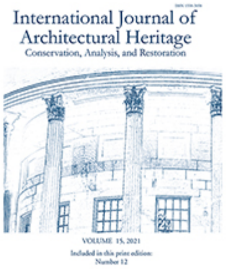

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Characterizing the Indoor Acoustical Climate of the Religious and Secular Rock-Cut Structures of Cappadocia

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ABSTRACT
Rock-cut structures of Cappadocia, which are enlisted as natural and cultural World Heritage Sites by UNESCO, have particular acoustics due to the specific tuff stone belonging to the region. This study, for the first time, discusses the indoor sound fields of the Cappadocia over five selected spots (one church and four residential halls) from Middle Byzantine sites of Hallaç, Açıksaray and Avanos with an aim of providing evidence regarding the spatial features and culture of the people inhabited these spaces. Acoustical data is collected during in-situ field tests. Acoustic parameters (EDT, T20, T30, C80, CD50, and STI) are obtained for the spaces under study. The rock-cut church is found to be the most reverberant among all the spaces and the most suitable for liturgical practices. The other four spaces are observed as comparatively more favorable for speech-related activities. The study also compares the sound absorption performance of Cappadocian tuff stone to those present in other natural caves and rock-cut structures investigated throughout the world in few prominent studies.

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Archaeoacoustics; Cappadocia Sounds; Cave Acoustics; Historical Acoustics; Rock-cut Architecture; Tuff Stone

1. Introduction

With the contemporary development in archaeoacoustics, there has been a shift from an initial interest in the history of music towards the current debates on soundscapes: acoustic environments based on functional context and perception by humans (Brown, Gjestland, and Dubois 2016). The advancements in technology have provided the researchers to be able to study aural characteristics of prehistoric sites more precisely. These sites include open-air monuments, natural caves, and man-made structures, which have been used for different activities. For instance, the acoustics of Neolithic structures, such as Stonehenge, have been studied and named as ritual sites built by humans (Till, 2014a& 2014b). Even though it cannot be proved if the architecture of megalithic monuments was shaped to enrich their acoustical climate, the behavior of sound would have been prominent in the use of such spaces (Watson 1999).

Researchers have also found it useful to study the acoustics of underground places and caves in understanding the prehistoric human interactions. Multiple ancient sites, including caves, have been studied (Plummer 1969; Reznikoff 2008). The articulation of sound in such spaces could provide additional evidence concerning the people that inhabited certain spaces as well as their context. The caves, dating from the prehistoric periods, feature a range of unusual visual characteristics such as paintings, engravings, patterns and, hand stencils which have been reinterpreted from a perspective that focused on their acoustical performance (González, Picó, and Redondo 2008; Plummer 1969; Reznikoff 2008). Paleolithic caves in Spain seem to have motifs at moderately reverberant locations (Fazenda et al. 2017) and the depictions tend to cover large areas at locations where distinct acoustic properties can be documented (Till 2019; Waller 1993; Debertolis and Bisconti 2014; Díaz-Andreu, García Benito, and Lazarich 2014).

Other studies have evaluated the acoustics of natural caves in comparison to modern-day spaces. Many natural caves have become tourist attractions and host musical performances. The monaural acoustic parameters of caves from Spain (González, Picó, and Redondo 2008), Italy (Iannace and Trematerra 2014), and Portugal (Carvalho and Sousa 2015) have been found to be comparable to modern performance spaces. The acoustics of the caves in Attica, Greece are found to be better than recent spaces of worship (church and mosque) of comparable volumes (Yioutsos et al. 2018). Hence, it is probable that the people were aware of the acoustic characteristics of these caves and were using them accordingly.

Apart from natural caves and cavities, studies have also been conducted on man-made spaces. In the acoustical analysis of six ancient man-made

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Neolithic and Iron Age structures in the UK and Ireland, Jahn observed strong resonances in the range of 95 Hz to 125 Hz (Jahn, Devereux, and Ibison 1996). The resonances in this frequency range could have helped in the augmentation of human chanting during sacred rituals in such spaces (Cook, Pajot, and Leuchter 2008). In another study, acoustic measurements were carried out in underground galleries in Peru; the results indicated acoustical characteristics which, according to the authors, could have contributed to the ritual experience (Abel et al. 2008). The acoustics of hypogea in Italy and Malta have also been analyzed; the authors conclude that the resonance in these spaces would have supported ritual practices (Debertolis and Bisconti 2014; Debertolis, Coimbra, and Eneix 2015). Other man-made structures that have acoustically been studied are catacombs; underground cemeteries constructed during the Roman Empire. These spaces are composed of negative spaces which are created by carving out alive tuff, a porous material. Researchers have tried to understand the type of rituals that were performed in such underground spaces; the short reverberation times and high STIs in such spaces make them suitable for religious purposes such as prayer (Ciaburro et al. 2020; Iannace, Trematerra, and Qandil 2014).

The rock-cut structures of Cappadocia, a significant element of the enlisted UNESCO World Heritage Sites, are similar to such catacombs in terms of their construction method, although drastically different in context. The rock-cut sites of Cappadocia are located in central Turkey scattered in an approximate area of 400 to 200 kilometers (Kostof 1972). As opposed to natural caves, Cappadocia's structures are designed and constructed, which had been created by cutting and carving the volcanic tuff (Kalas 2004; Öztürk 2017). The rock-cut structures from the Middle Byzantine Period (9th to 12th cent.) remain debated as the peculiarities of the region cannot be explained by textual sources alone and detailed archaeological studies are still limited (Ousterhout 2017). As a result, the archaeoacoustic qualities of multiple medieval sites, accommodating both religious and residential uses in Cappadocia, have been the focus of this study in order to provide a different perspective by documenting the sensorial aspects of these spaces.

Cappadocia was essentially considered as a region of Byzantine monastic communities, until the end of the 20th century (Epstein 1979; Kostof 1972; Ousterhout 1996; Tozer 1881). The recent studies convincingly challenged this perception (Kalas 2004; Kalas, Luyster, and Walker 2009; Ousterhout 2017; Öztürk 2014), while a number of domestic complexes have been studied in detail (Kalas 2007; Ousterhout 2005; Öztürk 2010). The rock-cut 'courtyard complexes' in Cappadocia that are mainly dated to the Medieval Byzantine period are an important group in this context, usually identified as elite residences (Ousterhout 2017; Öztürk 2014). While the details of the complexes are studied further and the discussions on their function and use are elaborated, the soundscape has never been a part of these discussions until present.

The acoustics of various spaces from three selected sites in Cappadocia have been documented and analyzed in detail within the scope of this study. The two medieval sites, Hallaç and Açıksaray are similar in the configuration of the settlement setting utilized for each domestic unit. Yet, while Hallaç Complex is an isolated single unit, Açıksaray comes forward as a compound of numerous similar residences. The contextual discussions on Açıksaray therefore vary; although it might still be perceived as a settlement of elite families where units, similar to Hallaç, were multiplied (Öztürk 2010 & 2014), alternative proposals such as an 'upscale stud farm' have been put forward (Ousterhout 2017). Whereas the state of conservation as well as their relatively complete on-site documentation prioritized Hallaç and Açıksaray among similar alternatives for this study, their characteristics offer comparative criteria that can provide additional data for the ongoing contextual debates. The third site is a dining hall which belongs to a traditional house transformed into a hotel at Avanos, a touristic town in Cappadocia.

2. A brief historical and architectural review of the sites

Although medieval Cappadocia and its art had been studied for years, the monastic myth attached to the region has been contested by recent scholarship (Kalas 2004, 2007; Kalas, Luyster, and Walker 2009; Mathews, Christine, and Mathews 1997; Öztürk 2010, 2012). Therefore, it is noteworthy to document the acoustic environments of Cappadocia's rock-cut structures to build upon the current discussion about their functions.

2.1. Hallaç complex

Hallaç complex, near Ortahisar, is identified as an example of an elite secular residence (Mathews, Christine, and Mathews 1997; Ousterhout 2017), despite early claims that it was a monastery (Rodley

1985). The spaces associated with the complex are distributed on the three sides of an open courtyard with a wide vestibule to the north connecting the two main spaces; the main hall, flanked by two unidentified small rooms, is positioned at the central entrance axis perpendicular to the vestibule and a smaller cross-in-square hall opens to the vestibule from the west. The area identified as the kitchen is located to the west of the courtyard and a small church with additional funerary spaces lies to the east. The complex has been almost entirely carved out of living rock with the exception of the south masonry wall of the vestibule that no longer stands but once provided a monumental façade for the entrance. The widely accepted mid-eleventh century dating of the complex is essentially based on architectural evidence (Mathews, Christine, and Mathews 1997).

For this study, acoustic data has been collected from the church and the main hall of the complex (Figure 1). The cross-in-square church is decorated by carving and there are not any documented traces of plaster except for a fresco limited to a small panel behind the altar. The size, location and the configuration of the main hall confirms its identification as a ceremonial setting used for formal gatherings. It is a longitudinal three-aisled hall divided by a colonnade of five columns and flanked by walls which are articulated by blind arcades.

2.2. Açıksaray

The areas in the complex are defined in various detailed studies by Öztürk (2010 & 2014), whose plans, as well as the organizational system are followed in this paper (Figure 2). Açıksaray is a settlement that contains nine courtyard complexes and thirteen individual churches (Figure 2); the selection of the site for settlement must have been based on the landform which was suitable for carving several complexes next to each other. Some of the courtyard complexes have monumental facades, reception areas and other utilitarian spaces similar to Hallaç Complex (Öztürk 2014). The courtyard complexes of Açıksaray have the features of tenth to eleventh-century Byzantine and secular architecture (Öztürk 2010).

For this study, the main halls at Areas 4 and 5 of the settlement have been chosen to perform the field tests. Area 4 comprises of an L-shaped organization around a narrow courtyard facing east. Although a major part of the vestibule has collapsed, the remains indicate a barrel-vaulted space with three arches (Öztürk 2010). Built on the east-west axis, a cruciform hall, with a central dome resting on four columns, opens into the vestibule. The columns emphasize the axis of the space towards the apse. The square-based columns in the hall are connected with arches; small arches have been used to link walls and columns from all directions. The complex has

Figure 1. (left) Hallaç complex plan drawn by the authors based on (Ousterhout 2017), p. 281, (top right) an interior view of the Hallaç Church, (bottom right) the ceiling of the Hallaç Church.

Figure 2. (left) an aerial view of Açıksaray from (Öztürk 2014), p. 787, (top right) an interior view of Açıksaray Cruciform hall in area 4, (bottom right) an exterior view of Açıksaray main hall in area 5.

six other spaces including a kitchen to the south, two barrel-vaulted rooms to the south and west, and a stable to the north-east of the courtyard (Öztürk 2014).

