DOI: 10.61782/fa.2023.1032

ACOUSTIC CHARACTERIZATION OF CULTURAL HERITAGE BUILDING

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ABSTRACT

Polytheama Theater, located in the Jundiai city and founded in 1911, is one of the few centennial theaters still operating in Brazil. It's one of the main heritage cultural building listed by the Council for the Defense of the Historical, Archaeological, Artistic and Tourist heritage of São Paulo (CONDEPHAAT). In 1996, it was reopened after restoration according to the design of the by Lina Bo Bardi, renowned Italian-Brazilian architect. The acoustic room has 1124 seats, distributed among audience, boxes and gallery. Its stage is in Italian style. Its intense program contemplates the most diversified artistic presentations. This work presents the results of the first acoustic characterization of the Theater. The acoustic characterization was realized through acoustic measurements using the Dirac software. The acoustic parameters evaluated were: Reverberation Time, Early Decay Time, Clarity, and Definition as a function of frequency and Speech Transmission Index. The measurement points were distributed in the different sections of the theater, accounting for 38 points. From the analysis of the results of the acoustic parameters, it was possible to identify the sections of the theater with the best acoustic performance indicators. It was also possible to identify which activities best fit the acoustic behavior of the room.
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Keywords: *theatre acoustic, acoustical performance, reverberation time, heritage building.*

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1. INTRODUCTION

Few centennial theaters are still in operation in Brazil. In the city of Jundiaí, São Paulo state, one of the main historical, cultural, and architectural heritage of the city is the Polytheama Theater. Founded in 1911, it was listed in 2012 by CONDEPHAAT (Council for the Defense of Historical, Archaeological, Artistic, and Touristic Heritage of the State of São Paulo) in the Culture and Leisure category. Closed in 1975 for a period of 20 years, it was reopened in 1996 with a project by Lina Bo Bardi, the renowned Italian-Brazilian architect who also designed the MASP (São Paulo Museum of Art), a great São Paulo icon. Currently, the theater hosts various cultural activities such as music, dance, and theater, and can be classified as a multi-use theater. Throughout its existence, the theater has never been acoustically evaluated. This context motivated the acoustic study carried out on-site to identify its acoustic potential, given the variability of the space's use. The results of this study are presented in this work.

2. KNOWING THE THEATER

The performance hall of the Polytheama Theater has 1,124 seats distributed among sectors: 566 in the audience, 116 in boxes, 136 in private boxes, and another 306 in the Gallery. The volume of the theater is 11,260 m³. Its Italian-style stage has a proscenium arch with 14 meters in length, 8 meters in depth, and 8.90 meters in height. The curtain openings allow a clear span of 14 meters, and the height of the grid is 9.50 meters. Figures 1 show internal views of the theater.

Figure 1. Internal view of the theater

3. MEASUREMENT PROCEDURE

The acoustic characterization of Teatro Polytheama was based on the measurement of acoustic parameters: Reverberation Time (RT), Early Decay Time (EDT), Clarity (C_{80}), Definition (D_{50}), and Speech Transmission Index (STI). The parameters were obtained by the impulse response technique, using the Dirac software, Type 7841 from Bruel & Kjaer, for acoustic measurement of rooms. The measurement procedure was based on ISO 3382-1:2009 [1] standard. The acoustic parameters RT, EDT, C_{80}, and D_{50} were obtained as a function of frequency in 1/1 octave bands between the central frequencies of 125 to 4000 Hz. The receiver points were distributed by sector, namely: the audience, boxes, and gallery. As the theater is symmetrical, the receiver points were allocated only in one half of the environment. A total of 38 receiver points were used, divided into three regions as follows: 14 points in the audience area, 14 points in the box area, and 10 points in the gallery area. In addition, for data analysis, the sectors were divided into three areas according to the proximity to the source. Figures 2, 3, and 4 show the positioning of the sound source and receiver points used in the measurement. The colors in these figures indicate the sectors: orange represents the main audience area, green represents the boxes, and blue represents the gallery. The lighter colors indicate the area closest to the source, the intermediate color indicates the middle of the room, and the darker color indicates the farthest area from the source, at the back of the room. The measurement setup consisted of an omnidirectional source model Type 4296 from Bruel & Kjaer and two omnidirectional microphones model RTA-M-dbx connected to audio interface Presonus model Audiobox 44USL. The source (S1) was placed in the center of the stage at a height of 1.5 m, and the receivers (R1-38) were placed at a height of 1.20 m.

