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Research Paper

# Mosque as a Bilingual Space – an Investigation on Speech Intelligibility in Mosque Acoustics Using Simulation Techniques

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Mosques are Islamic places of worship where speech and music rituals are performed. Since two different languages are spoken there, mosques are described as bilingual spaces. Among studies on the complex acoustic structure of mosques there are only few studies on speech intelligibility and none on the bilingual characteristics of the mosque. Therefore, a comprehensive study has been carried out to evaluate the acoustic comfort of the contemporary Turkish mosques (CTM) over speech intelligibility of Turkish and Arabic languages. In the study the CTM model providing optimum acoustic conditions recommended in the literature is examined on speech intelligibility by applying acoustic simulation and auralisation techniques, as well as word recognition tests. As a result, the acoustic condition in the model is found insufficient in terms of speech intelligibility of both languages. Also, with the decrease of Signal-to-Noise Ratio (SNR), the Turkish intelligibility ratio is observed to decrease at least two times faster than the Arabic ones.

This study is viewed as an outline for researchers to further study mosque acoustics in terms of speech intelligibility, and thus support the standardisation process of the acoustic comfort criteria for the mosques.

**Keywords:** mosque acoustics; bilingual space; acoustical simulation; speech intelligibility; word recognition tests; auralisation.



## 1. Introduction

### *1.1. Mosques and the rituals*

A mosque is a Muslims worship place where the rituals of the Islamic religion are performed. Mosques built as the places of worship are of significant importance to Turkish culture due to the great prevalence of Islam over the other religions in Turkey; the significant increase in the number of Turkish mosques since 2010 (Alic, Ozcevik Bilen, 2019); and the intensive use of the mosques throughout the years (Baktir, n.d.; Cirit, n.d.).

The most common religious rituals performed in mosques are **salah**, **sermon**, and **khutbah** (Akin, 2016). **Salah** is a ritual of worshiping God. During this ritual, the verses from the Quran, the holy book of Muslims, are recited in a melodic way by the imam (leader of the prayer; sound source) (Yaşaroğlu, 2006). Thereby, it can be said that salah is a religious music ritual. The language of the Quran is Arabic, therefore only Arabic is spoken during salah. **Sermon** and **khutbah** are the speech rituals. During both sermon and khutbah rituals, religious topics are conveyed by an imam (speaker) in the most explicatory way for the congregation (in this case, all participants in the mosque except the imam; the listeners) (Baktir, n.d.; Cirit, n.d.). Therefore, sermon and khutbah speeches are performed in the native language of the region where the mosque is located. The lectures given during the sermon and khutbah rituals always reference the verses from the Quran and hadith books (books about the life of the prophet of Muslims). These verses are firstly recited in Arabic and then translated into the native language (Baktir, n.d.; Cirit, n.d.). Thus, two different languages, Turkish and Arabic, are actively spoken in mosques during both sermon and khutbah rituals.

### *1.2. Mosques as a bilingual space*

Active speaking of two different languages is defined as bilingualism (Bilingualism, n.d.). Therefore,

Table 1. Difference between Turkish and Arabic languages in terms of origin, structure, and sound formation (Güler, Hengirmen, 2005; Pilanci, 2011; Ez-Züvey, Hanay, 2013; Fischer, 2015; Aydin, 2010).

| | | | | | | |
|---|---|---|---|---|---|---|
| Language | Name | | | | TURKISH | ARABIC |
| | Origin | | | | Ural Altaic | Semitic |
| | Structure | | | | articulated | inflexible/declinable |
| | Sound formation | Vowel | Formation | mouth | ✓ | ✓ |
| | | | | tongue root | × | ✓ |
| | | | Length | long | × | ✓ |
| | | | | short | ✓ | ✓ |
| | | Consonant | Formation | mouth | ✓ | ✓ |
| | | | | throat | × | ✓ |
| | | | | nasal | ✓ | ✓ |
| | | | | larynx | ✓ | ✓ |
| | | | | tongue root | × | ✓ |
| | | | Length | long | × | ✓ |
| | | | | short | ✓ | ✓ |
| | | | TYPE | sibilant | × | ✓ |
| | | | | fricative | ✓ | ✓ |

The presence of the features here is marked with the sign "✓" and the absence with the sign "×".

a place like a mosque where two different languages are spoken can be defined as a bilingual space. The bilingual adjective is generally used for individuals who speak and understand both languages equally (Bilingualism, n.d.), but the bilinguality of the Turkish mosques used in this study encompasses the languages spoken at two different levels: Turkish (native language level) and Arabic (Arabic level of the people who read, understand and properly pronounce the Quranic Arabic/classical Arabic). These language levels meet recruitment of imam (Presidency of Religious Affairs, 2016). In terms of origin, structure and sound formation Turkish and Arabic languages are quite different from each other (see Table 1).

The main aural difference between these languages is caused by the 'tongue root' and 'throat' sounds, sibilant and long sounds that exist in Arabic but not in Turkish language.

### *1.3. Assessment of the relevant literature (statement of the problem)*

Acoustic comfort in mosques is important as in every venue of the audible events. In the literature there are various studies in this context which can be summarised as:

- documentation of the mosque acoustics and development of acoustical improvement suggestions (Sü, Yilmazer, 2007; Carvalho, Freitas, 2011; Kavraz, 2014);
- investigation of the effects of different architectural elements in the mosque (mihrab, indoor coating materials, dome and other ceiling types etc.) on mosque acoustics (Elkhateeb *et al.*, 2016; Hafizah *et al.*, 2015; Ahmad *et al.*, 2013; Prodi, Marsilio, 2003);
- determination of mosque acoustic comfort criteria (Kayili, 1988; Karabiber, 2000; Orfali, 2007; Abdou, 2003; Elkhateeb *et al.*, 2016).

The most common evaluations in these studies are objective ones such as evaluating the mosque acoustic comfort using measurement and calculation methods based on measurable parameters (*reverberation time* – $T_{60}$, *Early Decay Time* – EDT, *definition* – $D_{50}$, *Speech Transmission Index* – STI etc.). Additionally, only three studies stand out in the literature that are based on the subjective evaluation of the mosque acoustics over speech intelligibility. In these studies, the word recognition tests prepared in the Turkish language were applied and the speech intelligibility was subjectively examined in Selimiye Mosque by Uretmen, in Muradiye Mosque by Erdem, and in Eminonu New Mosque by Yildirim (Üretmen, 1991; Yildirim, 2003; Erdem, 1992). Additionally, the decrease in speech intelligibility was observed when there was a big difference between Sound Pressure Level (SPL) of direct sound and total SPL values. Also it decreased in areas where direct sound could not reach or areas exposed to long and delayed reflections coming from the dome and other oblique forms. In these studies, word recognition tests were applied simultaneously at all specified receiver points. Therefore, subjective data obtained from different parts of mosques contained responses given by different subjects. However, subjective data obtained by comparing responses given by different subjects remain weak in terms of consistency.

