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Article

An Investigation on the Effects of Architectural Features on Acoustical Environment of Historical Mosques

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Abstract: In the historical period, different mosques were built in the Anatolian side; the differences in size, typology and style were affected by the climate conditions, cultural and social aspects, availability of materials and the construction techniques of the region they were built in. The ceiling structure, which is the most influencing factor for mosque acoustics, is designed with either curvilinear elements or a flat ceiling for mosques. In the context of our case study, the eight historical mosques in Turkey, with different materials and types of ceiling structures, are investigated in terms of acoustical characteristics in the main prayer hall. Acoustical data are collected by measurements to reveal how the formal differences and material change in ceiling structures affect the acoustic environments of mosques with similar volume. Distribution of acoustical parameters and the suitability of the values obtained through measurements are compared to reflect the effect of architectural features on the acoustical characteristics of the prayer hall.

Keywords: room acoustics; historical mosques; acoustical parameters

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1. Introduction

Worship buildings have been important in communities throughout the history, because they are the manifestation of religions and beliefs in a society. Religious structures are also iconic examples of architectural history and, on the urban scale, they enrich the cities with their size and decoration, not to mention the architectural elements such as domes and minarets. They also help to impress the community with their interior spaces, and it can be stated that the acoustical perception affects the prayers even more than the visual perception, in terms of experiencing the space and the divine feeling during religious rituals [1].

Historical buildings, especially historical worship spaces have been also evaluated for their acoustical ambiance in the literature. Most of the time "archaeoacacoustic" analysis of prayer halls is carried out by measurements and simulations [2]. Effects of the architectural styles on historical buildings are also investigated, especially for the churches [3–5].

Mosques contain worship rituals as a worship place for Muslim people. Expectation of the occupants varies depending on the needs of the ritual. For example, individuality is needed for praying, while a sense of unity is needed during the recitation of the Quran or hymns. The activities that take place in the prayer hall can be listed as; praying individually or with an Imam to hear prayer's order, listening to the Imam's speech on Fridays, and listening to the musical type of Holy Quran. Praying rituals need a high level of speech intelligibility; however, sometimes musical rituals need a more (reverberant) environment. Additionally, most of the time, the prayer hall is expected to make people feel close to God. These different uses also need different acoustical requirements. To create the desired feeling in the space at the required time, rooms should be evaluated in terms of acoustical conditions. All these activities require a high level of speech audibility and intelligibility. The main prayer hall consists of different building elements to maintain the activities that are listed above; such as the "mihrab", "mimbar", and "muezzin gallery". Khutba is read on the mimbar located on the right side of the mihrab. The mimbar provides the visual connection between listener and speaker because it includes steps. In addition to this, for the speaker on the steps in the mimbar during the Khutba and sermon, speaking provides a positive impact on acoustic conditions. The muezzin gallery is made for the muezzins to sit on the high platform, give the "tesbihat" sounds, and repeat what the imam is saying. This situation helps to keep the sound source over the audience and to stabilize the sound energy in the volume [6]. In the mosques, the feeling of individuality is desired in praying, and the feeling of unity is desired in the reading of the Holy Quran, and hymns, etc. Therefore, mosques are places that include both speech and music. However, instrumental music does not take place in mosques because it is not mentioned in the Holy Quran. In functional terms, speech and its intelligibility are the major acoustical considerations in the acoustical design of a mosque.

There is a significant relationship between the cultural heritage building and its acoustics [7]. Oleg Grabar, one of the leading Islamic art historians, says that the self-representation of Islamic culture is based on hearing more than seeing [8]. Ergin's study indicates that Ottoman architects see mosques as where the original revelation is restaged, and they are musical instruments that provide the voices of the Quran [9]. For these reasons, those historical examples are important subjects of studies on archaeoacoustics. On the other hand, there are many different historical mosques all over the world, with differences are in terms of architectural features and variety of used materials within the interior space. This variation in mosque architecture complicates the acoustical evaluation process. In addition to this, there is a lack of certain evaluation criteria or defined optimum parameter ranges which are written/published as standards for mosque acoustics.

There are some studies in the literature about acoustical requirements and evaluation parameters for mosques. In this study, the methods, and parameters, which have been used in recent studies, are investigated, as are the similar methods and parameters for the assessment and evaluation of mosque structures. Most of the time, existing recommendations, which are developed for the speech auditoriums or dramatic theatres, have to be used to evaluate the acoustic quality of the mosques. In other words, unlike auditoriums, there are no defined recommendations or rules for the acoustical parameters inside mosques. However, regarding mosques, the elaboration of general sound parameters requires a specific understanding of the acoustical and spiritual environment expected in such structures. In some studies, there have been some recommendations developed for the acoustical parameters by considering the activities in mosques [10,11]. To show the sacredness of religion, historical mosques were often built in large volumes by using high and wide dome structures [12]. Acoustical problems due to the large volumes are expected in these mosques, as with large cathedrals [13]. However, some ways of preventing this problem were considered. For example, the floors of mosques are covered by carpets, which are made of absorptive material, providing acoustic comfort. By using sound absorbent surfaces, most of the sound energy cannot be reflected, which prevents long reverberation times. In Sinan mosques, the mimbar and muezzin gallery are made by using perforated panels, which reduce the sound energy level and provide acoustic comfort [14].

The acoustical quality of the mosques has been discussed in the literature, and studies have mostly focused on the analysis of the ancient and/or contemporary examples of the mosque architecture. Such studies may include single mosque cases [15–18], or some of them include comparisons of mosques to other mosques [14,19–24] or comparisons of mosques to other worship spaces (churches and/or synagogues) [25].

This article aims to investigate the objective parameters of the sound of the main prayer hall of eight historical mosques from the Western part of Anatolia. The acoustical evaluation of these historical examples and a comparison of the results with a classification are objectives of the paper. As a result of the analyses, it has emerged that the acoustic parameters alone are not sufficient in the evaluation of the mosques and that the acoustic parameters should be considered as a whole with the architectural features of the volumes.

It is seen that the acoustic environments of mosques with domed masonry and completely wooden ceilings are quite different.

2. Method and Scope of the Study

Masonry-domed mosques with large volumes have been the subject of most of the studies in the field of architecture. Smaller ones with wooden or masonry ceiling structures are mostly not included in these studies, although the number of them is more than monumental mosques. Within the scope of this study, the aim is to focus on smaller examples of mosques in the Aegean Region of Turkey and to evaluate them in terms of acoustical ambiance of prayer hall under a classification. With some studies in the literature, it is concluded that historical mosques with large volumes work as a coupling space and differ from small-sized mosques with these features [12]. Small-sized mosques in the range of 1000–2000 m^3, which are found in large numbers in Western Anatolia, constitute the case group of the study, since they differ from large volume mosques in terms of acoustic perception.

In Figure 1, volumes and measured and/or simulated T30 values of historical mosques that are gathered from the literature review during the study are shown with the mean values of T30 values of the cases [21,22,26–31]. It also represents a summarized version of the literature and documentation of historical mosques that are evaluated in terms of acoustics.