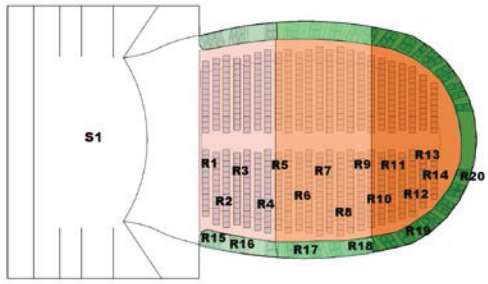

Figure 2. Position of receiver in the main audience and box seats at the ground floor.

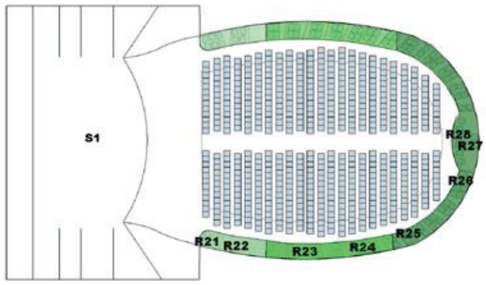

Figure 3. Position of receiver in the box seats at the first floor.

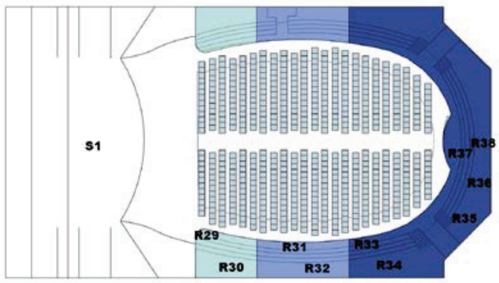

Figure 4. Position of receiver in the gallery at the second floor.

4. RESULTS AND DISCUSSION

The results and discussions are presented by acoustic parameter and also by sector and region of the theater.

4.1 Reverberation Time (RT)

To evaluate the appropriate reverberation time for use of the room, the optimal reverberation time at 500Hz was adopted as a criterion for various types of activity according to the volume of the room (Figure 5), as indicated by Metha et al. (1999) [2].

The Reverberation Time was measured as a function of frequency, in 1/1 octave bands. For the source positioned at the center of the stage, Figure 6, show the results of the average reverberation times and standard deviation for the audience seating area, the boxes, and the gallery.

In general, the behavior of the Reverberation Time as a function of frequency for the main audience seating area oscillates, having reached its lowest value at 250Hz and its highest values at 125 and 2000Hz.

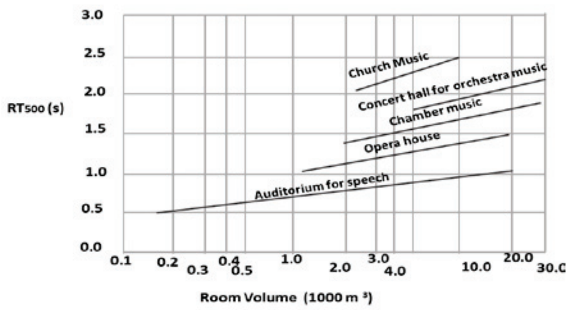

Figure 5. Optimum reverberation time.
Source: METHA et.al, 1999.

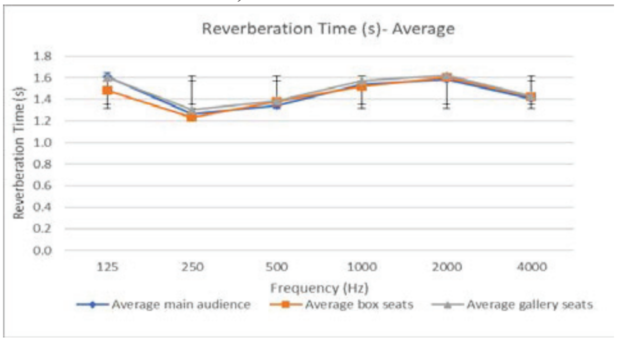

Figure 6. Average Reverberation Time (RT) of the main audience, box seats and gallery.

