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The Optimal Reverberation for Masjids

A Subjective Assessment for Worshippers' Demands

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ABSTRACT

This study investigates the optimal reverberation time in masjids (mosques) from worshippers' viewpoint for the two modes of performance: recitation and sermon/speech. It also examines the effect of both age and gender on worshippers' preferences. To this end, specially convolved five audio clips (five acoustic setups) for each mode were created and uploaded to Google Drive. More than 300, Arabic-speaking participants, males, and females of different ages, listened to these clips. The participants judged the ***quality*** (Q, or appropriateness) of these audio clips for listening either to the recitation (Q_R) or speech (Q_S) on a unipolar discrete five-grade scale via a questionnaire that was created on Google Forms. Results indicated that both Q_R and Q_S are functions of gender and age. Overall, younger worshippers preferred higher reverberation and vice versa, while gender significantly affected the perception of the desirable reverberation for both recitation and speech. Females tended to the shorter reverberant environment (1.38 s for recitation mode, 0.75 s for speech mode, in the mid-frequency range) than males who preferred longer reverberation for recitation in particular (1.77 s).

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1. Introduction

More than a hundred years have passed since Sabine defined "reverberation," a term that still attracts attention from researchers and practitioners in building acoustics. Over decades, although more additional acoustic indicators have been discovered or developed in the field of room acoustics, many of which were derived from the reverberation time, which certainly makes it "the mother of all room acoustical parameters" [1]. Research in reverberation can be divided into objective and subjective [2]. The objective section is related to the physical aspects of this indicator; from its definition to the objective metrics that can be used to describe, evaluate, and remedy the acoustic properties of the sound field [3-5], from the methods and formulae of calculation to the equipment, devices, and procedures of measurement [6,7]. On the other hand, the subjective section assesses and describes through either measurement, simulation, or both how the reverberation is received, perceived, or felt by a recipient. Research in this area includes, but not limited to, artificially created audio signals [8,9], subjective listening with audio devices [10-12], subjective evaluation of room acoustics parameters [13-15] and assessment of audio quality [16,17]. While considerable knowledge has been acquired and accumulated in the objective domain, the subjective domain is still "not fully understood" [2].

The masjid (mosque) is a place of worship for Muslims. Islamic law (*Sharīʿah*, see Appendix A) strongly encourages Muslims to attend their five daily prayers in congregation in the masjid. This enhances its role and effect in Muslim societies. Three main acoustic activities can be identified in masjids: listening to the Imam's ***recitation*** during the aloud prayers (will be called recitation mode henceforth), listening to the Friday sermon (***speech***, will be called speech mode henceforth), and listening to religious lessons that are given from time to time in the masjid (***speech***) [18]. A detailed description of masjid's architecture and the way in which the prayer (whether performed individually or in a group) is performed according to Islamic law was previously presented and discussed in several published works [19-22], it will not be repeated here. Nevertheless, brief descriptions are given in Appendix A.

As a listening space, researchers recognized the importance of acoustics in the success of the masjid's religious mission several decades ago. The research has been extensive, with tens of papers on this topic, most of which cover the different objective aspects of masjid acoustics, either historically or currently. In this context, the works of Hammad [23], Karabiber and Erdogan [24], Seogijanto and Henriza [25], Prodi and Marsilo [26], Kayili [27], António *et al.* [28], Al-Saleh [29], Othman and Mohamed [30], Elkhateeb *et al*. [31], Hossameldien and Alshawan [32], Gül [33], Sabbagh and Elkhateeb [34] are but a few examples. Kayili [27] was probably the first to propose an optimal reverberation curve for masjids, from which the optimal reverberation time T_{OM} can be concluded based on the masjid's volume V. The values on this curve can be calculated using the equation [21]:

$$\boldsymbol{T_{OM} = 0.822\, V^{0.1080}\ (s)} \qquad \text{Eq. 1}$$

Elkhateeb *et al*. [35] compared the measured reverberation times in a sample of contemporary masjids (located in Jeddah city, Saudi Arabia) to the optimal reverberation curve, as suggested by Kayili [27]. Results showed that none of the examined masjids met the recommended optimal values in the case of occupation. All masjids under consideration were equipped with artificial reverberation and echo systems as a requirement for their imams to compensate for this missing natural reverberation. In many cases, these systems were not appropriately adjusted; instead, they were entirely left to the desires of the imams. Thus, it may confuse the worshippers due to the lack of intelligibility and the distortion it causes to the subsequent syllables. However, the quality of the acoustic environment in historical masjids is much better, especially in the Mamluks era, where a recent study [22] showed that masjids of this era were distinguished by their long reverberation times. Moreover, the predicted reverberation times in these masjids (either occupied or unoccupied) not only significantly exceed the optimal values for symphony halls and churches but also T_{OM}, as proposed by Kayili [27].

In contrast to the objective aspects, studies and research that have investigated the subjective acoustic factors of the masjid, despite its importance, are relatively new and still growing. Under the subjective category, many researchers aim to identify the acoustic requirements and demands of either the worshippers (the audience) or the Imam (the sole performer, see Appendix A). For the former, Najmul Imam *et al*. studied the acoustic demands of twelve Bangladeshi male worshippers (non-Arabic speakers) who are almost in the same age (32 years old on average) [36]. For the latter, Elkhateeb recently published a detailed study of the acoustic demands of imams with Arabic mother tongue [37]. To the best of the authors' knowledge, the works of Najmul Imam [36,38] and the work of Elkhateeb are, perhaps, the only studies in this area. Still, the acoustic demands of Arabic-speaking Muslim worshippers of different genders and ages have not been studied yet.

1.1. The Difference between Performing a Recitation and Performing a Sermon

Recitation of the Noble *Qur'an* is a unique performance in the spoken Arabic language. It must apply a strict set of *Altajweed* rules (see Appendix A). It is obligatory to recite it in a "slow, (pleasant tone and) style" [39]. While the recitation should follow a melodic style, it is neither a song nor a piece of music. Performing recitation includes text priority, a pause between phrases, and not playing purposely with the text for melodic reasons, this makes it differ from the music performance that is subjected to the variants and versions [40]. Because the performance is melodic and because we prefer a longer reverberation for music than for speech [41], recitation needs a longer reverberation time for liveliness and to add the depth required for such type of spiritual performance [21,36]. There are two common styles (methods) in which the Qur'an can be recited: the very slow style (known as the *Mujawwad*, see Appendix A) or the slow style (known as the *Moratal*, see Appendix A) that is usually utilized during prayer either in a group or as individuals [21]. The main difference between the two styles is the number of syllables per second (SPs), consequently, the number of spoken words per second (WPs). In the *Mujawwad* style, the number of SPs is minimal (around 1–2 SPs or less than 1 WPs). Additionally, such a style usually contains long pauses (about 2 s or more), whether within the same "extended" verse or between successive verses. It is faster in the "*Moratal*" recitation, where the number of SPs may reach 3 SPs or about 1 WPs [21].

In addition to hosting congregational prayers, the masjid is also used to deliver religious lessons and speeches. Every Friday, the Imam should deliver a short to mid-length speech (Friday sermon, see Appendix A). The speech should be in a moderate tempo, which is usually slightly faster than the *Moratal* style. In this mode, the number of SPs is about 3–5 SPs (around 1.6 WPs). Such performance ensures no apparent acoustic conflict between the two modes (recitation and speech). For comparison, SPs in the usual spoken Arabic language can be up to 6–7 SPs (or about 3 WPs) [42]. Among other factors, these facts clarify why a relatively long reverberation time does not harm speech intelligibility in masjids.

1.2. When did Acoustics Become a Design Consideration in Masjids?

Despite its importance, there is no direct answer to this question. Nevertheless, because the worshippers are still committed to offering their group prayers in the masjid according to the teachings of Islam (which means that the density does not change), it is possible to trace the changes which have occurred in masjid's height (that is, the changes in volume per person V_P in m^3) since the prophetic masjid (*Almasjid Alnabawi*, see Appendix A) till the great masjids of Ottoman era, to induce when the acoustics historically attracted the attention of Muslim architects. In its original condition, the prophetic masjid had a large area with a minimal height (less than 3.00 m [22], which means a limited volume as well, V_P = 1.87 m^3). Additionally, one of its sides was utterly open to a courtyard. All these aspects certainly reflect a too-short reverberation, which, in turn, means that acoustics was not yet a design consideration during this era.

With the expansion of the Islamic state during the era of conquests, the Muslim architect began to be exposed to and influenced by the architectural products of other civilizations, the most important is of course, the Sassanid (Persian) architecture in the east and the Byzantine (Eastern Roman) architecture to the west. The Muslim architects had noticed the magnificence of sounds when bounced off the walls that defined these immense volumes of churches and temples, the religious architectural products of those civilizations. Thus, they realized the effect and impact of volume on the acoustics of religious buildings. The results of this exposure were evident in the architecture of the *Umayyad* masjid (705-715 CE, the crown of the *Umayyad* architecture in Damascus, Syria), which was inspired by Byzantine architecture. In this masjid, the V_P doubled several times to reach 5.25 m^3. The architecture of the masjids of *Ibn Tulun* (879 CE) [43], *Al-Azhar* (972 CE), *Al-Hakim* (992 CE), *Al-Aqmar* (1126 CE), and *Al-Salih Tala'i* (1160 CE) [44] in Egypt are good examples of the Abbasid architecture (750-1517 CE), that started in Baghdad and was inspired by the Sassanid architecture in Iraq and Iran. These masjids provide evidence for the effects of such exposure, where the mean V_P was again increased to 6.56 m^3 [45]. The impact of acoustics on masjids architecture was confirmed in the Mamluk era in Egypt (1250-1517 CE), where the mean V_P in the closed *iwan* (see Appendix A) masjids reached 9.00 m^3, higher in the semi-closed *iwan* masjids (10.95 m^3). It exceptionally exceeded 18 m^3/person in the masjid and school of *Sultan Hassan* (1362 CE), the masterpiece of the *Bahri* Mamluk masjids [22].

The *Ottoman* Empire in Turkey (1299-1923 CE) inherited the legacy of the Byzantine state. It coexisted with the Abbasid states in Baghdad and the Mamluk state in Egypt for over two centuries. It can be alleged that the conquest of Constantinople (1453 CE) was a turning point in masjid architecture and likely in masjid acoustics as well. All the great Ottoman masjids had been built after this conquest with their majestic architecture. They were initially influenced by the iconic architecture of Hagia Sophia (the sixth-century Byzantine church [46]), but it later took its distinctive character. The masjids of Sultan *Mihrimah* (1570 CE, V_P = 16.14 m^3), Sultan *Ahmed* (1616 CE, V_P = 22.47 m^3), *Süleymaniye* (1557 CE, V_P = 24.78 m^3), and *Selimiye* (1574 CE, V_P = 30.08 m^3) are other good examples for the effect of acoustics upon masjid architecture in this *Ottoman* era [47-49], all these masjids were built after the conquest of Constantinople. This conclusion is supported by the fact that *Mimar Sinan* (1488/1490-1588 CE) [50,51], the chief *Ottoman* architect, had seen many Byzantine and *Seljuk* monuments in Istanbul and Anatolia. "His travels with the army through a vast geographical region extending along the Mediterranean Basin from Anatolia to Italy and the Adriatic coast to Central Europe, and from Azerbijan [Azerbaijan] to Baghdad in Asia enriched his architectural knowledge and provided him with a wealth of ideas, resources, and solutions. The synthesis of his knowledge was reflected in his famous constructions as seen in his chief work of Suleymaniyye [*Süleymaniye*] Mosque (1550-1557)" [52]. This may justify the vast volumes of the Ottoman masjids, which have never existed before and may not again be built. Figure **1** illustrates the historical development in V_P (which reflects the increase in the masjid's height), beginning from the prophetic masjid in the seventh century CE to the *Ottoman* Empire, where masjid architecture was at its peak.

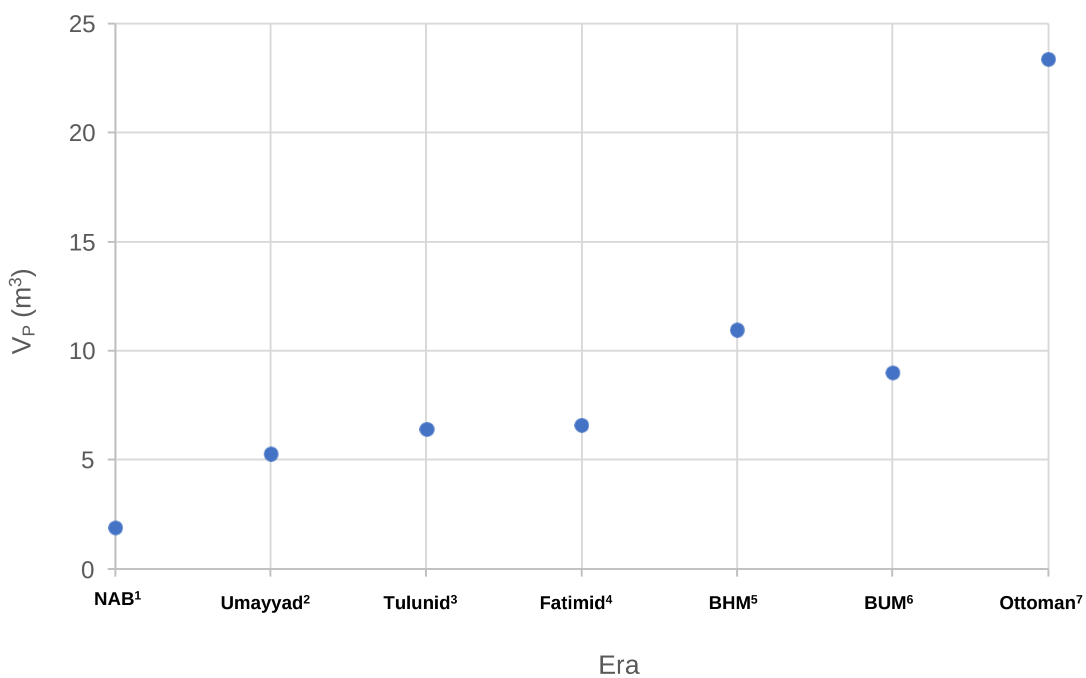

Figure 1: The historical development in the volume/person V_P (m^3) from the prophetic era in the seventh century CE till the Ottoman Empire, (1)The prophetic and the Rightly Guided Caliphs (Rashidun) era (622-660 CE), (2)Umayyad caliphate 661–750 CE, (3)Tulunid dynasty (868–905 CE), (4)Fatimid Caliphate (909–1171 CE), (5)Bahri Mamluk dynasty (1250 to 1382 CE), (6)Burji Mamluk dynasty (1382-1517 CE), (7)Ottoman empire (1299-1517 CE). Adopted and calculated by authors from different references [45,47,49]

1.3. Goals and Importance

Over decades, several researchers have pinpointed the importance of long reverberation time for religious buildings in general [53,54] and masjids in particular [20,21,37,55,56]. However, the optimal values of this time still require further investigation.

In light of the discussion above, this current work focuses solely on the acoustical demands of Muslim worshippers with Arabic mother tongue, regarding age and gender. It explores the **optimal reverberation time for masjids based on worshippers' viewpoints**. The optimal reverberation is defined in this current study as follows:

- Provides the appropriate ***liveliness*** (for masjids) that enhances the listening to the recitation of the Noble *Qur'an* (during the loud prayers) without compromising the clarity and intelligibility of the words.
- Ensures speech ***intelligibility*** during listening to the religious lessons (delivered in masjids) and Friday sermon/speech.

