The contribution of domes to speech intelligibility in mosques

Kivanc Kitapci[1], Melike Kayhan[1], Öğütnaz Çoban[2],

[1] *Department of Interior Architecture and Environmental Design, Faculty of Architecture and Design, TOBB Economics and Technology University, Ankara, Turkey*

[2] *Department of Audiology, Institute of Health Sciences, Ankara Medipol University, Ankara, Turkey*

Abstract

Mosques are multilingual spaces in non-Arabic countries. These mosques require intelligible speech in multiple languages, including the languages spoken by the majority of the population in the country and Arabic. For instance, in Türkiye, speech should be intelligible in both Arabic and Turkish. Speech intelligibility in enclosures is mainly influenced by reverberation time (RT) and signal-to-noise ratio (SNR). In the literature it is evident that languages are affected by RT and SNR differently. Additionally, due to the sacred nature of mosques, a divine feeling should be present by strong late reflections at certain frequencies. Therefore, early and reflections in mosques should be adequate for each language spoken in the enclosure, while maintaining divine feeling with strong late reflections at specific frequencies. This hypothesis requires multi-layered analysis of field measurements of room acoustic parameters, acoustic simulations and listening tests to achieve an optimization between multilingual speech intelligibility and divine feeling. This paper presents the first phase of an extensive research project. In this phase, our aim was to reveal the effects of dome geometry on speech intelligibility; therefore, we analyzed the difference of acoustic characteristics between domed and non-domed mosques. We conducted field measurements in Mogan Lake Mosque in Ankara, which is a unique example of non-domed mosques, followed by computer simulations evaluating an alternative multi-dome configuration of the same mosque. The results of the study will reveal the contribution of dome geometry to speech intelligibility in mosques.

Keywords: mosque acoustics, non-domed mosque, reverberation time, background noise

1. Introduction

Acoustics quality is an important aspect in the design of mosques.[1] Mosques are not only places of worship but also important structures where social and cultural interactions take place [2]. Activities carried out in these spaces, which are considered sacred in Islam, require intelligible transmission of speech [3].Activities such as congregational prayers, religious lectures, and Qur'an recitation are among the primary functions that require a high level of speech intelligibility [3]. Challenging acoustic conditions degrade the effectiveness of these activities, due to reduced speech intelligibility and eventually decreasing user comfort.

Intelligible speech requires low reverberation time and high signal-to-noise ratio [4]. However, in the literature there is evidence that different languages require different reverberation times and signal-to-noise ratios for intelligible speech [5]. Additionally, the spiritual feeling expected in sacred spaces requires higher reverberation times in specific frequency ranges [6]. It is also evident that mosques are multilingual spaces hosting Turkish and Arabic speech simultaneously [7]. The wide range of requirements for both multilingual speech intelligibility and sacred feeling in such spaces requires complicated solutions.

It is evident that the geometry and volume of an enclosure show a combined effect on speech intelligibility and the divine feeling. In a study conducted on the historical Aslanhane Mosque in Ankara, it was found that the small-volume spatial design without a dome, combined with the effect of wooden structural elements, significantly improved speech intelligibility [6]. However, it was also noted that the absence of architectural elements such as domes, which focus sound energy and increase reverberation, had a reducing effect on the spiritual atmosphere expected in a religious space [6]. This phenomenon regarding dome-less structures is also supported by a study conducted in typical contemporary dome-less mosques built in Saudi Arabia; objective parameters such as Reverberation Time (RT), Early Decay Time (EDT), and STI measured with the sound system turned off clearly demonstrate the critical effect of prayer hall geometries on acoustic performance [8].