This may indicate that the reverberation is highlighted for voices and higher-pitched musical instruments. Similarly, the behavior of the RT results as a function of frequency for the boxes and gallery areas oscillates, reaching their lowest values at 250Hz and their highest values at 2000Hz. Such behavior demonstrates that the reverberation highlights instruments or voices that produce higher-pitched sounds. For comparison purposes, the spatial averages of the reverberation times were calculated as a function of frequency by sector and region, and the results are presented in Figures 7, 8, and 9.

From the spatial average graphs of the Reverberation Time, it can be observed that there is no significant difference in RT values between the region closest to the stage, the central region, and the back of the room in the three sectors: main audience seating area, boxes, and grandstand. For the main audience seating area, the RT values for the 500Hz frequency range between 1.34s and 1.38s.

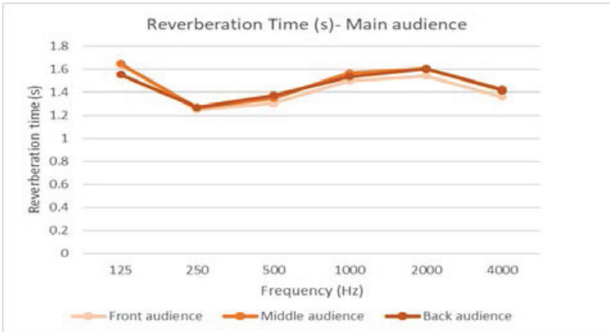

Figure 7. Average Reverberation time (RT) of the main audience by zones.

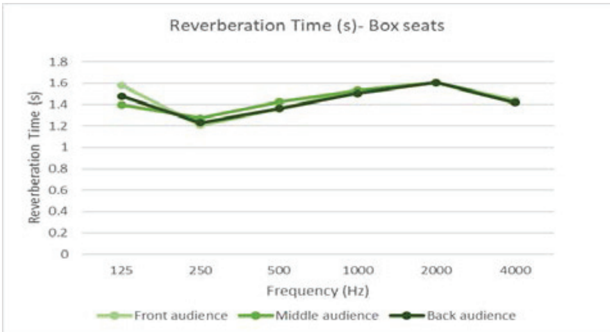

Figure 8. Average Reverberation time (RT) of the box seats by zones.

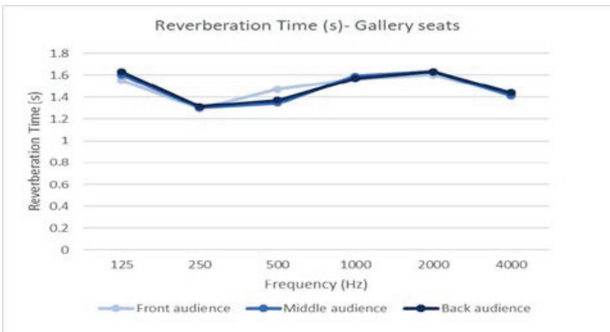

Figure 9. Average Reverberation time (RT) of the gallery seats by zones.

Considering the reference values recommended by Mehta et al. (1999) [2], it can be noted that these values are within the range indicated for opera performances and chamber music. However, these values are considered high for the optimal reverberation time interval indicated for theater activities. The variation in RT for the 500Hz frequency range for the boxes was between 1.35s and 1.41s, and for the grandstands, it was between 1.37s and 1.46s. Both are suitable according to Mehta et al. (1999) [2] for the range indicated for opera performances and chamber music. Once again, these values are considered high for the optimal reverberation time interval for theater activities. From this analysis, it can be perceived that there is a need for changes in the room so that, with some acoustic variability, it can better serve the function of theater for spoken word performances.

4.2 Early Decay Time (EDT)

According to Brandão (2016) [3], the Early Decay Time (EDT) is greatly influenced by the relative levels and temporal distribution of the first reflections. This parameter is considerably dependent on the source-receiver configuration in the room, which causes it to vary more throughout the space than the RT60. The EDT was measured as a function of frequency, in 1/1 octave bands. The average and standard deviation results are presented in Figure 10 for the receivers positioned in the audience, boxes, and grandstand, respectively.

Regarding the variation of EDT results based on the receiver points positioned in the main audience, it is observed that the smallest variation occurs in the 500 Hz band, compared to the other bands. On the other hand, a greater dispersion of EDT values is noted for the 125 Hz frequency.