Due to its size and prominent location, Area 5 seems to have been the main courtyard complex in Açıksaray (Öztürk 2017). The courtyard faces the north, while the vestibule and the main hall are towards the south. Such an organization with a barrel-vaulted horizontal vestibule and a perpendicular main hall create the inverted T-plan (Mathews, Christine, and Mathews 1997). The complex has a vestibule and a main hall in the south, a church in the southeast, a kitchen in the southwest, and a four barrel-vaulted rooms with unidentified functions. The façade, decorated with double recessed horseshoe-arched blind niches, is divided into three registers. The barrel-vaulted vestibule, which is behind the façade and is composed of five perpendicular arches, has the entrances to the main hall and another room. The main hall is carved along the axis that goes through the center of the courtyard. A transverse arch divides the main hall in two equal bays. At the end of the hall, opposite the entrance, a circular boss has been carved in the crest of the vault, which could symbolize the end of a sequential process (Öztürk 2010). All the spaces in the complex are arranged around the three-sides of the courtyard; such a three-sided organization around a central courtyard is a common feature in both Açıksaray Area 5 and Hallaç Complex (Ousterhout 2017).

2.3. Avanos

Avanos is one of the most visited towns in Cappadocia. The town is known to have become an important center during Hellenistic and Roman periods (Strabon 2000). Avanos has a vernacular morphology where large rock-cut spaces have been actively used in combination with masonry structures. For this study, an underground dining hall has been chosen (Figure 3). The longitudinal vaulted rock-cut dining hall, with a number of niches in its walls, serves as an adequate and fully preserved hall to be compared with the large halls, which are important components of the residential compounds at Hallaç and Açıksaray.

3. Acoustical field tests

Field tests were carried out on 27th and 28th of November, 2020. Due to the travel restrictions during the pandemic, the sites were unoccupied by any tourists. Furthermore, the sites are located further away from main roads; therefore, they are acoustically quite isolated. The purpose of the tests is to

Figure 3. (left) A general view of the town of Avanos, (right) an interior view of the dining hall in Avanos, photos by the authors.

record impulse responses at numerous positions in the rock-cut spaces in accordance to the guidelines in ISO 3382, 2009 (ISO 2009). The full set of measurements are held by using a B&K (Type 4292-L) standard dodecahedron omni-power sound source, a B&K (Type 2734-A) power amplifier, a B&K (Type 4190ZC-0032) microphone combined with a B&K (Type 2250-A) hand held analyzer, and a portable PC. The sampling frequency of the recorded multi-spectrum impulse is 48 kHz, covering the interval of interest between 100 and 8000 Hz. The impulse response length is kept at 10 seconds. Noise signals are generated using DIRAC Room Acoustics Software Type 7841 v.4.1. The same software is also used for post-processing of the measured impulse responses for all receiver positions. Three types of signals are tested: exponential sine sweep (ESS), maximum length sequence (MLS), and balloon pop. The balloon pops are treated as an external signal, while ESS and MLS are internal signals generated by the software. Rubber balloons have been also used in earlier studies under similar conditions, and they have presented satisfactory results (Ciaburro et al. 2020; Iannace and Trematerra 2014; Iannace, Trematerra, and Qandil 2014).

The omni-power sound source and the amplifier could only be utilized in Avanos. Due to the absence of an electrical supply in Hallaç and Açıksaray, the omnidirectional sound source is replaced by a Bang and Olufsen Beolit 17 speaker; the speaker had already been used in an earlier study (Fazenda et al. 2017) because of its battery autonomy and flat frequency response. The rest of the system comprised of units as described above.

Overall, different source and receiver positions are used to get an average acoustic response to characterize interior sound field conditions. At least two different sound source positions must be

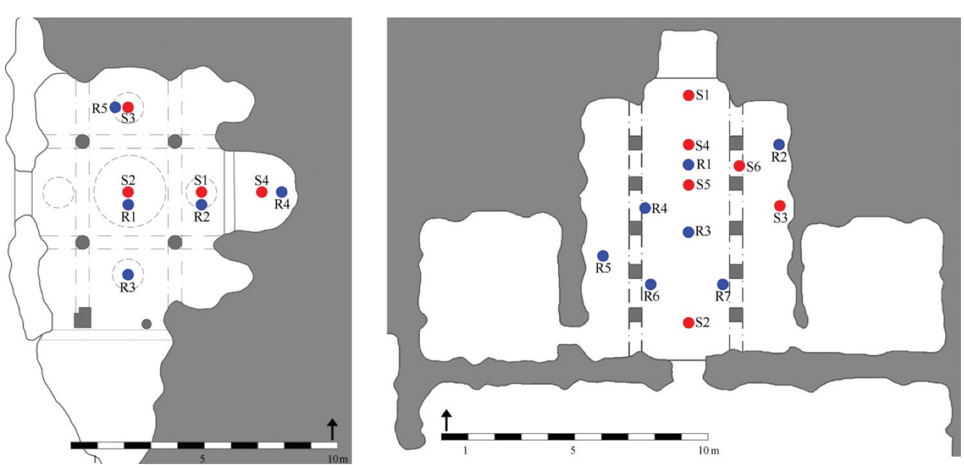

Figure 4. (left) Source (4) and receiver (5) positions at Hallaç Church, (right) source (6) and receiver (7) positions at Hallaç Main Hall (drawn by the authors based on Ousterhout 2017, 281).

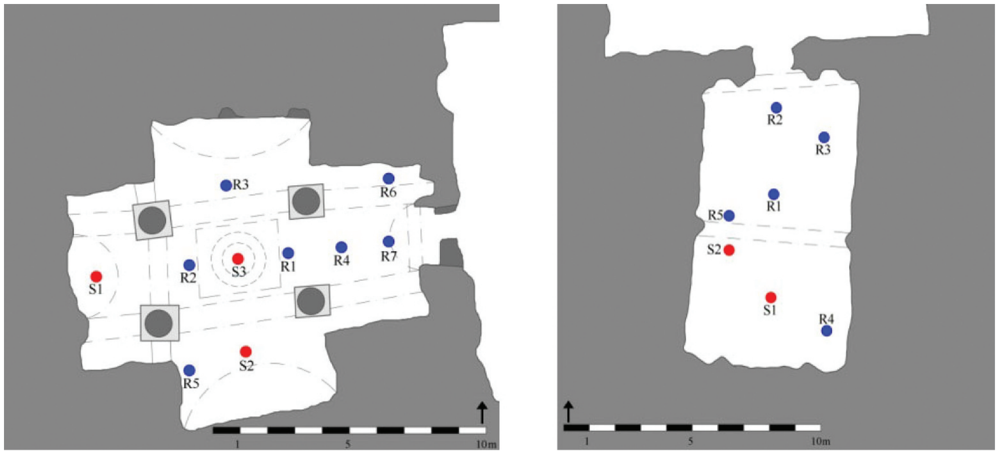

Figure 5. (left) Source (3) and receiver (7) positions at Açıksaray Cruciform Hall, (right) source (2) and receiver (5) positions at Açıksaray Main Hall (drawn by the authors based on Öztürk 2014, 795 and 789 respectively).

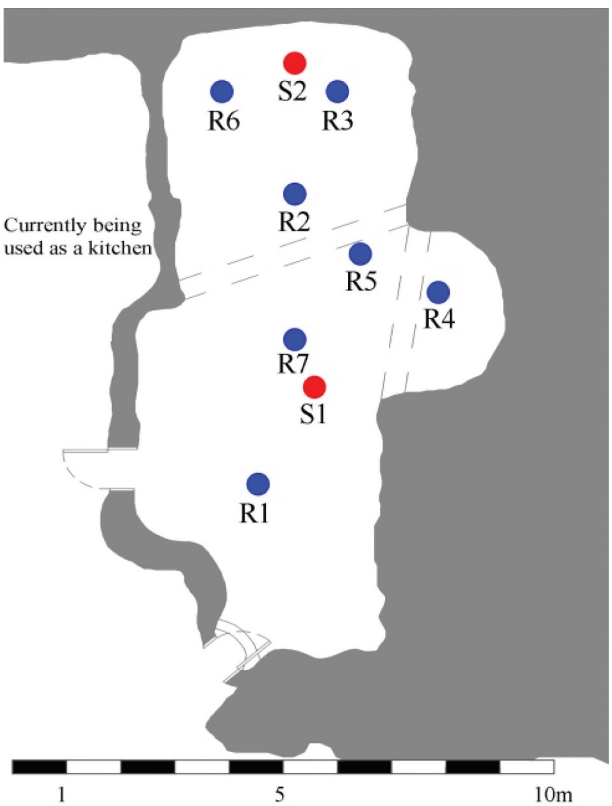

Figure 6. Source (2) and receiver (7) positions at the Avanos Dining Hall, also showing the neighboring kitchen space (drawn by the authors).

used to record the impulse response (International Organization for Standardization, ISO 2009). Therefore, 4 source and 5 receiver positions in Hallaç Church, 6 source and 7 receiver positions in Hallaç Main Hall, 3 source and 7 receiver positions in Açıksaray Cruciform Hall, 2 source and 5 receiver positions in Açıksaray Main Hall, and 2 source and 7 receiver positions in Avanos are used to record the impulse responses (Figs. 4, 5, 6). The sound and receiver positions are chosen in accordance to the function of the space. For instance, in Hallaç Church, the speaker was placed at the altar where a person would have stood to address the people in the church. Similarly, the same reasoning of addressing people is used in the main reception hall of Hallaç, and the halls of Açıksaray. The speaker height is kept around 1.5 m above the ground to imitate an average human body, while the microphone is held around 1.2 m above the ground level. Background noise levels are also measured during the data collection in each space.

4. Results and discussion

4.1. Assessment of source signals

Three different types of signals (ESS, MLS, and balloon pop) are employed during the field tests. It is advisable to obtain a signal which has at least a peak signal-to-noise ratio (PSNR) of 45 dB higher than the background noise in all octaves (Sü Gül 2019). Due to the lack of electricity in Hallaç and Açıksaray, electronic signals are produced with a limited sound level output. In order to obtain a high signal ratio, different source signals are also used to identify the signal that gives the highest PSNR values over the whole frequency spectrum. The availability of electricity in Avanos made it possible to use a standard omni-directional sound source with an amplifier, thus only ESS is used as the test signal within that space.

