ACOUSTIC CHARACTERIZATION OF ACOUSTIC VASES IN THE SYNAGOGUE OF TOMAR, PORTUGAL

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ABSTRACT

This work presents the *in situ* characterization of the acoustic effect of eight resonant vases, embedded in the walls of the 15th century Synagogue of Tomar (Portugal). The measurement of Reverberation Time (RT) with and without the occlusion of the acoustic vases (achieved by lids of black cork agglomerate coated on the outside with aluminum sheet) showed a very small effectiveness. In global average terms (all frequencies, all points' average), the room's RT changed from 4.89 s (closed vases) to 4.80 s (open vases) in an empty room (overall reduction of 1.4%). Per 1/3 octave frequency band, a small reduction in the reverberation time values was found in almost all frequency bands (except 160, 500, 1250, 2000, 3150 and 5000 Hz). The biggest RT reductions were in the 125 and 250 Hz bands (about 0.5 s or 9%). The acoustic resonance frequency in those cavity resonators was found between 100 and 200 Hz.

Figure 1. Interior of the synagogue, with a view of the vaults with edges based on the four pillars, the corbels, the various decorative interior elements and the seating arrangement [9].

1. INTRODUCTION

After the 11th century some churches (and not only) included in their interior ceramic vases open to the interior of the space, positioned in the domes and/or on walls perhaps in an attempt to improve the acoustic problems of the space and its effectiveness has been studied [1-7].

The Synagogue of Tomar (ST) was built in the 14th century and in 1496 it was closed and devoid of religious functions when Jews were expelled from Portugal. In 1946 it was classified as a National Monument and in 2019, after rehabilitation, it opened to the public (Figure 1).

Currently, the synagogue has two holes in each upper corner, which correspond to the nozzles of eight clay jars placed inside the walls and facing downwards (Figures 2 and 3, and Table 1). The acoustic vases are in dissimilar positions (vases numbers 1 and 8 are at an average height of approximately 4.40 m; numbers 2 and 3 at 4.15 m; numbers 4 and 5 at 4.25 m and numbers 6 and 7 at 5.30 m) (Figure 4) [8].

The aim of this project is to obtain data for a possible answer to the question: "Do acoustic vases improve the sound quality of the place?"

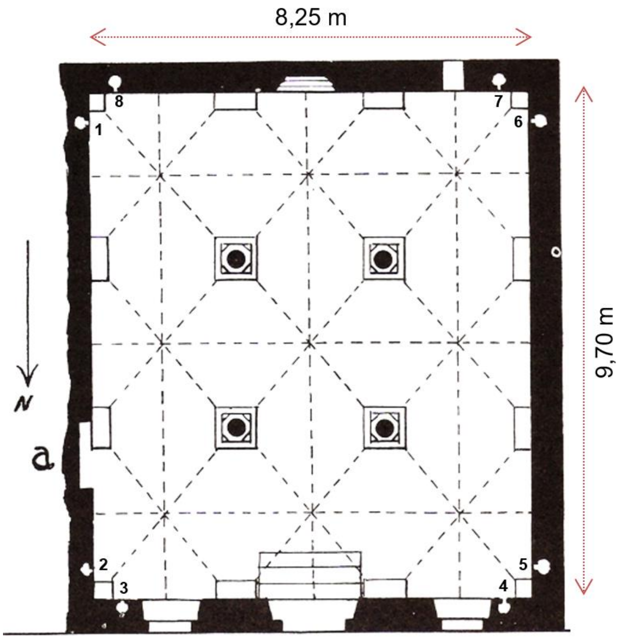

Figure 2. Synagogue plan, with detail of the acoustic vases locations and adopted numbering [10].

Figure 3. Acoustic vases: on the left the interior of one of the vases; on the right one of the uncovered vase [8].