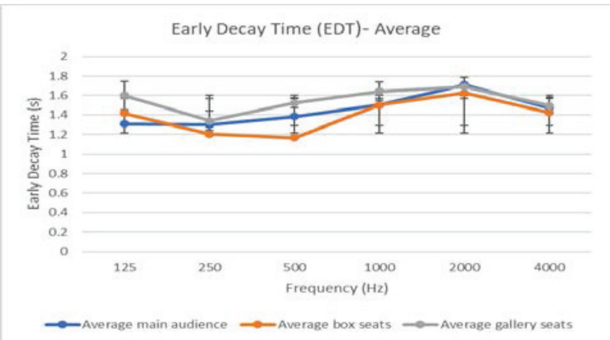

Figure 10. Average Early Decay Time (EDT) of the main audience, box seats and gallery

Another observation to highlight is the increase of EDT with the increase of distance between receiver point and sound source. This indicates that, in general, the receiver points closest to the analyzed sound source provide a lower reverberation sensation to the viewer.

For EDT results in the boxes, it is notable that the smallest variation occurs in the 250 Hz band, compared to the other bands. On the other hand, a greater dispersion of results is noted for the 125 Hz frequency.

The analysis of EDT in relation to distance allows us to point out that, in general, for points whose distances between receiver point and sound source are greater, EDT tends to decrease mainly in the central rows compared to the sides. This indicates that, in general, for these points, the reverberation sensation is lower for the viewer.

Considering the stands area, it is noted that the smallest variation in EDT occurred in the 1000 Hz band, compared to the other bands. On the other hand, there is also a greater dispersion of values for the 125 Hz frequency in other sectors. Still for the stands area, based on the obtained EDT results, it is not possible to establish a direct or inverse proportional behavior between EDT and the distance between sound source and receiver.

For the purpose of comparing EDT results by sector, the spatial averages of the parameter were calculated for each sector and the results are presented in Figures 11, 12, and 13 for the receivers positioned in the main audience, boxes, and stands area, respectively.

In terms of spatial averages of EDT for the frequency of 500 Hz, it is observed that for the audience area, the values ranged from 1.23 to 1.51s. Comparing TR and EDT values for the frequency of 500 Hz, it is interesting to note that EDT values are slightly higher than TR values. The central region of the audience area presented the highest EDT values.

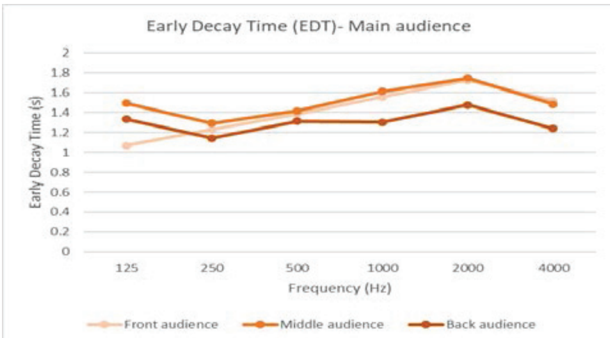

Figure 11. Average Early Decay Time (EDT) of the main audience by zones.

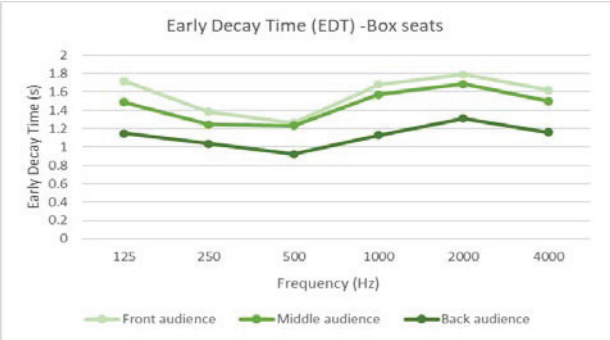

Figure 12. Average Early Decay Time (EDT) of the box seats by zones.