Table 2. Optimum acoustic conditions for mosques recommended in the literature.

| Parameter | Optimum value | | Reference |
|---|---|---|---|
| | Native language (Turkish) | Foreign language (Arabic) | |
| $T_{60}$ [s]* | 1.1–1.7 (for 4000 $m^3$) | | (Alic, 2019; Alic, Ozcevik Bilen, 2019) |
| EDT [s] | ±10% $T_{60}$ (0.99–1.87 for 4000 $m^3$) | | (Sü, Yilmazer, 2007; Templeton, 1993) |
| $D_{50}$ | 0.3–0.7 | | (Abdou, 2003; Karabiber, Erdoğan, 2002; TS EN ISO 3382-1, 2010) |
| Background noise | 35 dB(A); $NC_{25}$ | | (Abdou, 2003; BS 8233, 1999; ÇGDYY, 2010) |
| SNR** | > 10 dB(A) | > 14 dB(A) | (Bradley, 1986; BS EN ISO 9921, 2003) |
| STI | > 0.45 | > 0.60 | (BS EN 60268-16, 2011) |

* Value recommended for an unoccupied mosque.

** Value recommended for rooms with the sole purpose of speech communication.

Consequently, the subjective evaluations of the Turkish mosque acoustics over speech intelligibility seem to be scarse, lacking in terms of consistency and still have not been examined as a bilingual space.

### *1.4. Objectives*

In order to determine whether different languages have a significant effect on the speech intelligibility of the mosque, the subject of this paper has been set as the subjective evaluation of the Contemporary Turkish Mosque (CTM) acoustics over the speech intelligibility of Turkish and Arabic languages (Alic, 2019). For the good efficiency of the study results, the whole study was planned to be conducted in the mosque that meets optimum acoustic criteria recommended in the literature (see Table 2).

## 2. Methods

Unfortunately, a suitable mosque for the purpose of this study could not be found since the acoustic design of the mosques has not been done yet and this is related to the fact that the building acoustic regulations are quite recent in Turkey. Therefore, a CTM model with optimum acoustic conditions has been determined as a sample mosque for this study. Additionally, only rituals during which both languages are actively spoken are taken into consideration (sermon and khutbah), since the mosque is considered as a bilingual space. Therefore, the music ritual (salah), during which only Arabic is spoken, is left out from the scope of this study. Then, the subjective evaluation techniques is carried out in order to test the acoustic comfort conditions in the mosque in terms of speech intelligibility. As seen from the mosque literature review (see Subsec. 1.3), the most common subjective evaluation method for determining the speech intelligibility is the implementation of word recognition test, which is widely used in other studies on speech intelligibility (Houtgast, Steeneken, 1984; Tavares *et al.*, 2009; Zhu *et al.*, 2014; Kitapçi, Galbrun, 2014; Yang, Mak, 2018). To make this subjective evaluation method applicable in a virtual mosque, several auralisation techniques have been used. In this section, the whole procedure of this study is explained in detail.

### *2.1. Study area and its properties*

#### *2.1.1. Physical properties of the Contemporary Turkish Mosque (CTM) model*

To carry out this study, the architectural and technical properties (capacity, size, shape, etc.) of the sample mosque model are determined as a result of the statistical evaluation of the Contemporary Turkish Mosques. Physical properties of the mosque, such as size and interior coating material, are obtained by visiting and observing 28 Contemporary Turkish Mosques located in Eskisehir, Turkey (a city having the average population of the Turkish provinces). Information such as volume, floor space, and capacity of the mosque is obtained from mosque archives. The data obtained from the archives and observations are combined, and the average physical properties of the Contemporary Turkish Mosques are determined by using statistical trend analysis and arithmetic average calculation methods (see Table 3).

#### *2.1.2. Acoustical properties of the Contemporary Turkish Mosque (CTM) model*

A mosque with the physical properties summarised in Table 3 is modelled in a computer environment and arranged to provide the optimum acoustical properties recommended in the literature (see Table 2). Due to the fact that in the CTM model major sound absorption comes from the floor covered with a thick carpet, the required acoustic condition cannot be met there. For this reason some acoustic improvements are done. The acoustical properties of interior coating materials

Table 3. Average physical properties of the Contemporary Turkish Mosque (CTM) (Alic, 2019; Alic, Ozcevik Bilen, 2019).

| General information | | General coating materials in the interior | |
|---|---|---|---|
| Capacity | 1164 people (min 100; max 2500) | floor | carpet |
| Volume | 4000 $m^3$ (min 400 $m^3$; max 8600 $m^3$) | ceiling | plaster |
| Floor area | 647 $m^2$ (min 65 $m^2$; max 1470 $m^2$) | side and back wall | plaster + wood |
| Ceiling form in the main space | consisting of 12 domes | front wall | ceramic |

Here, min and max values represent the values of the smallest and largest mosque in the study area.

Table 4. The acoustical properties of the interior coating materials.

| Architectural element | | Coating material | Absorption coefficient | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1 kHz | 2 kHz | 4 kHz | 8 kHz | Scatt. |
| Floor | | 6 mm wood fibreboard on laths, cavity >100 mm deep (Bobran, 1973) + 6 mm pile carpet bonded to closed-cell foam underlay (Parkin *et al.*, 1979) | 0.30 | 0.30 | 0.20 | 0.25 | 0.31 | 0.33 | 0.44 | 0.44 | 0.1 |
| Ceiling | main dome* | perf. 13 mm gypsum board (11%), $d$ = 5 mm on studs and mineral wool | 0.18 | 0.18 | 0.32 | 0.71 | 0.99 | 0.50 | 0.29 | 0.29 | 0.1 |
| | other domes | concrete block, with or without plaster, painted | 0.11 | 0.11 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.1 |
| Wall | plastered surface | concrete block, with or without plaster, painted | 0.11 | 0.11 | 0.08 | 0.07 | 0.06 | 0.05 | 0.05 | 0.05 | 0.1 |
| | wooden surface | plywood on battens fixed to solid backing | 0.30 | 0.30 | 0.20 | 0.15 | 0.13 | 0.10 | 0.08 | 0.08 | 0.3 |
| | glazed surface | marble or glazed tile (Harris, 1991) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.2 |
| | glassed surface | glass, ordinary window glass | 0.35 | 0.35 | 0.25 | 0.18 | 0.12 | 0.07 | 0.04 | 0.04 | 0.1 |

* Material different than the average one (see Table 3).

attached to this model are determined by using the material library of the ODEON 14 Auditorium software (see Table 4).