Vase	Bottleneck area (S) [mm²]	Inside air volume (V) [dm³]	Bottleneck length (L) [mm]	Bottleneck radius (r) [mm]	Resonance frequency (f) [Hz]
1	8215.3	11.8	62.5	51.2	120
2	6486.3	4.5	34.0	45.5	200
3	8199.2	10.6	45.5	51.	134
4	8215.3	9.1	68.2	51.2	134
5	6486.3	10.1	68.2	45.5	116
6	8215.3	9.9	68.2	51.2	128
7	6486.3	9.9	79.5	45.5	113
8	6486.3	8.9	68.2	45.5	124

Table 1. Acoustic vases [8] and frequency of their maximum effectiveness.

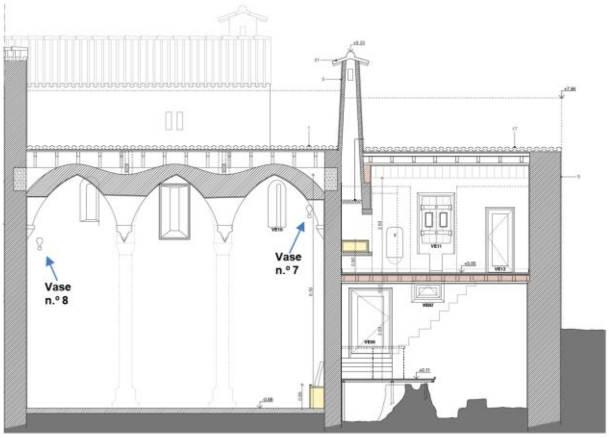

Figure 4. ST cut, check the asymmetry of the placement of acoustic vases 7 and 8 (marked with arrows) [11].

2. METHODOLOGY

The tests include the measurement of the reverberation time values *with* and *without* the occlusion of the vases' openings. The occlusion of the acoustic vases was achieved with the use of “lids” made of black cork agglomerate (30 mm thick and 100 kg/m^3), cut to the right size, encrusted and coated from the outside with aluminium adhesive tape to neutralize or minimize the possible sound absorption of the lids (Figure 5).

The measurements consisted of placing a sound source and recording the decay of the sound emitted, in various places within the synagogue where listeners would be, at their approximate height (1.40 m). The principle of symmetry of values in space was assumed and measurements were taken in half of the room at seven reference points (Figure 6).

Figure 5. Occlusion of acoustic vases, using "lids" of black cork agglomerated and externally covered with aluminum foil.

Figure 6. Location of the sound source (F) and the positions of the sound level meter for recording RT values (A, B, C and D represent the reading points near the corners and points 1, 2 and 3 represent the reading points in the center the room).

The B&K 4224 sound source emitted between 100 and 5 kHz, placed on the floor and positioned at an angle of about 35 degrees towards the center of the space, and the B&K 2260 sound meter calculated the RT values (Figure 7).

Figure 7. Sound source and sound level meter to perform RT measurements.

3. RESULTS

The acoustic "efficacy" of the vases, in relation to RT values, is presented as the difference between the RT value obtained *without* the occlusion of the vases' opening and the value obtained *with* the occlusion of the vases. It would therefore be considered acoustically "beneficial" if this difference were negative, thus pointing to a decrease in the RT values caused by the action of the acoustic vases.

3.1 In the corners of the room (points *A*, *B*, *C* and *D*)

The RT values in the corners named as *A*, *B*, *C* and *D* (Figure 6) tend to be higher at low frequencies and lower at high frequencies (Figure 8). The maximum RT value was 7.00 s for the 250 Hz frequency band, obtained in corner *A* with the jugs closed. The minimum value of RT was 2.46 s for the frequency band of 5 kHz obtained in corner *A* with open jugs.

The mean RT values tend to decrease after the frequency band of 250 Hz, starting with values close to 6 s and reaching the minimum values at high frequencies (Figure 8).

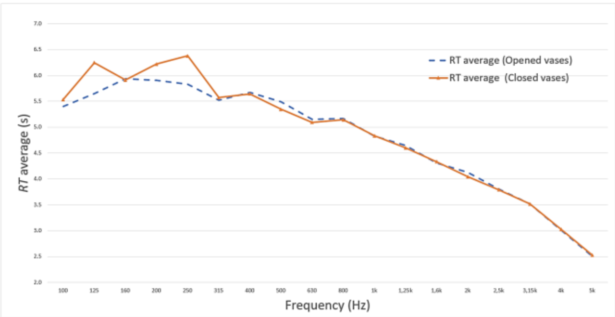

Figure 8. Average of the RT values with the opened and closed vases, by frequency band in the four corners (A, B, C and D).