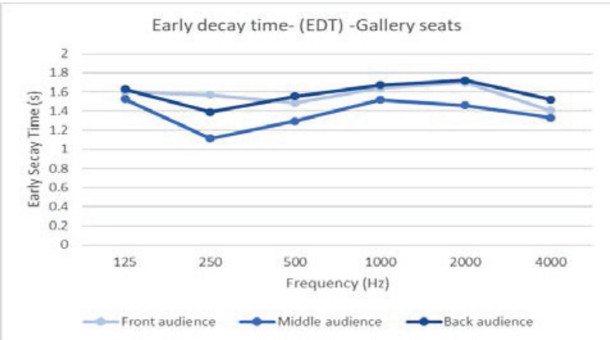

Figure 13. Average Early Decay Time (EDT) of the gallery seats by zones.

For the box seat area, the spatial average values of EDT for the frequency of 500 Hz ranged from 1.17 to 1.34s. Comparing TR and EDT results for the frequency of 500 Hz, it is interesting to note that EDT values are slightly lower than TR values, which is opposite to the behavior observed in the audience area. The front region of the box seat area presented, on average, the highest EDT values.

The spatial average EDT values for the frequency of 500 Hz obtained in the bleacher region ranged from 1.31s to 1.52s. The back area of the stands presented, on average, the highest EDT values.

4.3 Clarity (C_{80})

Clarity (C_{80}) is an important acoustic parameter to characterize environments intended for music. It is also a parameter strongly dependent on the source-receiver position. The average and standard deviation results of C_{80} as a function of frequency for the receivers distributed in the stalls, boxes and stands are presented in Figure 14.

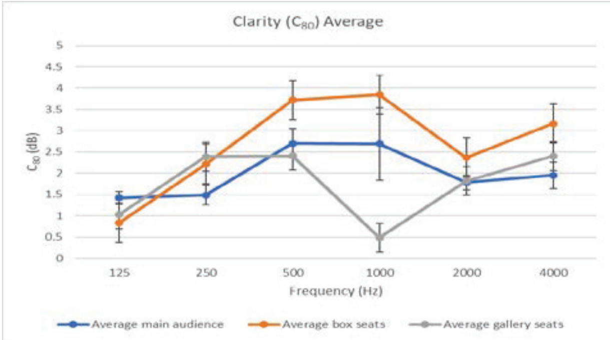

Figure 14. Average Clarity (C_{80}) of the main audience, box seats and gallery.

The ISO 3382-1:2009 standard indicates a typical range of values for C_{80} between -5dB and +5dB for the average of the values at the frequencies of 500Hz and 1000Hz. However, Beranek (2003) [4] proposes a range of -4dB to +4dB for the frequency of 500Hz in concert and opera halls. It was observed that no sector of the room had a value of C_{80} less than -4dB, but the upper limit of +4dB was exceeded in some points of the three evaluated sectors. It was also observed that at 500Hz, the values of C_{80} are mostly positive regardless of the room sector. For comparison purposes, spatial averages of EDT were calculated by frequency, sector, and region of the room, and the results are presented in Figures 15, 16, and 17 for the stalls, boxes, and balcony, respectively. For the frequency of 500Hz, the spatial average for all receiving points varied between 0.80dB and 3.84dB. The spatial average values of EDT in the main stalls show higher values in the front part of the room, while for the boxes, these higher values are found in the back of the room and in the balcony, the values are in the central region of the room. It can be observed that by region, the spatial average values of EDT at 500Hz are greater than 0dB.

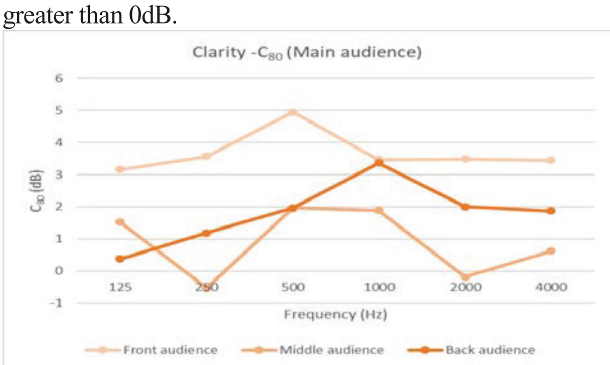

Figure 15. Average Clarity (C_{80}) of the main audience by zones.