These two activities are among the main goals of attending congregational prayer in masjids.

It is well known that the reverberation time of the masjid, the performance of the Imam (the performer, see Appendix A), and the efficiency of the sound system erected in the masjid (not included in this work) all affect the ***quality*** of the acoustic environment (Q) as perceived by the worshippers during the performance (either prayer or sermon). It also appears that the worshipper's age and gender affect this quality.

In this introductory study, the obtained results will be compared with (1) the suggested optimal reverberation time for masjids T_{OM} [27,35,55] and (2) the optimal reverberation time for imams T_{Imams} [37].

2. Methodology

The main idea behind this work is to expose the participants to a predefined set of acoustic environments (in terms of reverberation time), allowing them to express their subjective responses toward these environments via an especially designed questionnaire. The participants experience how these environments affect the quality of the same audio clip, hence how they affect their perception (pleasantness/annoyance) about these sounds, aiming to quantify the overall auditory impression of an audio stimulus. To this end, the affective measurement was selected rather than the perceptual measurement [57]. The affective measurement is the most appropriate for this current work because it sets a non-expert participant “in some form of integrative state of mind where the influence of the impression for the individual attributes, the context, the mood, the expectations, the previous experience, traditions and so on, are all combined into one single impression that establishes the basis for some form of action of the listener” [57]. The experiment prompts the participants to compare these different acoustic environments, judge their quality (Q, or appropriateness) for listening, either to the recitation (Q_R) or speech (Q_S) as illustrated in section 1.3, and finally choose the most appropriate one among them.

During the preparation for this experiment, three parameters were considered. The first is the employed verses from the Noble Qur’an (for recitation mode), and the employed words (for speech mode), must be chosen from unfamiliar wording; thus, participants’ evaluations and judgments on the quality of a clip depend solely on what they listen to, independent of any previous knowledge that the participants may have had. Based on this consideration, verses or chapters such as *Al-Fātiḥah* and wording such as the *Takbīr* (see Appendix A) … etc., which every Muslim memorizes, must be avoided. The second is related to the total duration of the test. It has been found that a 20-minute session is quite suitable, while 30-40 minutes can be considered acceptable [57]. Thus, a ten-minute duration for each mode (a total 20-minute for both) was determined. The last is a lesson learned from the previous work with imams [37]; the variations in the chosen reverberation times (which marked the different acoustic environments) must be evident so that a participant easily recognizes them; this will be controlled through the Just Noticeable Difference (JND) between the different selected reverberation times.

2.1. Experimental Arrangement

Following the conditions above, the recitation mode has chosen two verses from *Sūrat As-Sajdah* (the Prostration, chapter 32, verses 23 and 24). A short sermon in standard Arabic has been selected for the speech mode. In the anechoic room of the Faculty of Engineering, Ain Shams University, Figure **2**, the two mentioned samples (recitation and speech) were recorded with the voice of a professional imam (see: Appendix A, *Imam*). This imam did not later participate as a respondent since there could be an evident influence on his judgment due to his familiarity with the voices [36]. The duration of the recitation clip was about 40 s, and the time of the speech clip was about 44 seconds. Using AutoCAD software, a simplified model for a rectangular medium-size masjid (12.00 x 8.00 m, area of 96.00 m^2, and volume of 576 m^3) was created. The model's two boundaries (floor and walls) have a flexible design that allows easy modifications for its acoustic properties; a complete description of this model is given in Appendix B. Per condition three and using Odeon ver. 15.15 software, the acoustic properties of the model were systematically altered to generate Impulse Responses IRs that achieve four different reverberation times. In descending order and in the mid-frequency range, these reverberations are 5.01 s (too long reverberation time (T), will be henceforth called setup 1), 3.45 s (long T, setup 2), 1.47 s (moderate T, setup 3), 0.76 s (short T, setup 4), and lastly the case of almost zero reverberation (ZR, too short T, setup 5). Table **1** lists the calculated reverberation times for setups (1-4) using ODEON software and Weber's constant (K). As the just noticeable difference (JND) for the perceived reverberance is 5 % minimum between 500 and 1000 Hz [6]; these mentioned reverberations comply with the third consideration.

Figure 2: Recording the selected samples in the anechoic room at the Faculty of Engineering, Ain Shams University. Photo courtesy of the performer: Sheikh Muhammad F. Abdullah, (photo by authors)

Table 1: The calculated reverberation times (s) for setups (1-4) using ODEON software, Weber's constant K, and the JND

Setup	Octave Band Centre Frequency (Hz)								Mean			K[1] (%)			JND[2]
	Low			Mid		High						At (Hz)			
	63	125	250	500	1000	2000	4000	8000	Low	Mid	High	500	1000	SNFA[3]	
1	2.69	2.68	4.15	5.5	4.52	3.85	2.75	1.33	3.17	5.01	2.64	55	35	45	Rel. 5 %
2	1.48	1.48	2.17	3.55	3.35	3.21	2.41	1.24	1.71	3.45	2.29	99	189	135	Rel. 5 %
3	1.34	1.46	1.59	1.78	1.16	1.04	0.93	0.69	1.46	1.47	0.89	107	78	95	Rel. 5 %
4	1.65	1.44	1.14	0.86	0.65	0.62	0.58	0.47	1.41	0.76	0.56	-	-	-	-
5 (ZR)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-	-

[1]Weber's constant between each two successive setups (i.e., between setup 1 and 2, 2 and 3 etc.).
[2]The just noticeable difference (JND) for the perceived reverberance (see ISO 3382-1:2009, [6]).
[3]Single number frequency averaging (the arithmetical average for the octave bands 500 to 1000 Hz), (see ISO 3382-1:2009, [6]).

In the next step and using Odeon again, each of the mentioned clips was convolved to these IRs, in addition to the original clips, which were recorded in the anechoic chamber (almost ZR). This means that each audio clip can be heard in five different acoustic environments (or setups). Thus, the resultant is ten audio clips: five pertain to the recitation, and five pertain to the speech. This number “five” for each performance (recitation, speech) was chosen based on the previous work of Elkhateeb [37] with the imams, which indicated that more than five choices caused exhaustion and confusion for the participants. In contrast, a smaller number limits the available options, affecting the results' accuracy.

In the pre-final step, two video files were prepared. In addition to the aforementioned audio clips, these two files also contained an introduction to the experiment, its purpose, directions, and instructions for participation. The audio clips were distributed in the video files to guarantee a sixty-second-time interval between any two successive clips. The primary purpose of this break is to remove the effect of the current clip from the participants’ memory before proceeding to the next one [36] and to allow the participants to rate the current clip in the accompanying questionnaire. Hence, the video files were divided as follows:

- Recitation file (Recitation.Mov): The entire test duration is about 10 minutes (200 s for audio clips, 240 s the total time interval between the clips and 185 s for participation directions).
- Speech file (Speech.Mov), the entire duration of the test is about 11 minutes (220 s for audio clips, 240 s the total time interval between the clips, and 191 s for participation directions)

Therefore, the total duration of the test (two modes) is about 21 minutes, close to the recommended 20 minutes. The duration is divided into three nearly equal frames: one-third for the directions and preparations, one-third for listening/running the test, and the last frame for submitting the responses.

Before publicly launching the experiment and the questionnaire, a pilot test was administered to a limited group of individuals to verify the accuracy and clarity of the experiment’s objectives and settings. Comments from the respondents in this limited group included: a clear understanding of its purposes, participation in the experiment, the duration of the main audio clips, the time interval between every two successive clips, the total duration of the test, and the order of the audio clips (from the longest to shortest reverberation or vice versa). The two video files have later been modified considering these comments. The results of this group were excluded from the final sample.

In practice, the two video files were uploaded to Google Drive, and a questionnaire was created on Google Forms, whereby the participants could insert their responses. In Google Forms, the purpose of the experiment and the steps for participation were thoroughly explained in Arabic. The participants needed to specify their age group and gender. The participants also reported any apparent hearing problems or if they utilized any hearing aids. The form also contained a section allowing participants to add comments when required.

The two main questions that constituted the core of this work and required the participants’ responses were:

- In recitation mode, which of the mentioned five audio clips provides the appropriate ***liveliness*** that gives you the highest degree of pleasantness?
- In speech mode, which of the mentioned five audio clips provides the appropriate ***intelligibility*** that gives you the highest degree of pleasantness?

These questions were formulated to encourage the listeners to adopt an "integrative state of mind" in their responses to the perceived reverberation. With these questions in mind, the experiment was publicly launched through the researchers' social network and via email. Each participant was also asked to distribute the experiment's link to his/her social network. The experiment was halted when no more participation was received for an extended period. At this stage, more than 300 participations were received.

2.2. Participation Directions and Procedure

The respondents were asked to prepare themselves for participation by:

1. Evoking the feeling of praying or listening to the Friday sermon in the masjid so that their participation is as close to accurate as possible.
2. No meaning, responses, or impressions should be transferred to the others the participants may know so as not to affect their choices.
3. Listening to the clips only once, with full attention, so that the judgments (on the different environments) come correct, precisely express their impressions and what is hoped in the actual masjid. If a respondent was unable to listen and judge/choose from the first time, he/she must not repeat the listening. In this case, passing the test on to someone else who can participate is strongly recommended.
4. Listening through a headset.

2.3. Description of the Sample (Participants)

The participants should:

1. Speak Arabic as their mother tongue
2. Have normal hearing, which means that they do not use any hearing aids and do not have any apparent hearing defects.

a. Targeted Ages

For this work, the targeted ages were limited to the age of puberty (that is, the commissioning age according to the provisions of Islam, usually starting at the age of 15 years) and the old age of 65 years. The main reason for choosing these two age borders as a limiter for the participants in this work is that commissioning age makes the participant realize and appreciate the importance of prayer and masjid and thus has more responsibility towards the work. While older people (above 65 years), on the other hand, usually have a complete sense of responsibility towards the work, they may suffer serious hearing loss with aging (presbycusis), which may affect their judgments. Ages confined between these two borders were divided into five groups: 15-25, 26-35, 36-45, 46-55, and 56-65. Table **2** presents the number and percentage of participants per age group.

Table 2: Number and percentage of participants per age group

Description	Age Group (Years)					Total
	1	2	3	4	5	
	15-25	26-35	36-45	46-55	56-65	
Number of participants	78	84	68	49	30	309
Percentage %	25.20	27.20	22.00	15.90	9.70	100

b. Gender

Participation was requested from both genders (males and females). The final accepted sample comprised 165 males (53.40 %) and 144 females (46.60 %).

c. Rejected Participations

Participation is rejected if the conditions listed in (section 2.3) are violated.

2.4. The Scale

After listening to the audio clips as mentioned, the participant has to identify, based on his point of view, the most appropriate (highest quality) clip for each mode (recitation, speech) respectively.

The participant judges the quality of each clip (each acoustic environment) on a unipolar discrete five-grade scale starting with (1), "Bad" and up to (5), "Excellent" [58]. Figure **3** represents the distribution of the degrees in

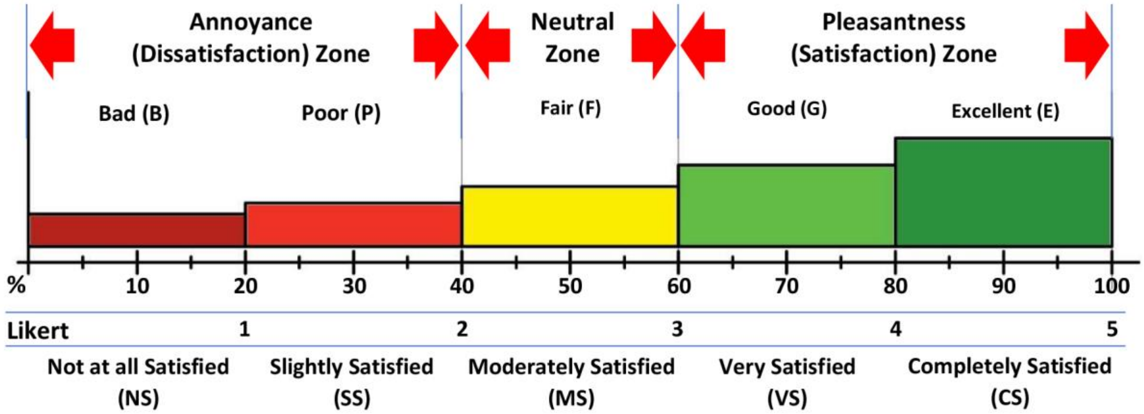

Figure 3: Unipolar discrete five-grade scale (see also Tables **3** and **4**)

this scale and the corresponding percentage. As can be concluded from this last figure, the scale can be divided into three zones:

- **The annoyance or Dissatisfaction Zone** (0-40 %) contains two categories: not at all satisfied (bad) and slightly satisfied (poor)
- **Neutral zone** (40-60 %), i.e., moderately satisfied (fair)
- **The pleasantness or Satisfaction Zone** (60-100 %) contains two categories: very satisfied (good) and completely satisfied (excellent).

a. Keywords

A set of keywords for both modes (recitation and speech) was prepared and illustrated in the video files to assist the participant with accurate evaluation and choices. The participant can use any or all of these keywords during the evaluation process for the mentioned clips. Tables **3** and **4** list and relate these keywords to the different subjective and objective judgments.

3. Results

Generally, results demonstrated that the quality of the acoustic environment (for both modes: recitation Q_R and speech Q_S) depends on the reverberation time. Results also demonstrated that both Q_R and Q_S are functions of age and gender, which deems the central hypothesis of this study acceptable. In the following parts, a detailed discussion of the findings of this study will be held. Results of the recitation mode will be presented first, followed by speech mode, and finally, the optimal reverberation (for both modes) ensues.

3.1. Recitation Mode

Regardless of age and gender, results indicate that the quality of setup 1 rates the worst ever (the mean μQ_R = 2.52 and the standard deviation σ = 1.16), while setup 4 is the best (μQ_R = 3.86, σ = 1.01). Then in ascending order from the worst to the best: setup 5 (μQ_R = 3.07), setup 2 (μQ_R = 3.32), and finally, set up 3 (μQ_R = 3.84) come too close to set up 4, see Table **5** and Figure **4**.