With the vases closed, in frequency bands above 315 Hz, the RT assumes very similar values in all corners, with values that tend to decrease from approximately 5.5 s.

With open vases, at frequencies above 630 Hz, the RT assumes very similar values in all corners, with values decreasing since approximately 5 s.

The most "beneficial" effect obtained by opening the vases (negative difference in the measured RT values) are found in the frequency bands of 125 and 250 Hz, with an average decrease of about 0.57 in the RT values (Figure 8).

The most "harmful" effect obtained by opening the vases (positive difference in the measured RT values) is found in the 500 Hz frequency band, with a slight average increase of 0.14 s in the RT value (Figure 9).

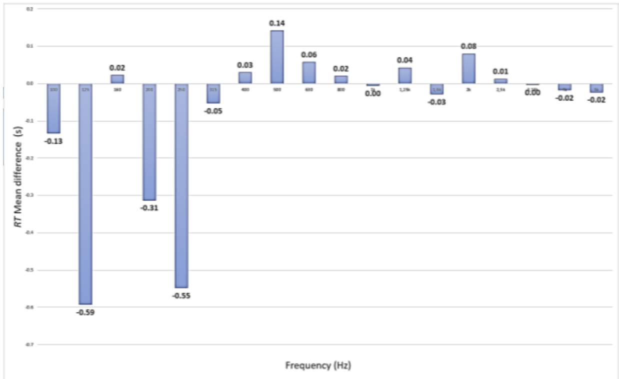

Figure 9. RT mean difference between *opened* and *closed* vases in the four corners (*A*, *B*, *C* and *D*). Negative values represent acoustic improvements due to the opening of the vases (decrease in RT value).

Points *A* and *D* are the ones that present the "best" average results of the RT values due to the opening of the acoustic vases, whose average benefits are a decrease of about 0.15 s in the RT. Point *B* shows an average "harmful" result, with a slight average increase of 0.06 s in the RT. At point *C* the differences are "beneficial" but only with a slight average decrease of 0.05 s in the RT.

The differences found in the RT values, at each point, with respect to the influence of the opening of the vases, demonstrate that:

- At point *A*, the greatest decreases in the RT values are concentrated in low frequencies up to 315 Hz, with reductions of almost 1 s, except in the 160 Hz band, which presents an increase of 0.44 s. Between 400 and 630 Hz there were increases in the value of RT, which reach more than 0.50 s in the 400 Hz band;
- In point *B* there is an increase of 0.80 s in the value of RT in the band of 160 Hz and the most significant reductions are only around 0.50 s in low frequencies;
- At point *C*, there are some decreases in the value of RT at low frequencies, never exceeding 0.65 s. The increases are always less than 0.25 s;
- In point *D*, the records show that in the great majority of low frequency bands the effect of opening the vases is "beneficial", with reductions that do not exceed 0.86 s.

3.2 Inside the room (points *1*, *2* and *3*)

Among locations *1*, *2* and *3* (Figure 6) the RT values tend to be higher at low frequencies and lower at high frequencies (Figure 11). The maximum RT value was 7.09 s for the 125 Hz frequency band obtained in the point *3* with the vases closed. The minimum RT value was 2.46 s in the 5 kHz frequency band obtained in the point *3* with the vases closed.

The mean values of the RT tend to decrease after the 400 Hz frequency band, starting with values close to 6 s and reaching the minimum values at high frequencies (Figure 10).