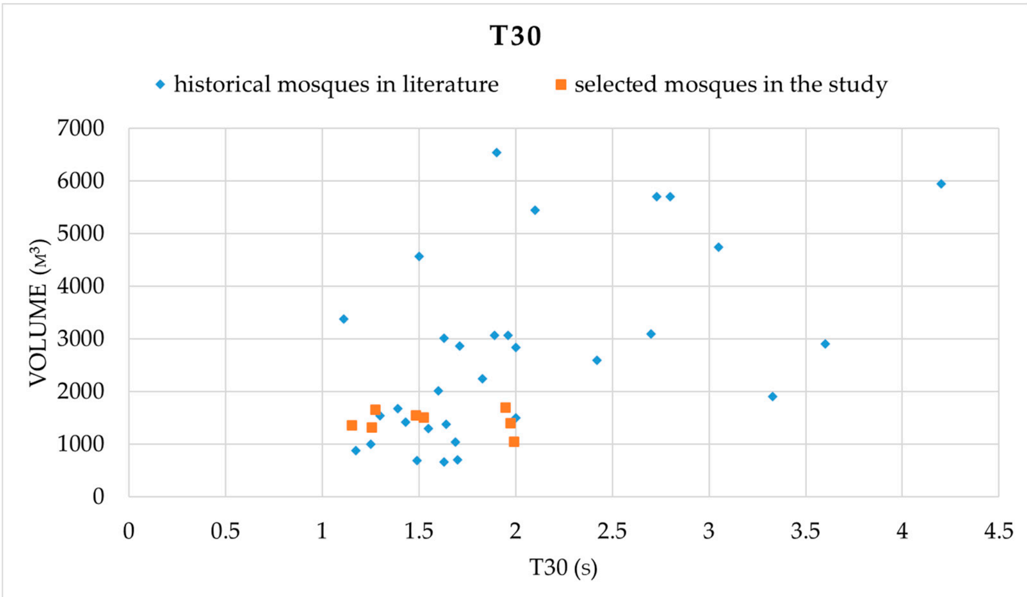


Figure 1. The T30 values of mosques in the literature and present study.

According to the graph in Figure 1, there are many historical mosques with a range of different volumes; mosque volumes in the range of 1000–2000 m^3 are more numerous than other examples that studied in the literature. In this study, as a part of the studies evaluating the acoustic comfort conditions of mosques built in different historical periods in Aegean Region, we want to focus on the group with volumes of 1000–2000 m^3. However, there is no material and top cover information of mosques in Figure 1. We plan to make evaluations by using information regarding material and ceiling structure of eight mosques that represent all mosques in this volume range.

However, it is problematic to say that there is a clear relationship between the prayer hall size and the T30 value for the mosques; this brings to light the fact that other architectural features and materials should be considered for a strict evaluation. Starting with this volume group, it is considered to analyze the effects of elements such as type of ceilings and materials on acoustic conditions. Thus, both wooden covered mosques, which are not much subject to studies, will be evaluated by making comparisons and masonry covered mosques are selected as cases for evaluation of acoustic environment. To evaluate the acoustic ambiance, in-situ acoustical measurements was held in eight mosques. Measurements process is described in heading 4. Before that, more detailed architectural and structural features of the cases are described in following section.

3. Architectural Features of Cases

Although most of the historical buildings that belong to society are made and remade with a classical typology, mosque structures have been the type of building that has undergone constant changes throughout the historical process. Although they have the same religious rituals, mosques were built in different regions, and because of the various cultures, that is why we find diversity in forms and shapes. Considering the whole of Anatolia, it is seen that mosques were built with both masonry and wooden materials, depending on many factors, such as climate conditions, cultural aspects, social structure and wealth of society as well as the opportunities of construction techniques at the date of construction.

In the Aegean Region, it is possible to see almost every size and construction techniques of mosque architecture. Single-domed masonry, multi-domed masonry, single- or multi-domed woodwork (combination of a centrally located lathing dome and side parts with flat ceilings or curvilinear top cover elements such as wooden dome or vault) or mosques with wooden flat ceilings have been built throughout history. An effort has been made to include all the combinations of the roof/ceiling structure in this study. Thus, eight mosques which have different roof configurations, similar volumes and located in the same region are the subjects of the study. Their unique architectural features are briefly described below in separate headings and tables (Tables 1–8).

3.1. Lalapaşa Mosque

The mosque has a square plan covered by a single masonry dome with a diameter of 9.77 m. The transitions to the dome from the walls are provided by pendentives. The distance from the floor of the building to the bottom of the pulley is approximately 8.85 m, the height of the pulley, which the dome sits on, is 1.55 m and the height of the dome is 3 m. There is a prayer hall for women, located to the north of the main hall, supported by two wooden posts of square section. The wooden lattice surfaces, which serve as a visual dividing panel between the main prayer hall and the prayer area for women, also act as the railing.

Table 1. The architectural features of Lalapaşa Mosque.

Lalapaşa Mosque	
Location	Manisa
Year of construction	1570
System of ceiling	Single-domed masonry
Plan dimensions	9.84 × 9.93 m
Average room height	10.4 m
Average room volume	1060 m^3
Plan typology	Square
Capacity	121
Volume per person	8.76 m^3

The mihrab, which is in the form of a semicircular niche, is covered with tiles. There is a wooden sermon chair in the southeastern part of the building and a marble mimbar in the west of the mihrab. The floor is covered with carpet, the dome and walls are covered with plaster and paint (Figure 2). The wall surfaces of the mosque are covered with wood up to a height of 1.2 m from the floor. The building is in a large courtyard surrounded by many trees.

Figure 2. Interior views of main prayer hall and exterior view of Lalapaşa Mosque (photos by the authors).

3.2. *İvazpaşa Mosque*

The mosque was built in 1484 in Manisa with a transverse rectangular plan. The mosque is covered by the main dome centrally and side aisles covered by four smaller domes with a masonry system. The main dome of the mosque has a diameter of 7.85 m (Table 2). The smaller domes have diameters of 2.53 m and 3.23 m, respectively. The walls have a thickness of approximately 1.20 m. The transitions of the domes are provided by muqarnas (Figure 3). The symmetry of the mosque plan is destroyed by the location of the grave chamber.

Table 2. The architectural features of İvazpaşa Mosque.

İvazpaşa Mosque	
Location	Manisa
Year of construction	1484
System of ceiling	Multi-domed masonry
Plan dimensions	16.39×8.23 m
Average room height	10 m
Average room volume	1406 m^3
Plan typology	Transverse rectangular plan
Capacity	121
Volume per person	8.76 m^3

The floor of the mosque is covered with carpet. The women's area, which is separated from the main hall with curtains, is located to the northeast of the mosque. The muqarnas headed mihrab niche is located on the south wall and is covered by painted plaster. The mosque is close to the city center, surrounded by trees, a cemetery, less used traffic roads, and residences.

Figure 3. Main prayer hall and side aisle of İvaz Paşa Mosque (photos by the authors).

3.3. *Çeşnigir Mosque*

The mosque was built in 1474 in Manisa and has a transverse rectangular plan. The mosque is covered with a large dome in the middle and four small domes in the side spaces. The domes are made by a masonry system. The main dome of the mosque has a diameter of 9 m. The smaller domes have diameters of 3.30 m. The side spaces are covered by oval domes supported by pendentives. The walls have a thickness of approximately 1.10 m.

Table 3. The architectural features of Çeşnigir Mosque.

Çeşnigir Mosque	
Location	Manisa
Year of construction	1474
System of ceiling	Multi-domed masonry
Plan dimensions	18 × 9.82 m
Average room height	8.2 m
Average room volume	1700 m^3
Plan typology	Transverse rectangular plan
Capacity	221
Volume per person	7.69 m^3

The sermon chair is made of marble, the mihrab is made of plaster and the mimbar is made of wood (Figure 4). The floor of the mosque is covered with carpet. The east part of the narthex is closed by panels for the prayer hall for women. In the month of Ramadan, the east part of the main worship area is closed with curtains for women. A public park, surrounded by lots of shops and coffee houses, is located at the north and east of the mosque. The mosque is surrounded by dwellings on the south side and a car parking area on the west side of the mosque.