The main dome of the CTM model is selected to be acoustically improved since there are examples of the sound absorptive domes in ancient times (Kayili 2005; Kayili, 1988), as well as in some contemporary mosques (Su Gul, Caliskan, 2013; Ismail, 2013; Hafizah *et al*, 2015). Contemporary mosques are usually coated with an acoustically improved perforated gypsum board. Furthermore one of the 28 mosque samples used in the scope of this study has also perforated gypsum board coated dome (e.g. Osmangazi University Divinity Mosque in Eskisehir, Turkey). The acoustically improved main dome supported the optimisation of the general acoustic condition of the CTM model.

Since background noise can affect the speech intelligibility, it is arranged as $NC_{25}$ in the CTM model so that the simulation results will be comparable to other results obtained in this study. The acoustic condition of the mosque is calculated using the grid response (simulation technique) at receiver points. During simulations sound source (adjusted as the "Tlknorm_NATURAL.SO8" source type of the ODEON 14 Auditorium software, presenting the speaker whose SPL is in the range of normal talk) is positioned 1.5 m far from the centre of the front wall at a height of 1.65 m. A grid positioned 1.7 m above the ground consists of 1.2 × 1.2 m units, see (Alic, Ozcevik Bilen, 2019). The results obtained for $T_{60}$, EDT, and $D_{50}$ parameters are shown in Fig. 1.

From Fig. 1 optimum acoustic conditions in terms of $T_{60}$, EDT, and $D_{50}$ parameters (excluding $T_{60}$ and EDT values simulated for 8000 Hz) seem to be successfully met in the CTM model. According to the close values of $T_{60}$ and EDT, uniform sound distribution is also provided in the CTM model.

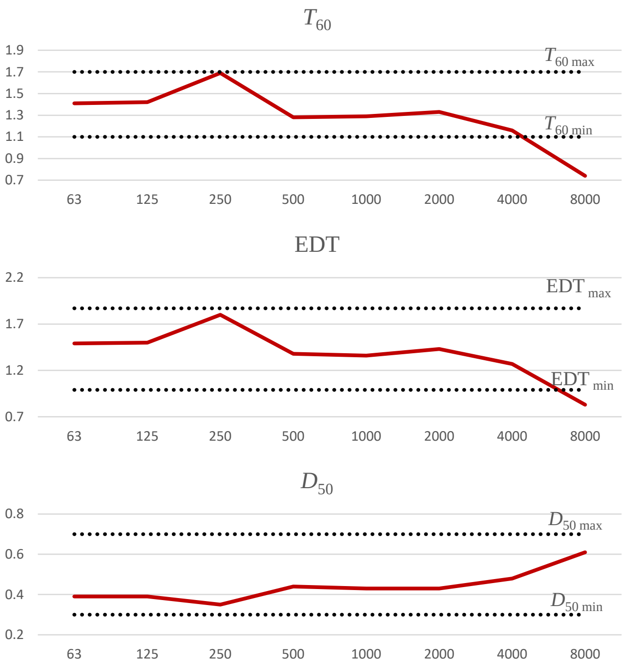



Fig. 1. Acoustic condition of the Contemporary Turkish Mosque (CTM) model in terms of $T_{60}$, EDT, and $D_{50}$ parameters.

STI and A weighted Sound Pressure Level SPL-A parameters are also simulated in the CTM model as objective parameters of speech intelligibility. These data are evaluated separately for Turkish (native) and Arabic (foreign) languages (see Table 5).

The **SPL-A** values in Table 5 are evaluated according to the recommended SNR values for the mosque. The recommended background noise for mosques is 35 dB(A) (Abdou, 2003; BS 8233, 1999; ÇGDYY, 2010), and the SNR value for the native language (Turkish) is 10 dB(A) (meaning that the speaker voice must be at least 10 dB louder than the background noise) (Elkhateeb *et al.*, 2016). To avoid masking defects caused by the high SNR, SPL-A values for the native language (Turkish) should be at least 45 dB(A). On the other hand, the lowest recommended SNR value for a foreign language (Arabic) is 14 dB(A) (BS EN ISO 9921, 2003). Therefore, for foreign language to be intelligible, the SPL-A value in the room must be at least 49 dB(A). Therefore, in the CTM model, the sufficient acoustic condition in terms of the SPL-A parameter of both Turkish and Arabic language is not satisfied. This occurs due to the big size of the mosque and the changes of the sound pressure level caused by the source-receiver distance change. As the distance between the source and receiver increases, the sound pressure level decreases. Therefore, SPL-A values of the CTM model are not expected to satisfy the optimum condition.

Short reverberation time stimulates high STI values unless there is a high background noise level that masks the speaker's voice and reduces its intelligibility. The STI value of the CTM model is expected to be in a fair range (0.45–0.60) according to its reverberation time (1.1–1.7 s) (Long, 2006). Further, due to the great width and large volume of the CTM model and the difference in sound pressure level between the average SPL-A value of the CTM model and the background noise (44.5 – 35 = 9.5 dB(A)) which is lower than the optimum SNR value (9.5 < 10 dB(A)), the average STI value of the CTM model is not expected to be very high. In this study, any STI value that meets "fair" intelligibility rating recommended in the literature is considered as the optimum **STI parameter**. In this case optimum STI values are those greater than 0.45 for the Turkish language (native language) and greater than 0.6 for the Arabic language (foreign language) (BS EN 60268-16, 2011). As seen in Table 5, the acoustic conditions in the CTM model are insufficient for the Arabic language in terms of STI. Since mosques have not been examined as bilingual spaces yet, a high probability is given by us for such a situation to occur. Therefore, the optimum acoustic criteria recommended in the literature is assumed to hold for the CTM model as well.

Table 5. Evaluation of the acoustic conditions of the Contemporary Turkish Mosque (CTM) model in terms of STI and SPL-A (SNR) parameters.

| Parameter [unit] | Value | | Optimum value | | | Average value evaluation | |
|---|---|---|---|---|---|---|---|
| | | | Native lang. (Tr.) | Foreign lang. (Ar.) | (reference) | Native lang. (Tr.) | Foreign lang. (Ar.) |
| SPL-A [dB(A)] | Min | 39.7 | > 45 | > 49 | (Bradley, 1986; BS EN ISO 9921, 2003; Abdou, 2003; BS 8233, 1999; ÇGDYY, 2010)) | insufficient | insufficient |
| | Max | 53.1 | | | | | |
| | Avg. | 44.5 | | | | | |
| STI | Min | 0.32 | > 0.45 | > 0.60 | (BS EN 60268-16, 2011) | sufficient | insufficient |
| | Max | 0.70 | | | | | |
| | Avg. | 0.48 | | | | | |

Here "Tr." stands for Turkish language and "Ar." stands for Arabic language.