Figure **4** shows that the “Poor” impression was mentioned as the highest percentage of participants (34.30 %) in setup 1, while the "Fair” impression was dominant in setup 2 (34.60 %). In contrast, feeling “Good” is the highest in the two setups 3 and 4 (35 % and 38.8 %, respectively); however, it is more pronounced in setup 4 while it is roughly in the middle of the two impressions “Fair” and “Excellent” in setup 3. Setup 5 shows a specific distribution, except for the “Excellent” impression, which appears to be the highest; feeling “Not Satisfied” increases gradually, in terms of percentages, until it reaches the feeling of being “Not at all Satisfied/Bad," as can be depicted from Figure **4**. However, if we assume that the “Fair/Neutral” impression mediates the two impressions of “Pleasantness”

Table 3: Keywords and scale utilized in the evaluation of the quality of the acoustic environment for recitation (Q_R), (see also Figure 3)

Keywords		Evaluation		
		Subjective Attributes		Objective
		A [58]	B [58]	Numerical
Pleasantness (Satisfaction)zone	Quite attractive, it means some or all the following meanings: Highest listening/pondering, makes me feel completely humbled, I really enjoyed listening to this recitation, great/perfect recitation, words touch my heart, I wish I could hear such sounds in the masjid where I actually perform, I wish that the imam continues reciting for a longer time, I'm totally drawn to this sound, my imagination do not go away from the imam.	**Excellent (E)**	**Completely Satisfied (CS)**	**5.00 ≥ 80 %**
	Attractive, it means some or all the following meanings: Makes me feel humbled, I enjoy listening to this recitation, good, fit, attracts me.	**Good (G)**	**Very Satisfied (VS)**	**4.00 60-80 %**
Neutral zone	Somewhat attractive, it is the degree of uncertainty, or neutral choice. This has some or all the following meanings: It's okay, I'm not comfortable, but I'm not bothered as well, I wish a better than that.	**Fair (F)**	**Moderately Satisfied (MS)**	**3.00 40-60 %**
Annoyance (Dissatisfaction) zone	Unattractive, it means some or all the following meanings: It does not help to ponder/reverence, the voices bother me, I hope the imam finishes his recitation soon, not acceptable for recitation.	**Poor (P)**	**Slightly Satisfied (SS)**	**2.00 20-40 %**
	Entirely unattractive, it means some or all the following meanings: Unbearable, lowest degree of reverence, lowest degree of listening/pondering, the voice annoys me too much, I never enjoy this setup (the voices), makes me feel distracted, the voice of the imam does not attract me anymore, I hope the imam stops immediately, I never wish to hear such sounds in the masjid where I actually pray.	**Bad (B)**	**Not at all Satisfied (NS)**	**1.00 ≤ 20 %**

Table 4: Keywords and scale utilized in the evaluation of the quality of the acoustic environment for speech (Q_S), (see also Figure 3)

Keywords		Evaluation		
		Subjective Attributes		Objective
		A [58]	B [58]	Numerical
Pleasantness (Satisfaction) zone	Quite clear, it means some or all the following meanings: I understand the words very clearly, I make no effort to understand the words	**Excellent (E)**	**Completely Satisfied (CS)**	**5.00 ≥ 80 %**
	Clear, it means some or all the following meanings: I understand the words, I need a little effort to understand the words	**Good (G)**	**Very Satisfied (VS)**	**4.00 60-80 %**
Neutral zone	Somewhat clear, it is the degree of uncertainty, or neutral choice. This has some or all the following meanings: It's okay, I somewhat understand, I need moderate effort to understand the words	**Fair (F)**	**Moderately Satisfied (MS)**	**3.00 40-60 %**
Annoyance (Dissatisfaction) zone	Unclear, this means some or all the following meanings: I don't understand many words, even with high effort, I miss many words	**Poor (P)**	**Slightly Satisfied (SS)**	**2.00 20-40 %**
	Entirely unclear, this means some or all the following meanings: I understand no word, the words are entirely unclear	**Bad (B)**	**Not at all Satisfied (NS)**	**1.00 ≤ 20 %**

and “Annoyance," then we can sum the percentages of participants who feel “Very Satisfied/Good” and “Completely Satisfied/Excellent”, and the percentage of those who feel “Slightly Satisfied/Poor” and “Not at all Satisfied/Bad” (the grey bars in Figure **4**), thereupon responses will be more transparent. In setup 1, “Annoyance” dominates the results in a total percentage of (55.34 %), while in setup 4, “Pleasantness” dominates (68.93 %), followed by setup 3 (62.46 %) and then set up 2 (42.39 %). Again, the results of setup 5 appear different; the percentage of those in the "Pleasantness Zone, 42.39 %" is very close to those in the "Annoyance Zone, 40.45 %". However, the "Pleasantness" impression is, in general, slightly higher in this specific case.

Table 5: The quality of the acoustic environment for recitation mode (Q_R), the general findings

Parameter	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5
µ	2.52	3.32	3.84	3.86	3.07
σ	1.16	1.09	0.92	1.01	1.48
Median	2	3	4	4	3
Mode	2	3	4	4	5
Min.	1	1	1	1	1
Max.	5	5	5	5	5

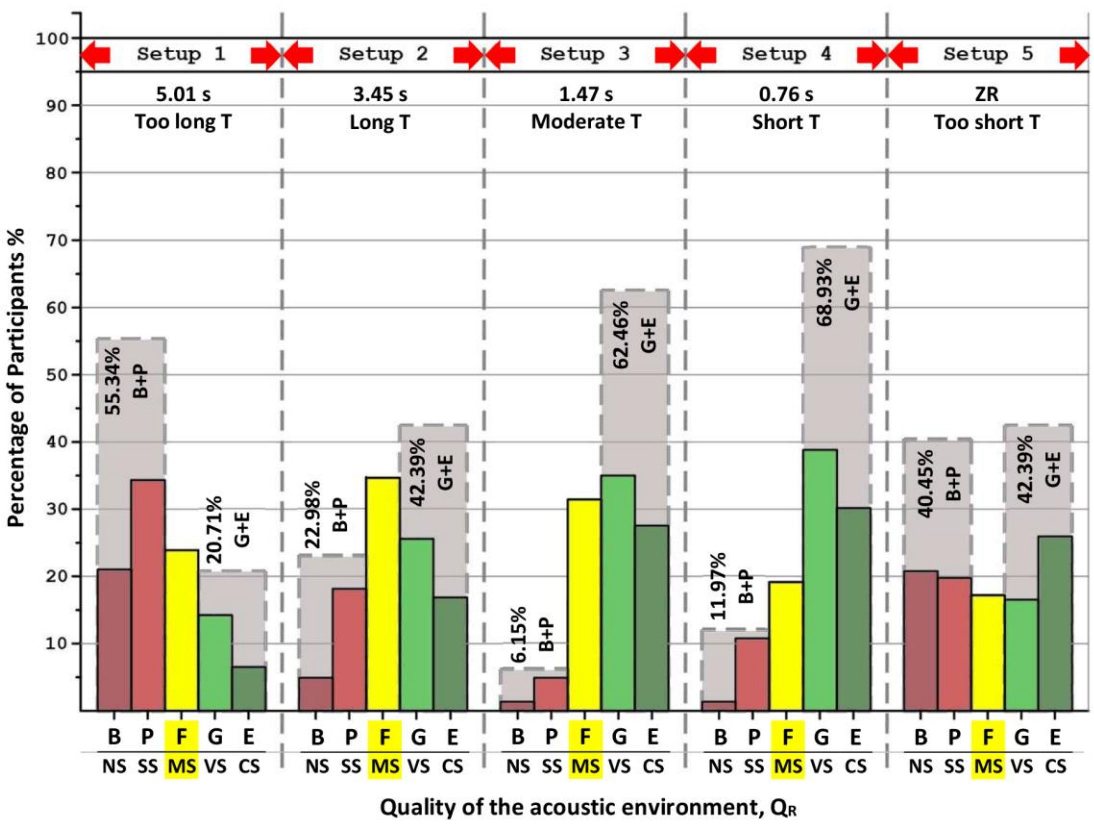

Figure 4: Alteration in participants' (worshippers') perception for the quality of the acoustic environment (recitation mode Q_R) with the alteration of reverberation (in different setups under study) regardless of their age and gender

In all cases, it seems that too-long reverberation, the same as too-short reverberation (ZR), negatively affects the worshippers regardless of their age and gender. However, too-short reverberation (setup 5) is better than too-long reverberation (setup 1).

a. Age Effect

In recitation mode, the relationship between the age and the quality of the acoustic environment Q_R does not follow a specific pattern, as shown in Figure **5**. Therefore, participants' responses to each setup should be interpreted independently. However, there are undoubtedly some general features. For example, and as previously mentioned, too short/too long reverberations both are "Annoying". The older participants (56-65) were the most offended by the too-short reverberation of setup 5, while they were the most satisfied with the moderate reverberation of setup 3.

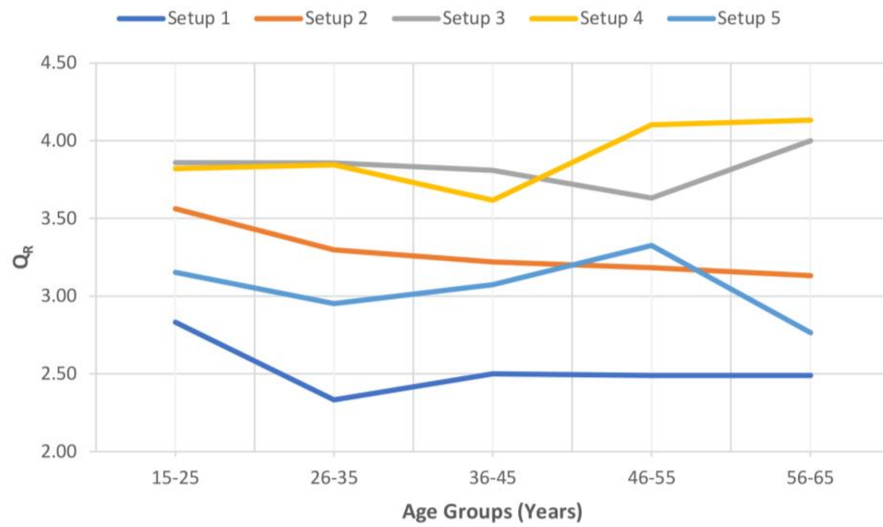

Figure 5: Age groups vs. Q_R

On the contrary, younger participants (15-25) were the most satisfied with the too-long reverberation of setup 1 and the long reverberation of setup 2. The age group (46-55) was the most satisfied with the too-short reverberation of setup 5 (ZR), while they were the most offended by the moderate reverberation of setup 3. The age group (36-45) was offended by the short reverberation of setup 4.

In setup 1, Q_R decreases with increasing age till the age group (26-35), then it rises again to be constant at 2.5 (that is almost the situation “Fair/Neutral”)

Setup 5 follows setup 2 as the second worst situation with one exception at the age group (46-55), where Q_R exceeds its counterpart in setup 2. Setup 5 also clarifies that Q_R decreases till the age group (26-35), then gradually increases till the age group (56-55). After that, it decreases for older people (the age group 56-65).

Setup 2 almost mediates all examined setups. In this setup specifically, it is clear that Q_R continuously decreases with increasing age.

The two setups, 3 and 4, alternate the better situation. In this case, Q_R depends on the age group. The two age groups (15-25) and (26-35) have an almost constant Q_R value. In setup 4 and the age group (36-45), Q_R slightly decreased to be lower than that of setup 3. Nevertheless, it remarkably exceeds setup 3 in the age group (46-55). However, both setups converge again at the age group (56-65).

After the age group (36-45), the two setups, 3 and 4, seem to be contradictory. In setup 3, Q_R slightly decreases after the age group (26-35), to a significant decrease up to the age group (46-55), then it remarkably increases for the older age group (56-65). Similar characteristics can be identified for setup 4 till the age group (36-45); after that, the situation reverses where Q_R clearly increases up to the age group (46-55), with a slight increase for the older age group (56-65), see Figure **5**. This character can be justified based on age. Hearing power usually weakens as individuals grow older, a phenomenon that is medically known as “Presbycusis”; thus, long reverberation may affect their ability to clearly understand the spoken words of the imam during the recitation. Hence, they prefer a shorter reverberation (setup 4). Nevertheless, they never prefer setup 5 (ZR).

b. Gender Effect

Gender also had a clear effect on Q_R, which is even more pronounced than the effect of age, see Figure **6**. Setup 3 seems to be the best from the males' viewpoint (μQ_R = 3.81), while it is set up 4 from the females' point of view (μQ_R = 4.08). Such a conclusion should directly influence the acoustic design of the ladies’ prayer area. Nevertheless, males are generally more satisfied than females with the two setups 1 and 2 (males: μQ_R = 2.64 and 3.40, female: μQ_R = 2.35 and 3.22 for the two mentioned setups, respectively). While females are generally more satisfied with the other three setups: 3-5 (females: μQ_R = 3.85, 4.08, and 3.28, males: μQ_R = 3.81, 3.66, and 2.89 for the three setups 3, 4, and 5, respectively), (Figure **6**).

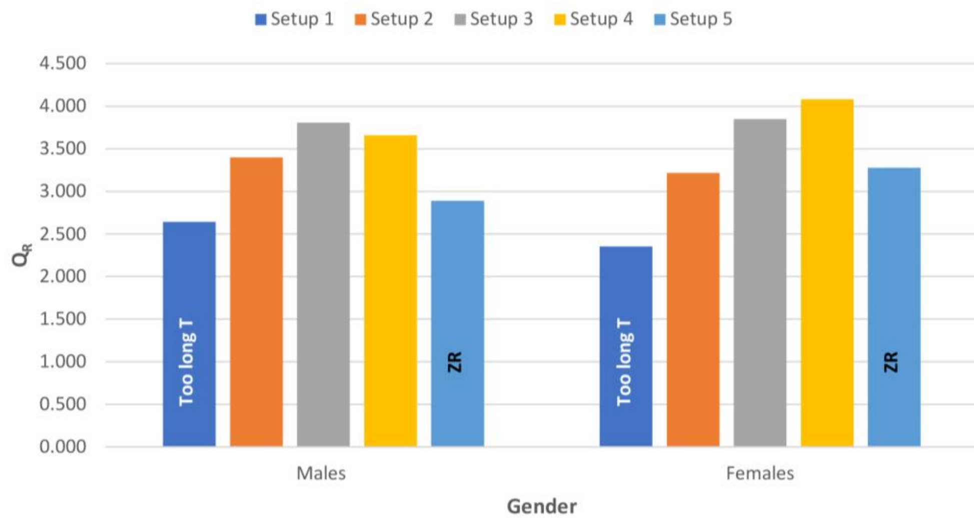

Figure 6: Gender vs. Q_R

c. The Statistical Significance of the Results

The methodology and procedure of this work satisfy the requirements of ordinal logistic regression OLR [59]. For each setup (in recitation mode), IBM-SPSS ver. 23 software was utilized to perform cumulative odds ordinal logistic regression with proportional odds to determine the effect of gender and age group on (Q_R), or in other words, on reverberation preferences as perceived by the participants. Results of OLR showed that, for all setups, gender has a statistically significant effect on Q_R. This means that gender affects a participant's reverberation perception, which proves this work's central hypothesis. Values in Table **6** also demonstrate that this effect is enhanced by increasing the reverberation, where males are more likely to choose the longer reverberation than females. In setup 1 (5.01 s), the odds ratio of males considering this setup is the most appropriate for recitation (i.e., has the best Q_R) was 1.833 (95 % CI, 1.208 to 2.779) times that for females, Wald χ^2 (1 df) = 8.118, *p* = .004. While the odds ratio of males considering setup 4 (0.76 s) is the most appropriate for recitation was only 0.403 (95 % CI, 0.262 to 0.620) times that for females, Wald χ^2 (1 df) = 17.092, *p* = .000. This means that, the shorter the reverberation time, the lower the gender effect. However, the effect of gender rises slightly again in setup 5 (ZR); see Table **6**.

The effects of age on reverberation preferences as perceived by a participant are more complex as they can be divided into two sections: between different groups and within the same group. Regarding the first section (between different groups), younger participants (15-25 years) are more likely to choose the longer reverberation of the two setups, 1 (5.01 s) and 2 (3.45 s), compared to the older participants (56-65 years), results of OLR showed that the middle age group (36-45 years) is more likely to choose the moderate reverberation of setup 3 (1.47 s) compared to the older participants. Finally, the fourth age group (46-55 years) is the most likely to choose the shorter reverberation times of the two setups, 4 (0.76 s) and 5 (ZR), see Table **6**.