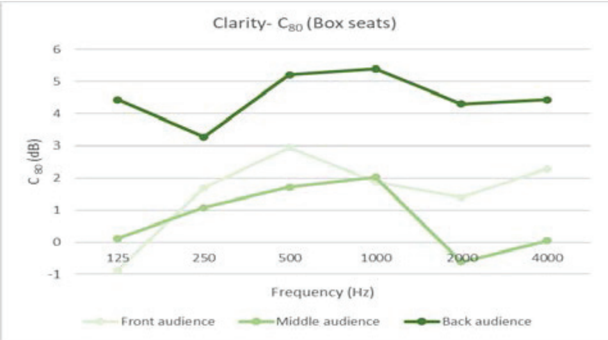

Figure 16. Average Clarity (C_{80}) of the box seats by zones.

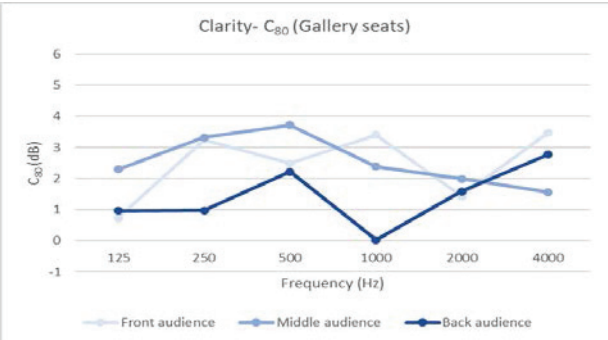

Figure 17. Average Clarity (C_{80}) of the gallery seats by zones.

According to Brandão (2016) [3], a positive value of the acoustic parameter EDT indicates that the amount of energy of the first reflections that occur within 80ms at a certain point has more energy than the reverberant tail region, while a negative value of C_{80} indicates that the amount of energy of the first reflections that occur within 80ms at the point has less energy than the reverberant tail region. It can be said that in the vast majority of its points, the room has energy from reflections occurring within 80ms that is superior to the energy of the reverberant tail. This behavior indicates that in a musical performance in this room, a sequence of rapid notes will be easily understandable. This observed pattern is associated with a greater sense of clarity in musical activities [4].

4.4 Definition (D_{50})

The D_{50} definition provides a measure of the ratio between the sound energy that arrives at the receiver in the first 50 ms and the total sound energy, and is associated with the quality of speech in an environment. The closer the D_{50} value is to 1.0, the better the intelligibility of activities related to human speech. For a sound source positioned in the center of the stage, Figure 18 show the average and standard deviation values of the Definition as a function of frequency for receptor points located in the stalls, boxes, and gallery, respectively.

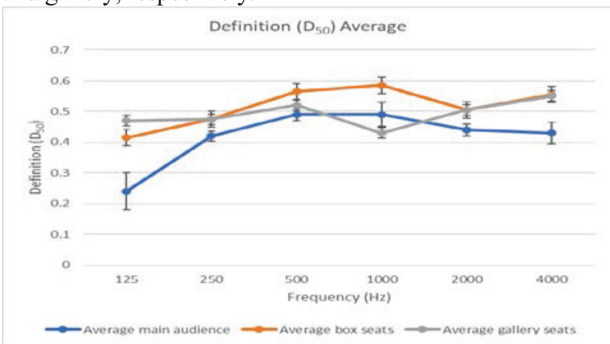

Figure 18. Average Definition (D_{50}) of the main audience, box seats and gallery

It is observed at 500 Hz that the D_{50} values for the grandstand are the results that showed the least variation among the receptor points. Points in the audience and boxes reached values of around 0.7. The points that have the best definition are located either in the region closest to the source or in the guardrail of the boxes.
For comparison purposes, the spatial averages of D_{50} were calculated by sector region, and the results are presented in Figures 19, 20, and 21 for the audience, boxes, and grandstand, respectively. This sectorization allows identifying that the D_{50} values for the main audience in the part closest to the stage can reach values between 0.6 and 0.7 at the frequency of 500 Hz, while in the central part, these values decrease to 0.32 and increase again in the back of the room.
In the boxes section, the same behavior is repeated, where places in the front and back regions of the stage present better D_{50} results than in the central region. The D_{50} values for the frequency of 500 Hz range from 0.32 to 0.75. It is observed that the points that presented, on average, the best values were the points in the back region of the room.
For the grandstand, the same D_{50} pattern is observed for the frequency of 500 Hz, in which the front and back regions of the room present better overall performance, that is, higher D_{50} values than the performance of the central region of the room.
It is interesting to note that the performance of the back part of the room, in terms of D_{50} values, is better than the performance of the central part of the room, which was not expected due to the distance between the sound source and the receptor points. This improvement in performance can be attributed to the shape and materiality of the room, which is close to reflective surfaces that increase lateral

reflections. According to Brandão (2016) [3], D_{50} values greater than 0.5 indicate that the region of the first reflections carries most of the energy contained in the impulse response, while values less than 0.5 indicate that the reverberant tail region carries most of the energy contained in the impulse response.