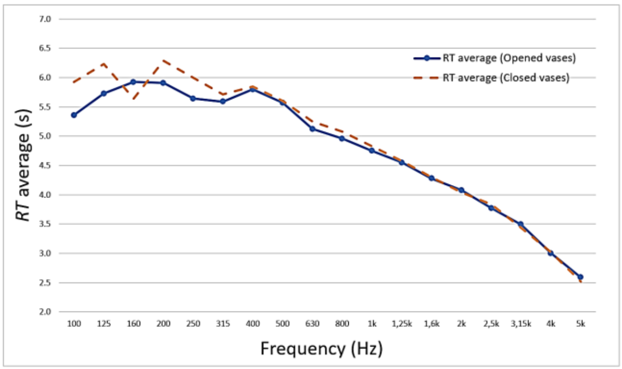

Figure 10. Average of the RT values by frequency band, with the vases *opened* and *closed*, at points *1*, *2* and *3*.

With the vases *closed*, in frequency bands above 250 Hz, the RT assumes similar values in all points of the room, with values that tend to decrease since approximately 6 s. With the vases *uncovered*, at frequencies above 200 Hz, the RT assumes similar values in all points of the room, with values decreasing from approximately 6 s.

The most "beneficial" effect obtained by opening the vases (negative difference in the RT values) is found in the frequency bands of 100 and 125 Hz, with an average decrease of about 0.54 s in the RT. The most "harmful" effect obtained by opening the vases (positive difference in the *RT* values) is found in the 160 Hz frequency band, with an average increase of 0.28 s, in the RT (Figure 11).

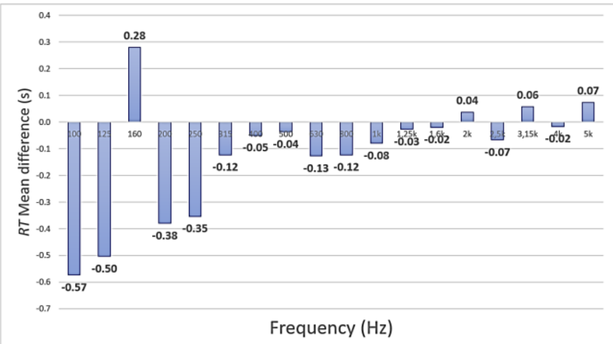

Figure 11. RT mean difference between *opened* and *closed* vases at the central points of the room (*1*, *2* and *3*). Negative values represent acoustic improvements due to the opening of the vases (decrease in RT value).

All points *1*, *2* and *3* of the room present "beneficial" average results of the RT values by opening the acoustic vases, with a decrease of 0.20 s, 0.02 s and 0.12 s, respectively.

The differences in the RT values, in each point of the room, with respect to the influence of the opening of the vases, demonstrate that:

- In point *1*, most records point to a decrease in RT value, whose highest value occurs in the 200 Hz band, with a reduction of 1.27 s;
- Point *2* shows a highlight increase of 0.78 s in RT value in the 160 Hz band. The reductions are slight with values never exceeding 0.39 s;
- In point *3* there is a significant decrease in RT, in the 100 Hz band of 1.59 s, but in the 160 Hz band there was an increase of 0.87 s.

3.3 All measurement points (*A*, *B*, *C*, *D*, *1*, *2*, and *3*)

With all seven measurement points (corners and center), the mean of the difference in RT values, with respect to the *opening* and *occlusion* of the acoustic vases, presents more expressive values for low frequencies. Noteworthy are the reductions seen in the frequency bands of 125 and 250 Hz, with average decreases in the RT of 0.55 and 0.46 s, respectively. The effectiveness of acoustic vases is not seen in some frequency bands, but the mean values of the increase in RT values are not greater than 0.13 s (Figure 12).

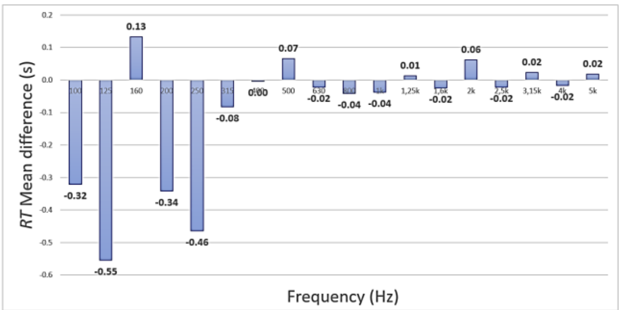

Figure 12. RT mean difference between *opened* and *closed* vases, considering all seven measurement points. Negative values represent acoustic improvements due to the opening of the vases (decrease in RT).