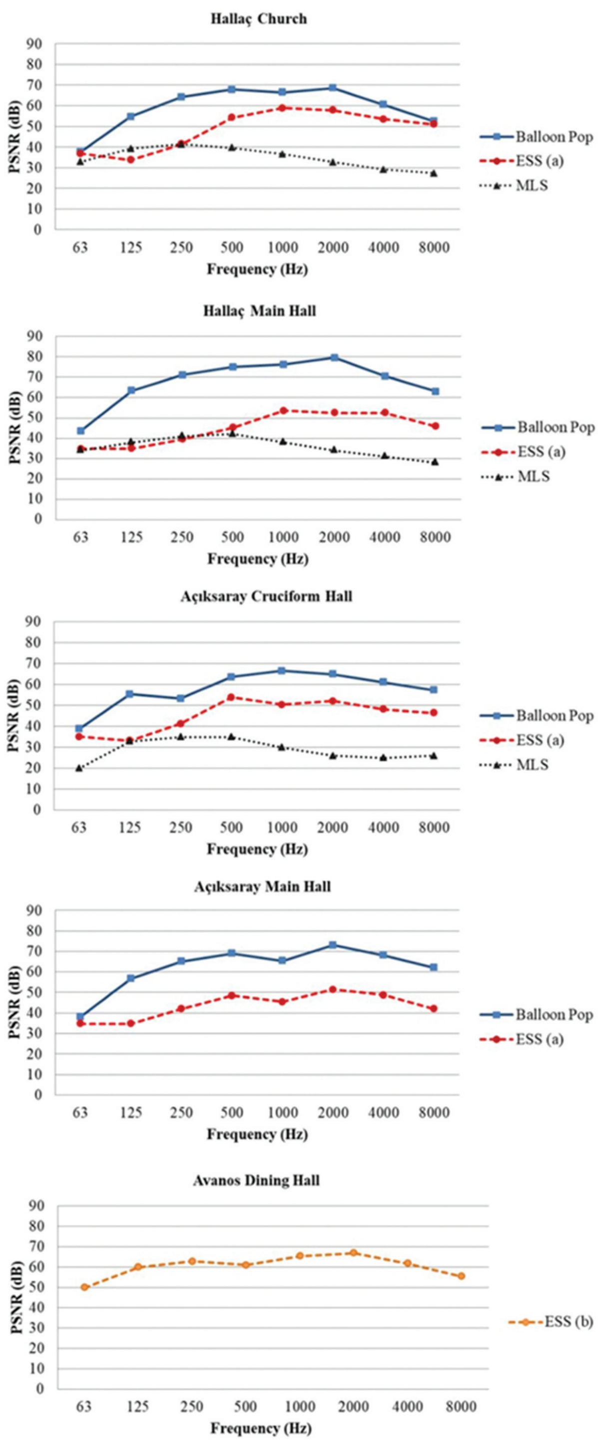

Figure 7. Comparison of PSNR over 1/1 octave bands in Hz; comparison of balloon pop, ESS (a) using a Bang and Olufsen Beolit 17 speaker, ESS (b) using a B&K (Type 4292-L) omni-directional speaker, and MLS signals for Hallaç, Açıksaray, and Avanos.

As can be observed in Figure 7, ESS has always resulted in higher PSNR values. For that reason MLS is not tested in Açıksaray Main Hall due to the lack of time; therefore, only ESS and balloon pop signals are utilized. The background noise level values are recorded to be around 32 dBA for both Hallaç and Açıksaray. Avanos has a slightly higher background noise level around 38 dBA. This is one other reason for the PSNR values to be high within these isolated spaces.

Different source signals have been compared with each other through PSNR values over octave bands for each space (Figure 7). Due to the small volumes of the spaces, a balloon pop excited the spaces sufficiently, and resulted in the highest PSNR values for all bands from 63 Hz to 8000 Hz in both Hallaç and Aciksaray. Among the three signals tested (Hallaç Church, Hallaç Main Hall, and Açıksaray Cruciform Hall) there is a little deviation between the PSNR values at lower octaves, especially between ESS and MLS. The MLS signal results in significantly lower PSNR values than the other two signals for mid and high octaves. At mid and high octaves, the difference in the PSNR of balloon pop and ESS is around 10–15 dB, except for Hallaç Main Hall where the difference rises up to more than 20 dB. The balloon pop signal results are also comparable to the ESS results generated by an omni-directional speaker in Avanos; except for the low octaves, the balloon pop resulted in lower PSNR values whereas it gives higher values at mid and high octaves. As a result, balloon pop signals are utilized in post-processing for extracting the monaural acoustic parameters for those spaces where the electricity is not available. In Hallaç and Açıksaray, ESS (output of Bang and Olufsen Beolit 17) has resulted in the second highest PSNR values, while MLS remained the weakest signal among all three.

4.2. Decay rate results and comparisons of the rock-Cut structures of cappadocia

Over collected room impulse responses within rock-cut structures, early decay time (EDT), and reverberation time (T20 and T30) decay rate parameters are analyzed. The primary room acoustics indicators T20 and T30 correspond to the time taken for the energy to drop from −5 dB to −25 dB and −5 dB to −35 dB, respectively. On the other hand, EDT is the time for the energy to decay by 10 dB immediately after the arrival of the direct sound. EDT is more dependent on the early reflections and local positions. It also correlates more with the subjective perception of reverberation (Barron 2009; International Organization for Standardization, ISO 2009; Kuttruff 2009).

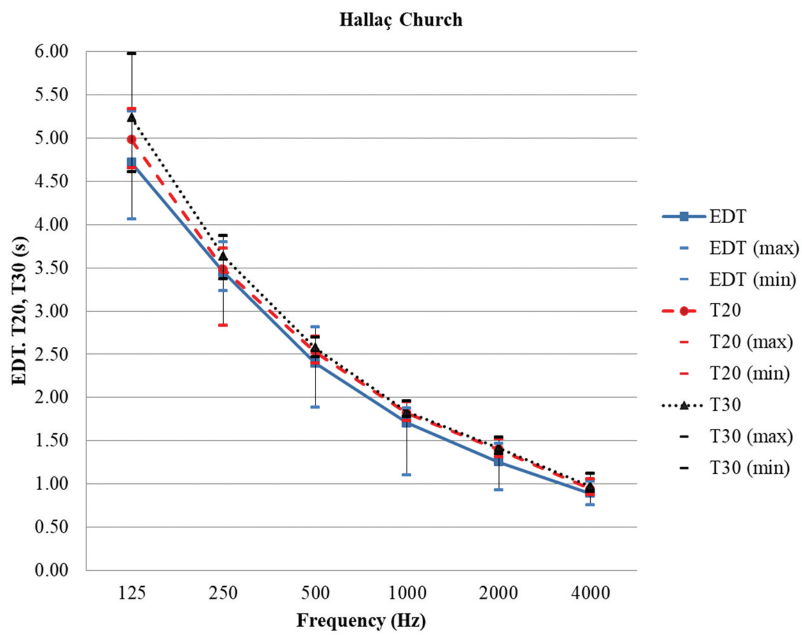

Figure 8. Maximum, minimum and average values for EDT, T20, and T30, for Hallaç Church over 1/1 Octave Bands.

Figure 8 shows the decay rate results for Hallaç Church. The space seems to be relatively reverberant considering the volume of the space (571 m^3). The EDT for the church is around 2 s at the mid-range frequency, and it drops down to 1 s at high frequencies. As expected, T20 and T30 are very close to each other over the whole frequency spectrum. Since EDT values are numerically very close to the values of T20 and T30, there is no major difference observed in the decay rate between the specific source positions and the overall space. All the parameters show similar trends of showing larger deviations from the average value at lower frequencies than at mid and high frequency ranges. An optimum range for liturgical music in the church has been estimated using the formula RT = 0.55*log10 (Vol.)-0.14 (Beranek 1988). The optimum range has the highest RT of 1.70 s at 125 Hz and the lowest RT of 1.10 s at 4k Hz. The decay rates in the church are

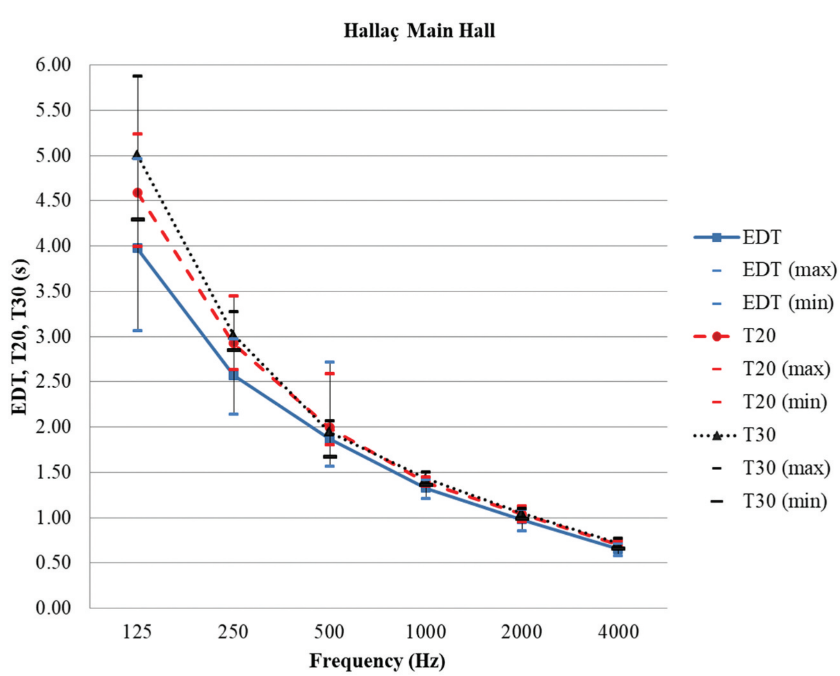

Figure 9. Maximum, minimum and average values for EDT, T20, and T30, for Hallaç Main Hall over 1/1 Octave Bands.

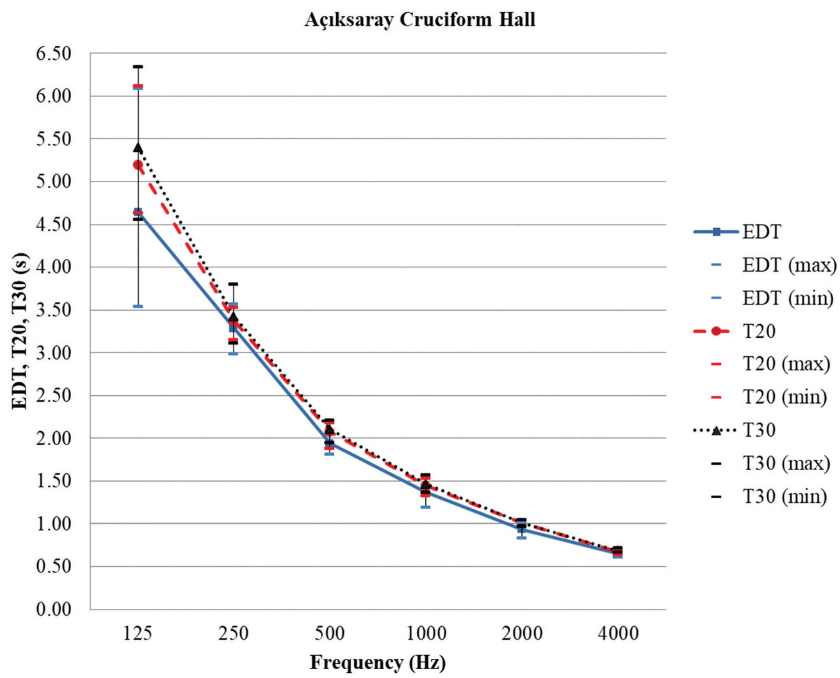

Figure 10. Maximum, minimum and average values for EDT, T20, and T30, for Açıksaray Cruciform Hall over 1/1 Octave Bands.