Beyond spatial geometry, recent literature emphasizes that mosque acoustics should be examined together with the linguistic and phonetic context of the local community. In a comprehensive study investigating the optimum RT in mosques for Bengali-speaking communities, it was determined that due to significant differences between the phonetic characteristics of Bengali, English, and Arabic, room acoustics create more challenging conditions for speech intelligibility. It was revealed that the melodious and non-instrumental recitation of the Holy Quran in Arabic requires higher RT for semantic liveliness, whereas sermons delivered in the local language (Bengali) require precise intelligibility [9].To balance these two conflicting requirements, an optimum reverberation time (RT) of approximately 0.9 seconds was proposed to preserve both recitation quality and speech intelligibility. Furthermore, a study on the historical domed Sultan Hassan Mosque and Madrasa in Egypt also pointed to a similar linguistic tolerance; despite high RT and pronounced echoes measured, it was observed that the congregation could clearly understand speech [10].This situation was explained by the ability of the Arabic language's temporal and phonetic characteristics to tolerate and mask difficult acoustic conditions [10]. As a result, the evaluation of mosque acoustics requires a holistic approach that integrates architectural form with local phonological perception.

Although mosque acoustics has been widely investigated in terms of RT, speech intelligibility, and architectural form, most studies have focused on the intelligibility of a single language. Research addressing speech intelligibility in multilingual worship environments remains limited [5].This represents an important gap, since mosques commonly host both Turkish and Arabic speech through activities such as sermons, religious lectures, prayers, and Qur'an recitation [7]. Previous studies have shown that speech intelligibility requirements may vary across languages due to differences in phonetic and linguistic characteristics [5]. Furthermore, acoustic conditions that enhance speech intelligibility may not always coincide with those that support the reverberant and spiritual atmosphere expected in sacred spaces [6]. Therefore, there is a need to understand how intelligible are different languages in the same mosque environment.

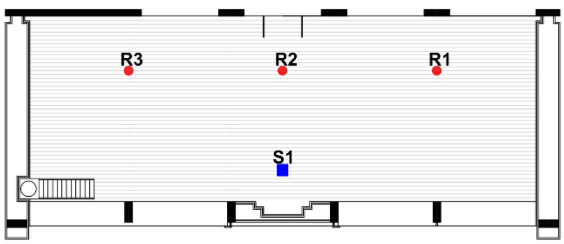
We hypothesize that a specific approach to designing mosques is achievable by considering two facts stated above: high multilingual speech intelligibility between Arabic and Turkish (1), preserving sacred feeling expected in sacred spaces (2). We structured a large-scale research project consisting of a 2-step analysis of mosque acoustics, specifically, speech intelligibility in such spaces. The first step consists of field measurements and recording of BRIRs of Mogan Lake Mosque, which is the context of the present paper. The second phase of the study will utilize the collected BRIR recordings to convolve Arabic and Turkish speech recordings, followed by listening tests. It is our aim to understand how multiple languages behave in the same environment while preserving sacred feelings.

This paper presents the initial results of the first phase of a larger research project, aiming to evaluate multilingual speech intelligibility in non-domed mosques, specifically focusing on the phonemic and temporal differences between Arabic and Turkish languages. The present study was conducted in the Mogan Lake Mosque located in Ankara, Türkiye. The mosque is one of the limited examples of non-domed mosques in the country. Various activities such as congregational prayers, religious lectures, and Qur'an recitation are carried out in the mosque. It is aimed to quantify the acoustic characteristics of the structure The analysis is particularly focused on the Reverberation Time (RT_{30}) and background noise levels. The current scope examines the dome form of the mosque and the physical characteristics of the space. Within this framework, in addition to the field measurements conducted in the existing non-domed structure, an alternative model of the same space with a dome was created, and its acoustic performance was tested through simulation. The obtained RT_{30} data were evaluated comparatively and established a solid foundation for the upcoming multilingual speech intelligibility testing phase.

2. Methods

Within the scope of the field study, background noise measurements were first conducted under unoccupied conditions using an NTi XL2 sound level meter at three receiver positions (right [R1], left [R3], and center [R2]), as illustrated in **Fig. 1** Subsequently, the NTi XL2 sound level meter was positioned at these same locations at a height of 1.50 meters above the floor, corresponding to the average ear level of seated worshippers, in accordance with the ISO 3382-1 [11]. The source loudspeaker was placed in the mihrab section at a distance of 1.50 meters from the nearest wall. Following this setup, RT_{30} measurements were performed by emitting a white noise signal in accordance with ISO 3382-1 [11].