The global mean values show an increase in RT at low frequencies and, then, a tendency decrease for high frequencies. The minimum and the maximum mean values are approximately 2.50 s and 6.20 s respectively (Figure 13).

Table 1 shows the estimated values of the resonance frequencies for each existing vase (between 100 and 200 Hz) none of them coinciding with the 160 Hz that, according to the records and calculations shown in Table 2, is one of the frequency bands in which there is no decrease in RT when opening the acoustic vases. By comparing these theoretical data with the differences found *in situ* for these frequencies in the measured RT value (shown in Table 2) it is possible to state that this data is consistent with the measurements made.

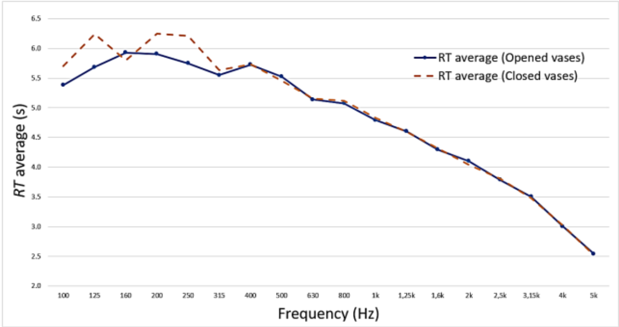

Figure 13. Global average values (all seven points) of the RT, with the vases *opened* and *closed*.

	RT Mean Difference (O-C) (s)								
Freq. (Hz)	A	B	C	D	1	2	3	Mean (s)	%
100	-0.89	0.13	0.25	-0.02	-0.25	0.12	-1.59	-0.32	-5.6
125	-0.92	0.06	-0.65	-0.86	-0.37	-0.32	-0.82	-0.55	-8.9
160	0.44	0.80	-0.55	-0.60	-0.81	0.78	0.87	0.13	2.3
200	-0.88	0.14	-0.19	-0.32	-1.27	0.01	0.12	-0.34	-5.5
250	-0.92	-0.58	-0.04	-0.65	-0.35	-0.37	-0.34	-0.46	-7.5
315	-0.52	0.28	-0.07	0.10	-0.08	-0.39	0.10	-0.08	-1.5
400	0.52	-0.50	0.02	0.08	0.02	0.00	-0.17	0.00	-0.1
500	0.15	0.25	0.20	-0.03	0.00	0.05	-0.16	0.07	1.2
630	0.34	0.00	-0.16	0.05	-0.26	-0.15	0.03	-0.02	-0.4
800	-0.16	0.54	-0.26	-0.04	-0.07	-0.25	-0.05	-0.04	-0.8
1k	-0.01	-0.09	-0.11	0.19	-0.04	-0.09	-0.11	-0.04	-0.8
1,25k	0.11	0.02	0.18	-0.14	-0.05	0.16	-0.19	0.01	0.3
1,6k	-0.07	-0.10	0.04	0.02	0.03	0.01	-0.10	-0.02	-0.6
2k	0.03	0.03	0.10	0.16	-0.06	0.05	0.12	0.06	1.5
2,5k	-0.08	0.03	0.13	-0.03	-0.13	-0.05	-0.02	-0.02	-0.6
3,15k	0.00	0.07	0.05	-0.13	-0.03	0.10	0.10	0.02	0.7
4k	-0.06	-0.05	0.10	-0.06	0.08	-0.09	-0.04	-0.02	-0.6
5k	-0.10	0.03	0.08	-0.10	0.03	0.07	0.12	0.02	0.7
	-0.17	0.06	-0.05	-0.13	-0.20	-0.02	-0.12	-0.09	-1.4
	RT mean difference of each point							Global Mean	

Table 2. RT mean difference between *opened* (O) and *closed* (C) vases at all measurement points, including the average of the differences at each point, the average by frequency, the percentage of variation and also the global average of registered changes (values with a green background indicate negative values, therefore "beneficial").