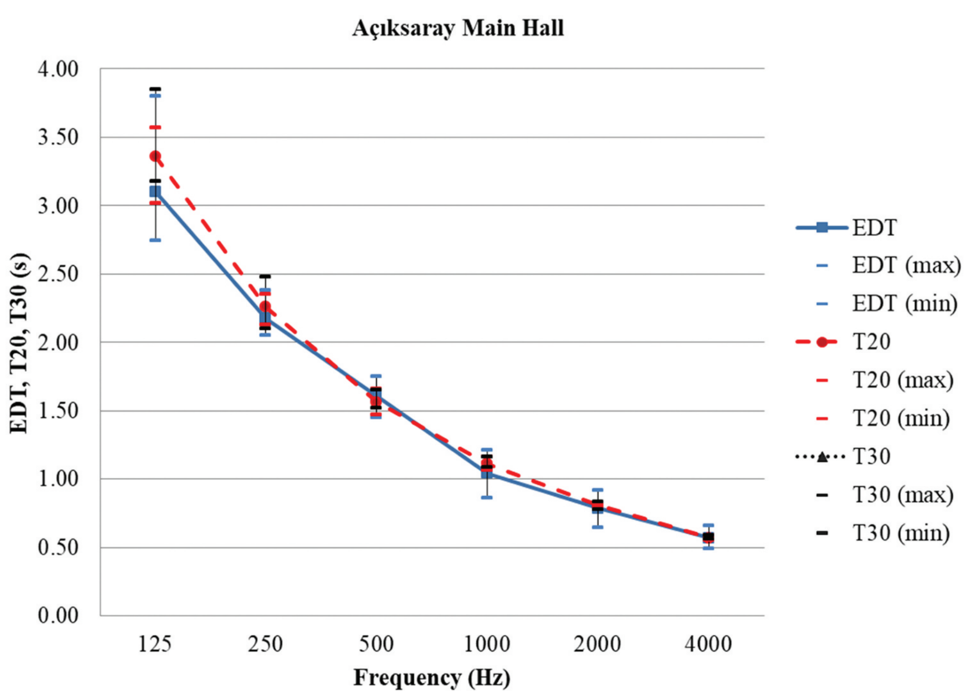

Figure 11. Maximum, minimum and average values for EDT, T20, and T30, for Açıksaray Main Hall over 1/1 Octave Bands.

much higher than the optimum range for liturgical music, except for the values from 1k Hz to 4k Hz. The decay rates indicate that the tuff stone absorbs high frequencies greater than the low frequencies, creating a high bass ratio (BR) of around 2.0. BR is a ratio of the reverberation times of low frequencies over mid frequencies. The high BR is a means of augmented male voice, which should have been important in the liturgical practices at the church.

In the Main Hall at Hallaç (322 m^3), EDT is around 1.5 s at the mid-range frequencies, while T20 and T30 are around 1.7 s (Figure 9). There is less than 10%

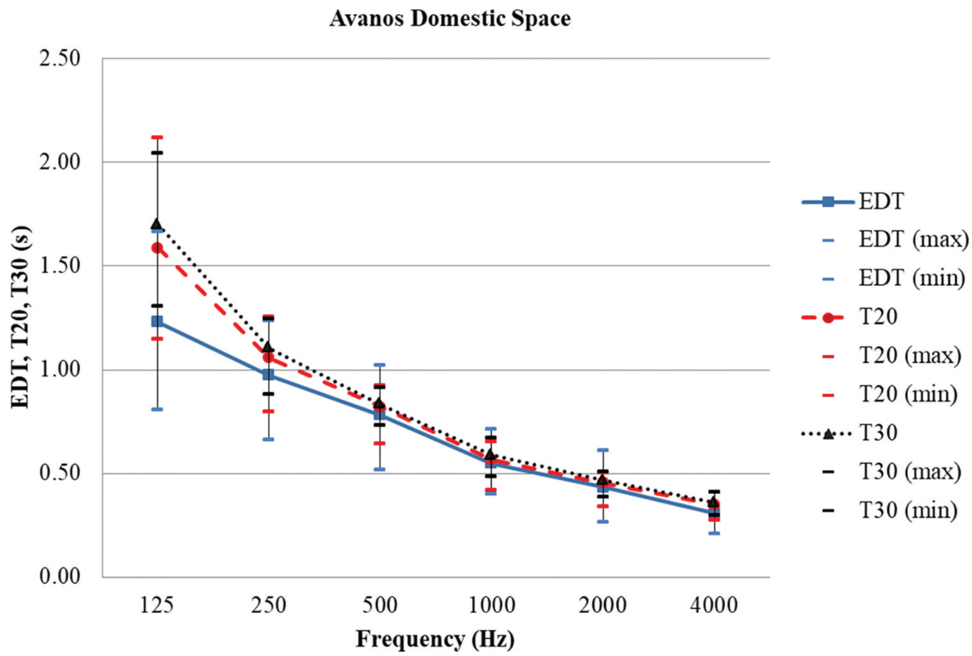

Figure 12. Maximum, minimum and average values for EDT, T20, and T30, for the dining hall in Avanos over 1/1 Octave Bands.

difference between EDT values in comparison to T20 and T30 except for low frequencies, where the difference is slightly higher. The same differences are observed in Açıksaray Cruciform Hall (400 m^3) as shown in Figure 10. Since the volume of the space is slightly larger than the Main Hall at Hallaç, the reverberation time is also slightly higher.

The third hall in the study, Açıksaray Main Hall (217 m^3), has an EDT of around 1.3 s at the mid frequency range (Figure 11). The EDT and RT for Avanos (114 m^3) are around 0.7 s with less than 10% difference between their values (Figure 12), which highlights a proper distribution of sound. All these halls are primarily known to be used for gatherings such as weddings, receiving guests, and funerals (Rautman 2006). Whether these gatherings employed only speech or both speech and music cannot be clearly distinguished based on the existing literature. In acoustical terms, it can be stated that the decay rates are much higher in comparison to speech-oriented spaces in modern world.

All the spaces show larger deviations from the mean value for the three decay rate parameters at low frequencies, whereas the differences between the highest values and the mean values become much smaller with increasing frequencies. As expected, the average decay rate values keep decreasing as the volume of the spaces get smaller (Figure 13). In terms of T20 and T30, the acoustic response in the spaces follows a general trend of higher reverberation values at low frequencies and a decrease at higher frequencies. The reverberation times are generally between 1.5 and 2 s, except for Hallaç Church where RT is a little higher than 2 s. The dining hall at Avanos, due to its small volume, is the driest space among all the five rock-cut structures.

4.3. *Energy ratios and comparisons of the rock-Cut structures of cappadocia*

Clarity (C80) and Definition (D50) parameters are analyzed for all field tested spaces. C80 and D50 are ratios of early sound energy to late sound energy (80 and 50 ms respectively), where C80 is directly correlated to music while D50 is used to analyze speech (Barron 2009). Both the parameters are dependent on receiver positions; therefore, there are larger deviations from the average values (Fig. 14 to 18) in comparison to the decay rates.

In Hallaç Church, the highest deviation from the C80 mean value is around 4.5 dB at 2 kHz, while the lowest deviation stays around 2 dB at 250 Hz. However, the deviations for D50 are the highest around the mid-range frequencies. The church has a C80 value of around 2 dB and a D50 of 0.5 (Figure 14). In general, considering the contemporary spaces, a satisfactory acoustical space should have clarity between −2 and +2 dB to satisfy both

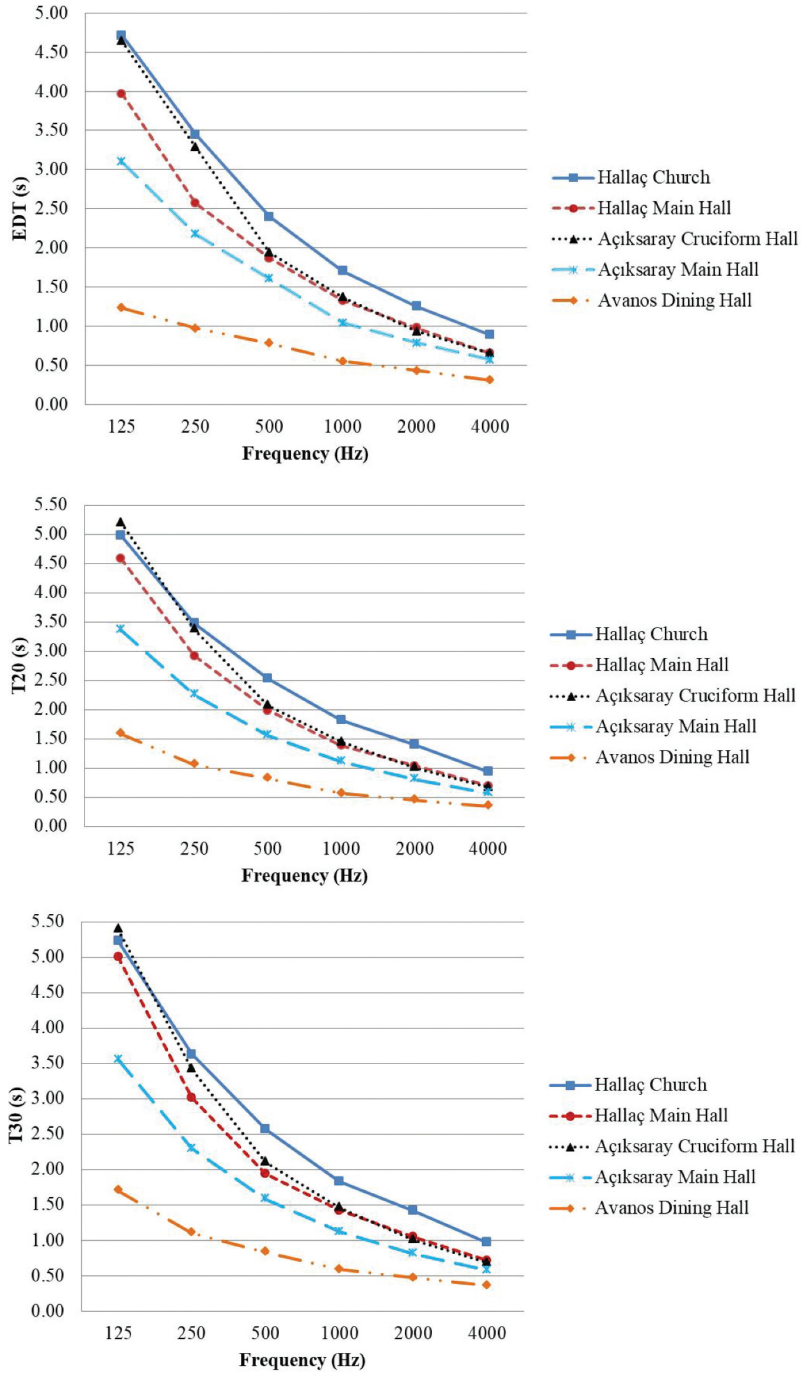

Figure 13. EDT, T20, and T30 for all five spaces over 1/1 Octave Bands.

music and speech criteria, and between −1 and +3 dB for choral music (Kuttruff 2009). C80 for liturgical music in the church can also be assessed by taking into account the location of the music source in relation to the receiver location. C80 values should be in between −2 dB and +3 dB for locations closer to the source where early energy dominates late energy. This early energy drops with increasing source and receiver distance and consequently, C80 can be in the optimum range of 0 to +5 dB for larger distances (Makrinenko 1994). Hallaç Church is a comparatively small space; therefore, the optimum values for close by positions for C80 can be utilized. Accordingly, C80 in the church is well within the optimum range for music except for the low frequencies.