Figure 1. Measurement setup showing the source position in the mihrab area and the receiver positions.



RT_{30} values exported from the NTi XL2 were tabulated across six 1/1 octave band frequencies. The 63 Hz and 8000 Hz bands were excluded due to measurement uncertainty at low frequencies and high-frequency air absorption effects, respectively. Spatial averages were calculated arithmetically across the three receiver positions.
Next, a multi-dome ceiling has been integrated into the existing dome-less structure to examine the acoustic effect of a domed alternative. The rationale for this design is based on an interview conducted with the mosque's architect, Hüseyin Bütüner. The architect

stated that due to the mosque's non-square, rectangular plan scheme, a single large dome would not be suitable, because such a dome would only cover a limited portion in the center of the area. Instead, the architect, drawing reference from the traditional Bursa Ulu Mosque typology, proposed a configuration consisting of ten equal, small-scale domes that would cover the rectangular volume in the most optimal way, and presented a preliminary design sketch in this direction. As a result, this alternative ten-domed geometry has been incorporated into the base model while preserving the original architectural configuration and material properties. Mogan Lake Mosque was modeled in the SketchUp 2021 program [12]. To ensure a controlled comparison, all other parameters have been kept constant, and the changes have been applied only to dome geometry.

The model was then exported to the open source I-SIMPA room acoustics analysis software [13]. The same source and receiver positions used in the field measurements were implemented in the simulation model. Acoustic simulations were carried out to obtain the RT_{30} values across the defined frequency bands. Material absorption coefficients were assigned based on values presented by M. David Egan [14], as shown in **Table 1.** Prior to the simulations, a calibration process was performed to achieve consistency between the measured and simulated acoustic responses. Concrete was selected as the calibration material because it represented the predominant surface area within the mosque, making it the most influential factor in the overall acoustic behavior. The absorption coefficients of the concrete surfaces were iteratively adjusted until the simulated RT_{30} values matched the field measurements.

Table 1. Sound absorption coefficients of the surface materials used in the simulation model (adapted from Egan [14]).

Band (Hz)	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Wood	0.15	0.11	0.10	0.07	0.06	0.07
Carpet	0.02	0.06	0.14	0.37	0.60	0.65
Window (glass)	0.18	0.06	0.04	0.03	0.02	0.02
Concrete, painted	0.10	0.13	0.12	0.12	0.9	0.10

The reliability of the simulation model was validated by comparing the measured and simulated RT_{30} values for the existing non-domed configuration. Both datasets were obtained using identical source and receiver positions and evaluated across six 1/1 octave band frequencies (125–4000 Hz). The agreement between measured and simulated results was assessed using the Just Noticeable Difference (JND) criterion. In room acoustics, a relative difference of 5% for reverberation time is commonly accepted as the perceptual threshold below which differences cannot be perceived [11]. The final comparative data, including the measured and simulated spatial averages alongside their corresponding acceptable JND ranges, are summarized in **Table 2**. Following calibration, the differences between measured and simulated RT_{30} values were found to be within the 1 JND limit across all analyzed frequency bands. These results indicate that the simulation model provides an accurate representation of the acoustic behavior of the mosque and can be considered reliable for subsequent comparative analyses.

Table 2. Comparison of measured and simulated spatial average RT_{30} values against acceptable JND ranges.

Freq. (Hz)	Measured Spatial Average (s)	Simulated Spatial Average (s)	Acceptable JND Range
125	1.87	1.88	1.77–1.96
250	1.55	1.58	1.47–1.63
500	1.49	1.49	1.42–1.57
1000	1.34	1.34	1.27–1.41
2000	1.36	1.37	1.29–1.43
4000	1.21	1.18	1.15–1.27