Regarding the second section (within the same group), the two setups 1 (5.01 s) and 5 (ZR), except for age group 1 (15-25 years), demonstrate that a decrease in the age group was generally associated with a reduction in the odds of considering these two setups satisfactory. The odds ratio of age group 1 (15-25 years), considering setup 1 is the best, was 3.327 (95 % CI, 1.525 to 7.257) times that of the older participants (56-65 years), Wald χ^2 (4 df) = 9.13, *p* = .003. The other age groups in these two setups showed statistically insignificant effects on Q_R. Setup 2 (3.45 s) exhibits the opposite behavior where an increase in age group, except for age group 4 (46-55 years), was associated with a decrease in the odds of considering this setup satisfactory. The odds ratio of age group 1 (15-25 years), considering setup 2 is the best, was 1.879 (95 % CI, 1.186 to 2.980) times that of the older participants (56-65 years), Wald χ^2 (4 df) = 7.221, *p* = .007. The other age groups in this setup also showed statistically insignificant effects on Q_R. The two setups, 3 (1.47 s) and 4 (0.76 s), do not show a specific character.

Table **6** lists the values of Wald χ², the statistical significance *p*, the odds ratio, and the 95 % Wald Confidence Interval CI lower and upper boundaries. The colored cells in this table indicate a statistically significant effect ($p \leq .05$, 95 CI).

Table 6: The statistical significance (recitation mode)

Decreasing reverberation

Dependent variable	Setup	Statistical Parameters		Full Model	Age Groups[1] 1	2	3	4	5	Gender[2] M	F
Quality of the acoustic environment (QR)	1 (5.01 s)	Wald χ²		19.501	9.13	0.524	1.112	1.37	-	8.118	-
		p		.002	.003	.469	.292	.242	-	.004	-
		Odds Ratio		-	3.327	1.324	1.520	1.636	-	1.833	-
		95% Wald CI*	Lower	-	1.525	0.619	0.698	0.717	-	1.208	-
			Upper	-	7.257	2.829	3.313	3.728	-	2.779	-
	2 (3.45 s)	Wald χ²		16.649	7.221	2.22	0.087	0.274	-	6.051	-
		p		.005	.007	.136	.768	.601	-	.014	-
		Odds Ratio		-	1.879	1.408	1.071	1.139	-	1.362	-
		95% Wald CI*	Lower	-	1.186	0.898	0.676	0.700	-	1.065	-
			Upper	-	2.980	2.206	1.699	1.855	-	1.740	-
	3 (1.47 s)	Wald χ²		11.723	5.06	7.325	1.426	8.292	-	4.947	-
		p		.039	.024	.007	.232	.004	-	.026	-
		Odds Ratio		-	0.439	0.374	0.649	0.323	-	0.644	-
		95% Wald CI*	Lower	-	0.214	0.184	0.320	0.150	-	0.437	-
			Upper	-	0.899	0.763	1.319	0.697	-	0.949	-
	4 (0.76 s)	Wald χ²		26.766	3.65	2.685	5.86	0.053	-	17.092	-
		p		.000	.056	.101	.015	.817	-	.000	-
		Odds Ratio		-	0.461	0.520	0.372	0.905	-	0.403	-
		95% Wald CI*	Lower	-	0.208	0.239	0.167	0.387	-	0.262	-
			Upper	-	1.020	1.137	0.829	2.115	-	0.620	-
	5 (ZR)	Wald χ²		12.029	1.543	0.251	1.012	2.215	-	8.699	-
		p		.034	.214	.616	.314	0.137	-	.003	-
		Odds Ratio		-	1.359	1.127	1.281	1.486	-	0.666	-
		95% Wald CI*	Lower	-	0.838	0.706	0.791	0.882	-	0.508	-
			Upper	-	2.203	1.799	2.077	2.502	-	0.872	-

Coloured cells indicate a statistically significant regression.
[1]Age groups (1) 15-25, (2) 26-35, (3) 36-45, (4) 46-55, (5) 56-65.
[2]Gender (M) Males, (F) Females.
*CI 95% Wald Confidence Interval.

3.2. Speech Mode

Results again explain that, regardless of age and gender, setup 1 still rates as the worst ever ($\mu Q_S = 1.78$, $\sigma = 0.98$), while setup 4 is the best ($\mu Q_S = 4.22$, $\sigma = 0.88$). Then in ascending order from the worst to the best: setup 2 ($\mu Q_S = 2.59$), setup 5 ($\mu Q_S = 3.66$), and finally, set up 3 ($\mu Q_S = 3.81$) appear to be too close to set up 4, see Table **7** and Figure **7**.

Table 7: The quality of the acoustic environment for speech mode (Q_S), the general findings

Parameter	Setup 1	Setup 2	Setup 3	Setup 4	Setup 5
μ	1.78	2.59	3.81	4.22	3.66
σ	0.98	1.05	0.93	0.88	1.44
Median	2	2	4	4	4
Mode	1	2	4	5	5
Min.	1	1	1	1	1
Max.	5	5	5	5	5

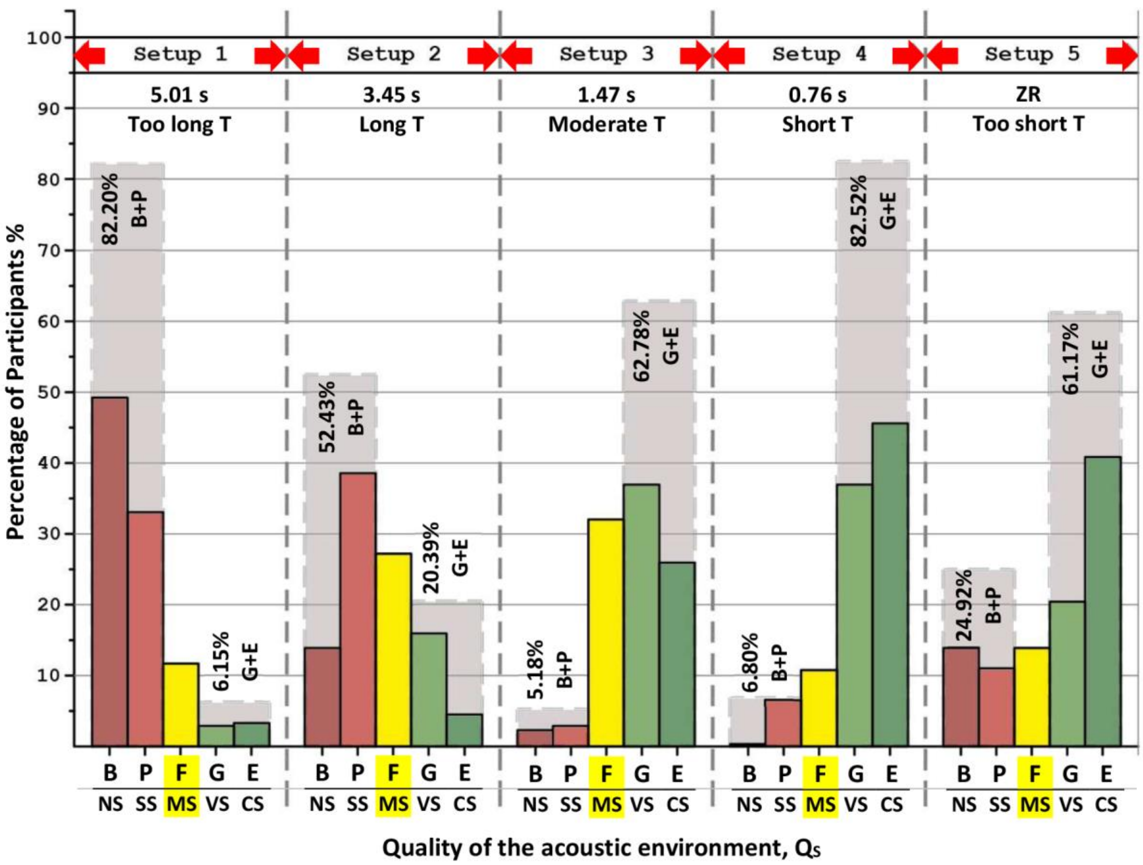

Figure 7: Alteration in participants' perception for the quality of the acoustic environment (speech mode Q_S) with the alteration of reverberation (in different setups under study) regardless of theirage and gender

Figure **7** shows that almost half of the participants (49.20 %) consider setup 1 "Bad," while (38.50 %) of them consider setup 2 "Poor". In contrast, the feeling of participants gradually transfers from the "Annoyance Zone/Unintelligible" toward the "Pleasantness Zone/Intelligible" in the other three setups. For setup 3, more than one-third of the participants (36.90 %) consider it "Good". Feeling "Excellent/Completely Satisfied" dominates the two other setups, 4 and 5 (45.60 % and 40.80 %, respectively). Again, and following the same approach previously applied in the case of recitation, assuming that a "Fair/Neutral" impression mediates all other impressions, thus the two responses of "Satisfied/Good" and "Completely Satisfied/Excellent" from the one hand, and the two responses of "Slightly Satisfied/Poor" and "Not at all Satisfied/Bad" from the other hand can be added (that is the grey bars in Figure **7**). In setup 1, "Dissatisfaction" remarkably dominates the results with a total percentage of (82.20 %) followed by setup 2 (52.43 %). Conversely, "Satisfaction" clearly dominates setup 4 (82.52 %), followed by setup 3 (62.78 %) and finally set up 1 (61.17 %).

a. Age Effect

While the general results of speech mode show that setup 1 is acoustically the worst and set up 4 is the best. Figure **8** shows the effect of age on the quality of the acoustic environment in speech mode Q_S. To some extent, the age group (36-45) appears to be a turning point in participants' responses. For example, this age group is the most satisfied (a higher Q_S) with the two setups, 1 and 2, as can be concluded from Figure **8**, while the age group (56-65) is the least satisfied (a lower Q_S). In stark contrast came the participants' responses for setup 4, where the age group (36-45) was tangibly the least satisfied, while the age group (56-65) was the most satisfied. In setup 3, satisfaction gradually decreases with age, but it roughly stabilizes between the two age groups (46-55) and (56-65). Setup 5 again shows a different response, where Q_S gradually decreases in the age group (36-45), increases in the age group (46-65), and then decreases again in the older age group (56-65).

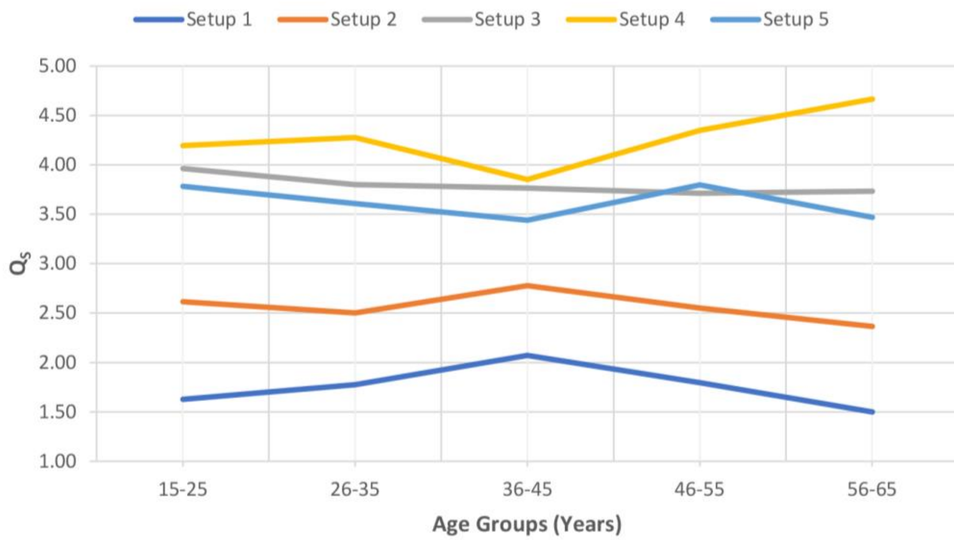

Figure 8: Age groups vs. Q_S

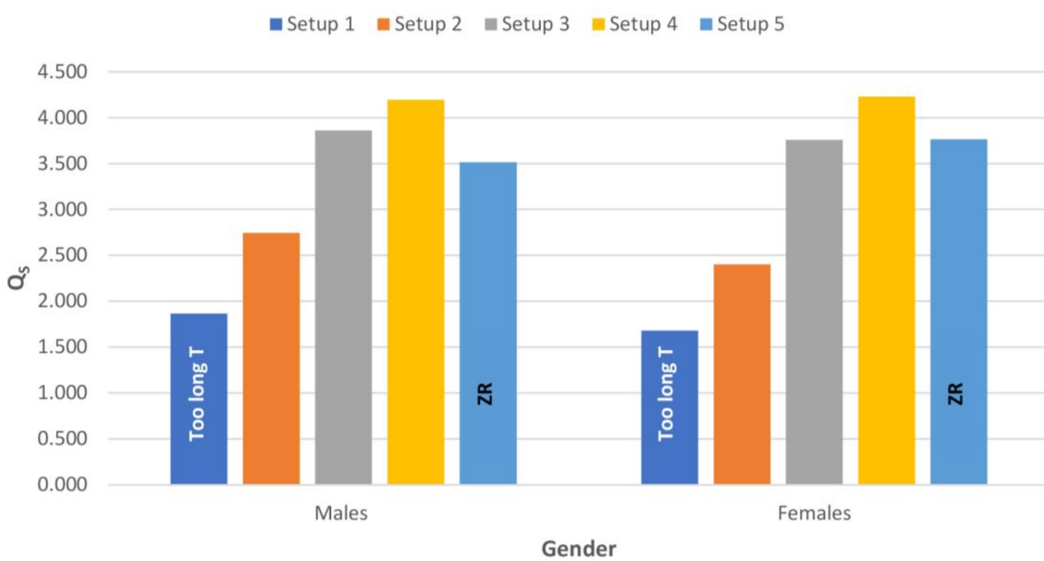

Figure 9: Gender vs. Q_S

b. Gender Effect

In contrast to the case of recitation, the results of speech mode show an almost identical impression between females and males regarding the five setups under study, with small differences in the values of Q_S, see Figure **9**. Both genders consensus that setup 4 is the most intelligible (the setup that acquires the highest Q_S) among all other setups, but Q_S for females in this case (μQ_S = 4.23) is slightly higher than that for males (μQ_S = 4.19). From the females' perspective, and in descending order from the best to the worst, are the two setups 5 and 3 (μQ_S =

3.76), setup 2 (μQ_S = 2.40), and finally set up 1 (μQ_S = 1.68). On the other hand, and from males' perspective, is setup 3 (μQ_S = 3.68), setup 5 (μQ_S = 3.52), setup 2 (μQ_S = 2.75), and finally set up 1 (μQ_S = 1.89). It is noticeable that, except for the two setups 4 and 5, where Q_S from females' viewpoint was slightly higher than that of males, Q_S from males' perspective in setups 1 to 3 was higher than that of females, as can be depicted from Figure **9**.

c. The Statistical Significance of the Results

Following the same method previously applied in recitation mode, IBM-SPSS ver. 23 software was employed to perform five OLR analyses (one for each setup). Based on the results of OLR and excluding setup 1, values in Table **8** again demonstrate that the shorter the reverberation time, the lower the gender effect on Q_S. However, only two setups (2 and 5) showed a statistically significant effect for gender on Q_S. In setup 2 (3.45 s), the odds ratio of

