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Acoustical Footprint of the Traditional Turkish Baths in Historic Settings

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ABSTRACT
The Turkish bath structure (hamam) is one of the key typologies in Anatolian architecture. In addition to its main "bathing" function, Turkish baths are chosen as the main venue for social organizations in the Ottoman period, with eating and dancing accompanied by live music. Thus, the construction of baths, in various sizes, was prioritized then and still holds its place in the social and cultural life of Anatolia. This study investigates the authentic acoustical characteristics of Turkish baths, over four selected baths in Bursa, Turkey; Karamustafa (15th c.), Yeni Kaplıca (16th c.), Kaynarca (17th c.), and Tahirağa (19th c.). Room impulse responses are collected through acoustical field measurements. Acoustical simulations are utilized to experiment with the materials, which reflect the historical origins, as well as used to test the effects of different humidity levels on acoustical parameters. The objective parameter analysis includes EDT, T20, T30, C80, D50, and STI assessments. Relationships between objective parameters and geometrical attributes are investigated. Lower T30 and higher STI values are obtained with historical plaster in comparison to the up-to-date conditions. Controlled analysis in decreasing the relative humidity resulted in lower T20 and T30 values, consequently higher STI values. Obtained data are discussed considering the usage of male and female baths, traditional activities as well as the nature of the sound sources.

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architectural acoustics; cultural heritage; historical acoustics; Ottoman baths; Turkish baths

1. Introduction

Traditional Turkish baths (hamams) are distinctive structures built for collective and private bathing functions with a special heating system. These unique structures have an important place both in the social and architectural aspects of Anatolian culture. Since the Ottoman period, various activities, entertainments, and rituals have been taking place such as the first bath of newborns, bridal and groom baths, feast baths, etc. which all may contain food & beverage honoring, and live music with singing accompaniment (Şehitoğlu 2000). Sound is one significant intangible element of architecture, and the authentic acoustic environments of such historic heritage structures are the main focus of this study. The archeoacoustics studies in Anatolia until now have focused either on historically significant religious structures as of mosques (Sü Gül 2019; Sü Gül, Xiang, and Çalışkan 2016) and churches (Adeeb, Sü-Gül, and Henry 2021; Iannace et al. 2019; Sü Gül 2021), ancient theaters (Ciaburro et al. 2020), or secular roc-cut structures in Cappadocia (Adeeb and Sü Gül 2022). The acoustical footprints of Turkish Baths, which are significant pieces of the cultural heritage of Anatolian region have not yet well been deeply investigated.

Traditional Turkish bath typology initially developed during Seljukians. A resemblance in architectural planning and heating system was observed with the Roman baths striking in the early periods and diverged subsequently (Tuna 1987). During the Ottoman period, a great majority of bath constructions took place between 14^{th} and 15^{th} centuries (Uğurlu and Böke 2009). These buildings generally consist of three main sections; changing room (lat.apodyterium), warm room (lat.tepidarium), hot room (lat.caldarium), occasionally cold room (lat.frigidarium) and private rooms. Commonly, tepidariums and caldariums are large areas covered with single or multiple domes and/or vaults.

Hamam buildings diverge according to their location as; private (mansion/palace) hamams, bazaar hamams, and hot springs (*kaplıca*). Private hamams are personal baths of the wealthy, located within their mansions/palaces, whereas bazaar hamams are public buildings located in commercial centers. Hot springs and bazaars are almost identical except for the heating system; one uses the hypocaust system, while the other uses the natural temperature of the water (Eravşar 2009; Tuna 1987). According to the registry, more than 50 baths have been constructed in Bursa, the first capital of the Ottoman Empire, since the 14^{th} century. Today, 39 among them have been identified, all or partially

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standing. Most of the examples have been destroyed or re-used as bazaars, restaurants cultural centers, etc. (Şehitoğlu 2000). Bursa is the hometown of *hamam* structures of Anatolia, and for this reason, the case buildings of this study are selected in this region.