Figure 4. Main prayer hall and side section of Çeşnigir Mosque (photos by the authors).

3.4. *Attar Ece Mosque*

The mosque, which was built in the second half of the 14th century in Manisa, was damaged in 1549. It was rebuilt on the old foundations of the building in 1923 [32]. The mosque has a rectangular plan and a flat ceiling made of wood. The plan dimensions are 9.75 × 21.5 m. The height of the building is 7.2 m.

Table 4. The architectural features of Attar Ece Mosque.

Attar Ece Mosque	
Location	Manisa
Year of construction	1480
System of ceiling	Wooden flat ceiling
Plan dimensions	21.5 × 9.75 m
Average room height	7.2 m
Average room volume	1510 m^3
Plan typology	Transverse rectangular plan
Capacity	263
Volume per person	5.74 m^3

The women's hall is located on the narthex, which is covered with glass surfaces and is separated from the main prayer hall by wooden lattice surfaces. The inner surface of the marble mihrab was covered with tiles. There is a marble mimbar in the west and a sermon chair made using marble in the east of the mihrab. There is a wooden muezzin lodge west of the entrance door. The walls of the mosque are covered with wooden panels up to 1.2 m from the floor. The floor of the building is covered with carpet, and the walls are plastered and painted (Figure 5). The mosque is located near the city center, surrounded by residences, and pedestrian and traffic roads.

Figure 5. Main and women's prayer hall of Attar Ece Mosque (photos by the authors).

3.5. *Eğlenhoca Mosque*

The mosque, built in 1902 in İzmir, has a longitudinal rectangular plan. The ceiling system consists of a central wooden dome and a wooden flat ceiling. The inner surface of mihrab is covered by wooden materials. The mimbar of mosque is also wooden. The women's hall is visually separated from the main prayer hall using perforated wooden panels. The women's prayer hall is supported by wooden pillars and expanded towards the main worship area. There are wooden, plaster and stone decorations inside. There are wooden decorations on the wooden dome, which is an element of the upper cover structure of the mosque, and plaster decorations on the mihrab. The floor of the mosque and the women's hall are covered with carpets (Figure 6). The mosque is surrounded by coffee houses, shops, houses, and car parks.

Table 5. The architectural features of Eğlenhoca Mosque.

Eğlenhoca Mosque	
Location	İzmir
Year of construction	1902
System of ceiling	Wooden dome and flat ceiling
Plan dimensions	12.54 × 14.9 m
Average room height	7.15 m
Average room volume	1360 m^3
Plan typology	Rectangular (mihrab is located on the long side)
Capacity	201
Volume per person	6.77 m^3

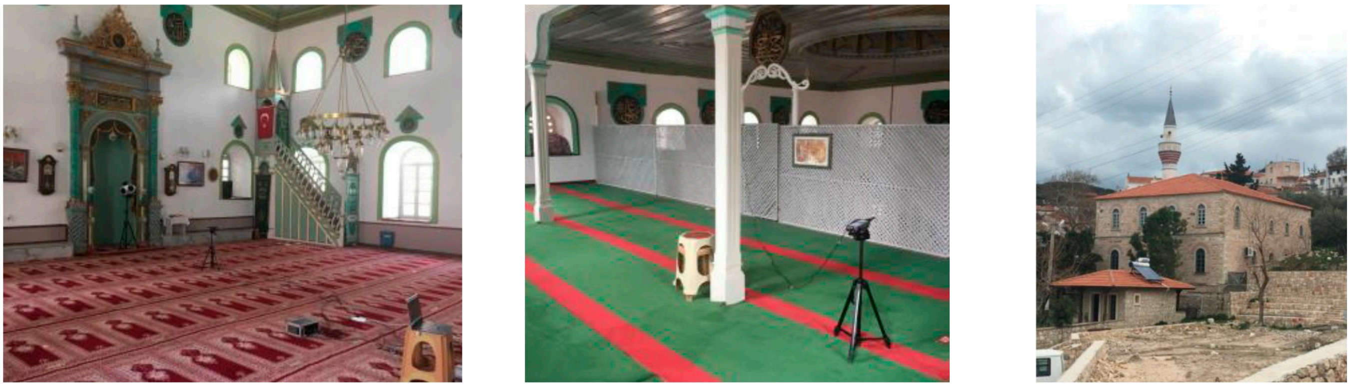


Figure 6. Main and women's prayer hall of Eğlenhoca Mosque (photos by the authors).

3.6. Mahkeme Mosque

This mosque, which was built in 1700 in İzmir has a transverse rectangular plan. The mosque is covered by a single wooden dome centrally and side aisles are covered by wooden flat ceilings. The perforated wooden panels of the women's prayer hall, located in the northern part of the mosque, separating the hall from the main worship area visually. The mimbar and the pulpit are made of marble. The mihrab has a half cylinder body and is painted over plaster. The floor of the mosque is covered by carpets (Figure 7).

Table 6. The architectural features of Mahkeme Mosque.

Mahkeme Mosque	
Location	İzmir
Year of construction	1700
System of ceiling	Wooden dome and flat ceiling
Plan dimensions	20 × 11.9 m
Average room height	5.85 m
Average room volume	1559 m^3
Plan typology	Rectangular (Mihrab is located on the short side)
Capacity	2497
Volume per person	5.25 m^3

Figure 7. Main prayer hall of Mahkeme Mosque (photos by the authors).

3.7. Çarşı Mosque

The mosque was built in 1311 in İzmir. Although walls were built on a masonry system, the top covering system consists of a central wooden dome with a diameter of 4.8 m and a wooden flat ceiling (Figure 8). The mosque, with plan dimensions of 15.3 × 13.8 m, has a plan close to a square shape.

Table 7. The architectural features of Çarşı Mosque.

Çarşı Mosque	
Location	İzmir
Year of construction	14th century
System of ceiling	Wooden dome and flat ceiling
Plan dimensions	15.3 × 13.76 m
Average room height	7.75 m
Average room volume	1659 m^3
Plan typology	Transverse rectangular plan
Capacity	263
Volume per person	6.31 m^3

Figure 8. Main and women's prayer hall of Çarşı Mosque (photos by the authors).

The main worship area and lodge for women have carpets as a floor-finishing material. The mimbar, sermon chair, women's prayer hall, columns, and wall coverings up to 0.9 cm from the floor are made of wood. The mosque is positioned higher than the level of road and the entrance of the mosque is reached by steps. It is located at the city center and surrounded by shops, a marketplace, dwellings, traffic, and pedestrian walkways.

3.8. Göçbeyli Merkez Mosque

This mosque, which was built in the 19th century in İzmir, has a plan with an interior length of 13.9 m and a width of 14.3 m. The ceiling structure of the mosque has a single wooden dome centrally with a diameter of 4.7 m. Side aisles are covered by wooden vaults. Wall surfaces are covered by plaster and paint. The carpet is used as a floor finish material in the mosque (Figure 9). Wood is widely used in the ceiling structure, prayer area for women, columns, sermon chair, and mimbar. The mosque is located in a village and is surrounded by many one story dwellings.

Table 8. The architectural features of Göçbeyli Merkez Mosque.