### 2.2. Preparations for auralisation

#### 2.2.1. Determination of vocal and subject groups

The implementation methods of the subjective acoustic evaluation are determined according to the ANSI/ASA S3.2 international standard (ANSI/ASA S3.2, 2009). These implementation methods include the determination of the vocal/subject group (see Table 6), and the selection and creation of the test material.

During the creation of the vocal and subject groups the ANSI/ASA S3.2 standard has not been fully met for the gender and Arabic level requirements since it contradicts the real practices in mosques. While both males and females attend as the listeners of the speech rituals in mosques, only males participate as speakers. For this reason female speakers requested by the related standard are left out of the selection (ANSI/ASA S3.2, 2009). Furthermore, Arabic levels of speakers in mosques not being clearly clarified by the Turkish recruitment of imam (Presidency of Religious Affairs, 2016) differ from imam to imam. For this reason, the vocals/subjects in this study are not necessarily selected as people whose level of Arabic is the same as of the native language requested by the ANSI/ASA S3.2 standard (ANSI/ASA S3.2, 2009).

The hearing threshold of vocals and subjects is determined by applying the AudioCheck online audiogram hearing test (Audio Check, n.d.; Kitapçi, 2016). The hearing test is applied with Sennheiser HD 202 noise-controlled headphones calibrated in the laboratory environment. Calibration of these headphones is made by measuring and adjusting the SPL of the headphone sound at 65 dB while “Calibration File” (taking place at the AudioCheck website) is playing through the headphones. Following the instructions of use of the AudioCheck online audiogram hearing test all subjects’ hearing sensitivity is checked and determined as normal (subjects hear sounds in the range of at least 250–8000 Hz and up to 20 dBHL) (Audio Check, n.d.).

The intent of this study was to include as many participants as possible, but the bilingual criteria for vocals and subjects, and the length of test implementation period negatively affected the participation, thus limited the number of subjects. The groups of five and seven undergraduates at the Eskisehir Osmangazi University, 19 to 23 years old, took part as vocals and subjects respectively in the preparation and implementation of the tests (8 male, 4 female; M age = 20.25 years, SD = 2.31).

#### 2.2.2. Preparation of the audible material for auralisation

The subjective evaluation of the speech intelligibility in the CTM model is carried out by applying monosyllabic phonetically balanced word recognition tests, as suggested by the ANSI/ASA S3.2 international standard (ANSI/ASA S3.2, 2009). For this purpose, the phonetically balanced monosyllabic Turkish word list used in Hacettepe University Audiology Department (Kilincarslan, 2016) and the phonetically balanced monosyllabic classical Arabic word list used in the Department of Audiology in Arab countries (Alusi *et al.*, 1974) have been used. Each list consists of 25 words (see Appendix). The related lists are read and recorded by 5 vocals in the anechoic room (see Fig. 2). Word lists are recorded at sound pressure level of 65–70 dB(A) with 4 seconds gap between words (ANSI/ASA S3.2, 2009).

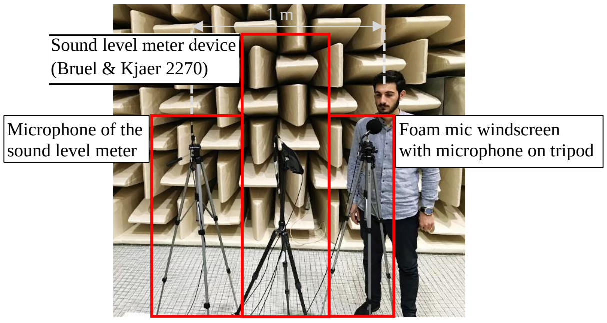



Fig. 2. Devices used during voice recordings.

Table 6. The requirements for creating the vocal and subject groups.

| Requirements | Vocal group | Subject group | Requested by |
|---|---|---|---|
| Gender* | Male | Male or female | (ANSI/ASA S3.2, 2009) |
| Native language | Turkish | | (Presidency of Religious Affairs, 2016), (ANSI/ASA S3.2., 2009) |
| Foreign language (Arabic) level* | The level of the people who read, understand and properly pronounce the classical Arabic | | |
| Hearing problems? | No | | (ANSI/ASA S3.2., 2009) |
| The lowest status of the simple Turkish and Arabic word knowledge | Properly read and pronounce them | Properly understand and write them | |
| The number of participants | At least 5 (5) | At least as many as the number of vocals (7) | |

* Those whose standard is modified according to the real ritual practices in mosques.

#### 2.2.3. Determination of receiver points for auralization

In the CTM model the receiver points are determined in order to be auralised for the subjective evaluation of the acoustic condition in the mosque. The intention was to specify as few as possible receiver points in the CTM model because their number directly affects the test implementation time. Too long duration can cause:

- fast memorization of the words from the list by subjects;
- negative influence of multiple times repeated words to subjects' mood and concentration, and the test efficiency.

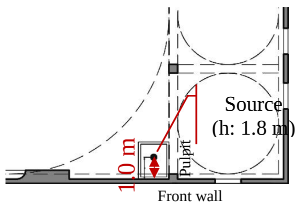
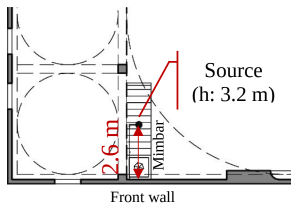
The evaluation of the acoustic condition in the mosque and the efficient collection of data is considered to be possible by auralising at least 3 receiver points during each ritual. Determining the number of points as 3 comes from the idea of dividing the mosque into 3 different zones with different acoustic condition that are evaluated as "good", "fair" or "bad" according to the objective parameters that directly affect speech intelligibility ($D_{50}$, STI, and SNR) (see Table 7).

Since source position in mosques changes according to the speech ritual that is practiced (sermon or khutbah) (Baktir, n.d.; Cirit, n.d.; Alic, Ozcevik Bilen, 2019), the sound distribution and the acoustic comfort in the mosque also change. Therefore, the zoning of the CTM model is made separately for sermon and khutbah rituals (see Fig. 3).

By superposing the zones presented in Fig. 3, the zones that meet the same evaluated acoustic condition are regrouped. Re-determined zones represent the acoustic condition of the CTM model evaluated as "good", "fair", or "bad" in terms of speech intelligibility that has place during the sermon and khutbah rituals. In order to be auralised, one representative receiver point is determined in each zone. These receiver points are described as Sg, Sf, Sb, Kg, Kf, and Kb, where the symbols represent the following abbreviations: sermon "S", khutbah "K", good "g", fair "f" and bad "b" (see Fig. 4).