Recent studies on Ottoman baths mainly focus on materials and construction techniques. Brick-lime (horasan) plasters are the most frequent interior finish material of the Ottoman period, especially in bath buildings. Physical, chemical, and microstructural properties and firing temperatures of brick-lime plaster samples collected from various Ottoman baths, dated 15th century, are previously investigated (Uğurlu and Böke 2009; Uğurlu Sağın and Böke 2013). Studies proved that the material is porous, low in density, and highly durable in humid, moist, and hot environments, which is the nature of the baths. A similar study discusses horasan plaster samples obtained from a 16th century Ottoman bath (İpekci, Uğurlu Sağın, and Böke 2019). A double layer of horasan plaster was found on the wall surfaces below 1.50, whereas surfaces above 1.50 consist of a single layer of horasan plaster and a layer of fine lime plaster. Both lower and upper-level horasan plasters show similar physical and chemical properties, compatible with previous findings.

In another study, physical, chemical, and mechanical properties are analyzed over samples collected from a partially collapsed Ottoman bath dated 14th century (Bağbancı, Özcan, and Köprülü Bağbancı 2013). This study investigates the possible relationship between construction techniques and materials with deterioration. The results indicate the durability of brick-lime mortars. Construction techniques of Ottoman dome structures are investigated in relation to span, height, and thickness in another study (Reyhan, İpekoğlu, and Böke 2013).

Angelini et al. (2019) and Asscher et al. (2019) conducted multidisciplinary studies on Sarno Baths, which is an apartment complex with public bathing levels, in Pompeii. Pigments of painted walls of the *fridgidarium* of Sarno Baths are measured with archeometric analysis for gathering information on Roman painting and pigmenting techniques. Additional studies investigate the consolidation and preservation techniques of historical baths (Durmuşlar et al. 2020) and seismic responses of structural materials (Ruggieri, Galassi, and Tempesta 2018).

There is rather limited literature available on the acoustical characteristics of historical baths. The contribution of the sound absorption capacity of historical brick-lime plasters (*horasan*) to Ottoman baths are previously investigated through laboratory analyses (Aydin, Tavukcuoglu, and Caliskan 2008). Sound absorption coefficients of original horasan plaster samples collected from a historical bath are measured under wet, damp, and dry conditions. Obtained values are used in simulations in which the original and current situation scenarios are investigated. Compared to the original condition of simulated baths, EDT and RT values of the current uses (due to the modifications in the plaster) are found higher, whereas STI and C80 values are lower.

The HAMMAM consortium carried out between 2005 and 2008 as a European Commission project (Hammam, Aspects, and Multidisciplinary Methods of Analysis for the Mediterranean Region) conducted research under the scope of ecology, economy, sociocultural, built environment, and management for a sustainable-oriented bath approach in six different countries (HAMMAM 2005–2008). The project investigates acoustical and thermal performances through field measurements and computer simulations of five selected baths in Egypt, Algeria, and Turkey. Ambient sound level, sound level distribution, and reverberation time are measured parameters within historical baths and simulations are carried out to improve current acoustic properties (Mahdavi et al. 2008; Orehounig and Mahdavi 2011).

The common argument of these substantial studies from different approaches is that more elaborative studies are needed in order to fully understand the authentic acoustical features of traditional bath typology. Historical structures, such as Turkish baths, hold the essential information regarding material and construction techniques of their period, therefore they are worthy of archive studies in every aspect. However, wetness, high temperatures, and humidity of bath structures are thought to be the main limitations of prior researchers, to conduct field measurements, and also the biggest challenge faced through this study. In addition, devices affected by humidity and high temperature levels have to be calibrated frequently and repeated measurements need to be taken to confirm the accuracy of the results. Accordingly, another challenge is to conduct these repeated measurements late at night, out of hours.