Table 8: The statistical significance (speech mode)

Decreasing reverberation

Setup		Statistical Parameters		Independent Variables							
				Full Model	Age Groups[1]					Gender[2]	
					1	2	3	4	5	M	F
Dependent variable Quality of the acoustic environment (Qs)	1 (5.01 s)	Wald χ^2		11.209	0.626	1.947	4.986	1.229	-	3.415	-
		p		.047	.429	.163	.026	.268	-	.065	-
		Odds Ratio		-	1.406	1.800	2.609	1.657	-	1.508	-
		95% Wald	Lower	-	0.604	0.788	1.124	0.679	-	0.975	-
		CI*	Upper	-	3.277	4.116	6.062	4.043	-	2.335	-
	2 (3.45 s)	Wald χ^2		11.26	2.407	0.717	2.624	0.659	-	8.257	-
		p		.046	.121	.397	.105	.417	-	.004	-
		Odds Ratio		-	1.852	1.391	1.912	1.409	-	1.850	-
		95% Wald	Lower	-	0.850	0.648	0.873	0.615	-	1.217	-
		CI*	Upper	-	4.035	2.986	4.191	3.232	-	2.815	-
	3 (1.47 s)	Wald χ^2		7.905	2.818	1.073	0.012	0.015	-	2.504	-
		p		.162	.093	.300	.912	.902	-	.114	-
		Odds Ratio		-	1.483	1.269	0.974	1.031	-	1.221	-
		95% Wald	Lower	-	0.936	0.809	0.614	0.633	-	0.953	-
		CI*	Upper	-	2.351	1.990	1.543	1.679	-	1.564	-
	4 (0.76 s)	Wald χ^2		18.225	5.111	4.144	14.234	2.791	-	0.061	-
		p		.003	.024	.042	.000	.095	-	.805	-
		Odds Ratio		-	0.362	0.405	0.181	0.451	-	0.946	-
		95% Wald	Lower	-	0.150	0.170	0.074	0.177	-	0.614	-
		CI*	Upper	-	0.874	0.967	0.440	1.148	-	1.461	-
	5 (ZR)	Wald χ^2		8.518	0.991	0.654	0.029	0.414	-	4.437	-
		p		.130	.320	.419	.864	.520	-	.035	-
		Odds Ratio		-	1.318	1.244	0.955	1.208	-	0.723	-
		95% Wald	Lower	-	0.765	0.733	0.563	0.679	-	0.534	-
		CI*	Upper	-	2.273	2.111	1.621	2.149	-	0.977	-

Coloured cells indicate a statistically significant regression.
[1]Age groups (1) 15-25, (2) 26-35, (3) 36-45, (4) 46-55, (5) 56-65.
[2]Gender(M) Males, (F) Females.
*CI 95% Wald Confidence Interval.

males considering this setup is the most appropriate for speech (i.e., has the best Q_S) was 1.850 (95 % CI, 1.217 to 2.815) times that for females, Wald χ^2 (1 df) = 8.257, p = .004. While the odds ratio of males considering setup 5 (ZR) is the most appropriate for speech was 0.723 (95 % CI, 0.534 to 0.977) times that for females, Wald χ^2 (1 df) = 4.437, p = .035.

Similar to the case of recitation, the effects of age are divided into two sections: between different groups and within the same group. For the first section, third age group participants (36-45 years) are the most likely to choose the longer reverberation times of the two setups, 1 (5.01 s) and 2 (3.45 s), compared to the older participants (56-65 years), while younger participants (15-25 years), surprisingly, are the most likely to choose the moderate reverberation of setup 3 (1.47 s) and the ZR of setup 5 compared to the older participants (56-65 years). Finally, the fourth age group (46-55 years) is the most likely to choose the short reverberation of setup 4 (0.76 s), see Table **8**.

Regarding the second section (within the same group), in setup 1 and except for age group 4 (46-55 years), an increase in the age group was associated with an increase in the odds of considering this setup as the best. The odds ratio of age group 3 (36-45 years), considering setup 1 is the best, was 2.609 (95 % CI, 1.124 to 6.062) times that of the older participants (56-65 years), Wald χ^2 (4 df) = 4.986, p = .026. The other age groups in this setup showed statistically insignificant effects on Q_s. The two setups, 3 (1.47 s) and 5 (ZR) exhibit the opposite behavior where an increase in age group, except for age group 4 (46-55 years), was associated with a decrease in the odds of considering these two setups satisfactory. Additionally, these last two setups showed statistically insignificant effects on Q_s. The two setups, 2 and 4, do not exhibit a specific character. However, while setup 2 showed statistically insignificant effects, setup 4 showed that the three age groups (1-3) had statistically significant impacts on Q_s. Table **8** lists the values of Wald χ^2, the statistical significance p, the odds ratio, and the 95 % Wald Confidence Interval CI lower and upper boundaries. Again, the colored cells in this table indicate a statistically significant effect ($p \leq .05$, 95 CI).

3.3. The Optimal Reverberation for Both Modes (Recitation and Speech)

Figure **10** represents the two curves: Q_R and Q_S. As can be concluded from this figure, both "too long"/"too short" reverberation negatively affect the quality of the acoustic environment within the masjid from the worshippers' viewpoint. Still, the effect of "too long" reverberation is the worst. Figure **10** also reveals that the optimal reverberation for both recitations and speech lies between setups 3 and 4. Lastly, while females were satisfied with setup 4 for both modes, their satisfaction with this setup in speech mode was slightly higher than with recitation (see Figures **6** and **9**).

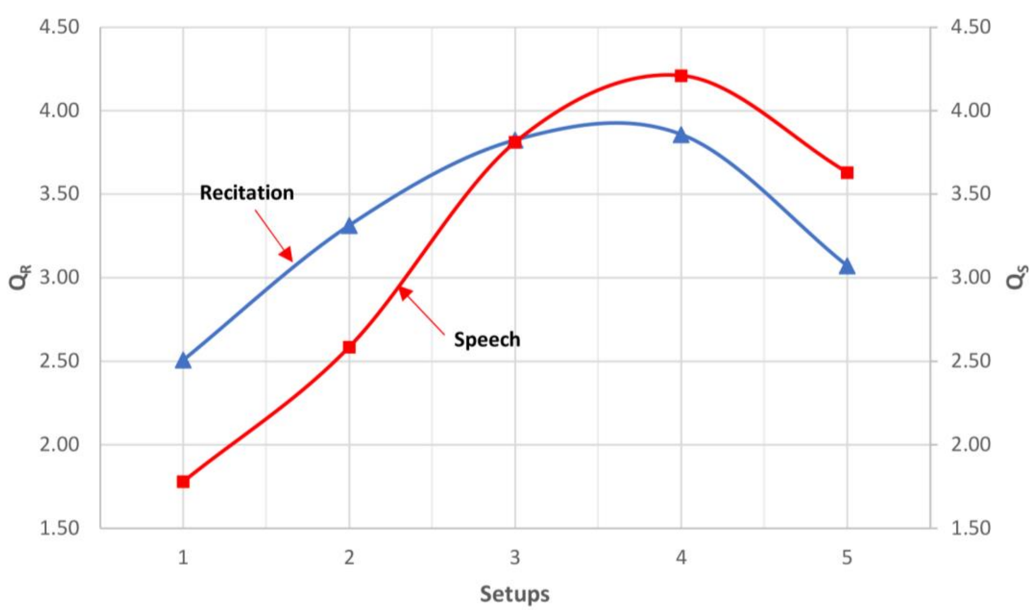

Figure 10: Participants' responses for both modes: recitation and speech, the general case

Based on the findings of this work, the optimal reverberation should not be taken as an absolute value isolated from at least gender. In the case of recitation, results showed that while males prefer setup 3, females oppositely prefer setup 4 (see Figure **6**). Both males and females agree to set up 4 in the case of speech. Fortunately, and in light of the Islamic law that requires males to offer their group prayer separately from females, it could be easy to offer each gender the optimal reverberation they prefer. In contrast, this option is impractical in the case of age, as it is hard to offer each age group (of the same gender) the optimal reverberation they prefer as long as they share the same space during congregation.

Figure **11** relates the mean preferences (μQ_R and μQ_S) for the five examined setups (as the dependent variable) to the mid-frequency bands reverberation time (as the independent variable) for both modes: recitation and speech (see Tables **5** and **7**) in the general case (regardless of age and gender). Figures **12a** and **12b** also represent the same relationship but consider the effect of gender. Both figures present the polynomial 3rd-degree trendlines that best fit these data sets along with its R-squared. According to these trendlines, the equations that relate both Q_R and Q_S to the mid-frequency reverberation time T can be concluded as follows:

- **Recitation mode, general**

$$Q_R = 0.0415\,T^3 - 0.4603\,T^2 + 1.1443\,T + 3.1119 \qquad \text{Eq. 2}$$

- **Speech mode, general**

$$Q_S = 0.0634\,T^3 - 0.5685\,T^2 + 0.8786\,T + 3.683 \qquad \text{Eq. 3}$$

- **Recitation mode, males**

$$Q_R = 0.0381\,T^3 - 0.4444\,T^2 + 1.2169\,T + 2.9123 \qquad \text{Eq. 4}$$

- **Recitation mode, females**

$$Q_R = 0.0455\,T^3 - 0.4785\,T^2 + 1.0611\,T + 3.3406 \qquad \text{Eq. 5}$$

- **Speech mode, males**

$$Q_S = 0.0613\,T^3 - 0.5757\,T^2 + 1.0073\,T + 3.5688 \qquad \text{Eq. 6}$$

- **Speech mode, females**

$$Q_S = 0.0658\,T^3 - 0.5603\,T^2 + 0.7311\,T + 3.8137 \qquad \text{Eq. 7}$$

The optimal reverberation time that ensures the best quality for worshippers (regardless of their age or gender) $T_{RG|Mid}$ while they are listening to the imam's recitation in the prayer spoken aloud, according to the Islamic faith, occurs when the first derivative of Eq. 2 equal zero, that is:

$$\frac{dQ_R}{dT} = 0.1245\,T^2 - 0.9206\,T + 1.1443 \qquad \text{Eq. 8}$$

Applying the rules of algebra to Eq. 8 reveals that the $T_{RG|Mid}$ = 1.58 s. Following the same approach, the other optimal reverberations can be calculated as listed in equations 3 to 7. Table **9** lists the calculated optimal reverberations for the six cases. It is worth mentioning here that the acoustic design of the masjid should ensure this reverberation in the case of complete occupation.

The intersection between the two curves of recitation and speech in the general case (i.e., regardless of age and gender, Figure **11**) determines the “balanced [36]” optimal reverberation in the mid-frequency bands $T_{BG|Mid}$ for both recitation and speech in masjids. This intersection can be mathematically calculated by concurrently solving the two equations, 2 and 3. Likewise, the “balanced” optimal reverberation considering the effect of gender for males $T_{BM|Mid}$ can be mathematically obtained by solving both equations 4 (recitation mode) and 6 (speech mode) concurrently, and lastly for females $T_{BF|Mid}$ by solving both equations 5 and 7 together. These values are given in Table **9**.

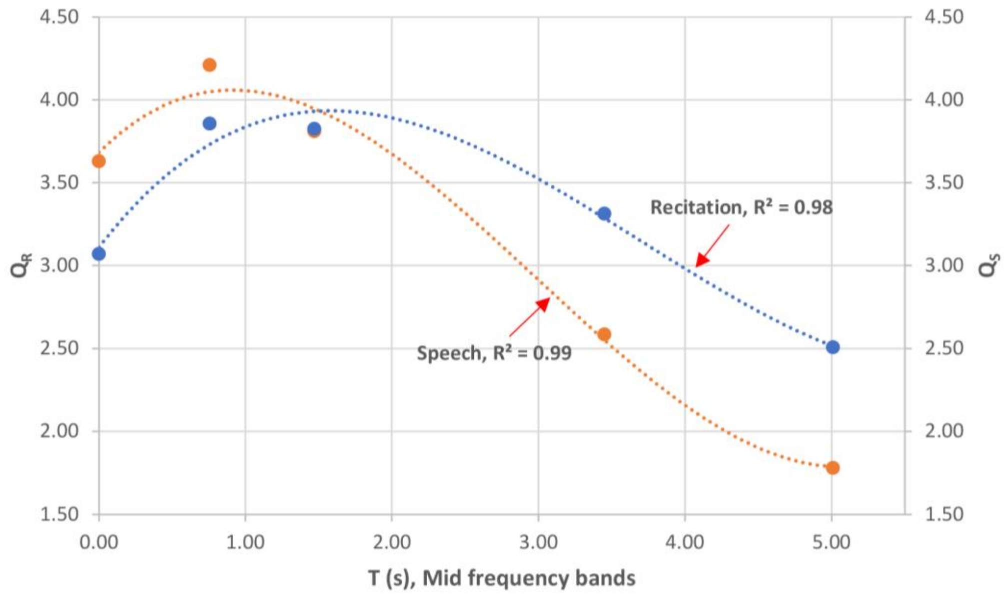

Figure 11: Relationship between the mid-frequency bands reverberation and the quality of the acoustic environment: Q_R and Q_S in the five examined setups, the general case

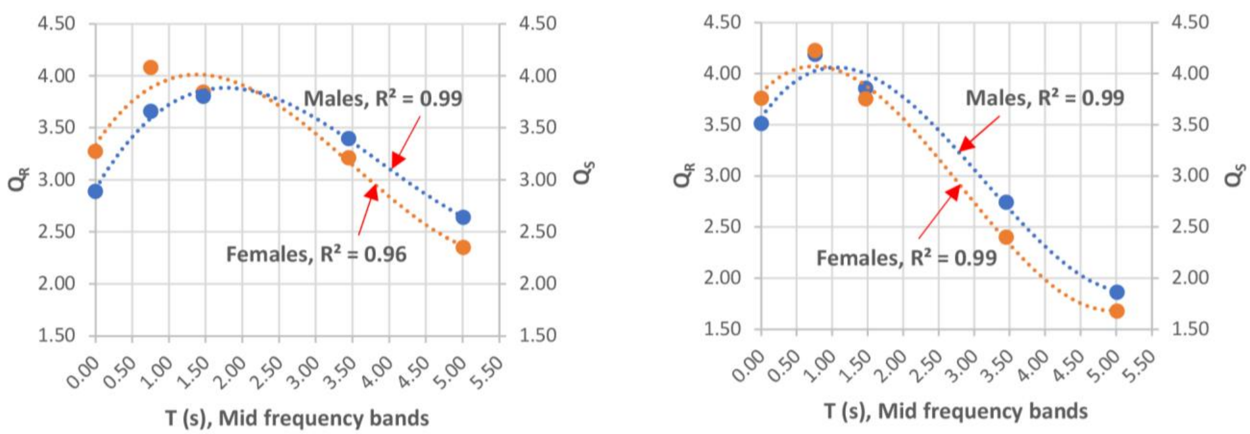

Figure 12: Relationship between the mid-frequency bands reverberation and the quality of the acoustic environment: Q_R and Q_S in the five examined setups taking into consideration gender effect

Table 9: The optimal mid-frequency band reverberations (s) for the examined modes

Mode	General		Gender			
			Males		Females	
Recitation	$T_{RG\|Mid}$	1.58	$T_{RM\|Mid}$	1.77	$T_{RF\|Mid}$	1.38
Speech	$T_{SG\|Mid}$	0.91	$T_{SM\|Mid}$	1.05	$T_{SF\|Mid}$	0.75
Balanced (both modes:recitation and speech)	$T_{BG\|Mid}$	1.51	$T_{BM\|Mid}$	1.78	$T_{BF\|Mid}$	1.19

4. Discussion

Masjid architects have realized early the importance of long reverberation in prayer halls, an idea that was initiated in the Umayyad era and was most likely crystallized in the Mamluk and Ottoman eras, where masjid architecture had practically reached its "golden age" [60-62]. A recent study shows that Mamluk masjids, for example, had applied an almost fixed criterion by which it maintained a volume per person V_P between 8.10 and 15.00 m^3/person in the semi-closed iwan masjids (see Appendix A), 6.90 and 11.15 m^3/person in the closed iwan masjids (V_P was an increasing function of masjid's volume). On the contrary, contemporary masjids miss any specific acoustic standard [35]. This may be partially due to the lost optimal reverberation time from the perspective of worshippers, which leaves the whole decision to the acoustician, who mainly cares about the sound reinforcement system SRS of the masjid. This system is designed based on "Audibility, not speech intelligibility," while "the acoustical considerations are not thought of either in the design phase or in the selection or installation of SRS in mosques" [19].