According to the zones determined in the CTM model it can be said that the "good" zones where speech is intelligible, are always the receiver areas close to the speaker; the "bad" zones that do not meet sufficient acoustic comfort condition are the receiver areas in the backmost corner of the mezzanine floor on the speaker side. The other receiver areas of the mosque are under the "fair" zone. Due to the long source-receiver distance, the sound pressure level of the speech is low in the backmost corner of the mezzanine floor of the mosque. In these receiver areas, the speaker's voice is masked by background noise, and the degree of speech intelligibility is reduced.

Table 7. The procedure for the acoustical zoning of the Contemporary Turkish Mosque (CTM) model.

<table>
<tr><td rowspan="5">Method</td><td rowspan="3">Simulation</td><td>Parameter</td><td colspan="3">$D_{50}$, STI, and SNR*</td></tr>
<tr><td>Technique</td><td colspan="3">grid response</td></tr>
<tr><td>Source location**</td><td colspan="2">Sermon 
</td><td>Khutbah 
</td></tr>
<tr><td colspan="5">The comparison of the simulated results with the optimum values</td></tr>
<tr><td colspan="5">The determination of the zones with "good", "fair", and "bad" acoustic conditions</td></tr>
<tr><td rowspan="5">Zone characteristics</td><td colspan="2">Type</td><td>"good"</td><td>"fair"</td><td>"bad"</td></tr>
<tr><td colspan="2">STI</td><td>0.6–1.00</td><td>0.45–0.6</td><td>0–0.45</td></tr>
<tr><td colspan="2">$D_{50}$</td><td>0.6–1.00</td><td>0.3–0.6</td><td>0–0.3</td></tr>
<tr><td colspan="2">SPL-A</td><td>> 55 dB(A)</td><td>45–55 dB(A)</td><td>0–45 dB(A)</td></tr>
<tr><td colspan="2">Comfort condition evaluation</td><td>Sufficient</td><td>According to $D_{50}$ and STI values: sufficient but not the best one<br>According to SPL-A: insufficient but has the values close to optimum ones</td><td>Insufficient</td></tr>
</table>

* Note: Since the grid responses of the SNR values are not given in the ODEON software program, the values of the related parameters are calculated according to SPL-A values/ SNR values are calculated by subtracting the background noise value considered to be 35 dB(A) from simulated SPL-A values).

** See (Alic, 2019).

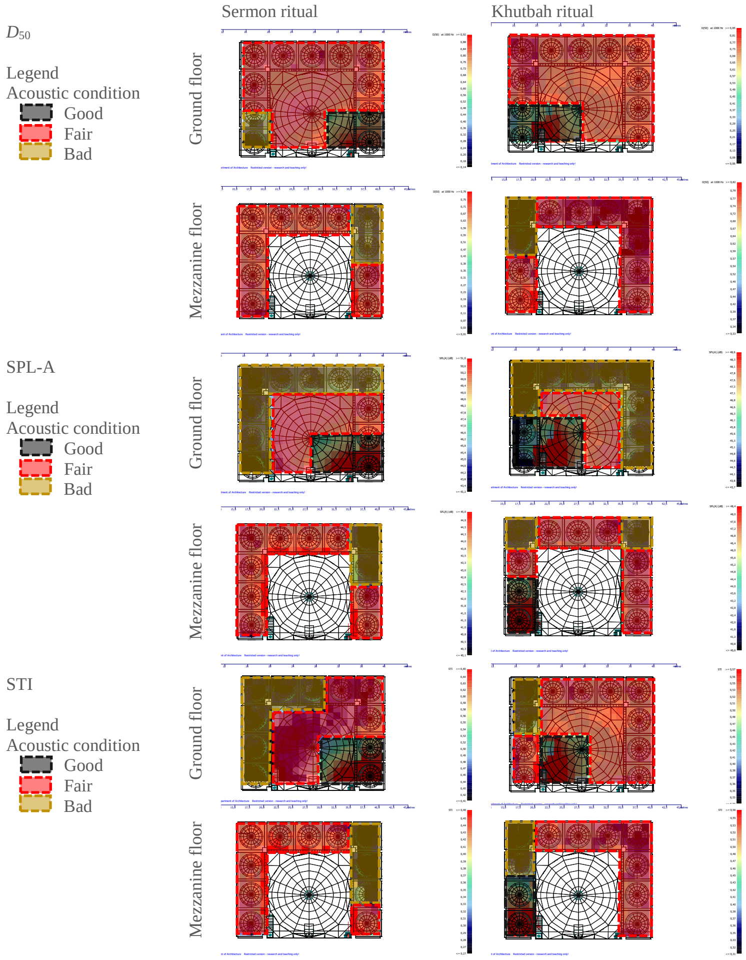



Fig. 3. Evaluation of the acoustical zones of the mosque over the $D_{50}$, SPL-A, and STI parameters simulated in the Contemporary Turkish Mosque (CTM) model.

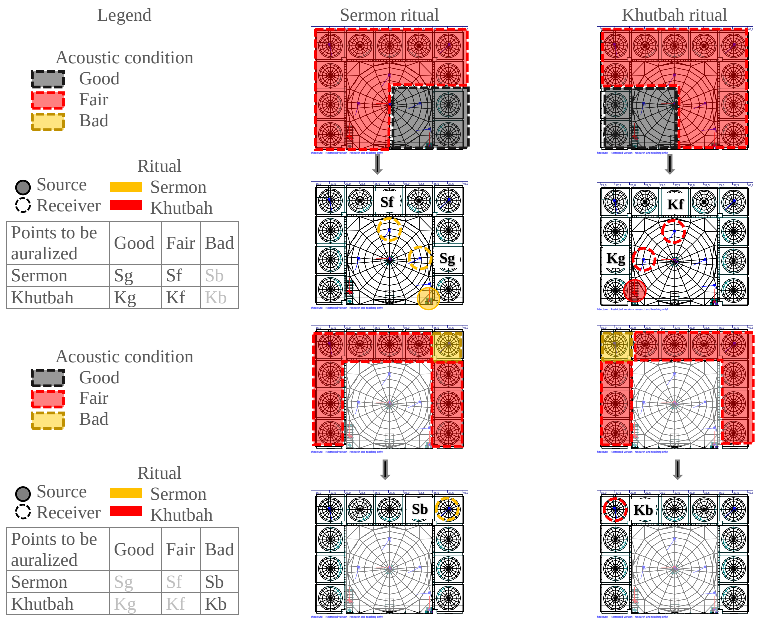



Fig. 4. Receiver points to be auralised in the Contemporary Turkish Mosque (CTM) model for: Sg, Sf, Sb, Kg, Kf, Kb, where the following abbreviations are used: sermon "S", khutbah "K", good "g", fair "f" and bad "b", and zones representing the acoustic condition in the CTM model that is evaluated as "good", "fair", and "bad" in terms of the speech intelligibility of sermon and khutbah rituals.