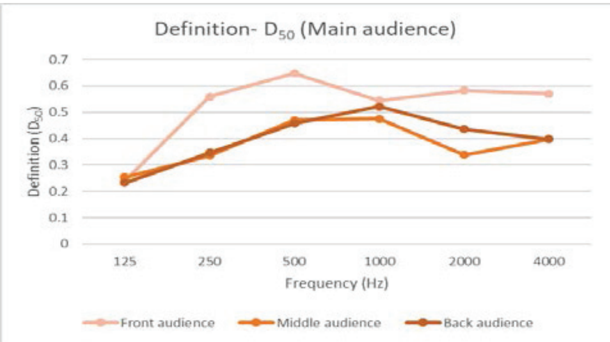

Figure 19. Average Definition (D_{50}) of the main audience by zones.

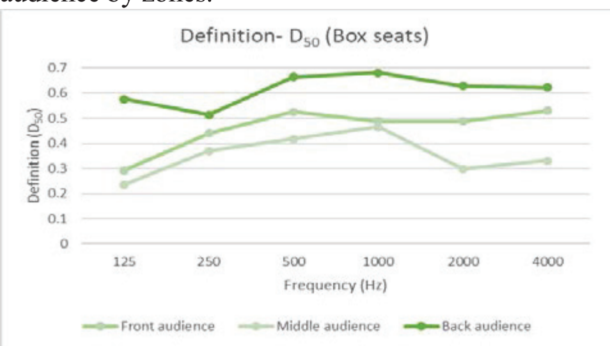

Figure 20. Average Definition (D_{50}) of the box seats by zones.

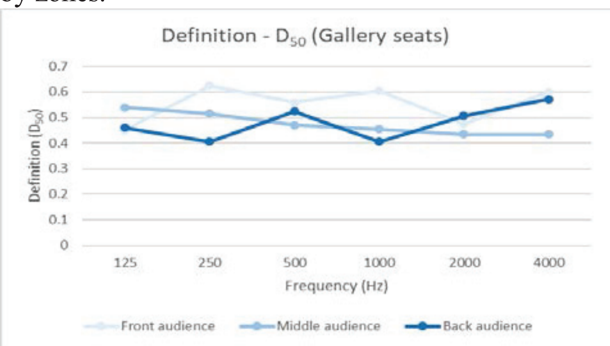

Figure 21. Average Definition (D_{50}) of the gallery seats by zones.

According to Barron (2010), suitable D_{50} values for a space intended for speech (theatrical performances) should be above 0.5 for better speech intelligibility. Therefore, for the studied environment, some adjustments would be necessary to meet this acoustic parameter, especially in the central area of the room.

4.5 Speech Transmission Index (STI)

Rooms intended for spoken word, such as classrooms, conference rooms, and theaters, have intelligibility as one of the most important acoustic requirements. This characteristic requirement can be evaluated through the acoustic parameter speech transmission index (STI).

The STI value varies from 0 to 1. The closer the STI value is to 1, the better the intelligibility. STI values can be classified quantitatively and qualitatively according to the IEC 60268-16 (2020) [6] standard, whose values are presented in Table 1. For the purpose of analyzing the STI results for the theater, the quality of speech was considered according to the STI range based on the values in the same table. The values of Speech Transmission Index (STI) obtained for each receiver point in each sector of the theater are presented in Figures 22, 23, and 24. The darker the color of the bars in the figures, the further away the receiver points are from the sound source.

Table 1. Quantitative and qualitative evaluation of intelligibility

Quantitative evaluation of intelligibility STI	Qualitative evaluation of intelligibility (subjective impression)
0,75 - 1,00	Excellent
0,60 - 0,75	Good
0,45 – 0,60	Fair
0,30 – 0,45	Bad
0,00 – 0,30	Very bad

Source: IEC 60268-16 (2003)

Figure 22 shows the STI values for receiver points 1 to 14 located in the main audience area. It can be observed that all STI values are within the ranges classified as adequate and good, with the best-rated receiver points being closer to the stage or to the back of the room, confirming the behavior already presented and discussed for the D_{50} parameter, which also evaluates speech quality in the environment.