Few studies have tackled the subjective aspects of the reverberation within masjids and how worshippers and imams perceive it. Because human voices are the exclusively allowed sounds during religious rituals inside masjids, reverberation plays a vital role in the satisfaction of both worshippers and imams, particularly during the long prayers recited aloud [37]. Therefore, this study presents a valuable link in a series of research that addresses the subjective aspects of masjid acoustics.

The current work reveals an important set of facts related to masjids acoustics:

- There is consensus among the participants on the necessity of having a specific and accurate amount of reverberation in masjids to ensure the quality of the acoustic environment. This entirely agrees with Kayili, who highlighted the importance of reverberation for listeners "The human ear always seeks reverberation and in order not to separate sound components from one another wants to connect each one to the following one with a reverberation (sound energy decay) curve. So, realizing optimum reverberation time gives better hearing conditions. A short reverberation time leads the ear to feel unsatisfied, and a long reverberation causes components to mask the following ones, which results in insufficient intelligibility or even unintelligible hearing" [27]
- From the participants' perspective, there are differences in the optimal reverberations between recitation and speech. This agrees with Cremer and Muller "We prefer higher reverberation times for music than for speech" [41]. In this context, two comments we received from some participants may be useful. The first highlights the importance of "some reverberation" to impart an atmosphere of reverence, while the second considers that space with "too long reverberation" distracts the attention and/or reduces the intelligibility of words, which interferes with the function of the masjids. The contradiction between these two commentaries can be resolved in light of the mode; while the former is more suitable for recitation, the latter is more suitable for speech.
- The reverberation time of masjids depends on gender. Females, in general, prefer a shorter reverberation time than males by about 22 % in the case of recitation, 28.6 % in the case of speech, and 33 % in the general case (recitation and sermon)
- There are some indicators that age also affects reverberation preferences. However, some of these indicators do not show statistical significance.
- In setup 5 (ZR), participants' responses depend upon the mode:
  - Recitation mode is more likely to be rejected than speech mode. For males, ZR ranked fourth, followed directly by setup 1 (the too-long reverberation time, 5.01 s). From females' viewpoint, it ranked third with a ratio very close to setup 2 (3.45 s). It means that ZR is more acceptable for females than males. This conclusion is consistent with the preceding female's general tendency to a reverberation that is shorter than what is preferred by males.
  - Speech mode: speech also requires a certain amount of reverberation to be perceived pleasantly by the worshippers. Setup 5 (ZR) came as the third choice for males while it is the second for females, almost equal to setup 3 (1.47 s)
- The optimal reverberation time for masjids in the general case (regardless of gender and age) is a fixed number = 1.51 s. This value corresponds to the optimal reverberation time for a church of about 2,000 m^3 and a symphony hall of approximately 20,000 m^3 [63]. However, this reverberation is almost unmatched by any speech room of a practical volume.

- Considering the results proven here, it is possible to calculate the volume per person V_P for Muslim worshippers (either males or females) applying Sabine's equation, see details in Appendix C. Using the illustrated method and for recitation mode, it can be concluded that the volume per male person $V_{P|M}$ = 8.13 m^3/person, whereas for females ($V_{P|F}$) it is 5.43 m^3/person. The value of $V_{P|M}$ is located within the recommended range for concert halls (8-12 m^3/person), while for females, it is in the range of opera houses (4-6 m^3/person) [64]. Nevertheless, these figures are noticeably far from the recommended V_P for the classical speech rooms, at least for male worshippers. It is worth mentioning that $V_{P|M}$, as calculated here, agrees with Elkhateeb and Eldakdoky, based on the Mamluk masjids, that V_P should not fall below 7.00 m^3/person [22].

The findings of the current study align with Elkhateeb *et al*. They emphasized the necessity of considering the masjid as a particular type of speech room requiring a relatively long reverberation time [21], [55]. Elkhateeb also clarified that such long reverberation would not negatively affect the intelligibility of speech, whether recitation or sermon, due to the nature of the performance in masjids which differs from the classical speech rooms. The findings of Yilmazer and Acun support this last conclusion: "The average Speech Transmission Index (STI) value of the mosque is 0.56, which corresponds to a fair amount of speech intelligibility. During the survey, participants stated that they can clearly understand Imam's speech most of the time" [65].

The presence of gender differences in the preferences of reverberation perception was unexpected, but not excluded, result. We definitely know that there are gender differences in many aspects of the human body. In the hearing tract, for example, Don *et al*. [66] showed that there is a significant gender difference in response time between frequency regions of the cochlea, where young females with normal hearing showed shorter delays than males between the derived bands. This is due to the stiffness gradient in the cochlea that is 13 % larger in females than males. Such a conclusion is generally consistent with the recent anatomical studies of cochlear length and gender. There are also proven gender differences in the configuration of the vocal tract. In addition to the gender differences in the length, tightness, and thickness of the vocal folds [67], Simpson [68] also mentioned that the patterns of tongue movement in males and females are very dissimilar. There are also noticeable gender differences in overall brain size, where male's brains are, on average, between 10 and 15 % larger than females, but they are not related to differences in intelligence [69]. Lastly, Girón *et al*. [15] showed the dependence of reverberation perception/recognition with the auralised signals on the type (instrumental music) and gender (female and male voices) of the stimuli. All these facts and others enhance the conclusion that there could be gender differences in the way the reverberation is perceived and reverberation preferences.

Given the novelty of these findings, as it may be the first time to mention such gender differences in reverberation perception, there are no other previous studies that either approve or disprove it. Perhaps, because other researchers have not been exposed to such a point before. Although the authors have no clear definitive justifications, the closest explanation, which the authors currently adopt, is that females are more inclined to lower voices (shorter reverberation) than males who prefer louder voices (longer reverberation). This may return to the presence of some gender differences in the mechanism of sound perception in the brain. In both cases, it is up for more investigation in the future.

While the study presents such results, we should bear in mind that the experiment was entirely based on a simulation that "could generate mostly plausible but not authentic auralizations" [70]. But it undoubtedly sheds light on a crucial design issue in the acoustics of masjids that is still missing. Nevertheless, as an introductory study, the results presented here may need further research in the future. For instance, validating the proposition that the occupation impact can be absorbed by simulating a smaller unoccupied room instead of a larger occupied room when generating the impulse response using (ODEON), and replicating the experiment using a real IRs as collected from field measurements instead of the simulation.

4.1. Imam vs. Worshippers

Figure **13** compares the optimal reverberation for both masjid users: worshippers, as concluded from this current work, and the imams T_{Imams} [37]. The figure also illustrates the optimal reverberation for masjids T_{OM} as suggested by Kayili [27] and calculated by Elkhateeb *et al*. [35,55]. As can be inferred from this figure, both values

$T_{RM|Mid}$ and $T_{SF|Mid}$ constitute the absolute upper and lower borders, respectively, of worshippers' optimal reverberations. Also, it seems these values are constant and independent of room volume. It is clear that the optimal reverberation for masjids T_{OM} is closer to the optimal for recitation mode (in descending order: male worshippers, general case, and female worshippers, respectively), but it is far from the speech mode. In recitation mode, the intersection between T_{OM} and the optimal for male worshippers ($T_{RM|Mid}$) exists at volume 1239.8 m^3; in the general recitation case ($T_{RG|Mid}$), this intersection exists at 426.76 m^3 and finally at 121.99 m^3 for female worshippers ($T_{RF|Mid}$). Contrarily, in the speech mode, no valid intersections are expected between T_{OM} and the optimal for worshippers. On the other hand, comparing the results of this current work with T_{Imams} indicates a crucial conflict, especially for male worshippers who usually share the same space with their imam. While the imam needs a long reverberation time of about 3.62 s in the mid-frequency range [37], worshippers prefer a shorter reverberation of around half (1.77 s in recitation mode, 1.05 s in speech mode), see Figure **13**.

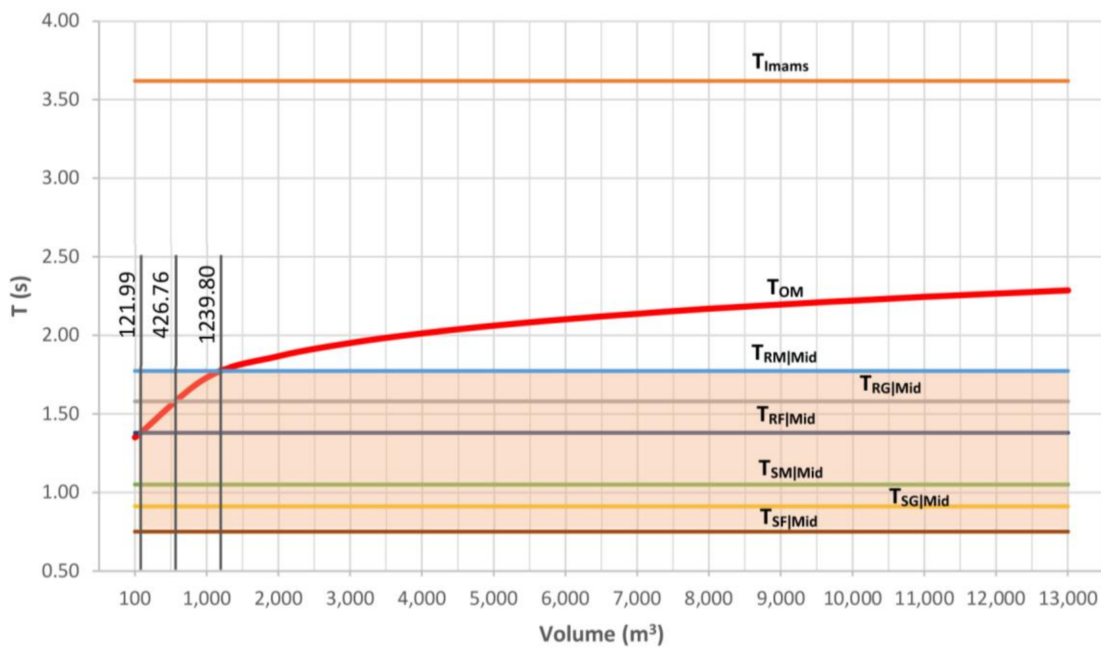

Figure 13: Comparsion between the mid-frequency bands reverberation times for the two examined modes (recitation and speech) considering the effect of gender. The optimal for imamsT_{imams} and masjids T_{OM} are also presented

There are several acoustic approaches to Solve this conflict, some of which may need unconventional solutions. One of the easiest solutions is to utilize electroacoustic systems. In this case, a separate loudspeaker(s) should be installed for the imam. This loudspeaker(s) is connected to an artificial reverb and echo system that ensures the optimal reverberation for the imam. The main masjid volume, in this case, should be acoustically designed in such a way that it achieves the optimal reverberation for worshippers.

The second approach is a compromise between the preferences of the imam and those of worshippers; this approach can be fulfilled via different solutions. For example, the optimal reverberation curve for masjids T_{OM} could be one of these compromised solutions that are "appropriate for both Imams and worshippers" [37]. The mean of both optimal values (for the Imam and the male worshippers) is another compromised solution. In this last case, the optimal value for both becomes 2.70 s.

The last approach is to utilize what might be called an "imam's cockpit" (an analogy for a pilot's cockpit). In this case, the niche (mihrab, see Appendix A) is enlarged to create a small compartment (cubicle). This compartment must be acoustically designed to ensure the appropriate reverberation time for the Imam, while the main volume of the masjid (where male worshippers gather) is designed to ensure the appropriate reverberation time for them. Such an approach was previously found (on a different scale) in some of the Ottoman masjids in Turkey and the masjid of Muhammad Ali Pasha in the Citadel of Cairo, Egypt. The design of such masjids offers a smaller volume annexed to the main masjid's volume, see Figure **14**. This small volume contains the mihrab, where the imam stands, and a limited number of worshippers behind him. The main difference between what we have historically known in the Ottoman or Egyptian masjids (during Muhammad Ali Pasha) and the concept of the imam's cockpit, as proposed here, is that the latter will accommodate only the imam. At the same time, the worshippers will line up outside it.

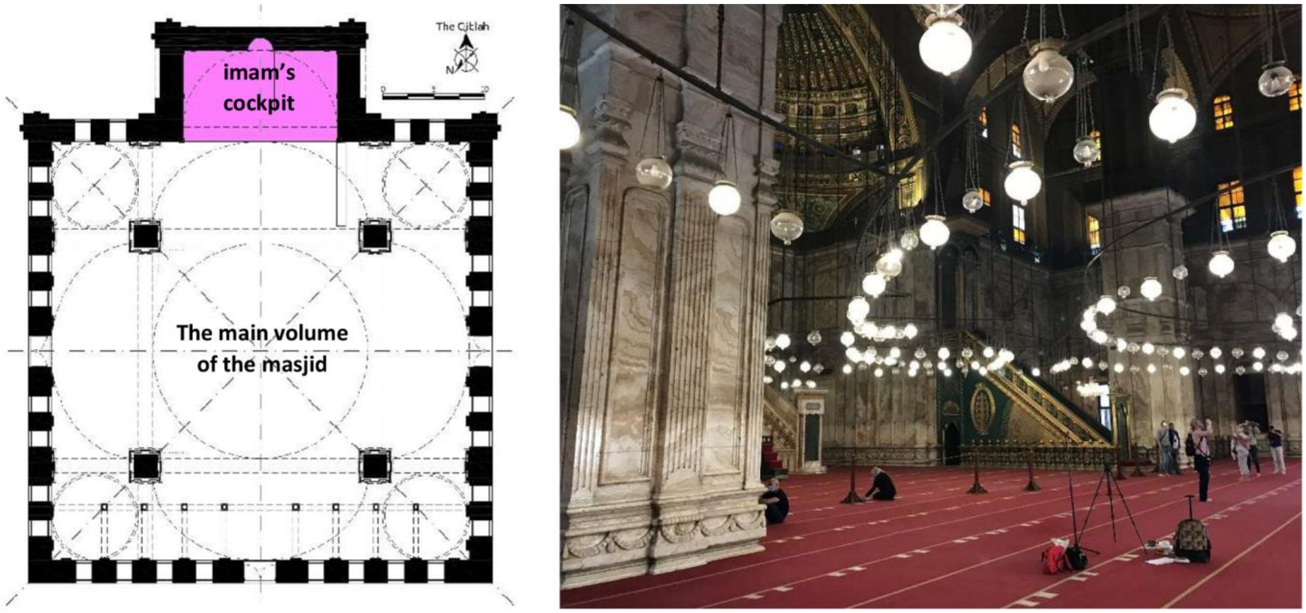

Figure 14: Masjid of Muhammad Ali Pasha in the Citadel (completed 1848 CE, capacity 10,000 persons), Cairo, Egypt, the coloured area indicates imam's cockpit (photo by authors)

For female worshippers, achieving their optimal reverberation is easier. As previously mentioned, females pray in a separate or semi-separate space from the main volume of masjid.