This study aims to comprehensively investigate the unique acoustical properties of traditional Turkish baths for the first time by acoustical field tests. The recording and archiving the acoustical characteristics of baths in their current versus original state is significant for conservation and preservation purposes of historic structures and as well for architectural history studies. In addition, by analyzing today's repair conditions, this study provides a framework for a conscious approach of material selection for future repairs and consolidations. With this aim, a group of *hamam* complexes is selected for detailed investigations from the area of Bursa Bazaar and Khans Area, Sultan Complexes and Cumalıkızık which are in the UNESCO World Cultural Heritage List (2014). undefined Bazaar and Khans area is still the main socio-cultural center of the city. The selected *hamam* complexes namely, Yeni Kaplıca (YK), Kara Mustafa Bath (KM), Kaynarca Bath (KY), and Tahirağa Bath (TA) are studied through field measurements and acoustical simulations in this research. In the first step, field measurements are conducted in order to record and analyze the existing indoor acoustical characteristics of selected bath structures. Obtained field measurement results are used as a base to tune the acoustical models, which are later on used to simulate the original conditions of the current structures. In the follow-up stages, acoustical models of bath structures are developed to run a series of simulations. Room acoustics simulations are conducted to examine the unique properties of *hamam* structures, by replacing current plasters with the information gathered from the literature on the sound absorption coefficients of original *horasan* plasters. Simulations are also used to investigate the humidity effects on acoustical parameters as in their in-use conditions.

This paper is structured as follows. Section 2 sets out the historical and architectural features of selected hamam complexes. Section 3 gives details of the methodologies used for collecting and analyzing the data, including field tests and computer simulations. In Section 4, the results are presented and discussed in detail and Section 5 concludes the paper by emphasizing major findings.

2. Materials

In the scope of this study, four different hamam complexes are selected from the 15th to 19th century, located in Bursa, which is the ex-capital city of Ottoman Empire with the fame of its numerous beautiful *hamam* structures. In this section, analyzed hamam complexes (Figure 1) are introduced in terms of their historical, geographical, and architectural aspects.

Figure 1. Location maps of baths; Osmangazi District (left), Mudanya District (right). 1: Yeni Kaplıca, 2: Karamustafa Bath 3: Kaynarca Bath, 4: Tahirağa Bath.

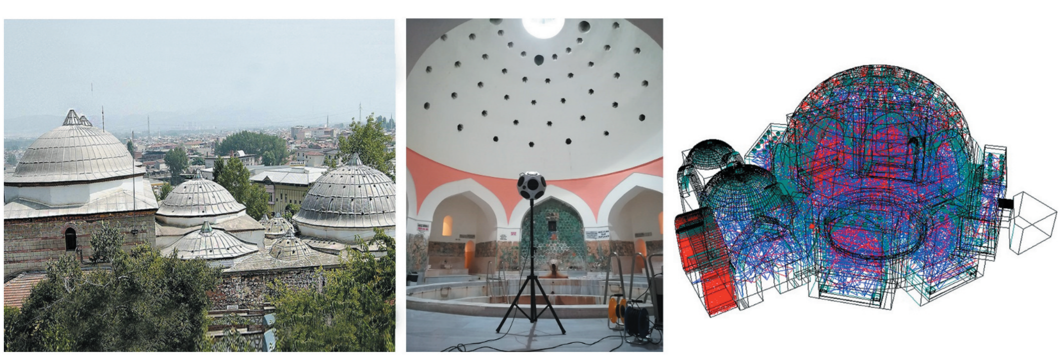

Figure 2. Yeni Kaplıca, exterior view (left), interior view (middle) measurement set-up, ray tracing model of caldarium (right).

Figure 3. Karamustafa Bath, exterior view (left), interior view (middle) measurement set-up, bridal bath decorations (right).