Göçbeyli Merkez Mosque	
Location	İzmir
Year of construction	1895
System of ceiling	Wooden dome and vault ceiling
Plan dimensions	14.26 × 13.9 m
Average room height	5.65 m
Average room volume	1330 m^3
Plan typology	Square
Capacity	247
Volume per person	5.38 m^3

Figure 9. Main prayer hall and women's prayer hall of Göçbeyli Mosque (photos by the authors).

3.9. Preliminary Classification of Cases Depending on Ceiling Structure

In the literature, there are some studies on the classification of mosques according to spatial, chronological, typological, functional features and urban locations. A few studies have received attention on the acoustical characteristics of mosques with a classification [19,30]. They show that the features of geometrical parameters such as plan typology, volume, etc. affect the acoustical conditions of mosques.

Similarly, selected mosques are classified according to architectural features of the main prayer hall, in this section. Eight mosques with wooden and masonry ceilings, which were expected to show different acoustic behavior, are divided into two main groups. Masonry top-covered mosques are divided into two groups depending on whether they have a single-domed or curvilinear (multi-domed) composition. The mosques with wooden ceilings are divided into two separate classes: mosques with a curvilinear composition, such as a dome, and a vault or a flat ceiling in the top cover system, and mosques covered with a flat wooden ceiling (Table 9). Under the headings of suggested classifications in the Table 9, different ceiling structures and material properties of selected cases of the study are shown in Table 10.

Table 9. The classification of mosques in the study according to features of the roof/ceiling systems facing the interior.

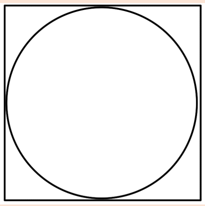
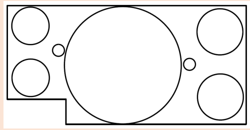
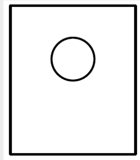
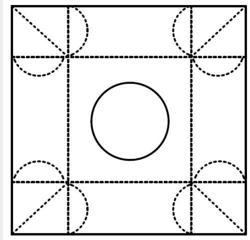
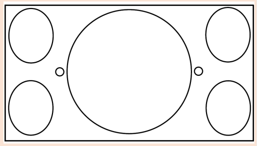
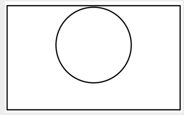
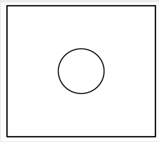
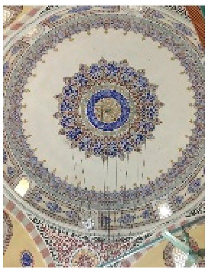
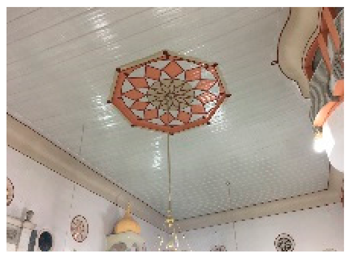
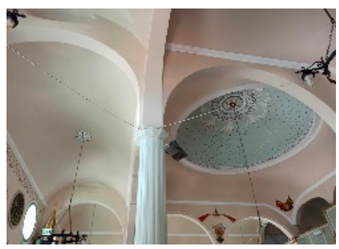
Masonry Roof Construction		Wooden Roof + Ceiling Construction		
Single-Domed	Curvilinear Composition (Multi-Domed)	Flat Ceiling	Curvilinear Composition Dome + Flat Ceiling	Dome + Vault
Lalapaşa Mosque	**İvazpaşa Mosque**	**Attarece Mosque**	**Eğlenhoca Mosque**	**Göçbeyli Mosque**
 $Ø_{dome}$ = 9.77 m H_{dome} = 3 m V = 1060 m^3	 for central dome; Ø= 7.85 m H = 3.5 m for side domes; Ø= 3.23 m H = 1 m Ø= 2.53 m H = 1 m V = 1406 m^3	 plan dimensions: 9.75 × 21.5 m the height of mosque: 7.2 m V = 1510 m^3	 $Ø_{dome}$ = 4.3 m H_{dome} = 1.9 m V = 1360 m^3	 $Ø_{dome}$ = 4.7 m H_{dome} = 1.7 m V = 1330 m^3
	Çeşnigir Mosque		**Menemen Mosque**	
	 for central dome; Ø = 8.87 m H = 3.45 m for side domes; Ø = 3.31 m H = 1.55 m V = 1700 m^3		 $Ø_{dome}$ = 8.7 m H_{dome} = 4.3 m V = 1559 m^3	
			Çarşı Mosque	
			 $Ø_{dome}$ = 4.8 m H_{dome} = 2.8 m V = 1659 m^3	

Table 10. The photos from the ceiling structures of eight historical mosques (photos by the authors).

			
Lalapaşa Mosque	**İvazpaşa Mosque**	**Çeşnigir Mosque**	**Attarhoca Mosque**
			
Eğlenhoca M.	**Mahkeme Mosque**	**Çarşı Mosque**	**Göçbeyli Mosque**

4. Acoustical Measurements and Results

Eight historical mosques built in the Aegean Region of Turkey were determined as research subjects to be compared and classified according to their acoustical characteristics. The geometrical parameters such as volume, area, the height of volume, and the diameters of domes are measured during the fieldwork.

Selected mosques were evaluated by using objective acoustic parameters and measurements were carried out following by ISO 3382-1 standard, as in the literature [33]. According to Aletta and Kang; "For the measurements, the researchers' work should always be commended, for the considerable challenges they face in implementing standardized measurement protocols in locations that often present serious accessibility and operability issues" [2]. Since there are no particular standards or definitions for mosques, T30, bass ratio, EDT, C80, D50, STI, and background noise level were chosen to be used to investigate the acoustic conditions of volumes due to the presence of both music and speech rituals in mosques.

4.1. Measurement Conditions

Acoustical field measurements were held during the daytime in unoccupied halls following ISO 3382-1:2010 [33]. During the measurements, the windows were kept closed. The omni power sound source (B&K Type 4292-L), connected to power amplifier (B&K Type 2734-A), was located in front of the mihrab and 1.50 m from the floor to represent the position of the Imam while he is talking and giving orders to prayers. The receiver points were placed in the main worship area and women's worship area at 0.85 m representing the height of the ear of a person praying in a sitting position on the floor. The receiver points are placed in such a way that they dominate the whole prayer area in mosques (Figure 10). DIRAC Room Acoustics Software Type 7841 v.6 was used to generate MLS signals with a longer period than the estimated reverberation time of the volume. Dirac is also used to postprocessing impulse responses for each receiver point. Impulse responses were recorded using the omnidirectional microphone (B&K Type 4189ZC-0032) that integrated with the handheld analyzer (B&K-Type 2250-A) for all the receiver points. Background noise levels were measured inside and outside of eight mosques by using a sound level meter. The aim carrying out of inside and outside measurements is to understand the acoustical conditions around the mosques. The background noise levels were recorded for 15 min for each mosque.

T30 and EDT parameters are evaluated in the range of 125–4000 Hz for mosques. However, results for parameters D50 and C80 will be interpreted for frequencies of 500, 1000 and 2000 Hz, because frequencies below 500 Hz are insignificant for speech intelligibility and can be neglected [34]. Although the energies of the consonants that are active at high frequencies are low, these letters are important for the speech intelligibility. Vowels are active in the low-frequency range. High-frequency sounds (800–2300 Hz) are the main determinants of speech intelligibility. Frequencies of 4000 Hz and above affect intelligibility approximately 5% [35]. The masking of high-frequency due to low-frequency sounds reduce understandability of speech. This is a problem that can often be encountered in large volumes, where the reflections occur from large/ concave surfaces.

