS is not totally appropriate for those halls.

In relation to the background noise, a sound level of 49 dB(A) was obtained due to the weak airborne noise insulation face to aircraft and traffic noise.

The Mosque of Lisbon presents an acoustical behavior a little worst than other mosques in the world and better than Portuguese Catholic churches both controlling for a similar room volume.

Acknowledgments

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