4.2. Comparison with Related Studies

Results of this study show that the optimal reverberation time for worshippers with an Arabic mother tongue in the case of recitation is almost twice that of worshippers in Bangladeshi masjids (0.90 s as an overall balanced acoustic performance for both recitation and speech according to the findings of Najmul Imam *et al*. [36,38]). This difference can be justified in light of the differences in tempo (the number of syllables per second SPs) between the two languages (Arabic and Tamil). Wilson [42] clarified that the mean SPs in the Arabic language is about 5.5 SPs, while in Tamil (that is the spoken language by the nations of South Asia [71,72]), it reaches 6.5 SPs. A higher tempo may require a shorter reverberation; thus, the late reflections of the old sounds do not mask the direct and early reflections of the new ones.

5. Conclusions

This work investigates the optimal reverberation time for masjids for both modes: recitation and sermon/speech from worshipper's viewpoint taking into consideration the effect of their gender and age. For this purpose, a specially convolved five audio clips for each mode, in addition to a questionnaire, were created. The participants compared and judged the ***quality*** (Q, or appropriateness) of these audio clips for listening either to the recitation (Q_R) or speech (Q_S) on a unipolar discrete five-grade scale (from 1 to 5). Results explained that both Q_R and Q_S are functions of gender and age. In recitation mode, results showed that gender has a statistically significant effect on Q_R, while not all age groups have this significant effect. In speech mode, results showed that both gender and age groups have statistically significant effects on Q_S in some, but not all setups.

The analysis demonstrated that, generally, the longer the reverberation time, the higher the impact of gender on reverberation preferences. Moreover, longer reverberation is preferred by younger worshippers and vice versa. Regardless of participant's age and gender, it is apparent that too long, same as too short, reverberation, both have negative effects on worshippers' acoustic satisfaction (pleasantness). Nevertheless, too short reverberation is better than the too long. Worshippers, regardless of their age and gender, prefer a reverberation of 1.58 s (recitation mode) and 0.91 s (speech mode). A reverberation of 1.51 s can be considered a balanced value (for both modes). Results also indicated that females have an obvious tendency to shorter reverberant environment (1.38 s for recitation, and 0.75 s for speech) than males, who prefer longer reverberation (1.77 s for recitation, and 1.05 s for speech). Such conclusion should directly affect the acoustic design of ladies' prayer area in masjids. Both values (1.78 s and 1.19 s) can be considered balanced values (for both modes: recitation and speech respectively) for both genders (males and females respectively). However, comparing these results with the optimal reverberation for imams indicates a crucial conflict, especially for male worshippers. Several acoustic approaches to solve such conflict were presented and discussed. The main difference between this current work and the similar work of Najmul Imam et. al. [36,38] is that Najmul Imam investigated the optimal reverberation for only Bangladeshi male worshippers, almost all in the same age. Thus, this work takes a further step by incorporating the effects of both age and gender. In future work, this study will be followed by a second part in which the participants should have a personal attendance in the acoustic lab to validate, verify, and confirm these results.

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Appendix A. List of terminologies and abbreviations

AA.1 Arabic terminologies

In alphabetical order, whenever the following Arabic terms appear in the text they mean:

Āyah/pl. Āyāt	آيَةٌ (الجَمْعُ: آيَاتٌ)	A verse in the Noble *Qur'an*, one of the statements of varying length that make up the chapters of the Quran
Al-Fātiḥah	سُوْرَةُ الفَاتِحَة	The opening, the first chapter of the Noble Qur'an
Friday sermon (Speech)	خطبة الجمعة	A short to mid-length religious lesson. It is obligatory to be delivered by a preach every Friday before the noon prayer (*Ṣalāt Azuher*). The speech should address, in the light of Islam teaching, the most important issues that arose during the week and those which affect the Muslim society. The sermon must be delivered in a formal Arabic language and should contain some verses of the Noble *Qur'an* and at least one saying (*Hadith*)
Group (congregational) prayer	صَلَاةُ الجَمَاعَة	Similar to the individual prayer (see *Ṣalāt*), but the worshippers need to align themselves, foot to foot and shoulder to shoulder, in well-defined rows (1.20–1.33 m apart) behind the *imam* and follow him exactly
Hadith	حَدِيْث	What was reported about the Prophet *Muhammad* (peace be upon him), of saying, deed, acceptance, character, or biography, whether before his mission (i.e., the beginning of the revelation) or after that. In Islam, *Hadith* is the second source of Islamic legislation after the Noble *Qur'an*
The Holy Ka'aba	الكَعبةُ المُشَرفَة	The building that Muslims should face while performing their prayers. The Holy *Ka'aba* located in *Almasjid Alharām*
Imam	إمَام	A male who leads the worshippers during group prayer, and sometimes delivers the Friday sermon. The *imam* is the sole performer particularly in the aloud prayers while the worshippers just follow him. In their preparation, imams must go through rigorous trainings before they are permitted to lead the congregational prayer. A professional imam must own two basic qualities: a good voice and a true recitation. The first, good voice, is attributed to sound rhythm that should ensure a smooth flow of recitation in a manner neither too fast nor too slow. The voice must be pleasant, distinctive, and stylish. From worshippers' viewpoint, it means a strong attraction to this voice, an interest in listening to it, an interest in praying behind this imam as a follower (worshipper). Generally, in the case of recitation of the Noble *Qur'an*, deeper pitch voices tend to be more attractive to the ears of most worshippers. The later (true recitation) means a good memorization of the Noble *Qur'an*, the full knowledge and adherence to the rules of *Altajweed*, the correctness of recitation, excellent accent, and accurate pronunciation.
Intelligibility of the sermon	وضوح كلمات الخطبة	The acoustic suitability of a space for delivering the Friday speech or religious lessons. The term "Intelligibility" describes qualitatively the ability of an acoustic environment to transmit speech accurately. It is expressed in the percentage of correctly received phrases.
Iwan	إيْوَان	A room free (or almost free) of columns, with domed or wooden roofs; it is usually open on at least one side
Liveliness for recitation	حيوية الفراغ لتلاوة القرآن الكريم	The acoustic suitability of a space to the recitation of the Noble *Qur'an.* The term has twofold; the first is related to the imam (the performer), the last is related to the worshippers (the listeners/audience). According to Britannica: "Liveliness" refers directly to reverberation time. A live room has a long reverberation time and a dead room a short reverberation time.
Makkah Almukarramah	مَكَةُ المُكَرمَة	A city located in the west of Saudi Arabia. It is the site of *Almasjid Alharām*
Masjid	مَسْجِد	Mosque, the house of worship for Muslims. In its original form, the masjid has a right prismatic form with a rectangular plan. The long side of the prism (that allows the longest first row) must be perpendicular to the direction to the Holy *Ka'aba* in *Makkah*. This side is known as *Qiblah* wall and contains a small semi-cylindrical niche in the middle. This niche (Mihrab) determines the *Qiblah* wall and the position of the Imam (facing the *Qiblah* wall) during the group prayer. Internally, the space must be very simple free of any decoration, ornaments or magnificence that may distract the attention of

		worshippers. It is also recommended to use the minimum internal supports (columns) to enhance the ability of worshippers to see and follow the imam (preacher) during Friday sermon. Traditionally, masjid's boundaries have low absorption characteristics excluding the floor. Walls are usually covered with marble to a height of 1.50–2.00 m, the rest of the walls and roof are rendered with a paint on cement mortar plaster. Glass windows, either small or large, normally penetrate the walls. The roof is mostly flat and contains a centralized or decentralized dome that allows natural lighting. If not occupied, floors are covered with carpets. Usually, carpets are either installed directly over a cement tile or above padding of 10 mm thick polyethylene foam. Thus, floors, either occupied or unoccupied, constitute the main absorbing surface inside any masjid
Almasjid Alharām	المَسْجِدُ الحَرَام	The sacred masjid, the masjid that contains the Holy *Ka'aba*
Almasjid Alnabawi	المَسْجِدُ النَبَوي	The prophetic masjid, the masjid built by the Prophet *Muhammad* (peace be upon him) in the year 622 CE
Mihrab	مِحْرَاب	Niche, the position of the imam when leading the group prayers
Minber	مِنْبَر	Pulpit, an elevated plane on which the preacher stands during the delivery of Friday sermon. Originally, it consists of three steps (about 0.45 m). Later, its height has been increased gradually to exceed 2 m. In many of the contemporary Masjids, the traditional *Minber* has been replaced with a small terrace, 2.5 m above worshippers' plane in order to provide more space for worshippers. *Minber* is located to the right of the Mihrab, looking from worshippers' side.
Moratal or *Altadwir*	تِلَاوَةٌ مُرَتَّلة، أو تِلَاوَةٌ بِطَرِيْقَةِ التَدْوِيْر	A method of recitation in which the *Qur'an* is read in a slow rhythm. This method is usually applied either in group or individual prayer
Mujawwad or *Altahaqeeq*	تِلَاوَةٌ مُجَوَّدة، أو تِلَاوَةٌ بِطَرِيْقَةِ التَحْقِيْق	A method of recitation in which the *Qur'an* is read in a very slow rhythm
The Noble *Qur'an*	القُرآن الكَرِيم	According to the Islamic faith, the Noble *Qur'an* is the words of *Allah* (God Almighty), revealed by him to the Prophet *Muhammad* (peace be upon him) through the angel *Gabriel*. It consists of 114 chapters, each chapter (known as *Sūrah*) consists of many verses (known as *Āyāt*). It is strongly recommended that every Muslim memorize the whole *Qur'an*, yet it is obligatory for every Muslim to memorize and correctly recite *Al-Fātiḥah* in every *Rakʿah*, otherwise the prayer is incorrect according to the Islamic law
Qiblah	القِبْلَة	The direction towards the Holy *Ka'aba* in *Makkah Almukarramah*
Rakʿāh/pl. Rakʿāt	رَكْعَة (الجَمْعُ: رَكَعَات)	A set of coordinated and successive postures (standing, bowing, standing, two prostrations with one sitting down in between) accompanied by specific words and some verses of the Noble *Qur'an*, which collectively represents a unit (or Rakʿāh) of prayer. The number of units (*Rakʿāt*) in a prayer and its type (i.e., aloud, or private) depend upon prayer time
Ṣalāt	صَلَاة	In Islam, the term "prayer" means a special ritual that must be performed by every adult Muslim at prescribed times in a predefined direction. According to the Islamic teaching, prayer has twofold: physical, and moral. Physically, the worshipper has to perform the required (*Rakʿāt*). Although it could be performed individually, it is strongly recommended, particularly for adult males, to be offered in the masjid in congregation. The moral part of the prayer is related to the mental and spiritual condition of the worshipper. In Islamic heritage, reverence is the soul of the prayer. Thus, a worshipper must offer his/her prayer with reverence and humility (i.e., submission, with the body parts still, and supplication to *Allah* Almighty), pondering what he/she recites during the prayer (i.e., thinking deeply in the meanings of the words, with the mind fully immersed in thought to the extent that it turns away from other things), and a full listening, (see also *Group (congregational) prayer*)
Sharīʿah	شَرِيْعَة	Islamic law
Sūrah/pl. Suwar	سُوْرَة (الجَمْعُ: سُوَر)	Chapter of the Noble *Qur'an* that consists of many verses
Altajweed rules	قَوَاعِدُ التَجْوِيْد	To make well, a set of rules via which the Noble *Qur'an* should be recited
Takbīr	التَكْبِير (قَوْلُ: اللهُ أَكْبَرُ)	Magnification of God [*Allah*], declaration that *Allah* is the greatest

AA.2 Acoustic abbreviations

Whenever the following acoustic abbreviations appear in the text, they mean:

Reverberation time (s)			
	Occupied	$T_{RG\mid Mid}$	The general optimal mid-frequency bands reverberation (s), recitation mode
		$T_{SG\mid Mid}$	The general optimal mid-frequency bands reverberation (s), speech mode
		$T_{BG\mid Mid}$	The general balanced (recitation and speech) optimal mid-frequency bands reverberation (s)
		$T_{RM\mid Mid}$	The optimal mid-frequency bands reverberation (s) for males, recitation mode
		$T_{SM\mid Mid}$	The optimal mid-frequency bands reverberation (s) for males, speech mode
		$T_{BM\mid Mid}$	The balanced (recitation and speech) optimal mid-frequency bands reverberation (s) for males
		$T_{RF\mid Mid}$	The optimal mid-frequency bands reverberation (s) for females, recitation mode
		$T_{SF\mid Mid}$	The optimal mid-frequency bands reverberation (s) for females, speech mode
		$T_{BF\mid Mid}$	The balanced (recitation and speech) optimal mid-frequency bands reverberation (s) for females
		T_{OM}	Optimal reverberation time for masjids
		T_{Imams}	The optimal reverberation time for *imams*

References of Appendix A

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Appendix B. Description of Odeon Model

Odeon is a room acoustic simulation and measurement software. The first version of the program has been released in 1984 with the purpose of providing reliable prediction software for room acoustics. Since that, different updates and developments have been performed. Today, Odeon has wide applications either for indoor or outdoor spaces with complicated geometry. Odeon can be used to predict room acoustics and PA-systems parameters in concert and opera halls, theatres, worship spaces, … etc. Odeon software is based on a hybrid algorithm (a combined image source - ray tracing algorithm) that allows reliable predictions at modest calculation times [1], [2]. This section describes in detail the model and settings that were applied in Odeon to generate the ten required audio clips.

The shape and form of the utilized model, or room, for this analysis were derived from the basic model [3]. In plan, the room has a rectangular shape (12.00 x 8.00 m) which represents a medium size masjid, Figure AB.1. In the third dimension, it is a rectangular prism of height 6.00 m. Table AB.1 lists the main architectural data of the room.

During the simulations, three sound sources were utilized: two Omni-sound sources (O_{SS1} and O_{SS2}) and one human source H_S, see Figure AB.1. The Omni-sound sources were used to predict the reverberation time as per specification [4]. Values of the reverberation and the other acoustic parameters were averaged on a grid of 1.00 x 1.00 m. The H_S had a human directivity pattern and was used to simulate imam's voice. This last source was utilized twice, the first simulates the recitation mode in which it was placed at 1.65 m above the floor, facing, and in the middle of, one of the two long sides of the room, that is the case during the actual performance. The second simulates the sermon mode in which the source faced the worshippers at height 3.65 m from the floor (i.e., as if it was placed on a 2.00 m height pulpit, this simulates the case of Friday sermon), see Figure AB.1. The human source was used to generate two impulse responses IRs at a receiver that was located at a point not so close to the source (about 3.29 m behind the source in recitation mode, see Figure AB.1 a). The source-receiver distance was chosen so that the receiver should be in the reverberant field. Accordingly, the critical distances d_c for the different setups at each frequency band were calculated. Results showed that the minimum d_c is 0.60 m while the maximum is 2.00 m. Consequently, a receiver located about 3 m from the source will satisfy this condition. Using Odeon software, the recorded IRs were later convolved to the audio clips that were collected in the anechoic room. No sound reinforcement system was considered during the simulations. The background noise was set to NC 25, room temperature to 24 ^{o}C, and the relative humidity to 50 %.