The STI values obtained for receiver points 1 to 14 in the box sector are presented in Figure 23. It is noted that the best performance found for speech in this sector is in the positions at the back of the room, with almost all values above 0.6. For receiver points closer to the stage and in the middle of the room, performance continues within the range classified as adequate, but with values between 0.45 and 0.6. In the grandstand area, the STI values obtained for the receiver points are shown in Figure 24. These values do not exceed the adequate level for intelligibility. It is noteworthy the behavior of two receiver points close to the stage with STI values very different from each other (P1 with 0.58 and P2 with 0.49).

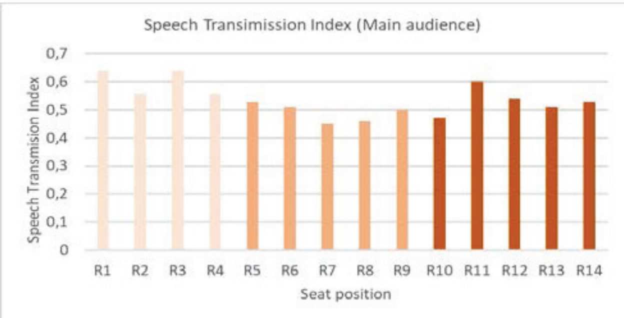

Figure 23. Speech Transmission Index of the main audience

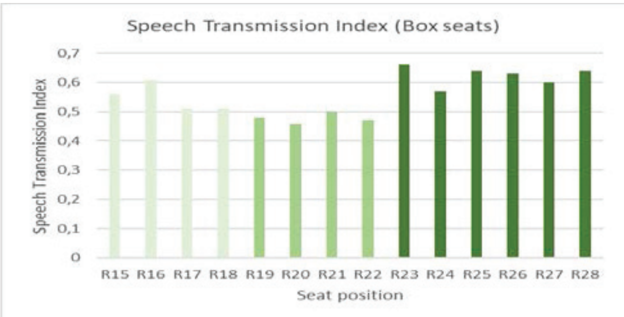

Figure 24. Speech Transmission Index of the box seats

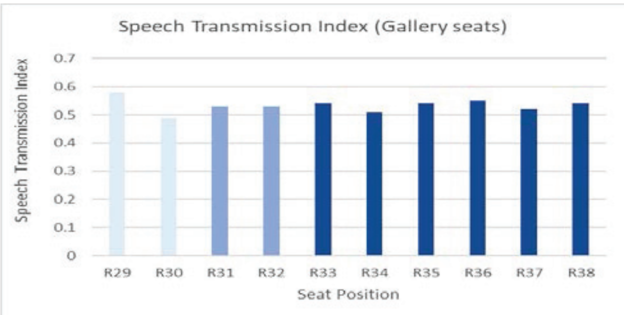

Figure 25. Speech Transmission Index of the gallery seats

It is also observed that in the main audience, the points located on the central axis of the room, whether closer to the source or not, also present STI values, relative to performance, slightly better than those located on the same alignment but closer to the side of the room. The positioning of the source on the stage, which brings these points closer to the sound source, favors this behavior.

Given the results of STI and the classification of speech quality obtained for the room, regardless of position, it would be recommended to improve intelligibility for theater performances and lectures.

5. CONCLUSIONS

The acoustic characterization of Teatro Polythema was crucial to understanding its potential for use, given that the space is used for various activities that require different acoustic requirements and does not have any variable acoustic resources. The different sectors of the theater (audience, boxes, and bleachers) offer different acoustic experiences for both music and speech.

Its horseshoe shape resembles spaces designed for music, specifically opera. It even has an orchestra pit that has never been used. The results of the reverberation time indicate desirable acoustic quality for musical activities but not as suitable for speech activities. This behavior is confirmed by the values found for C_{80} for musical activities and D_{50} and STI for speech activities. Variable acoustics are recommended to ensure the acoustic quality of spaces for proposed activities.

6. ACKNOWLEDGMENTS

Thank you to the Director of the Theater for allowing us to access and conduct the measurements in the theater.

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