2.1. Yeni Kaplıca (16th century)

Yeni Kaplıca (YK) is located in Osmangazi district, Bursa, adjacent to Kara Mustafa and Kaynarca Baths. It was built by the order of Rüstem Pasha, the grand vizier of Suleiman the Magnificent, in 1552. It is still being used as a men's bath. This structure is a competent example of the traditional Ottoman bath architecture, consisting of a dressing room, cold room, hot room, and private rooms (Figures 1, 2). The dressing room is 23 m × 11 m, covered with two large domes with a diameter of approximately 12 m, separated from each other by arches. The warm room is 19 m × 9 m, covered with a single dome (Ø 9 m) at the center and two semi-domes on the sides. The hot room (~178 m^2) is in the form of an octagonal star and is covered with a single majestic dome (Ø 11 m). The *iwans* on each side of the octagon unite with the pool area in the middle with an arch. A snapdragon (water fountain feeds the pool) is located in one of the *iwans*. Wall surfaces are covered with hand-painted glazed tiles up to 2 m high, and are preserved as they were originally built (Şehitoğlu 2000, Asscher et al. (2019); "Bursa Khans Area" (2013–18); 1983.

2.2. Kara Mustafa Bath (Akça Bath) (15th century)

The exact construction year is uncertain; it is estimated that Akça Bath is from the Byzantine period. It was rebuilt by Kara Mustafa Pasha, the son-in-law of Bayezid the Second, in 1490 and renamed the Karamustafa Bath (KM). Today, it is still being used as a double bath (çifte hamam), by women and men on different days, and as a health center with hotel functions (Figures 1, 3). The dressing room (~118 m^2) was added to the building later. The warm room in the men's section is 6.5 m × 3.5 m, covered with a diameter of approximately 3 m. The hot room (~73 m^2) contains a hot pool covered with a vault (Şehitoğlu 2000; "Bursa Khans Area" 2013–18; 1983).

2.3. Kaynarca Bath (17th century)

The Kaynarca bath (KY) was constructed around the 1690s. Today, exclusive to women; Kaynarca bath is being used as a bathing and sports facility with hospitality units (Figures 1, 4). The warm room consists of two sections. The larger section (~30 m^2) is covered with a dome (Ø3 m) and a vault. Second warm room (19,6 m^2) is a smaller image of this section. The hot room (~38 m^2) is covered with two semi domes (Ø3,3 m). A snapdragon and a pool are located under one of the domes. A dressing room is added to the main building during repairs in 1802 (Şehitoğlu 2000; "Bursa Khans Area" 2013–18; 1983) .

2.4. Tahirağa Bath (19th century)

The Tahirağa Bath (TA), also known as Nur Bath/Aşağı Bath, is located in the Mudanya district, Bursa. The bath consists of both men's and women's sections (double bath) (Müderrisoğlu 2018). Nowadays, only the women's section maintains its original function (Figure 1, Figure 5, Figure 4). The dressing room of this section has a square ground plan (~60 m^2) and is covered with a flat ceiling. The rectangular-planned warm room is (~18 m^2) covered with two semi domes (Ø 2,9 m). A square-planned hot room (~45 m^2) is covered with a pendentive dome (Ø 6,6 m). The men's section has a similar plan. It was transformed into a cultural center after the repairs in 2016 (1983).

3. Methods

Acoustical field tests and ray tracing simulations are the two main tools for data collection in this study. Field tests are carried out within four historical baths from different periods in Bursa Turkey, which are still in use. Later, field-test tuned acoustical models are utilized for acoustical simulations for further experimentation.