The general auralisation settings apply Odeon recommendations. In summary, the main settings are:

1. Apply dither and noise shaping (enabled)
2. Wave result file: 16 bit PCM

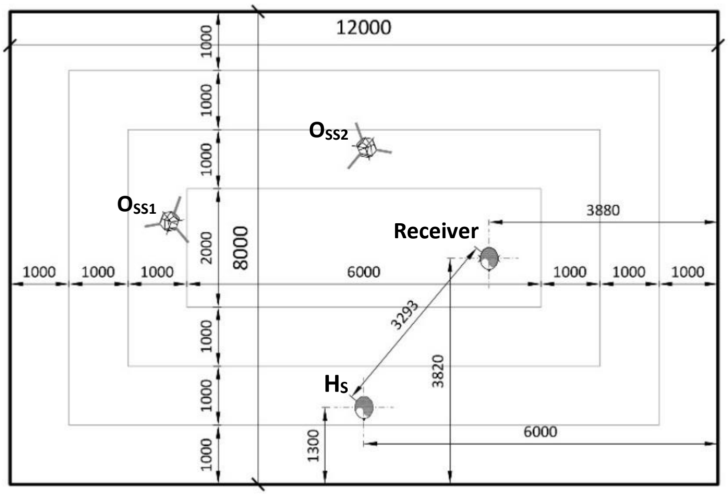
Binaural settings

1. Create binaural impulse response file (.Jnn) (enabled)
2. HRTF: subject_021Res10deg_M3,0_SRate44100_Apass0,50_Astop40,00_BOvrLap100%_PPrHRTF256
3. Headphone: Subject_021Res10deg_diffuse.wav
4. Low cut filter (10 Hz)
5. Overall Recording level: was systematically changed till the max. output (in Job/auralisation window) be between -10-0 dB as recommended by Odeon
6. Phase approximation: Random

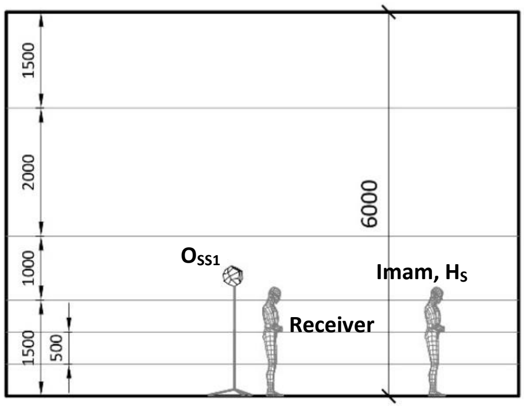
In this phase, since we are principally concerned with generating Impulse Responses IRs that ensures the targeted reverberation times for this study, not investigating an actual room in actual operating conditions which certainly necessitates considering the effect of occupation either partial or full, using a simple (unoccupied room) could be a proper decision. Accordingly, during the simulations, rooms were considered unoccupied. The finishing materials for the different setups were chosen from the standard Odeon material list in addition to the relevant publications [5]. Table AB.2 illustrates the absorption characteristics of selected materials, its noise reduction coefficient NRC, and the weighted absorption coefficient α_W. Table AB.3 shows the distributions, areas, and percentages of the different materials per setup. The scattering coefficients for the different surfaces were chosen as recommended by Odeon [6], see Table AB.4. Finally, Table AB.5 lists the values of the main acoustic parameters as calculated by Odeon.

Table AB.1. Room's architectural data

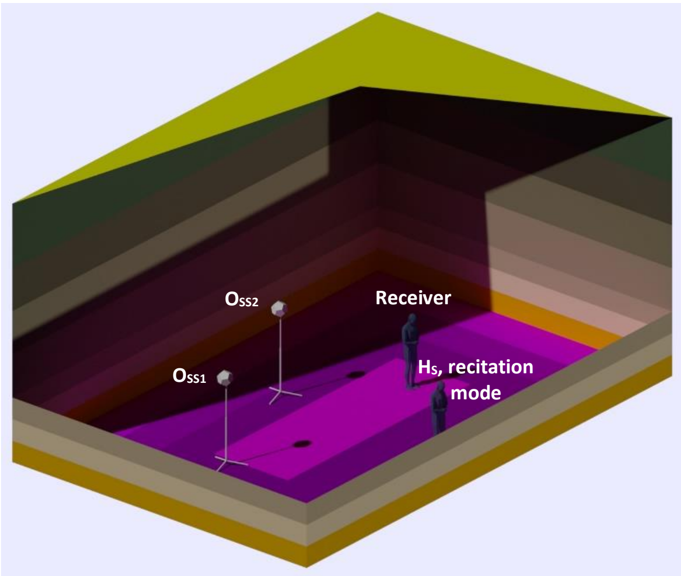
Area (m^2)			Volume (m^3)	Aspect ratio (Length L: Width W: Height H)		
Floor	Walls	Total		L	W	H
96	240	432	576	1.00	0.67	0.50



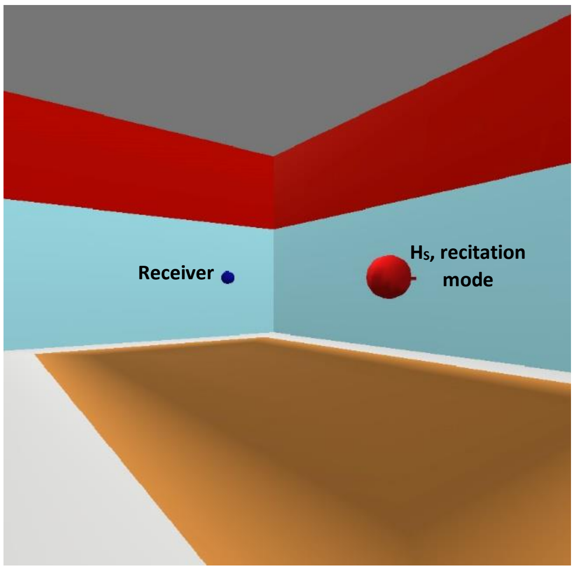
a. Room plan



b. Room cross section



c. Exterior view (walls and ceiling were partially removed to enhance clarity)



d. Interior view extracted from ODEON

Figure AB.1. Room model

Table AB.2. List of finishing materials, their codes, and absorption coefficient as used in the model (see the distribution of the materials per setup in Table AB.3)

Boundary	Material Description	Code	63	125	250	500	1000	2000	4000	8000	NRC[1]	α_w[2]	Class
			Octave band centre frequency (Hz)										
Ceiling	Painted plaster surface	4002	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.05	NC[3]
Walls	Painted plaster surface	4002	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.05	NC[3]
Walls	Thin plywood panelling	3063	0.42	0.42	0.21	0.1	0.08	0.06	0.06	0.06	0.10	0.10(L)	NC[3]
Walls	Plywood panelling, 10 mm thick	3068	0.28	0.28	0.22	0.17	0.09	0.1	0.11	0.11	0.15	0.10(L)	NC[3]
Walls	Rebond Polyurethane Foam 30 mm DOW	14301	0.02	0.06	0.22	0.64	0.91	0.98	0.98	1.00	0.70	0.50(MH)	D
Walls	Rebond Polyurethane Foam 50 mm on 50 mm Air gap	14309	0.03	0.23	0.68	1.00	1.00	1.00	1.00	1.00	0.90	0.95	A
Floor	Marble or glazed tile	2001	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.00	0.00	NC[3]
Floor	6 mm pile carpet bonded to open-cell foam underlay	7002	0.03	0.03	0.09	0.2	0.54	0.7	0.72	0.72	0.40	0.25(MH)	E

[1] Noise Reduction Coefficient, the average of the absorption coefficient at the four centres 250, 500, 1000, and 2000 Hz. The result is rounded in increments of 0.05, see [7]

[2] Weighted sound absorption coefficient, ≥ 0.90 (A), 0.80–0.85 (B), 0.60–0.75 (C), 0.30–0.55 (D), 0.15–0.25 (E), ≤ 0.10 (not classified), see [8]

[3] Not Classified

Table AB.3. Distribution of the materials per setup, (see material's codes and colours in Table AB.2)

Setup	T_{Mid} (s)	Boundary: Ceiling	Walls	Floor
1	5.01	100% 96 m² (4002)	30 % / 70 % 72 m² (3063), 168 m² (4002)	87.50 % / 12.50 % 84 m² (2001), 12 m² (7002)
2	3.45	100% 96 m² (4002)	79.20 % / 20.80 % 190 m² (3063), 50 m² (4002)	87.50 % / 12.50 % 84 m² (2001), 12 m² (7002)
3	1.47	100% 96 m² (4002)	93.30 % / 6.70 % 224 m² (3063), 16 m² (14301)	100% 96 m² (7002)
4	0.76	100% 96 m² (4002)	58.30 % / 5 % / 36.70 % 140 m² (3063), 12 m² (3068), 88 m² (14309)	37.50 % / 62.50% 36 m² (2001), 60 m² (7002)

Numbers in parentheses represent material's code in Odeon software, which is also the numbers presented in Table A.II.1

Table AB.4. Scattering coefficients for various materials as suggested by Odeon, (see also Table AB.2) [6]

Material	Scattering coefficient at mid-frequency (707 Hz)	Applied for
Brickwork, filled joints but not plastered	0.05–0.1	Material # 7002
Smooth surfaces, general	0.02–0.05	Materials # 3063, 3068, 14301 and 14309
Smooth painted concrete	0.005–0.02	Materials # 2001 and 4002

Table AB.5. Values of the acoustic parameters as calculated by ODEON[1]

Setup	Parameters	Octave band centre frequency (Hz)							
		63	125	250	500	1000	2000	4000	8000
1 (5.01 s)	EDT	2.68	2.67	4.18	5.52	4.55	3.88	2.77	1.32
	Ts	193	191	301	401	329	278	198	93
	D_{50}	0.24	0.25	0.16	0.13	0.15	0.18	0.24	0.44
	C_{50}	-4.9	-4.8	-7.1	-8.4	-7.5	-6.6	-5	-1
	STI	0.35							
	T_{30} (Average)	5.00							
	Al_{cons}(STI)	25.31							
2 (3.45 s)	EDT	1.2	1.19	2.13	3.57	3.38	3.23	2.43	1.23
	Ts	83	82	151	257	243	231	172	87
	D_{50}	0.49	0.5	0.3	0.19	0.2	0.21	0.27	0.46
	C_{50}	-0.2	-0.1	-3.6	-6.3	-6	-5.7	-4.3	-0.6
	STI	0.42							
	T_{30} (Average)	3.40							
	Al_{cons}(STI)	17.91							
3 (1.47 s)	EDT	0.98	0.97	1.56	1.81	1.15	1	0.88	0.62
	Ts	66	65	109	127	77	66	58	41
	D_{50}	0.57	0.58	0.4	0.35	0.52	0.59	0.63	0.74
	C_{50}	1.1	1.3	-1.8	-2.6	0.4	1.5	2.3	4.5
	STI	0.59							
	T_{30} (Average)	1.50							
	Al_{cons}(STI)	7.74							
4 (0.76 s)	EDT	1.5	1.15	0.94	0.79	0.62	0.55	0.51	0.4
	Ts	104	78	63	53	41	38	36	29
	D_{50}	0.41	0.51	0.58	0.64	0.72	0.75	0.77	0.83
	C_{50}	-1.5	0.2	1.5	2.5	4.1	4.9	5.3	7
	STI	0.69							
	T_{30} (Average)	0.80							
	Al_{cons}(STI)	4.8							

1 For the detailed values of the reverberation times see Table 1

References of Appendix B

[1] ODEON Room Acoustics software. [Online]. Available<: https://odeon.dk/>. [Accessed 20 November 2021].

[2] Elkhateeb A. Acoustical environment assessment in enclosures, developing a new parameter among speech intelligibility, shape and volume using digital simulation. Ph.D. thesis, Ain Shams University, Egypt; 2002.

[3] Elkhateeb A, Eldakdoky S. The acoustics of Mamluk masjids: A case study of Iwan-type masjids in Cairo. Appl Acoust 2021; 178:1-23.

[4] British Standard, (ISO 3382-2:2008), Acoustics — Measurement of room acoustic parameters, Part 2: Reverberation time in ordinary rooms.

[5] Sabbagh M, Elkhateeb A. Sound Absorption Characteristics of Polyurethane and Polystyrene Foams as Inexpensive Acoustic Treatments. Acoustics Australia 2019; 47: 285–304.

[6] ODEON Room Acoustics Software User's Manual. July 2016, 78.

[7] American Society for Testing and Materials, (ASTM C423 - 17- 2017), Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method.

[8] International Organization for Standardization, (ISO 11654-1997), Acoustics – Sound absorbers for use in buildings – Rating of sound absorption.

Appendix C. Estimation of V_P based on the findings of this work

As mentioned in section AA.1, masjid's boundaries have low absorption characteristics excluding the floor. Thus, in light of the findings of this work, Sabine's equation can be employed to calculate the optimal volume per person V_P, based on worshippers' gender, for masjids. The following steps can be applied:

1. Determine the total number of worshippers N_{OW} and their gender.
2. Calculate their total absorption A = N_{OW} x A_{Obj} (m^2 absorption). The values of A_{Obj} for worshippers standing in rows on carpet and sitting down randomly on carpet are listed in Table AC.1 [1]. These two postures are the most important postures from the acoustic point of view during the actual performance (the first for recitation mode, the last for speech mode) [2], [3].
3. Using Sabine's equation, and the findings of this work, calculate the **optimal volume** of the room for the given number and gender of the occupants. For simplicity, air absorption (4mV) can be set to zero and the values of the balanced optimal reverberation can be utilized (See Table 9):
4. To get V_P, divided the **optimal volume** as calculated in step 3 by N_{OW} (according to their gender) as determined in step 1.

By applying the previous steps, it can be concluded that $V_{P|M}$ (recitation mode) = 8.13 m^3/Person and $V_{P|F}$ = 5.43 m^3/Person. For speech mode, $V_{P|M}$ =7.00 m^3/Person and $V_{P|F}$ = 4.70 m^3/Person.

Table AC.1. The absorption per object (A_{Obj}) in m^2

Posture	Octave band centre frequency (Hz)						Mean		
	125	250	500	1000	2000	4000	Low	Mid	High
Worshippers (standing on carpet)	0.07	0.22	0.59	0.88	1.12	1.39	0.145	0.735	1.255
Worshippers (sitting down randomly on carpet)	0.14	0.36	0.65	0.61	0.76	0.89	0.250	0.630	0.825

References of Appendix C

[1] Sabbagh M, Elkhateeb A. Effect of body posture on sound absorption by human subjects. Appl Acoust 2021;183: 108317.

[2] Elkhateeb A, Adas A, Attia M, Balila Y. Are our Masjids Suffering Excessive Reverberation!. In: The 23rd International Congress on Sound and Vibration, Athens, Greece; 10-14 July 2016.

[3] Elkhateeb A, Adas A, Attia M, Balila Y. The acoustics of masjids, why they differ from the classical speech rooms. In: The 22nd International Congress on Sound and Vibration ICSV 22, Florence, Italy; 12-16 July 2015.