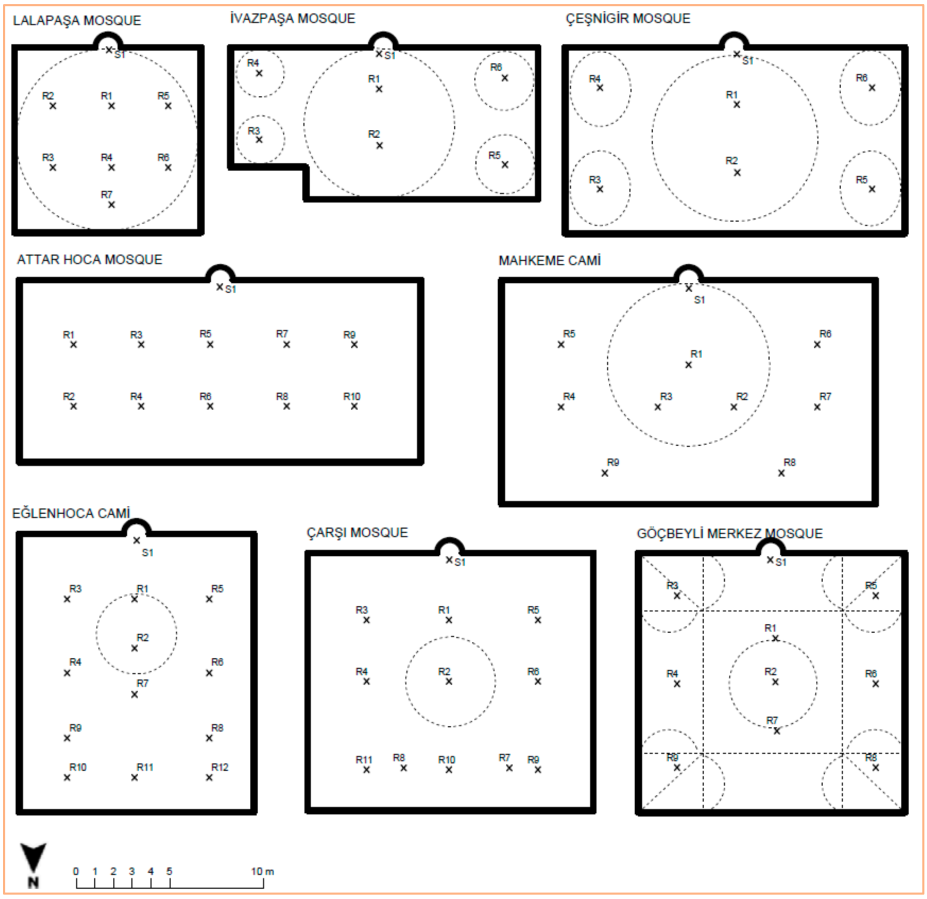


Figure 10. Sound sources and receiver points determined in the field measurements of selected mosques.

4.2. Results of Acoustic Measurements

4.2.1. T30

The average T30 values obtained from receiver points for the eight mosques and their distribution in the frequency range of 125–4000 Hz are shown in the graph in Figure 11. According to the graph, mosques with masonry ceiling structures have higher T30 values than mosques with wooden ceiling structures at almost all frequencies. T30 values are higher at low frequencies in masonry structures, while change by the frequency is not distinctive within the wooden covered mosques. In other words, T30 values can create a flatter line depending on frequency. This can be explained by the absorbing characteristics of the wooden construction, since it works as a panel resonator. On the other hand, higher T30 values in low frequencies help to create a more appropriate environment for musical rituals in masonry top-covered mosques.

It is observed that the number of domes does not affect the average T30 values at medium frequencies in mosques with masonry tops. Additionally, it can be said that the presence of a wooden dome or vault in wooden-covered mosques reduces the average T30 values for all frequencies compared to a flat wooden ceiling mosque.

It can be seen from Figure 12 that averages of reverberation time in mosques with masonry top cover are higher at low frequencies than at medium and high frequencies. The average values at low, medium, and high frequencies show a more balanced distribution in mosques with wooden ceilings. It has been determined that the types of material used in the ceiling structure in mosques have an effect on the change in acoustic parameter value on all frequencies. In other words, the most effective criterion is material of the ceiling construction, so it can be said that the classification of the selected mosques into two groups according to the material type is appropriate. The wooden top-covered mosques have a similar reverberation time range with the literature data in Figure 1, while masonry ones have T30 values of around 2 s.

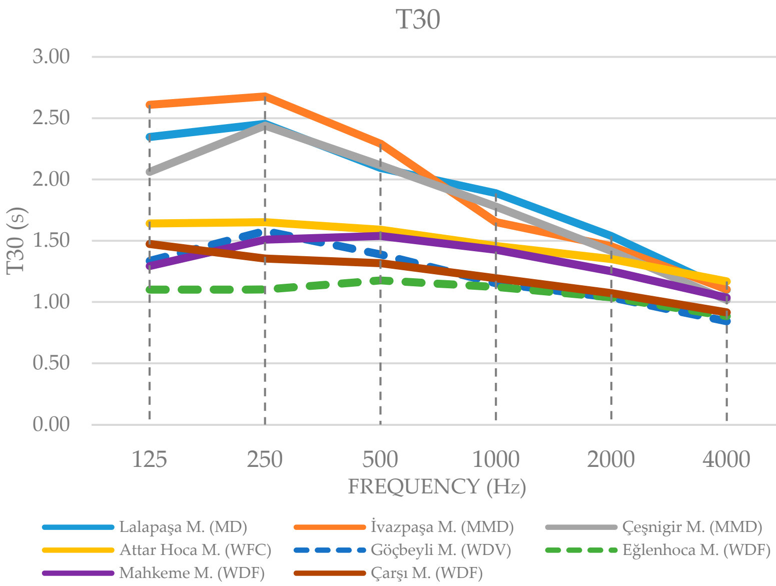


Figure 11. The average values of T30 measured in the eight mosques. (MD; masonry single-domed, MMD; masonry multi-domed, WFC; wooden flat ceiling, WDV; wooden dome and vault, WDF; wooden dome and flat ceiling).

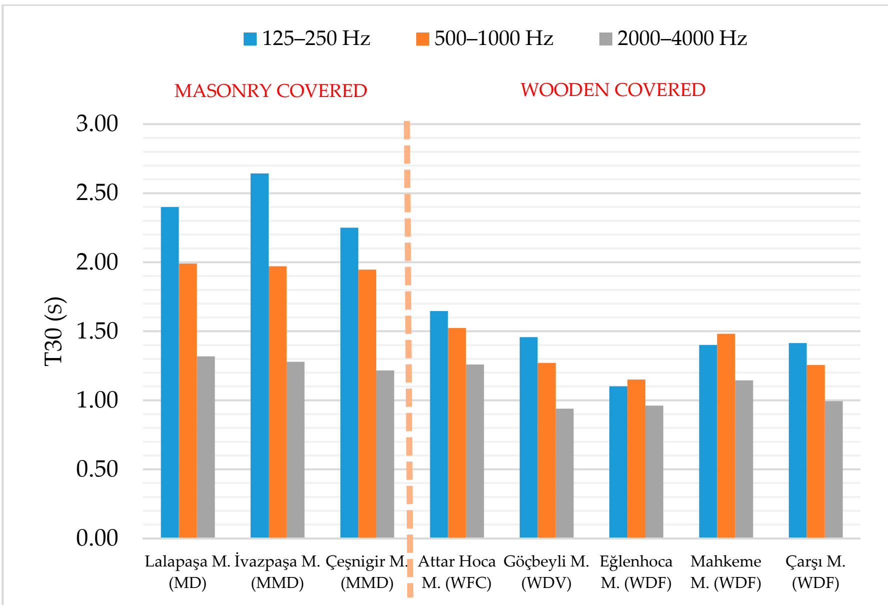


Figure 12. The average T30 values of mosques at low, mid, and high frequencies.