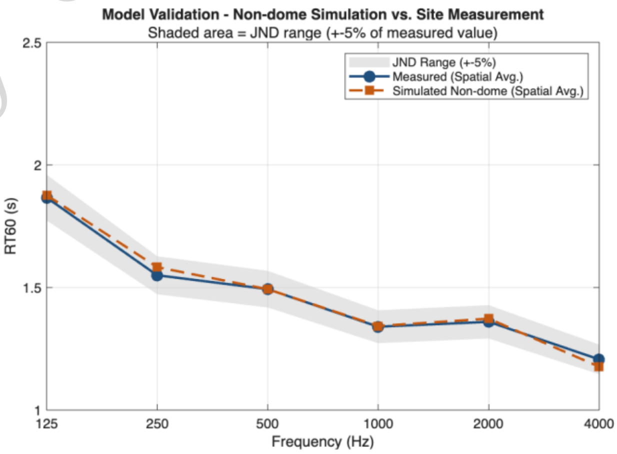


Figure 2. The comparison between simulation results and the field measurements in the non-domed structure.

3. Results

The results of the field measurements are presented in **Table 1**. It was observed that the spatial average of the RT_{30} is highest (1.87 s) at 125 Hz and lowest (1.21 s) at 4000 Hz. The largest deviation between the receiver positions was observed at 125 Hz (0.68 s), and the lowest deviation was observed at 4000 Hz (0.08 s).

Table 1. Measured RT_{30} values by Receiver Position

Position	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Center	1.56	1.48	1.37	1.26	1.29	1.17
Left	1.80	1.66	1.50	1.34	1.39	1.20
Right	2.24	1.51	1.61	1.42	1.40	1.25
Deviation	0.68	0.18	0.24	0.16	0.11	0.08
Spatial Avg.	1.87	1.55	1.49	1.34	1.36	1.21

Simulation results for both configurations are presented in Table 2 and Figure 2. For the non-dome case, the spatially averaged RT_{30} values ranged between 1.88 s at 125 Hz and 1.18 s at 4000 Hz. Furthermore, the simulated RT_{30} values were observed to vary between 1.78 s and 1.24 s across the same frequency bands.

The influence of dome geometry on the simulated RT_{30} can be seen in Figure 2. Two major deviations were observed. The first deviation was the increased RT_{30} in the domed structure at 500 Hz, 1000 Hz, and 2000 Hz; in which the largest difference was at 2000 Hz. The second deviation was the decreased RT_{30} in the domed structure at 125 Hz. Furthermore, it was seen that the dome geometry does not have any distinguishable effects at 250 Hz and 4000 Hz.

Table 3. Simulated RT_{30} values by receiver position in the non-dome configuration.

Position	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Non-domed Simulation						
Center	1.84	1.54	1.45	1.31	1.31	1.12
Left	1.90	1.61	1.51	1.34	1.43	1.21
Right	1.89	1.60	1.52	1.38	1.38	1.20
s	**1.88**	**1.58**	**1.49**	**1.34**	**1.37**	**1.18**
Domed Simulation						
Center	1.78	1.55	1.53	1.39	1.49	1.23
Left	1.79	1.58	1.54	1.45	1.51	1.25
Right	1.77	1.58	1.54	1.43	1.47	1.24
Spatial Avg.	**1.78**	**1.57**	**1.54**	**1.42**	**1.49**	**1.24**

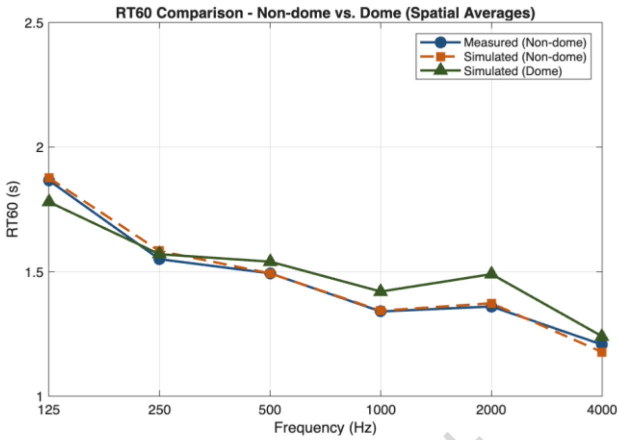


Figure 3. Average RT_{30} Comparison between the non-domed (measured and simulated) and domed (simulated) structures.