In global terms, this reduction is more significant at point *A*, with a decrease of 0.17 s in the average RT of all measured frequencies. It is also noteworthy that only at point *B* there is a total average that does not prove the favorable effectiveness of acoustic vases, with an increase of 0.06 s in the RT after opening them. These results are not justified by the characteristics and location of the vases existing in these locations (locations *A* and *B* symmetrical to the source and those closest to the source, slightly behind the point of emission.). Note that in corner *A* there are vases number *2* and *3*, with a combined volume of approximately 15.12 cm^3 and located at an average height of approximately 4.15 m. In corner *B*, there are vases *1* and *8*, with a volume of approximately 20.71 cm^3 and located at an average height of approximately 4.40 m. Although the volumes are a little different, this fact does not justify the results obtained since, in the other points located closer to the corners, where the acoustic vases are (*C* and *D*), the volume of the vases is 19.79 cm^3 and 19.21 cm^3 (values very similar to the existing vases in point *B*), respectively, and in these (*C* and *D*) there are reductions in the overall RT values.

Still in relation to the values determined in the corners of the cult room, it appears that points *A* and *D* are the ones that present the greatest reductions in the RT value. These points are the closest to the exit of the room, where the wooden door and the windows that communicate with the outside street are located, which may influence these results (putting in question the symmetrical agreement of the reading points according to the practically symmetrical plan of the room).

At point *C*, the acoustic vases are situated a little higher than the rest, at a value of approximately 5.30 m (practically 1.0 m above the rest). Although there was a global average reduction (including all frequencies) in the RT value at this point, this is quite reduced in relation to those observed in the other reading points in the corners where the acoustic efficiency of the vases is proven.

At the points located in the center of the room (*1*, *2* and *3*) there is a reduction in the RT value when opening the acoustic vases, also proving its effectiveness. The point *1*, with a reduction of 0.20 s in the average RT, contradicts the results obtained in point *B* (mentioned above) because it is also very close to this point and to the existing vases in this corner (vases *1* and *8*).

The volume of the room is approximately 473 m^3 and its interior surface is approximately 400 m^2. The simplified mathematical forecast of the average sound absorption coefficient of the room can be obtained by *Sabine's formula*. A frequency analysis (Table 3) shows which band has the greatest variations in the average sound absorption coefficient of the room.

	Opened vases		Closed vases		Absorption coefficient variation	
Freq. (Hz)	RT average (s)	Average absorption coefficient	RT average (s)	Average absorption coefficient	Absolute difference	Relative difference
100	5.38	0.035	5.70	0.033	0.0020	6%
125	5.68	0.033	6.24	0.030	**0.0030**	**10%**
160	5.93	0.032	5.80	0.033	-0.0007	-2%
200	5.91	0.032	6.25	0.030	0.0018	6%
250	5.75	0.033	6.21	0.030	0.0025	8%
315	5.55	0.034	5.63	0.034	0.0005	1%
400	5.73	0.033	5.73	0.033	0.0000	0%
500	5.52	0.034	5.46	0.035	-0.0004	-1%
630	5.14	0.037	5.16	0.037	0.0002	0%
800	5.08	0.037	5.12	0.037	0.0003	1%
1k	4.80	0.039	4.83	0.039	0.0003	1%
1,25k	4.60	0.041	4.59	0.041	-0.0001	0%
1,6k	4.30	0.044	4.32	0.044	0.0002	1%
2k	4.10	0.046	4.04	0.047	-0.0007	-1%
2,5k	3.79	0.050	3.81	0.050	0.0003	1%
3,15k	3.51	0.054	3.48	0.054	-0.0004	-1%
4k	3.01	0.063	3.02	0.063	0.0004	1%
5k	2.54	**0.074**	2.52	**0.075**	-0.0005	-1%

Table 3. Calculation of the average sound absorption coefficient, by frequency band, with vases are *opened* and *closed*, as well as the variation observed in their value (both in absolute and relative value). The color gradation indicates the highest values in green (in bold) and the lowest values in red.