The C80 at Hallaç Main Hall also shows the highest deviations at low and high frequencies. The hall has a C80 value of slightly higher than 2 dB and a D50 value of 0.5 (Figure 15). C80 values are in the

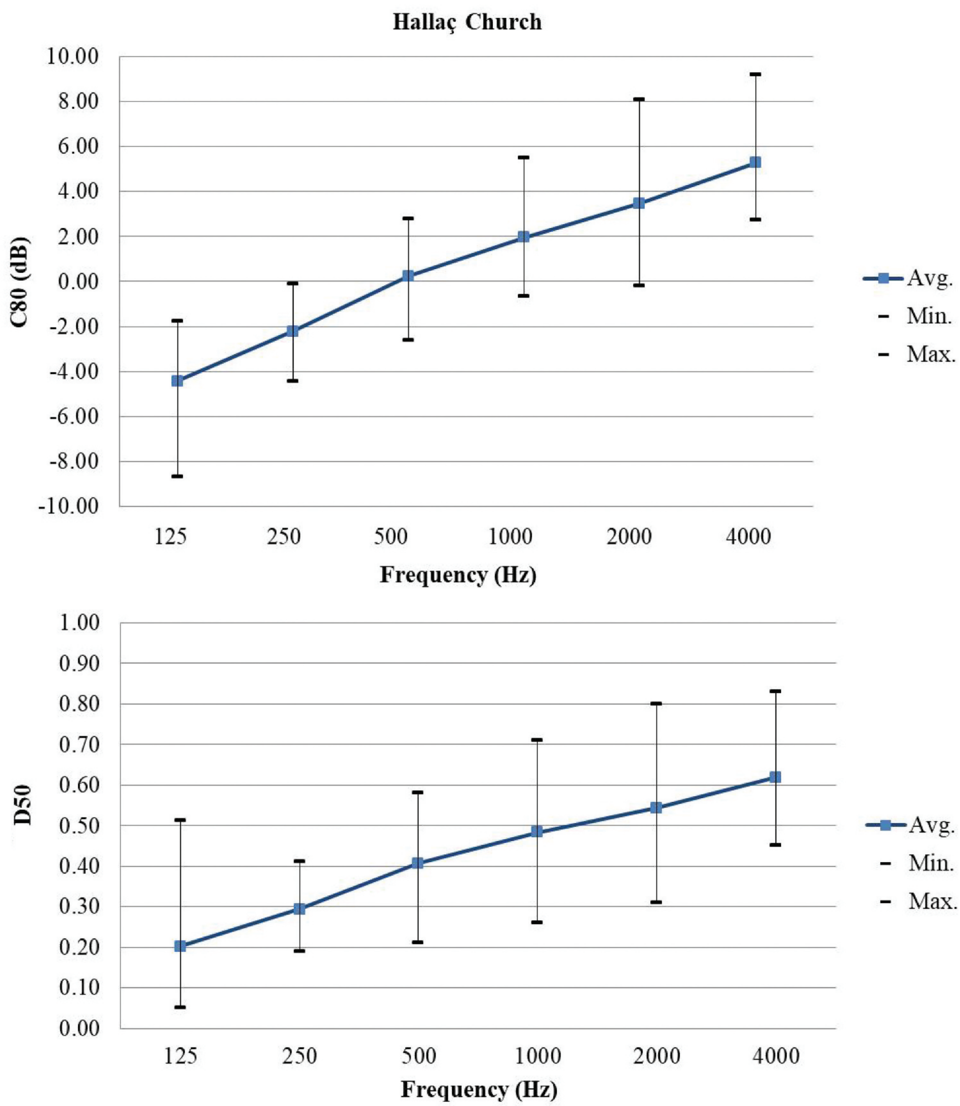

Figure 14. Maximum, minimum and average values for C80 and D50 for Hallaç Church over 1/1 Octave Bands.

optimum range except for 125 Hz where the value is much lower than −2 dB. For a speech-oriented hall, positive values of clarity are desirable as they result in crisp acoustics (Templeton 1998). Hallaç Main Hall has positive C80 values after 500 Hz, which is an important spectrum range for speech intelligibility. The values of D50 should be less than 0.25 for music purposes; however, they should be higher than 0.15 for speech activities (Templeton 1998). According to the D50 values, Hallaç Main Hall is proper for speech-related functions, but not for musical performances. This goes in accordance to the speech-related function of the hall as opposed to a liturgically significant space such as a church.

Figures 16 and 17 show C80 and D50 results for the two halls at Açıksaray. For C80, both the graphs indicate the least deviations from the mean value at the mid-range frequencies. The deviations for D50 are more irregular over the whole frequency spectrum. The results show a C80 of around 3.5 dB and a D50 of 0.5 for Açıksaray Cruciform Hall. A C80 of 4 dB and a D50 of more than 0.5 are observed for Açıksaray Main Hall. Therefore, the halls at Açıksaray do not have the −2 dB to +2 dB range for clarity but are suitable for speech-oriented activities as D50 values are higher than 0.15 for the whole frequency spectrum.

Avanos has comparatively much larger values for both C80 and D50 than the other spaces (Figure 18). The results show that the dining hall in Avanos has a C80 of approximately +9 dB and a D50 of 0.7. Considering the small volume of the dining hall, the high value of C80 does not make it a suitable space for music. In addition, the D50 values indicate good

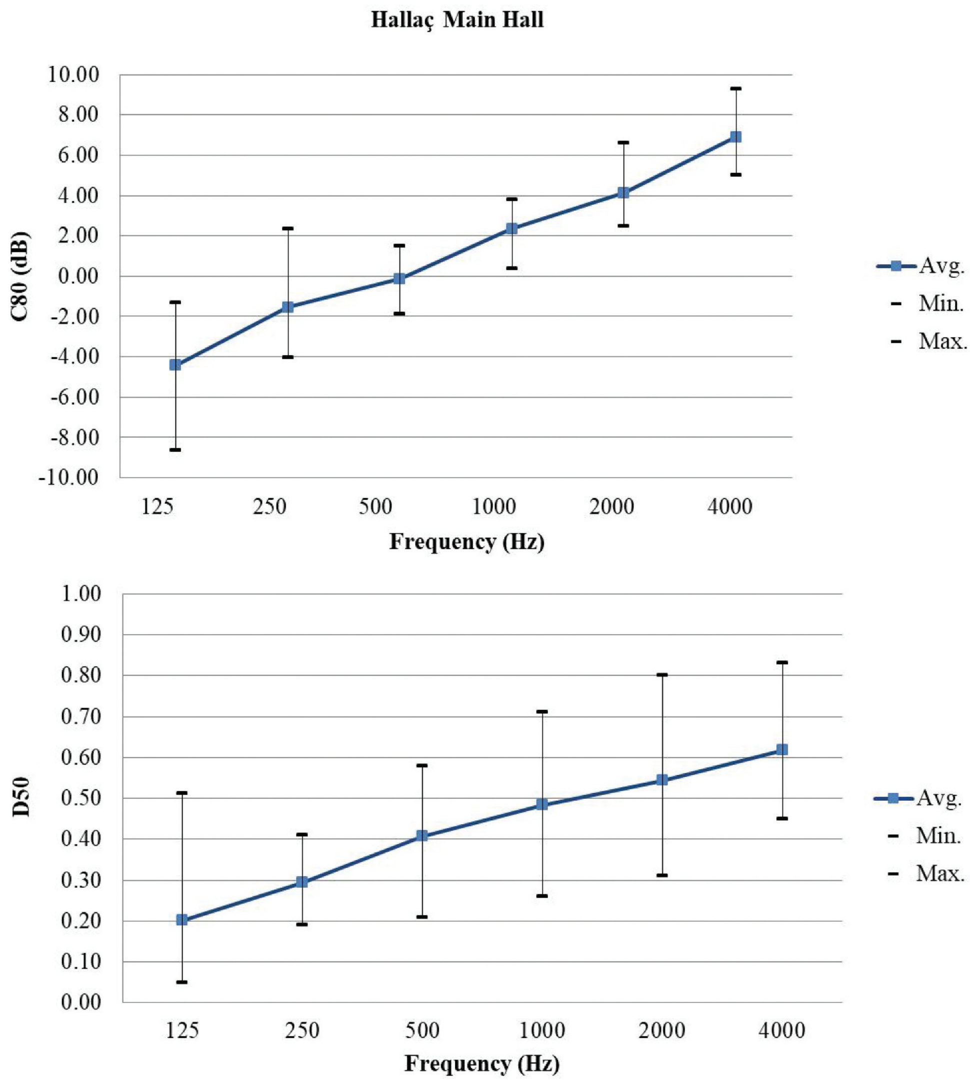

Figure 15. Maximum, minimum and average values for C80 and D50 for Hallaç Main Hall over 1/1 Octave Bands.

speech intelligibility. The large difference in the C80 and D50 values of the dining hall, as compared to the other spaces, is due to its smaller volume, where surfaces are much closer to the receiver positions; therefore, the early reflected energy is greater.

The largest deviations in C80 and D50 values from the mean value are seen at low frequencies. The deviations from the average values are due to the fact that these parameters are dependent on the receiver positions in a space. When analyzing the acoustics of Apulian-Romanesque churches, it was concluded that both C80 and D50 were related to source-receiver distance because of the attenuation of direct sound and the early reflections. The individual values obtained for C80 and D50 at different locations have been correlated to different architectural features such as the volume of the space, its surface area, and RT (Cirillo and Martellotta 2003). Among all acoustic parameters observed in churches, C80 shows the highest variation as a function of source-receiver distance (Cirillo and Martellotta 2007).