4.2.2. Bass Ratio

The bass ratio is related to the warmth of indoor spaces. If the ratio is higher than 1.2, the warmth of the mosque can be evaluated as excellent [36]. It is regarded as poor when the ratio lower than 0.9. Table 11 shows that masonry-covered mosques have higher bass ratios than wooden ceiling types. This parameter can be used to evaluate "sacred sensation" of the main prayer hall, since the low frequencies are important for that feeling. According to results, the feeling of sacred sensation in the prayer halls of Lalapaşa and İvazpaşa Mosques can be evaluated as better than other mosques.

Table 11. The bass ratio values measured in the eight mosques.

Lalapaşa M. (MD)	İvazpaşa M. (MMD)	Çeşnigir M. (MMD)	Attarhoca M. (WFC)	Göçbeyli M. (WDV)	Eğlenhoca M. (WDF)	Mahkeme M. (WDF)	Çarşı M. (WDF)
1.21	1.34	1.16	1.08	1.15	0.96	0.95	1.13

4.2.3. EDT

EDT is related to the early part of the decay process which measures the rate of sound decay for the first 10 dB of decay [37]. The values should be within ±10% of RT for good acoustical conditions [34]. The ratio of EDT/T30 being close to 1 is desirable for indoor spaces. Additionally, the graph in Figure 13 shows the similarities on the EDT and T30 values which proves to be an indication of the diffuseness and directedness of volumes [37]. At the average of mid frequencies, the values of EDT/T30 ranges are obtained as follows: 1.05, 1.02, 1.02, respectively, for mosques with masonry ceilings, and 0.99, 0.97, 0.98, 1.00, 0.99, respectively, in the mosques with wooden ceilings. It is seen that the ratio is close to 1 for all mosques. However, in wooden mosques, the ratios tend to have values closer to 1. It can be said that sound distribution is more balanced and diffuse in mosques with wooden ceilings.

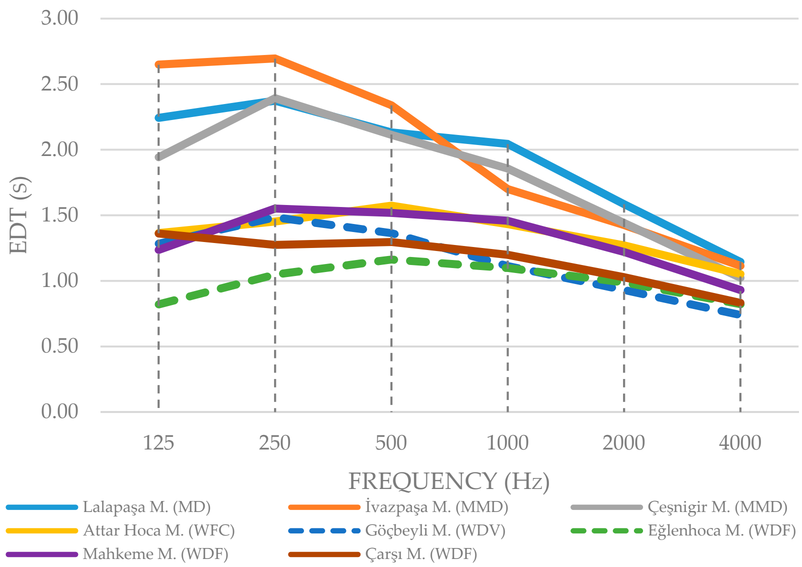


Figure 13. The average values of EDT measured in the eight mosques.

4.2.4. D50

D50, which is related to speech intelligibility, is expected to be greater than 50%. The optimum value range for the D50 parameter in speech functional volumes is defined as 30–70% range in TS EN ISO 3382-1. In addition to this, according to some studies, D50 values higher than 20% are sufficient for volumes with music and speech functions [38,39].

According to the graph of D50, the values obtained between 20% and 50% in the recommended ranges (Figure 14). The values for wooden top-covered mosques are higher than masonry-covered mosques. According to the average measured values of D50, wooden covered mosques, especially with wooden dome or vaults, have better speech intelligibility for worship rituals.

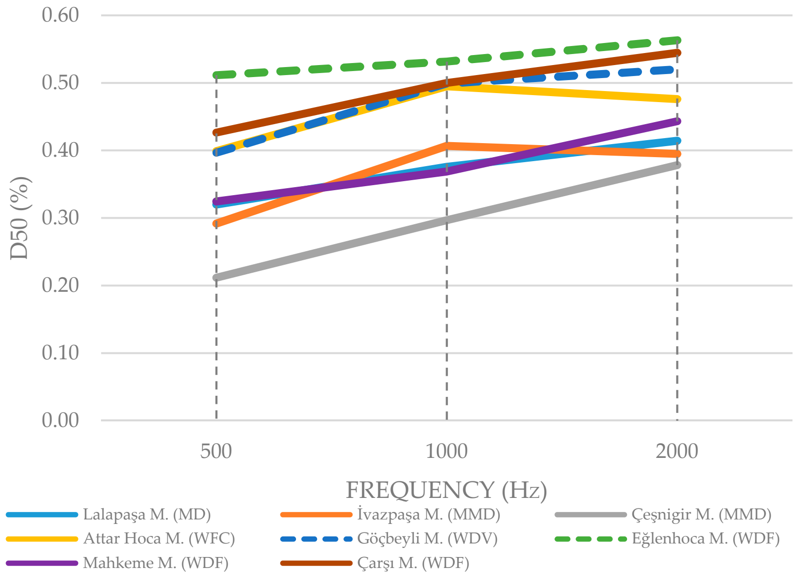


Figure 14. The average values of D50 measured in the eight mosques.

4.2.5. C80

C80 is defined as the ratio of first sound energy reaching within the first 80 ms to the late sound energy that comes to the receiver after this period of energy. The optimum value range for mosques is recommended between −2 and +2 dB to satisfy music and speech activities in mosques [16].

The acceptable C80 values are obtained in masonry-ceilinged mosques at an average of 500, 1000 and 2000 Hz (Figure 15). C80 averages obtained in masonry-ceilinged mosques revealed that they are more suitable for musical rituals or Quran recitals.