As expected, the highest RT values imply the lowest sound absorption coefficients and these are mostly concentrated at low frequencies. However, despite the lower values of this coefficient, it is in the low frequencies that the greatest variations are evident, with increases that reach up to 10% (in the frequency band of 125 Hz, Table

3). At high frequencies, the variation is insignificant, with some records of decreases in the average sound absorption coefficient.

With average records *in situ* of almost 5 s (measurements with the room almost empty), this place does not have characteristics that allow a good understanding of speech. These (so high) values can be explained by the room's geometry and that its interior surfaces are mainly of very sound reflective materials (granite, painted grout, etc.).

Although, the room occupation with people (supposing 20 people) and with the vases open, the RT value would fall, with reductions that could reach 2.29 s (about 40%) in the octave band frequency of 500 Hz (values calculated). It would be expected, according to prediction, that the presence of people, on prayer days, would have led to an improvement in these values and, consequently, a better understanding of speech. In a comparative analysis, the variation in the RT values with people occupation with the occlusion of the vases was estimated. Results are again very similar to those obtained with open vases and that point to reductions that reach 2.29 s (about 40%) in the 500 Hz frequency octave band.

With the occupation of the room, it is possible to verify that the acoustic vases are more effective at low frequencies, mainly up to 250 Hz (with the exception of the 160 Hz band, as previously noted) (Table 4).

	Standing person	Closed vases	Open vases	Variation	
Freq. (Hz)	Localized absorption	Final RT average (s)	Final RT average (s)	Absolute difference (s)	Relative difference
100		4.43	4.24	-0.20	-4%
125	**0.19**	4.75	4.42	**-0.33**	**-7%**
160		4.49	4.57	0.08	2%
200		4.04	3.90	-0.15	-4%
250	**0.33**	4.03	3.83	-0.20	-5%
315		3.78	3.74	-0.04	-1%
400		3.44	3.44	0.00	0%
500	**0.44**	3.34	3.36	0.02	1%
630		3.23	3.22	-0.01	0%
800		3.26	3.25	-0.02	-1%
1k	**0.42**	3.15	3.13	-0.02	-1%
1,25k		3.04	3.05	0.01	0%
1,6k		2.83	2.82	-0.01	0%
2k	**0.46**	2.71	2.74	0.03	1%
2,5k		2.60	2.59	-0.01	0%
3,15k		2.60	2.61	0.01	0%
4k	**0.37**	2.33	2.32	-0.01	0%
5k		2.02	2.04	0.01	1%

Table 4. Frequency analysis of the estimated changes in the RT values, by the difference obtained between the *open* and *closed* vases, in the hypothesis of the existence of 20 people in the room. Color gradation for the relative variations in RT, where green indicates the largest reductions, yellow indicates the smallest reductions and red indicates increases in the RT.

To note the reductions in the 125 Hz band (0.33 s or about 7%) and in the 250 Hz band (0.20 s or about 4%). At high frequencies, the reductions are not significant.

These data show that the capacity of the room (in the hypothesis that there are 20 people inside) decreases the "effectiveness" of the acoustic vases in reducing the RT value. With the room empty, the maximum efficiency would point to a reduction of 0.55 s (around 9%) in the 125 Hz band, while with the capacity of the room the maximum efficiency would be a reduction of about 0.33 s (around 7%) in the 125 Hz band (Figure 14).

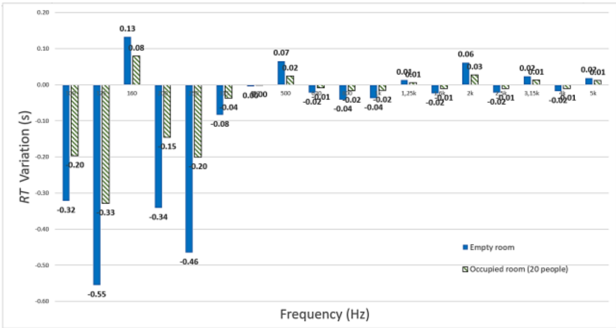

Figure 14. RT difference between *opened* and *closed* vases in situations where the measurement was performed with the room empty (bars in blue filled) and in the calculation estimate for the room occupied with 20 people (bars in green listed).