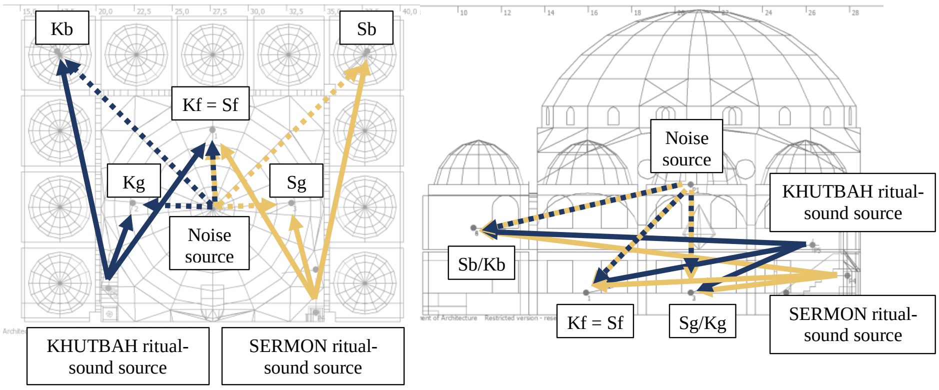



Fig. 5. Schematic representation of the auralisation procedures.

*2.3. Auralisation/preparation of the test material*

Since the background noise of the space can affect speech intelligibility during auralisation (which can lead to the masking of the speech), in addition to the speaker sound source, the noise source is added in the CTM model. While anechoic room records are played through speaker sound sources, pink noise record adjusted at 35 dB(A) (Abdou, 2003; BS 8233, 1999; ÇGDYY, 2010) is played through noise source (see Fig. 5) (Long, 2006). Both source sounds are recorded at all 6 different receiver points (Sg, Sf, Sb, Kg, Kf, Kb) and mixed with each other. The process that takes place during auralisation is schematically presented in Fig. 5.

The sound records obtained as a result of mixing anechoic room records and pink noise records are used in word recognition tests for subjective evaluation of the CTM model. These sound records obtained as a result of auralisation are played to the subject group.

*2.4. Implementation of word recognition tests*

The subjects individually listened to the auralisation records using Sennheiser HD 202 noise-controlled headphones in the laboratory environment (see Fig. 6).

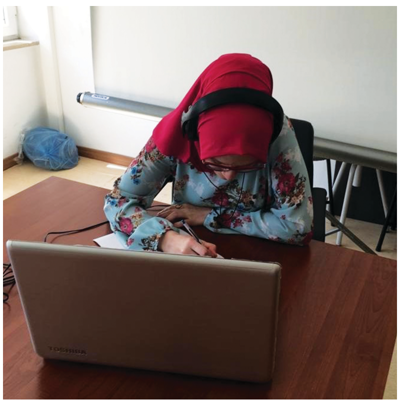


Fig. 6. Listening to the auralisation records through noise-controlled headphones.

Before implying the word recognition tests, the physical conditions of the environment and the settings of the devices are made suitable. The subjects are informed about the experiment. Thus:

- attention has been paid to ensure that the environment in which the subjects are located is quiet (< 35 dB) and that there are no factors that will decrease the concentration of the subjects (the presence of other individual is not allowed in the room, the noisy or illuminated devices such as telephones and televisions are shut down etc.),
- noise-controlled headphones have been calibrated,
- after informing subjects about the qualification and implementation of the word recognition tests, a 10-word trial test is implemented and the heard words are written.

After this preliminary preparation, the real implementation of the tests is started. A 10-minute or 30-minute break is taken between the tests. Also, 30 seconds of classical music is played behind each test to slow down the memorisation of words. Although the total duration of tests per person is planned as 2 hours and 25 minutes, the test duration varies from subject to subject and may take a longer time.

The tests were carried out in April and May of 2019, in the morning hours when the environmental noise is minimal. The words heard from the word recognition tests are written by subjects on the prepared blank form. The accuracy of the data obtained is measured on the basis of words and sounds (letters/characters).

*2.5. Evaluation of speech intelligibility in the Contemporary Turkish Mosque (CTM) model*

The speech intelligibility of Turkish and Arabic languages is subjectively evaluated over the results of the word recognition test that are recorded at Sg, Sf, Sb, Kg, Kf, Kb receiver points in the CTM model (see Table 8). Thus, the bilingual characteristics of the mosques has been tested in terms of intelligibility of

Table 8. Subjective evaluation of the acoustic condition in the Contemporary Turkish Mosque (CTM) model (Long, 2006; Kuttruff, 2009).

| Ritual | Acoustic condition (auralised receiver points) | Language | Word recognition test results | Subjective evaluation of the acoustic condition in the CTM model according to 3 different evaluation scales of intelligibility based on STI, $D_{50}$, and SNR parameters (Long, 2006; Kuttruff, 2009) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Evaluation scale of intelligibility based on STI (Long, 2006) | | Evaluation scale of intelligibility based on $D_{50}$ (Kuttruff, 2009) | | Evaluation scale of intelligibility based on SNR (Long, 2006) | |
| | | | | Proposed ratio* | Evaluation | Proposed ratio* | Evaluation | Proposed ratio* | Evaluation |
| Sermon | Good (Sg) | Tr. | 77% | > 70% | **sufficient** | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 80% | > 90% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | Fair (Sf) | Tr. | 75% | > 70% | **sufficient** | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 75% | > 90% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | Bad (Sb) | Tr. | 61% | > 70% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 71% | > 90% | insufficient | > 80% | insufficient | > 95% | insufficient |
| Khutbah | Good Kg) | Tr. | 75% | > 70% | **sufficient** | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 74% | > 90% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | Fair (Kf) | Tr. | 73% | > 70% | **sufficient** | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 72% | > 90% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | Bad (Kb) | Tr. | 65% | > 70% | insufficient | > 80% | insufficient | > 95% | insufficient |
| | | Ar. | 72% | >90% | insufficient | >80% | insufficient | >95% | insufficient |

Here "Tr." stands for Turkish language; "Ar." stands for Arabic language; "Opt" stands for optimum.
* In the literature, the scales defining the relationship between word intelligibility and STI, $D_{50}$, and SNR parameters (Long, 2006; Kuttruff, 2009) are read based on the recommended STI, $D_{50}$, and SNR optimum values for the mosque (see Table 3).

different languages. The test answers from the subjects are compiled and their accuracy is checked separately on the basis of **words** and **sounds**.