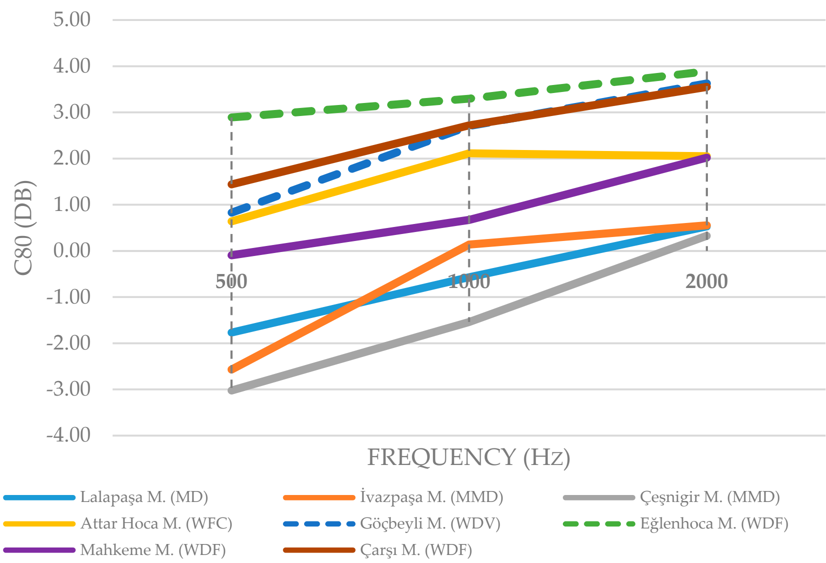


Figure 15. The average values of C80 measured in the eight mosques.

4.2.6. STI

STI is an objective parameter used to measure speech intelligibility in a closed volume. STI is evaluated in the range of 0–1. The optimum values for STI are defined as follows; 0–0.32 is bad, 0.32–0.45 is poor, 0.45–0.60 is fair, 0.60–0.75 is good, 0.75–1.0 is excellent [40].

According to the graph, the average STI values of masonry top-covered mosques are obtained between 0.45–0.60, which is considered fair. In general, wooden top-covered mosques have higher STI values (Figure 16). This reveals a better speech intelligibility level in wooden-covered mosques than masonry-covered ones, although it can be said that all the volumes have acceptable levels of speech intelligibility by considering their monumental features and function.

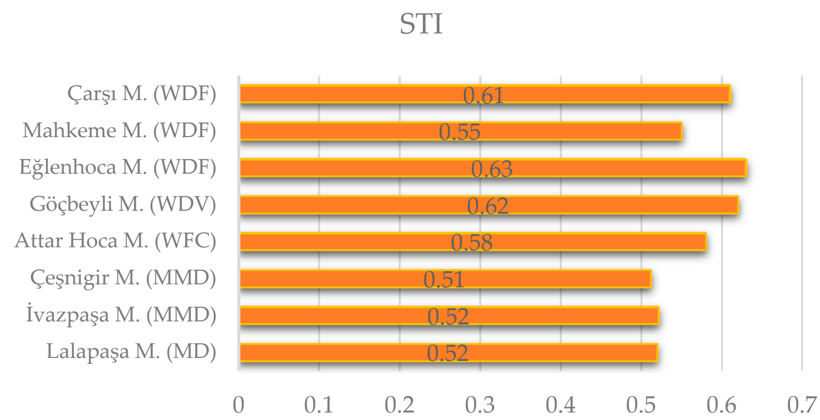


Figure 16. The average values of STI measured in the eight mosques.

4.2.7. Background Noise Level

It is expected that background noise should be between suggested interval limits for good speech intelligibility. The interval limits vary according to the function of the building. In the literature, NC25-30 is the recommended noise interval for religious buildings [41]. Knudsen and Harris emphasized in their book that religious buildings have the necessity for insulation from outside noise. The background noise of the inside shouldn't exceed 30 dB in worship buildings [42]. Acun and Yılmazer found that a quiet environment is described as tranquil by users [27].

Most of the mosques are located among noisy streets and surrounded by shops. However, Göçbeyli Mosque and Lalapaşa Mosque are far from the city center and surrounded by elements of a quiet environment such as a cemetery, trees, and dwellings. The mean LAeq values inside and outside for each mosque are listed in Figure 17. According to the graph, all mosques in the study, except the İvazpaşa Mosque and Mahkeme Mosque, which slightly exceeded the recommended limit value for background noise level, are obtained to have values below 30 dbA. It has been recognized that the noise level outside has little effect on the indoor environment in the examined mosques. It can be related to design criteria of historical mosques, such as wall thicknesses of mosques, garden walls and the building materials used, which all help to create suitable acoustic conditions inside. On this issue, it is important to look at historical mosques regarding noise control between the inside and the outside for the future projects. In addition to this, the differences between the sound levels measured on the inside and outside were similar for the mosques.

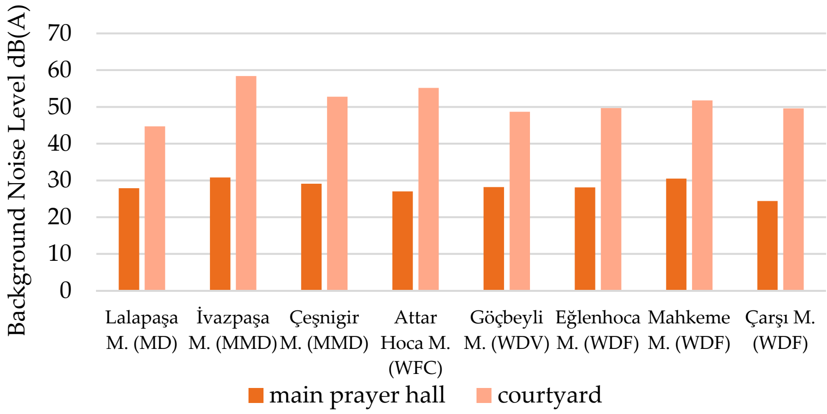


Figure 17. The background noise levels from indoor and courtyard of mosques.

5. Discussion

Mosques are expected to create the ideal environment for both speech and music. Most studies conclude that long reverberation time inside mosques is expected by being compared to the classical speech rooms. However, while it is appropriate to evaluate the parameters related to speech for situations where the intelligibility of speech is important during rituals such as sermons, it is stated in various studies that a reverberant environment is preferred in mosques so that the desired spiritual atmosphere can be experienced by the worshipers.

5.1. The Acoustic Evaluation of Mosques

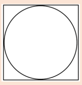
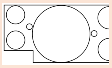
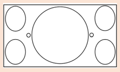
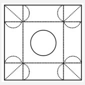
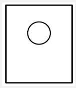
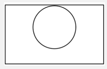
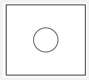
Although there is a lack of certain acoustic data that are specifically oriented to mosques (masjids) [11], the acoustic requirements for achieving the desired conditions in the prayer hall of the mosques are summarized as follows [43];

- lower but controlled RTs for mid and high frequencies, in comparison to low frequencies, for the intelligibility of sermons;
- higher but controlled RTs for low frequencies, in comparison with mid and high frequencies, to enhance the spiritual aspects of musical rites and to balance sound absorption of interior surface materials over the frequency range;
- Minimal acoustical defects such as sound glare, echoes, and dead spots;
- Low background noise that does not hide or reduce speech intelligibility.

According to Orfali (2007); "High Reverberation Time will lead to unacceptable intelligibility levels, while low reverberation time will result in so called "dead" spaces where spiritual ceremonies lose the attention of the worshippers." [10]. In Sü Gül and Çalışkan's study, the acoustical characteristics of the prayer hall are described: "Although the speech intelligibility is the upmost priority; a mosque is not a classical speech room as a conference hall or auditorium. The acoustical environment of a mosque should satisfy the spiritual aspects of worship while enabling the most proper environment for the perception of the imam and muezzin conveys. The functional space of a mosque should not be acoustically dull, as well as not excessively reverberant" [44]. Elkhateeb et al. proposed a model for the optimum RT values: "There is much evidence to prove that long reverberation inside masjids is recommended because it enhances its spiritual role, whereas a short reverberation is neither functional nor reasonable. It appears that the optimal reverberation curve suggested by Kayılı, is the most appropriate. Values on this curve compromise the wishes of Imams and the requirements of the worshippers" [11].