The largest deviation in C80 is seen at low frequencies in the Avanos Dining Hall (Figure 18), where the range between the maximum and minimum values is above 10 dB. In the Avanos Dining Hall, at 125 Hz, the highest C80 value is +6.56 dB while the lowest C80 value recorded is — 4.54 at the locations S_2R_5 and S_2R_3 respectively (Figure 6). As can be seen from Figures 3 and 6, R5 is on the second sub-volume coupled to the volume where the source is located. while R3 is within the same volume where sound source is and it is the closest receiver position to the source. The different

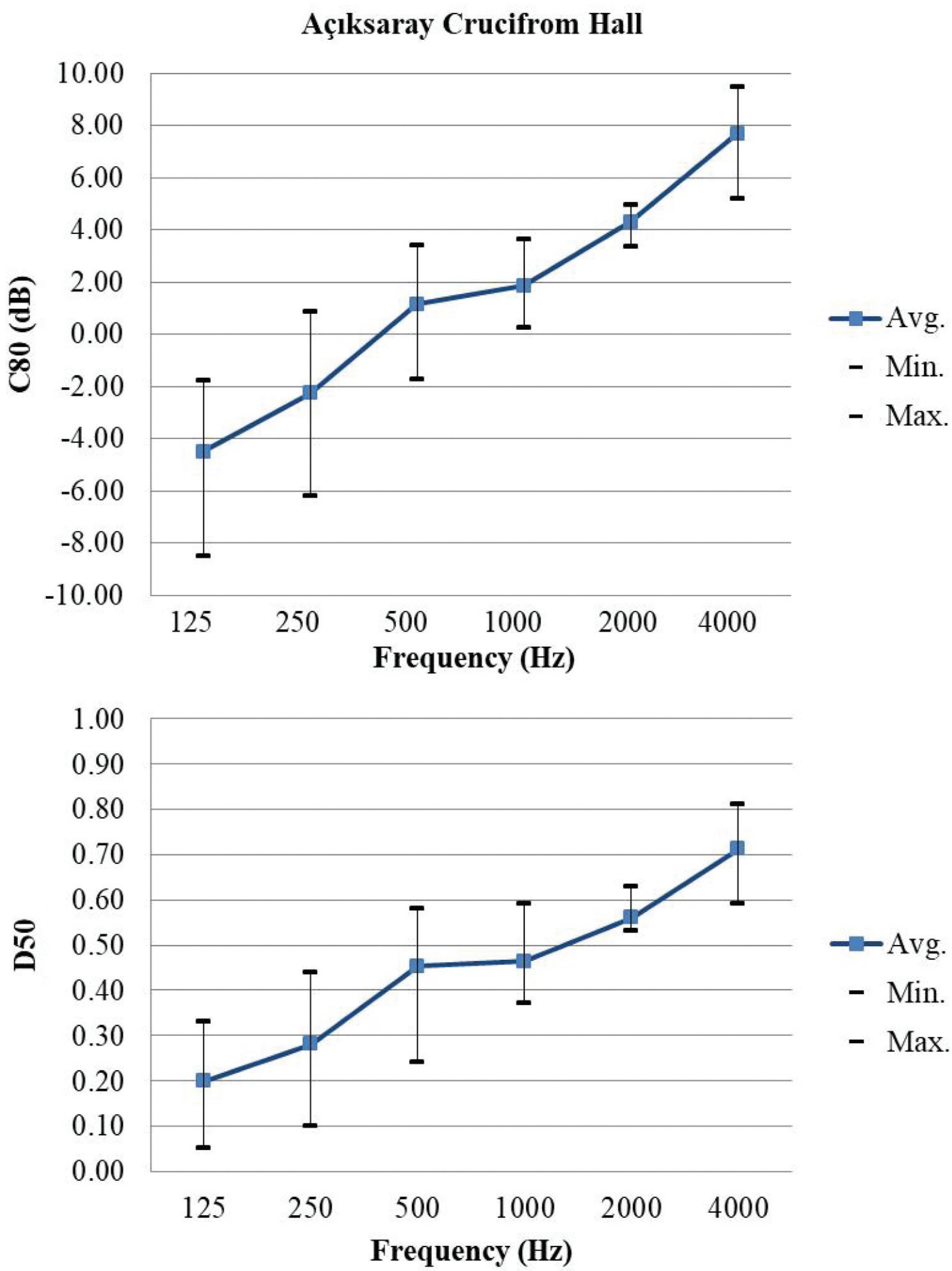

Figure 16. Maximum, minimum and average values for C80 and D50 for Açıksaray Cruciform Hall over 1/1 Octave Bands.

positions of the receivers in this rock-cut space, which is divided into different segments by arches, have a direct impact on energy ratios which is seen in the form of the large deviations in the results.

There is a similar deviation in the values of C80 at low frequencies in the Hallaç Church where the difference is around 10 dB (Figure 14). At 125 Hz, the highest value of C80 is — 1.78 dB with the S_2R_1 configuration. The lowest value of C80 recorded is — 8.69 at S_4R_5. As can be seen from Figure 4, the source and the receiver positions are both different for these extreme cases. When considering S_2R_1, both the source and the receiver are in the main space of the church while in the case of S_4R_5, the source is close to the altar and the receiver is placed behind the colonnade on the east. Due to the different sound-receiver positions and the presence of architectural elements such as colonnades, on the direct sound path for specific positions, the energy ratios in the space show different patterns and hence, there are larger deviations from the mean value.

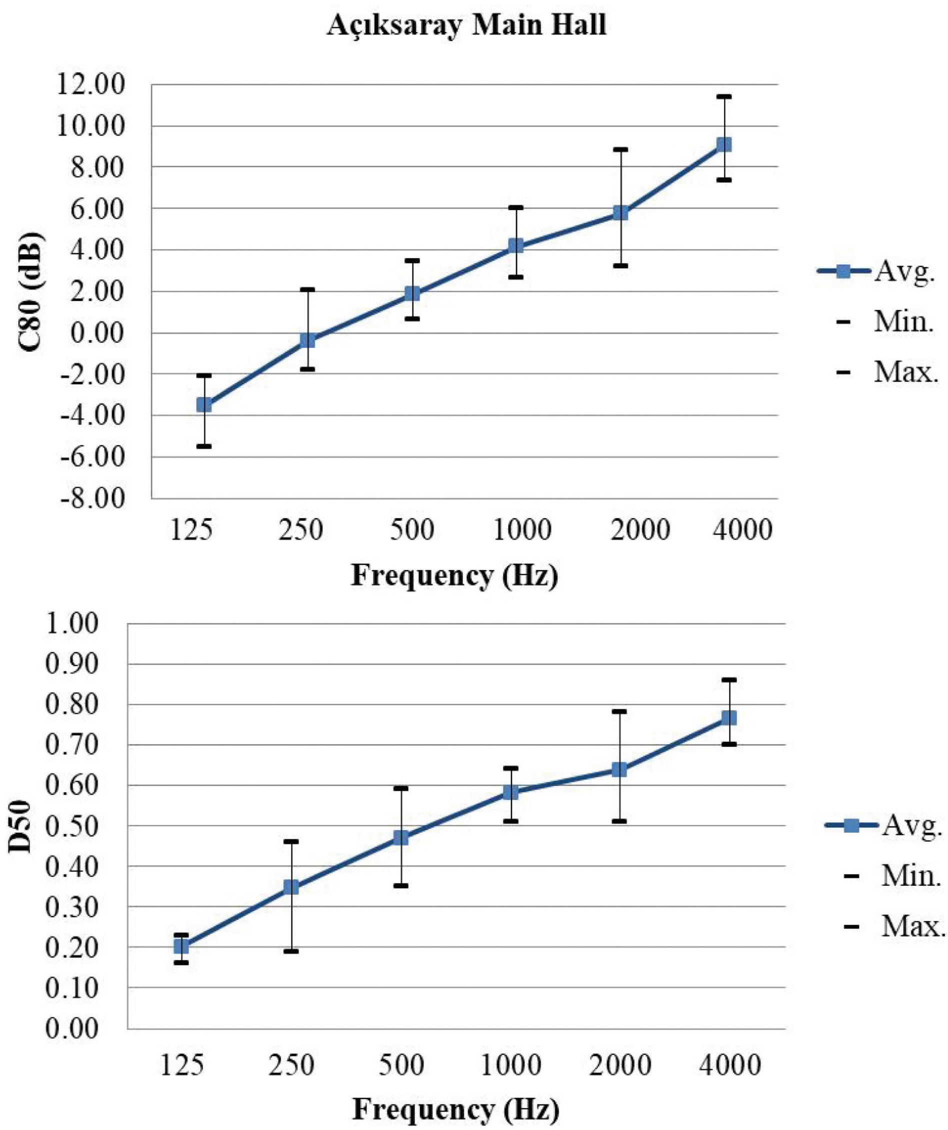

Figure 17. Maximum, minimum and average values for C80 and D50 for Açıksaray Main Hall over 1/1 Octave Bands.

Figure 19 shows the decay ratio plots of all the spaces over the frequency spectrum from 125 to 4k Hz. The comparison graph indicates that with decreasing volumes, the values of C80 and D50 keep getting higher for these rock-cut structures. This is similar to the trend seen in the C80 values of a number of Orthodox churches in Poland (Małecki, Wiciak, and Nowak 2017). There is a strong relationship between D50 and speech intelligibility; D50 values should be greater than 0.15 in order to satisfy speech-related activities (Templeton 1998). Considering this threshold, all the five spaces under study show values greater than 0.15. This signifies that the spaces are suitable for intelligibility of speech signals. The following section further discusses speech intelligibility.