#### 2.5.1. *Evaluation based on the intelligibility rate of words*

According to **the number of words spelled correctly**, the ratio of the speech intelligibility is calculated and evaluated at each receiver point auralised in the CTM model (see Table 8). In this study, 3 different evaluation scales proposed in the literature are used. These scales define the relationship between word intelligibility and the STI, $D_{50}$, and SNR parameters, and show the acceptable limits where the sufficient acoustic condition is met.

From Table 8, the acoustic condition of the CTM model in general is observed to be "insufficient" in terms of speech intelligibility of Turkish and Arabic language according to the STI, $D_{50}$, and SNR based intelligibility scales. Under the "good" and "fair" acoustic conditions (at Sg, Sf, Kg, and Kf receiver points) observed the during sermon and khutbah rituals, speech intelligibility of Turkish language is evaluated as "sufficient" according to the STI based scale, and "insufficient" according to the $D_{50}$ and SNR based scales. Therefore, it can be said that the sufficient speech intelligibility of Turkish language is not met throughout the CTM model. **Consequently, neither Turkish nor Arabic language is observed to be intelligible enough in the CTM model**. For the accuracy of these results, Cronbach's Alpha statistical method is used to analyse reliability according to the success rate in terms of word intelligibility, and the results are found to be reliable (Cronbach's Alpha value for Turkish is calculated as 0.85 and Cronbach's Alpha value for Arabic is calculated as 0.89).

From the results of the word recognition tests, the speech intelligibility of Turkish and Arabic languages is observed to have values close to each other. Still they show different intelligibility properties in the mosque. The speech intelligibility of Turkish and Arabic languages is observed to differ from 0% to 3% under the "good" and "fair" acoustic condition (at Sg, Sf, Kg and Kf receiver points), and from 7% to 10% under the "bad" acoustic condition (at Sb and Kb receiver points), (see Table 8).

Additionally, change in the speech intelligibility ratio, which occurs with the change of the acoustic condition in the mosque, is quite different for these two languages. While for the Turkish language it is from 8% to 14%, for the Arabic language it is only by 4% (see Sf-Sb and Kf-Kb differences from Table 8). Based on this finding, **Arabic language is more intelligible/gives better results than Turkish language under acoustic conditions evaluated as "bad" in terms of SNR, $D_{50}$ and STI parameters (at Sb and Kb receiver points)**. Sounds that appear in Arabic but not in Turkish (sounds formed in tongue root and throat), are seen as a main reason for this, since they represent the main aural difference between these two languages. Therefore, the results obtained from the word recognition tests are also examined on the basis of sound.

#### *2.5.2. Evaluation based on the intelligibility rate of sounds*

The speech intelligibilities of the Turkish and Arabic languages are tested by calculating the **average error ratio of the incorrectly spelled sounds by subject groups** (see Fig. 7).

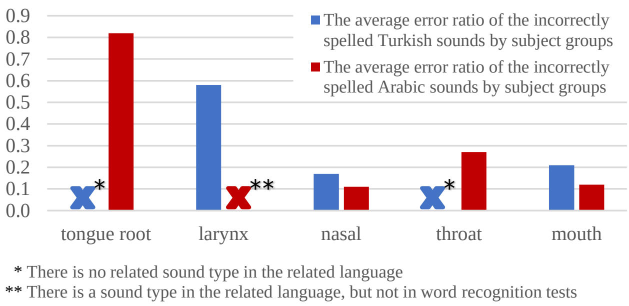



Fig. 7. Comparison of the average sound intelligibility error rate of Turkish and Arabic languages calculated in the Contemporary Turkish Mosque (CTM) model.

From Fig. 7, the sounds formed in tongue root and throat that do not exist in Turkish but are frequently used in Arabic language, are observed to not be heard correctly in average 82% and 27% according to the intelligibility ratio of sound calculated per subject. These highly unintelligible sounds, listened to under different acoustic conditions, do not affect the general speech intelligibility in mosque. So these sounds formed in the tongue root and throat are equally unintelligible under every acoustic condition.

Since the sounds formed in mouth and nasal area are the same for both Turkish and Arabic languages, the intelligibility error rates of these sounds obtained from the word recognition tests in both languages are compared. These sounds are observed to be differently intelligible when spoken in different languages. Also, they have a higher intelligibility ratio when spoken in Arabic rather than Turkish language in 6% and 9% respectively.

Although the sounds formed in larynx exist in both languages ("H" in Turkish, "ه (he)" in Arabic language), their intelligibility ratio is calculated only for Turkish language due to the fact that these sounds appear in the Turkish but not in the Arabic word recognition test. From Fig. 7 the intelligibility ratio of these sounds is observed to be quite low, and on average 58% of them are not heard correctly. Sounds formed in the nasal area and mouth, and sounds formed in the larynx are the same in both languages. Therefore, since sounds formed in the nasal area and mouth have a higher intelligibility when spoken in Arabic rather than Turkish language, sounds formed in the larynx are also expected to give the same results.

#### *2.5.3. General evaluation*

*The results of the word-based subjective evaluation* show the decrease in speech intelligibility ratio in the zones that are evaluated as acoustically "bad" and represented as Sb and Kb receiver points. This decrease is caused by the size of the mosque, source-receiver distance related reduction of the sound pressure level, and the formation of reverberant sound area in that zone. As distance between receiver and source grows, the value of SNR changes and intelligibility decreases. In the related zones, the intelligibility of Turkish language decreases from 77% to 61%, while the intelligibility of Arabic language decreases from 80% to 71%.

*The results of the sound-based subjective evaluation* show that the intelligibility ratio of the sounds existing in Arabic but not in Turkish language (sounds formed in throat and tongue root) is low. Even though these sounds are highly unintelligible they do not negatively affect the overall speech intelligibility of the Arabic language. So Arabic seems to be more intelligible than Turkish. The intelligibility difference between these two languages is more noticeable in the zones evaluated as acoustically "bad" that are represented as Sb and Kb receiver points. The speech intelligibility ratio of Turkish and Arabic languages in zones evaluated as acoustically "good" and "fair" (represented as Sg, Sf, Kg, Kf receiver points), is observed to have values close to each other (value difference is up to ± 3%) during both speech rituals. Besides, even though the sounds formed in the nasal area, mouth, and larynx are the in Turkish and Arabic, they are observed to be differently intelligible when spoken in both languages. Consequently this phenomenon is thought to be caused by long sounds that exist in Arabic but not in Turkish language. This hypothesis is checked by comparing the intelligibility rates of correctly written Arabic long and short sound words that are obtained as a result of the word recognition tests for "good" and "bad" acoustic condition. It is observed that the intelligibility rate of long sound words decreased significantly slower than of short sound words. While the intelligibility ratio of long sound words decreases by only 1–3%, the ones of short sound words decreases by 3–15% (see Table 9).