Within the context of this study, the results obtained from the acoustical measurements of mosques for the relevant frequency ranges and the optimum parameter value ranges compiled from references for this volume range are brought together in Table 12. According to the table, it can be said that there are differences in values depending on whether the material of the ceiling structure is wood or masonry.

Table 12. The measured values of acoustical parameters in eight mosques and recommended values. (masonry top-covered mosques, wooden top-covered mosques).

PARAMETERS	RECOMMENDED RANGES	MASONRY TOP-COVERED			WOODEN TOP-COVERED				
		LM	İM	ÇM	AHM	GMM	EM	MM	ÇM
									
T30 (500–1000 Hz)	0.7–1.1 [10] 1.75–1.9 [14]	1.99	1.97	1.95	1.52	1.27	1.15	1.48	1.26
Bass ratio	1.2< excellent 0.9> poor [36]	1.21	1.34	1.16	1.08	1.15	0.96	0.95	1.13
EDT (500–1000 Hz)	RT − (%10x RT) ≤ EDT ≤RT + (%10x RT) [34]	1.79 < 2.09 < 2.19	1.77 < 2.02 < 2.17	1.75 < 1.98 < 2.14	1.37 < 1.5 < 1.68	1.14 < 1.24 < 1.40	1.04 < 1.13 < 1.27	1.33 < 1.49 < 1.63	1.13 < 1.25 < 1.38
C80 (500–1000–2000 Hz)	−4< < 0 dB; for music −2< <+2 dB for speech [6]	−0.60	−0.63	−1.41	1.60	2.39	3.36	0.86	2.57
D50 (500–1000–2000 Hz)	0.3< <0.7 [33] 0.2 < [38,39]	0.37	0.36	0.30	0.46	0.47	0.54	0.38	0.49
STI	0.00–0.30 (bad); 0.30–0.45 (poor); 0.45–0.60 (medium); 0.60–0.75 (good); 0.75–1.00 (excellent) [40]	0.52	0.52	0.51	0.58	0.62	0.63	0.55	0.61
Background Noise Level	<30 dbA [6]	27.9	30.8	29.1	27	28.2	28.1	30.5	24.4

5.2. The Evaluation in Terms of the Effects of Architectural Features on the Acoustic Environments

When the average values of reverberation times for mid frequencies are examined, it is seen that the mosques with masonry tops have reached higher values than the wooden ones. While the masonry covered mosques have higher values for the speech rituals, wooden mosques have reached more suitable values for this function. Moreover, the lower reverberation times in wooden mosques indicate that there is a dry environment for musical rituals. In the group of wooden ceiling mosque, the variation in the ceiling doesn't reveal significant differences in the reverberation time values. It is clearly observed that the T30 values vary according to the material of ceiling.

According to the T30 results, masonry covered mosques have values as 1.99, 1.97, 1.95 and wooden covered mosques have the averages as 1.52, 1.27, 1.15, 1.48, 1.26. Just noticeable difference for T30 has specified to be 5% (0.1 s) in the literature [44]. In the group of masonry covered mosques, the perception does not change among the mosques. However, it is expected that someone coming out of the masonry covered mosque will have a completely different perception of the environment when you enter a wooden mosque.

Masonry-covered mosques have higher T30 values in bass frequencies than in mid frequencies, and bass ratios imply the feeling of warmth which is to be ensured indoors. The line of T30 forms an almost flat line in the transition from low frequencies to mid frequencies in wooden-covered mosques. Therefore, bass ratios in the mosques with wooden ceilings are obtained as lower than mosques with a masonry top.

EDT values for all mosques are found in the range of recommended values in the literature. In wooden mosques, the differences between EDT and T30 have been obtained less than the masonry-covered mosques. The ratio of EDT/T30 was close to 1 in all mosques. It is seen that the distribution of sound energy is balanced for six mosques.

According to the graph of C80 values, it can be said that most of the mosques with masonry ceilings provide the appropriate conditions for music rituals. C80 averages show that all masonry mosques provide a suitable living environment for music function, while values of wooden mosques are obtained above 0 as being dry spaces. The values of D50 have been found in the appropriate range in all mosques. However, this parameter has reached higher values in wooden-ceilinged mosques, and it seems that speech intelligibility is better than masonry-ceilinged mosques.

The differences in background noise levels for eight mosques are obtained as similar between inside and outside. This analysis was carried out to observe the behavior of the building envelope for sound transmission between the indoor and outdoor environment. In these examples, where the building walls were built with a masonry system and the interior surface materials are similar, the ceiling material and shape differ. Despite this, it can be said that mosques with different types of ceilings do not create great differences in sound transmission behavior, and almost all mosques behave similarly.

According to the evaluation results, it has been determined that the values of acoustical parameters of the mosques show different behaviors concerning the ceiling types. The wooden-ceilinged mosques seem to be more appropriate for rituals with speech functions such as Friday's sermon or informative speech from the lecture chair. However, masonry-covered mosques have a better acoustical environment for musical activities such as the recital of the musical version of the Holy Quran. However, it should also be stated that they are important examples of architectural history and have their own characteristics and reflect that the communities were using them to experience different acoustical environments, but none of them are far away from the decent limits.

6. Conclusions

Although acoustical parameter values of cases are different depending on the typology of the examined mosques, it is determined that all of them are in the acceptable range. On the other hand, it can be concluded that there will be differences in the user perceptions of the praying halls depending on the acoustical ambiance. This is because the differences between the values of acoustical parameters are above the JND range, when the mosques are compared. In addition, it is found that the material of the ceiling construction has more singular effect than its formation on acoustic characteristics of the sound volume.

While reverberant environments are more appropriate for creating the desired sacred feeling, in some cases, short reverberation times and good speech intelligibility are desired during rituals such as Friday sermons or praying. In other words, acoustic evaluation of the mosque volume is quite a difficult process because of the challenge between T30 requirements of the intelligibility of speech and the need of sacred feeling. While these debates continue for the reverberation time values in mosques, the acoustic environments in historical mosques that have been used for centuries have been accepted as they are by people that use them. Electro-acoustic reinforcement can be used as a solution in wooden-ceilinged mosques with low reverberation times, in accordance with the recommendations of acoustic consultants, to create the vitality of the volume and spiritual feeling for rituals with musical functions such as Quran recitals or hymns. However, it should be kept in mind that musical instruments are not included in these sermons.

Another important aspect of the study is to emphasize the preserving and sustaining the original acoustical perception of the historical volumes. In the context of the importance of evaluating the intangible values specific to societies as cultural heritage in terms of diversification and enrichment of cultural heritage, the genuine acoustic environment of mosques is an issue that should be taken into consideration in renovation studies. In the renovation works of historical mosques, it is necessary to consider the unique acoustic perceptions of the volumes rather than the architectural features of the mosques. It is important to choose suitable and sustainable materials, especially in the renovation of historical mosques, to sustain rituals with speech and musical functions without harming the original acoustic environment of the prayer hall. Finally, it can be said that increasing the number of studies in which acoustic comfort conditions of mosques are analyzed by subjective evaluation methods and evaluating the data obtained from such studies together with objective findings are expected to be developed in this field.

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