4.4. Speech intelligibility results and comparisons of the rock-Cut structures of cappadocia

Speech intelligibility can also be assessed by means of the Speech Transmission Index (STI), which is a metric that denotes the quality of speech while considering the loss of speech articulation caused by reverberation (Steeneken and Houtgast 1980). Figure 20 shows both male and female STIs for all the spaces studied. The differences between the average male and female STI values are considerably small in every rock-cut structure. The lowest STI value is 0.57 (STI female, Hallaç Church), whereas the highest value is 0.77 (STI male, Avanos). STI values between 0.60 and 0.75 indicate good speech intelligibility, while any value higher than 0.75 is

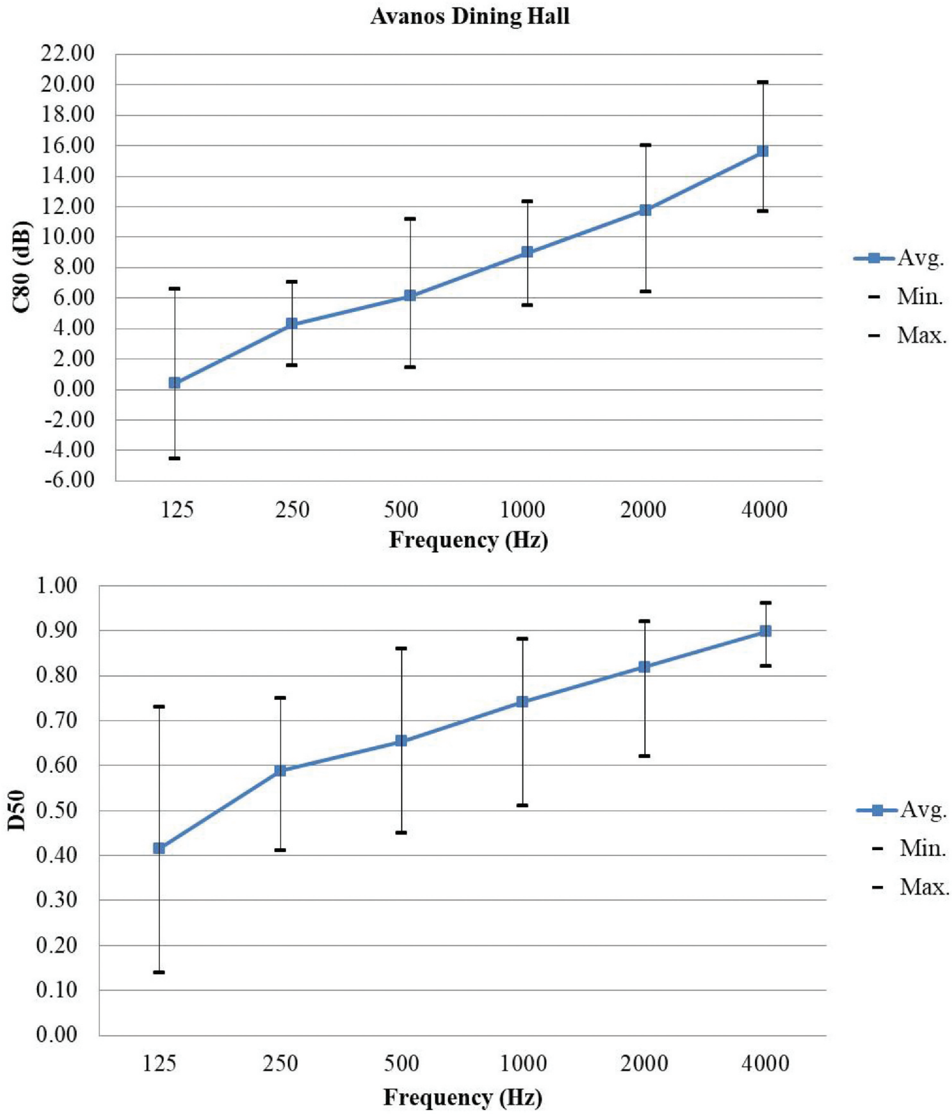

Figure 18. Maximum, minimum and average values for C80 and D50 for the dining hall in Avanos over 1/1 Octave Bands.

considered excellent (Beranek 1988). Therefore, the spaces under study are proper for speech intelligibility.

Good speech intelligibility is also supported by the values of D50 in Hallaç Main Hall, Açıksaray Cruciform Hall, Açıksaray Main Hall, and the Avanos Dining Hall. Although the reverberation times of the Hallaç Church are higher in comparison to the other spaces, the very low background noise levels in the vicinity helped for high STI levels. This also helps the church to acoustically benefit for a multi-function activity pattern; where both the sermons of the orator are intelligible and the high decay rates in low frequencies augment male voice supporting the spiritual soundscape of this religious space.

4.5. Acoustical review and the comparison of natural caves and man-made structures

This section is an overview of a few prominent studies that have been conducted in both natural caves and man-made structures in the literature together with the findings of this research. The purpose of the data accumulation is to comparatively exhibit the acoustic characteristics of all previously collected data. Previously studied caves or man-made rock-cut spaces originally belong to different eras and different regions, with differing interior volumes and various functions. As one acoustical parameter that is commonly discussed, in Table 1 EDT values for a number of natural caves from Italy and Spain are listed (Iannace and

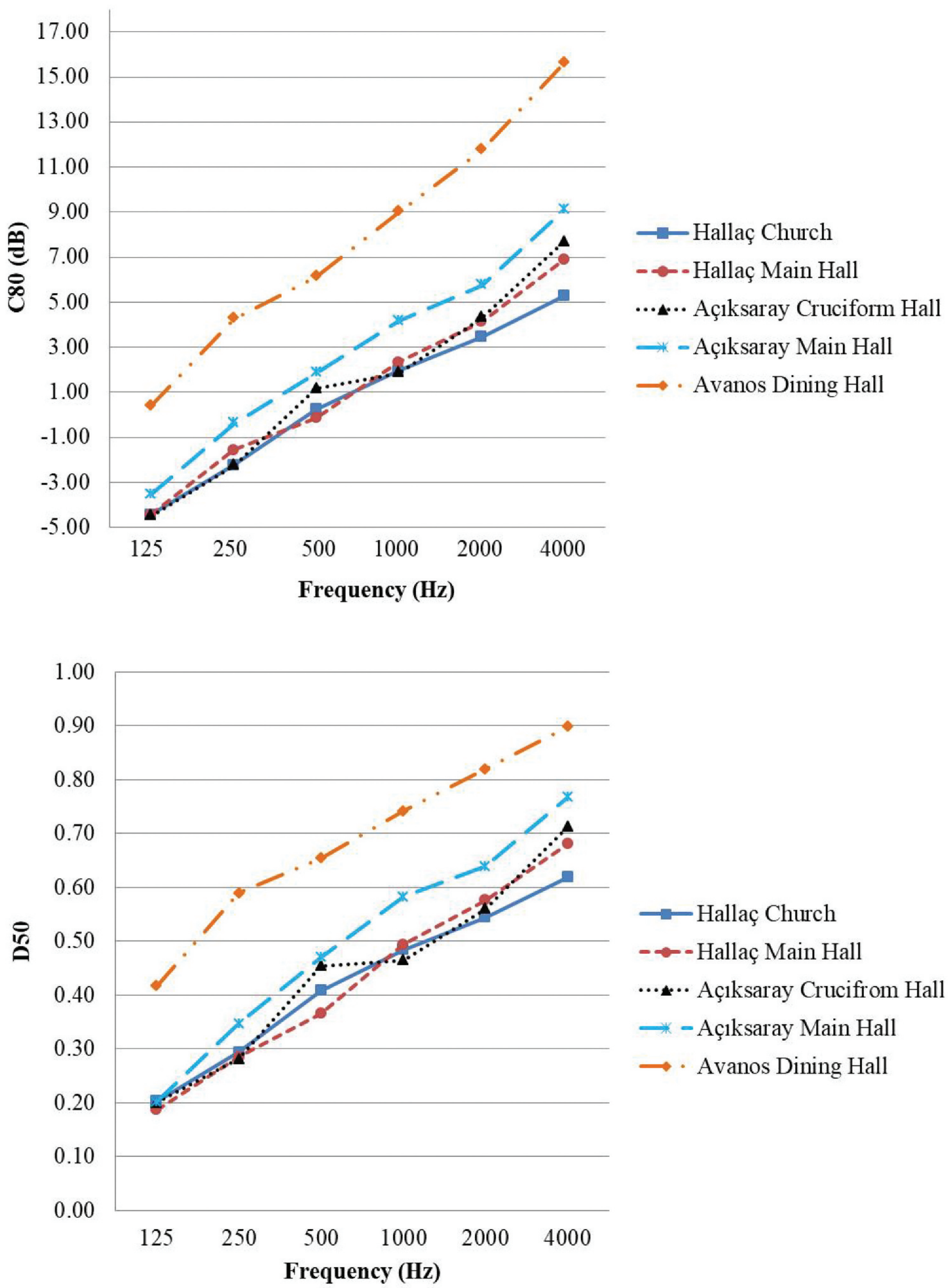

Figure 19. C80 and D50 for all five spaces over 1/1 Octave Bands.

Trematerra 2014; Till 2019). The volumes of these spaces (if provided) have also been included in the table to get a better grasp of the spaciousness of the caves, in comparison to the obtained decay rates and other metrics. When Table 1 is observed it can be stated that Grave Cave has the highest EDT of around 6 s; this could be because it is also the largest space with a volume of 30,000 m^3. Most of these caves are much larger in terms than the Cappadocian rock-cut structures of this study. Although Castle Hall (220 m^3) has the closest volume to those spaces in Cappadocia (especially Açıksaray Main Hall that has a volume of 217 m^3), its EDT of around 1.6 s is slightly higher than the EDT of Açıksaray Main Hall which is around 1.3 s. The interior surfaces of the natural Caves of Pertosa are more reflective than the rock-cut Cappadocian structures. Thus, this may mean that higher sound absorption performance of the volcanic tuff of Cappadocia has resulted in lower decay rates. Accordingly, it may be much more porous than the natural stone (karst) of the Caves of

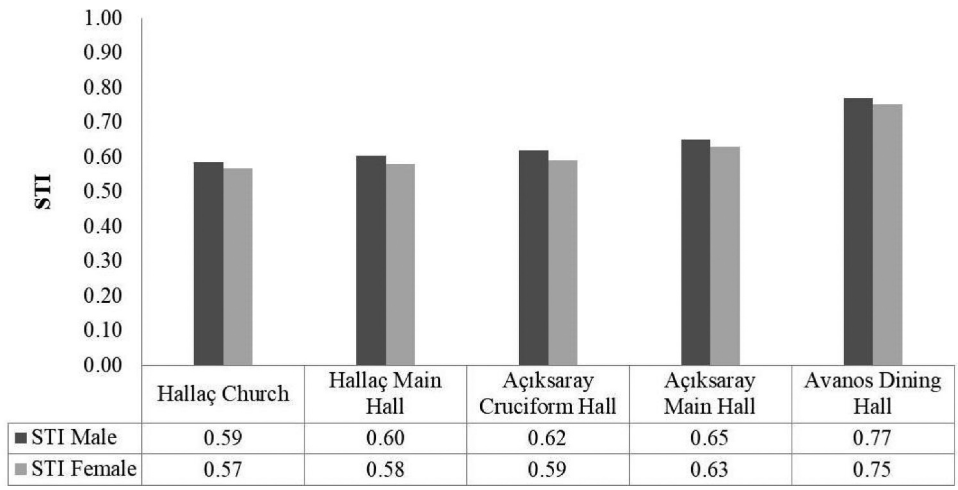

Figure 20. Male and female STIs for Hallaç, Açıksaray, and Avanos.

Table 1. EDT (s) values over 1/1 octave bands of different Paleolithic natural caves in Italy and Spain (based on the studies by Iannace and Trematerra 2014; Till 2019).