Table 9. The audible test results of Arabic language obtained at the Kg, Kb, Sg, and Sb receiver points in the Contemporary Turkish Mosque (CTM) model separately evaluated for short sound words and long sound words.

| Word types and the total number of Arabic words in the audible tests | | The count and the intelligibility rate of the Arabic words spelled correctly by the subject groups | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Sermon ritual | | | | Khutbah ritual | | | |
| | | Good A.C. (Sg) | | Bad A.C. (Sb) | | Good A.C. (Kg) | | Bad A.C. (Kb) | |
| | | CNT | PCT | CNT | PCT | CNT | PCT | CNT | PCT |
| Long sound words | 455 | 356 | 78% | 341 | 75% | 342 | 75% | 338 | 74% |
| Short sound words | 420 | 343 | 82% | 282 | 67% | 306 | 73% | 294 | 70% |
| Total | 875 | 699 | 80% | 623 | 71% | 648 | 74% | 632 | 72% |

Here "CNT" stands for count; "PCT" stands for percentage; "A.C." stands for acoustic condition.

Since it is observed that long sound words have better intelligibility ratio than the short sound words do, it can be said that long sounds improve the general intelligibility of the language it has been spoken in. In the case of Turkish and Arabic languages this means that **Turkish sounds are absorbed/masked quickly inside the room due to their shortness, and therefore their audibility rate decreases. In Arabic sounds, the opposite situation occurs: the sounds spread more easily in the room due to their large length and therefore they have better audibility.**

## 3. Conclusion

Mosques are places of worship where the audible events of the Islamic religion take place. Providing comfort conditions in mosques is of great importance due to the intensity of their use and rapid growth in their count. Various studies are carried out in the context of mosque acoustics but none of them have examined the bilingual characteristics of the mosque yet. For this reason, the mosque is examined as a bilingual space and the results from the subjective evaluation of the mosque acoustics are shared in this paper.

In this study, the mosque acoustics is subjectively evaluated by examining the speech intelligibility of Turkish and Arabic language in Turkish mosques. For this purpose, firstly the Contemporary Turkish Mosque model with optimum acoustic conditions is developed, and then subjective evaluation is made by using auralisation techniques and word recognition tests.

As a result of the **word based evaluation** of the data obtained from the tests, the following facts are observed:

- In the CTM model, neither Turkish nor Arabic language is sufficiently intelligible;
- Turkish and Arabic languages have values close to each other in terms of speech intelligibility, and
- Arabic language is more intelligible than Turkish under acoustic conditions evaluated as "bad" according to $D_{50}$, STI, and SNR parameters.

When Turkish and Arabic languages are **examined on the basis of sound**, the sounds formed in throat and tongue root, which lack in Turkish but are frequently used in Arabic, are observed to have equally low intelligibility ratio regardless of the room's acoustic condition. Also, all sounds except the sounds formed in tongue root and throat have different intelligibility ratios depending on the language (Turkish or Arabic) they are spoken in. As a result, in the mosque, the long sounds that exist in Arabic but not in Turkish language are observed to provide a higher intelligibility ratio of the Arabic rather than the Turkish language.

In addition, the speech intelligibility determined as a result of the subjective evaluation is found not to be sufficiently provided even in the zones that provide "good" acoustic conditions determined as a result of the objective evaluation made in the CTM model. Even though the zones evaluated as acoustically "good" are located close to the sound source and are in the field of direct sound, the speech intelligibility ratio decreases in these zones. The reason for this is that due to the high volume of the room and the properties of the coating materials the sound grows, has delayed reflections and is masked by the background noise.

## 4. Findings and recommendations

The acoustic condition of the mosque model developed within the scope of this study has been qualified as insufficient in terms of speech intelligibility of Turkish and Arabic languages. The factors that might cause insufficient acoustic conditions in CTM model fall into:

- Objective factors that are based on the acoustical properties of the mosque, such as:
  - the *probability of $T_{60}$ values* considered as optimum values for the mosque (values between 1.1 and 1.7 seconds) *not being suitable for the purpose*,
  - the possibility of failing to provide the STI value for foreign languages in the mosque, and

  - the possibility of failing to provide the SNR value throughout the mosque.
- Subjective factors that are based on subjects participating in the word recognition tests, such as:
  - the possibility of not being able to perceive the words due to the shortness of the audible records of the monosyllabic words from the word recognition tests, and
  - the probability of the subjects, participants of this study, to have the perceptual deficit caused by the lack of experience due to their young age (19–23 years).

For the future studies on the mosque acoustics in terms of speech intelligibility, it is recommended that the following steps should firstly be pursued to reveal whether the causes of low speech intelligibility depend on the perception of the subject groups rather than the objective properties of the mosque:

- diversification of subjective tests (two syllable word recognition test, diagnostic rhyme test; modified rhyme test, sentence recognition test etc.)
- diversification and increase of subject groups depending on age.

If the related problem is revealed to not be dependent on the perception of the subject groups, the optimum $T_{60}$ values will need to be reconsidered. The following point is considered to be beneficial for improving the $T_{60}$ optimum values recommended for mosques:

- Investigation of the sound frequencies that negatively affect the speech intelligibility by evaluating the sound based results of the subjective tests in terms of sound frequencies with the support of audiologists and phonologists.

## Appendix

| Monosyllabic phonetically balanced word lists used for word recognition tests | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Turkish word list (KILINCARSLAN, 2016) | | | | | | Arabic word list (ALUSI *et al.*, 1974) | | | | | |
| 1. | Kir | 10. | Mes | 19. | Kor | 1. | بَرْدٌ | 10. | خَاصٌّ | 19. | حَبٌّ |
| 2. | Çan | 11. | Kim | 20. | Tay | 2. | مَاءٌ | 11. | نَارٌ | 20. | فِكْرٌ |
| 3. | Öl | 12. | Çit | 21. | Şu | 3. | فَأْرٌ | 12. | رُزٌّ | 21. | أُمٌّ |
| 4. | Sen | 13. | Harf | 22. | Ek | 4. | جِسْرٌ | 13. | تِبْنٌ | 22. | دُودٌ |
| 5. | Kalp | 14. | Nar | 23. | İz | 5. | عُودٌ | 14. | حُوتٌ | 23. | بِئْرٌ |
| 6. | An | 15. | Söz | 24. | Kaç | 6. | دِينٌ | 15. | زَاغٌ | 24. | سَيْفٌ |
| 7. | Hiç | 16. | Cop | 25. | Lif | 7. | زَيْدٌ | 16. | عَيْنٌ | 25. | بُومٌ |
| 8. | Şok | 17. | Fiş | | | 8. | كَفٌّ | 17. | جَوْفٌ | | |
| 9. | Far | 18. | Bas | | | 9. | لَحْمٌ | 18. | نَخْلٌ | | |

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