4.Discussion

The findings demonstrate that domes play an important role in determining reverberation characteristics, particularly at mid-frequency bands. According to the simulation results, the introduction of a multi-dome configuration into the existing non-domed structure led to an increase in reverberation time at mid-frequencies. This finding confirms, from a physical standpoint, that curved surfaces and dome geometries sustain reflections by retaining sound energy within the space, thereby prolonging reverberation. As also reported in previous studies on the non-domed Aslanhane Mosque [6], the absence of architectural elements such as domes may reduce the sense of envelopment and spiritual ambiance (perception of sacredness), while improving speech intelligibility (STI). In this regard, the present study supports the existing literature by quantitatively demonstrating the increase of reverberation time caused by dome geometry. Furthermore, while previous studies on contemporary non-domed mosques in Saudi Arabia, [7] have emphasized the influence of prayer hall form on acoustic performance, this study contributes to the field by conducting a controlled comparison of alternative geometries within the same architectural context. When frequency-dependent behavior is examined, it is observed that the difference in RT_{30} between the domed and non-domed configurations becomes negligible at 4000 Hz. This indicates that, at higher frequencies, material absorption and air attenuation becomes the dominant factor governing acoustic behavior, while the influence of geometry appears to be limited. Conversely, the slightly lower RT_{30} values observed in the domed model at 125 Hz should not be interpreted as a true physical effect, but rather as a limitation of geometric acoustics methods at low frequencies. In addition, the variations observed between receiver positions in the field measurements, particularly at 125 Hz (ranging from 1.56 s to 2.24 s), are indicative of irregular modal behavior, which is commonly encountered in enclosed spaces of this scale.

Lastly, the study has certain limitations. The acoustic measurements and simulations were conducted only under unoccupied conditions, which may not fully represent real-use scenarios. Future studies should incorporate occupied conditions to account for the absorptive effect of the congregation, include the Early Decay Time (EDT), Clarity (C_{50}), Speech Transmission Index (STI), and other relevant acoustical indicators for a more comprehensive evaluation of speech intelligibility, and investigate the acoustic impact of different dome geometries beyond multi-dome configurations.

5. Conclusion

This study investigates the acoustic behavior of non-domed mosques, a typology that remains relatively underrepresented in the literature, and evaluates the effect of dome geometry on reverberation time through the case of the Mogan Lake Mosque. The results of the present study fill a gap that exists in the mosque acoustics literature, where dome less typologies have received comparatively little attention.

Mogan Lake Mosque served as the subject of this investigation, which brought together field measurements and geometric acoustic simulation to assess the acoustic character of the space. Under unoccupied conditions, spatially averaged RT_{30} ranged between 1.87 s at 125 Hz and 1.21 s at 4000 Hz. Initially, the non-domed configuration was verified against the field measurements: simulated RT_{30} stayed within one JND of the measured RT_{30} at each octave band. A domed configuration of the same space was then simulated. Mid-frequency bands (between 500 Hz and 2000 Hz) showed longer decay times, whereas the gap between the two configurations narrowed considerably toward 4000 Hz as absorption took precedence over geometry. The results indicate that domes increase reverberation time especially at mid-frequency, in which the majority of acoustical energy related to speech intelligibility are carried. However, in the literature, there is evidence that spatial requirements of intelligible speech vary between different languages [5]. Therefore frequency based reverberation time analysis must be evaluated against multilingual listening tests to observe the effects of dome configuration on multilingual speech intelligibility.

Mosques are multilingual spaces. If the mosque is not located in one of the Arabic speaking countries, depending on the geographical location, at least two languages should be equally intelligible: Arabic and the native language of the host country. Therefore, traditional room acoustical analysis methods to quantify speech intelligibility should be questioned. Geometrical configuration of the dome structure is one of the most influential aspects defining the volume of such spaces. The present study was the initial step of a larger research project investigating multilingual speech intelligibility in mosques. Further steps of the research project will aim to incorporate other speech intelligibility related acoustical parameters besides reverberation time (EDT, C50, D50, and STI) and utilize multilingual/bilingual listening tests to achieve a more comprehensive and holistic analysis of speech intelligibility multilingual spaces.

6.Acknowledgments

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