4. CONCLUSIONS

The RT measurements performed *with* and *without* the occlusion of the eight acoustic vases existing in the room prove a small effectiveness.

In global average terms, considering all frequencies, the RT value in the room is 4.89 s with the covered vases and 4.80 s with open vases, much higher than ideals (for speech) that would be less than 1.5 s. These high values have a greater contribution to low frequencies and are mainly related to the room's geometry and the reflective surface materials. Very high frequencies are those that present lower values (still above 2.5 s) mainly due to the air sound absorption (volume) at high frequencies.

The overall average reduction in the RT values (average of all frequencies and at all points in the room) was 0.09 s (or 1.4%). These average values do not reflect the true effectiveness of acoustic vases, which was evidenced in a detailed analysis by frequency bands.

An analysis by 1/3 octave frequency band shows a reduction in the RT values in practically all bands, except for those of 160, 500, 1250, 2000, 3150 and 5000 Hz. Note the reductions in the 125 Hz band (from 0.55 s or about 9%) and in the 250 Hz band (from 0.46 s or about 8%).

Still in relation to the measured values, in the corners of the cult room it is verified that points *A* and *D* present the greatest reductions in RT values. These points are the closest to the exit of the room, where the wooden door and the windows that communicate with the outside street are located, which can influence these results (putting into question the symmetry agreement of the measuring points according to the plan practically symmetrical (square) of the room).

At point *C*, the acoustic vases are located a little higher than the rest, at approximately 5.30 m (practically 1.0 m above the others). Although there was a global average reduction (including all frequencies) in the RT values at this point, this value is quite low in relation to those observed in the other points in the corners where the acoustic efficiency of the vases is proven.

At the points located in the center of the room (*1*, *2* and *3*) there is a reduction in the RT value when opening the acoustic vases, also proving its effectiveness. The point *1*, with a reduction of 0.20 s in the average RT, contradicts the results obtained in point *B* (mentioned above) because it is also very close to this point and to the existing vases in this corner (vases *1* and *8*).

The simplified mathematical forecast of the average sound absorption coefficient of the room points to a non-significant increase of about 0.001 (or 2%) in the overall sound absorption coefficient of the room by the action of the acoustic vases.

A finer analysis, by frequency band, makes it possible to show in which band the greatest variations in the average sound absorption coefficient of the room occur. In the low frequencies were obtained the lowest sound absorption coefficients (approximately 0.03 in the 100 to 400 Hz bands) and in the high frequencies were reached peaks of 0.07 (in the 5 kHz band). However, despite the lower values of this coefficient, it is in the low frequencies that the greatest variations are evidenced by the opening of the acoustic vases, with rises that reach up to 10% (variation of 0.003 in the frequency range of 125 Hz). At high frequencies the variation is negligible.

All the records presented so far have been made with the room practically empty. Was this the reality when the cult room was full of people for prayer, the most realistic and most interesting situation?

To answer this question, the existence of 20 people in the room was simulated. It was calculated that with the vases *open* or *closed*, the RT value would tend to be reduced, at most, by about 2.29 s (approximately 40%) in the octave frequency band of 500 Hz. The comparison by frequency band between *open* and *closed* vases, in a occupied room, states that acoustic vases would be more effective at low frequencies, mainly up to 250 Hz (with the exception of the 160 Hz band). Of note are the reductions in the 125 Hz band (0.33 s or about 7%) and in the 250 Hz band (0.20 s or about 4%). At high frequencies, the reductions are not significant. As expected and according to this forecast, the place's capacity on prayer days would have led to an improvement in the RT values and, consequently, a better understanding of speech. However, these data do not evidence the influence of room capacity on the effectiveness of acoustic vases.

The comparison between the effectiveness of acoustic vases in an *empty* or in an *occupied* room shows that people in the room decreases the relative effectiveness of acoustic vases in reducing the RT values. With the empty room, the maximum reduction would be around 0.55 s (9%) in the 125 Hz band while with the maximum room capacity the predictable reduction would be around 0.33 s (7%) in the 125 Hz band.

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