Region	Individual Space	125	250	500	1000	2000
Caves of Castelcivita (Till 2019)	Guano Hall (1,800 m^3)	3.46	1.99	1.85	1.73	1.29
	Castle Hall (2,750 m^3)	2.49	1.96	1.29	0.93	0.87
	Carbonic Acid Hall (2,000 m^3)	3.39	3.15	2.74	1.80	1.52
	Ballerina Hall (2,500 m^3)	3.39	3.15	2.74	1.80	1.52
	Cavern of Bertarelli (5,600 m^3)	3.26	2.89	2.30	2.27	1.74
Caves of Pertosa (Till 2019)	Large Hall (1,300 m^3)	3.85	5.46	4.57	3.83	3.29
	Castle Hall (220 m^3)	2.77	2.40	1.66	1.61	1.22
	Throne Hall (1,000 m^3)	5.71	3.89	3.69	3.18	2.58
Caves of Castellana (Till 2019)	Grave Cave (30,000 m^3)	8.60	6.20	6.60	5.62	4.56
	Cave of the Civetta, (1000 m^3)	2.98	2.02	2.13	1.59	1.70
	La Fonte (3,300 m^3)	2.19	2.17	2.25	2.00	1.79
Caves in Northern Spain (Iannace and Trematerra 2014)	Las Chimeneas	1.13	0.96	0.85	0.70	0.51
	El Castillo	1.33	1.20	1.28	1.15	1.12
	La Garma	1.20	0.68	0.65	0.56	0.42
	La Pasiega End	1.05	1.19	0.75	0.49	0.24
	La Pasiega Turret	1.92	1.62	1.58	1.40	1.16
	Tito Bustillo	2.24	1.11	1.36	1.35	1.46

Table 2. EDT (s) values over 1/1 octave bands of Roman catacombs of Italy and medieval rock-cut structures of Cappadocia (based on Ciaburro et al. 2020 and the data collected by the authors).

Region	Individual Space	125	250	500	1000	2000
Catacombs of San Callisto in Rome (Ciaburro et al. 2020)	Crypt of the Popes (81 m^3)	0.95	0.75	0.72	0.64	0.56
	Crypt of S. Cecilia (171 m^3)	0.88	0.96	0.96	0.91	0.79
Catacombs of San Gennaro in Naples (Ciaburro et al. 2020)	Lower Level (3,790 m^3)	1.80	1.58	1.20	0.90	0.72
	Upper Level (2,184 m^3)	2.12	1.72	1.23	0.91	0.65
Catacombs of Vigna Cassia in Syracuse (Ciaburro et al. 2020)	Cemetery of Marcia (4,394 m^3)	0.69	0.54	0.45	0.38	0.31
	Cubicle of the Well (2,494 m^3)	0.63	0.65	0.69	0.60	0.54
	Cubicle of Gennara & Ciriaco (1,985 m^3)	0.68	0.87	0.61	0.37	0.27
	Santa Maria del Gesù Cemetery (3,600 m^3)	1.30	1.05	0.72	0.49	0.35
Rock-cut Structures of Cappadocia	Hallaç Church (571 m^3)	4.72	3.45	2.40	1.71	1.25
	Hallaç Main Hall (322 m^3)	3.97	2.57	1.87	1.33	0.98
	Açıksaray Cruciform Hall (400 m^3)	4.64	3.28	1.94	1.37	0.93
	Açıksaray Main Hall (217 m^3)	3.10	2.18	1.60	1.04	0.78
	Avanos Dining Hall (114 m^3)	1.23	0.97	0.78	0.55	0.43

Pertosa. On the other hand, the Paleolithic caves of Northern Spain have EDT values in the range of 0.6 s to 1.5 s at mid-range frequencies. These values are generally closer to the EDT values of Cappadocian rock-cut structures.

Table 2 is a collection of acoustic measurements conducted in man-made structures including the rock-cut Cappadocian spaces and catacombs. These underground spaces are similar to the rock-cut spaces of Cappadocia as the two types of spaces are man-made

Table 3. Monaural acoustic parameters for Crypt of the Popes and Crypt of S. Cecilia over 1/1 octave bands (based on Ciaburro et al. 2020) and for Cappadocian rock-cut structures.

	STI	Freq. (Hz)	125	250	500	1000	2000
Crypt of the Popes (Ciaburro et al. 2020)	0.70	T30 (s)	0.90	0.80	0.73	0.68	0.60
		C80 (dB)	3.40	4.93	5.85	7.23	8.02
		D50	0.51	0.57	0.67	0.70	0.72
Crypt of S. Cecilia (Ciaburro et al. 2020)	0.70	T30 (s)	0.95	0.93	0.89	0.83	0.77
		C80 (dB)	4.42	4.19	3.56	3.51	4.83
		D50	0.55	0.55	0.49	0.51	0.58
Hallaç Church	0.58	T30 (s)	5.23	3.63	2.57	1.83	1.42
		C80 (dB)	−4.43	−2.22	0.24	1.96	3.46
		D50	0.20	0.29	0.41	0.48	0.54
Hallaç Main Hall	0.59	T30 (s)	5.01	3.02	1.94	1.43	1.05
		C80 (dB)	−4.42	−1.55	−0.14	2.35	4.14
		D50	0.19	0.29	0.37	0.49	0.58
Açıksaray Cruciform Hall	0.61	T30 (s)	5.40	3.42	2.10	1.46	1.01
		C80 (dB)	−4.48	−2.26	1.16	1.86	4.31
		D50	0.20	0.28	0.45	0.46	0.56
Açıksaray Main Hall	0.64	T30 (s)	3.56	2.30	1.58	1.12	0.81
		C80 (dB)	−3.53	−0.39	1.85	4.16	5.76
		D50	0.20	0.35	0.47	0.58	0.64
Avanos Dining Hall	0.76	T30 (s)	1.70	1.10	0.83	0.59	0.47
		C80 (dB)	0.40	4.28	6.13	9.01	11.77
		D50	0.42	0.59	0.65	0.74	0.82

(carved) (Ciaburro et al. 2020; Iannace, Trematerra, and Qandil 2014). In terms of volume, Crypt of the Popes (81 m^3) and Crypt of S. Cecilia (171 m^3) from the catacombs of San Callisto are similar to the rock-cut structures under study, specifically Açıksaray Main Hall (217 m^3) and Avanos Dining Hall (114 m^3). The EDT values for these spaces range from 0.5 s to 0.9 s at mid frequency range.

Due to the similarity in their volumes, other monaural parameters of Crypt of the Popes and Crypt of S. Cecilia can also be compared with the rock-cut structures of Cappadocia (Table 3). The T30 values for these catacombs are in the range of 0.65 s to 0.85 s. These values are lower than the T30 values of the Cappadocian structures which are usually higher than 1 s, except for the dining hall in Avanos. This means that the porous tuff that the catacombs are excavated in has a higher sound absorption performance than that of the Cappadocian tuff.

Energy ratios (C80 and D50) of Crypt of the Popes and Crypt of S. Cecilia are generally higher than the ratios observed in the rock-cut structures of Cappadocia. All C80 values are positive in these catacombs and within the range of acceptable values as discussed above. D50 values range from 0.5 to 0.7, which means that these spaces are good for speech intelligibility. This is further supported by a high STI value of 0.70 in both of the spaces. With lower reverberation times and high speech intelligibility parameters, these spaces are appropriate for religious activities involving a verbal performance by a single speaker (Ciaburro et al. 2020; Iannace, Trematerra, and Qandil 2014). Such acoustical data, except for all positive values of C80, are also observed in Cappadocian rock-cut structures, especially in Hallaç Church which is suitable for both speech and music as would be required for the liturgical practices at the church. The other halls at Cappadocia have D50 values of around 0.50, except for Avanos Dining Hall which has a higher average D50 of around 0.70. These halls also have STI levels of around 0.60, which indicate good speech intelligibility. Consequently, the residential halls in Cappadocia are similar to the two crypts of the Catacombs of San Callisto in terms of favoring speech-related activities.

5. Conclusion

In this study, with an aim of characterizing the indoor acoustical environment of rock-carved, religious and secular spaces of Cappadocia are studied in detail. In this regard, one church and four halls from three different regions of Cappadocia are chosen to study their acoustical environments in relation with their associated original uses. While the recent scholarship focuses on the settlement features and compounds of Cappadocia, it is important to document the indoor soundscape of these rock-cut structures in order to proceed further for a better understanding of their context.

In accordance with ISO 3382, in-situ field tests were performed; necessary modifications had to be made to the set-up mainly due to the lack of a power supply. Three main types of signals are used: balloon pops, ESS, and MLS. Comparing the peak noise to signal ratio (PSNR) values from the three signals, balloon pops proved to be the most efficient type of signal to excite the rock-cut spaces. Balloon pops are even better than the ESS signal used by an omni-directional sound source in Avanos. For this reason, as a methodological outcome, for rock-cut structures or caves in similar volumes, there is no need to set-up a full-scale measurement system including the speaker amplifier, and associated parts and cables. The use of balloon pops may make it more feasible and time saving to do research in many more such caves.

Decay rates (EDT, T20, T30), energy ratios (C80, D50), and intelligibility metric (STI) are obtained for each space. Due to their similar volumes and materiality, overall, the spaces have similar reverberation times, except for the Hallaç Church which is the most reverberant space with T30 values of around 2 s. The high BR (2.0) of the church signifies augmented male voice which is consistent with the liturgical practices of the space. With decreasing volumes, the reverberation times of the other halls keep getting shorter. Apart from the Hallaç Church, all other spaces are assumed to be used either for gatherings and celebrations such as weddings, funerals, and receiving guests (Rautman 2006).

The Hallaç Church has a C80 of around +2 dB which, as discussed before, is within the optimum range of liturgical music. With favorable D50 and STI values, the church is also appropriate for a verbal performance by a single speaker. The other four halls do not show equally optimum C80 values, which become higher than +5 dB, especially in the case of the dining hall in Avanos. On the other hand, these halls have better D50 and STI values, which mean that they are more favorable spaces for speech-related activities. Hence, these spaces are acoustically performing in accordance to the functions that they are known for.

In the last section of the paper, acoustical data of previous sources regarding both natural caves and man-made structures are summarized in order to draw parallel comparisons. Most of the natural caves that have been studied are much larger in volume than the Cappadocian rock-cut structures. For those with comparable volumes, the decay rates of natural caves are higher, indicating that they have a more reflective interior surface made of karst stone, than that of Cappadocia which is made of tuff. The Italian catacombs, on the other hand, are made of tuff as well but these spaces have comparatively lower reverberation times. Therefore, it can be deduced that the tuff from Rome is much sound absorptive than the tuff of Cappadocia.

To sum up, through data collection and analysis, this study gives an insight to the acoustic makeup of Byzantine rock-cut structures of Cappadocia, in relation to different possible authentic activity patterns. Furthermore, it provides a ground for discussion among limited number of studies on the acoustics of caves and man-made rock-cut spaces throughout the world. As a next step of this research on the sounds of Byzantine Cappadocia future work will include the virtual and aural reconstruction of remains, by the help of archival information and by in-depth investigation of the material properties of the Cappadocian tuff in support of the findings out of this research.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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