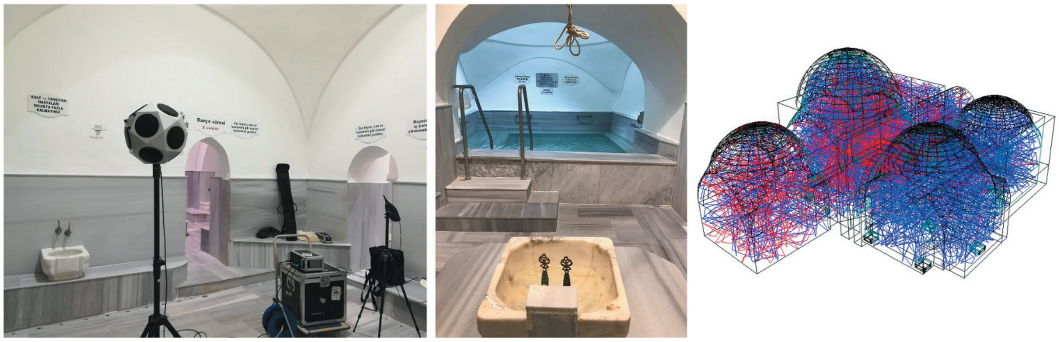

Figure 4. Kaynarca Bath, interior view measurement set-up (left), caldarium part (middle), ray tracing model of caldarium (right).

Figure 5. Tahirağa Bath, exterior view (left), interior view measurement set-up (middle), ray tracing model of caldarium.

Acoustical models are tuned to be compatible with the field measurements and materials in use. The simulations aim to acoustically construct the spaces in their in-use humidity levels as realistically as possible. The room responses in selected domed structures are investigated under different relative humidity levels. In addition, the effects of different plasters applied throughout the lifespan of traditional Turkish baths is also examined to further discuss the effects of alterations through contemporary repairs in comparison to the original acoustical conditions of the baths.

3.1. Acoustical field tests

Field measurements of unoccupied baths were carried out right after the end of working hours (21:30–02:00) on October 29–30, 2020, to ensure minimum background noise conditions. The test procedure and equipment are in accordance with ISO 3382–2:2008. A standard dodecahedron (cluster of 12 loudspeakers) omni-directional sound source (A Brüuel & Kjær type 4292-L) was used for acoustic excitation with a B&K (type 2734-A) power amplifier. This omni-directional sound radiates sound evenly with a spherical distribution. The room impulse responses at various measurement points were collected by a B&K Type 2250 single-channel hand-held instrument with a mounted microphone (Type 4190ZC–0032). The sampling frequency of the recorded multi-spectrum impulse is 48 kHz, covering the interval of interest between 100 Hz and 8 KHz. The impulse response length is kept at 10 s. The height of the omni-directional sound source is 1.5 m off the floor. The height of the microphone is 1.2 m fixed with B&K (Type UA 0801) holder tripod. The B&K DIRAC Room Acoustics Software type 7841 v.6.0.64701 is used to generate exponential sine sweep (ESS) and maximum length sequence (MLS) noise signals and is used for post-processing (Figure 6). DIRAC enables the recording of room impulse responses (RIR) and post-processing (RIRs), to estimate ISO standard acoustical parameters such as EDT, T20, T30, D50, C80, and STI.

Overall, different source-receiver positions in caldarium and tepidarium sections are used to get an average acoustic response to characterize the acoustical conditions of baths separately. According to the measurement standard, a minimum of two source and receiver positions are required. Consequently, measurements are carried out in; 4 source-8 receiver positions in YK, 4 source-8 receiver positions in KM, 3 source-6 receiver positions in KY, and 4 source-6 receiver positions in TA (Figure 7). In addition, background noise levels (LAeq), temperature, and humidity values are recorded within

Figure 6. Measurement setup of the Karamustafa Bath.

the spaces during the measurements (Table 1). Before the measurements, the baths are emptied and ventilated for half an hour to prevent excessive humidity and heat from damaging the equipment.

The hot pool in the caldarium section of YK was empty and out of use during the measurements, whereas the hot pool in KY was full and continuously running water through the measurements. In the caldarium section of KM, a ventilation fan was running and contributed to the background noise. No additional sound sources were observed during field measurements.

3.2. Room acoustics simulations

Simplified 3D acoustical models of caldariums are developed from measurements taken from the site. Additional drawings are obtained from Gabriel (1958) and the building survey registry (1983). The estimated acoustical volume of the caldarium of YK, KM, KY, and TA is 2,600 m^3, 335 m^3, 365 m^3, and 725 m^3, respectively. Simulations are carried out with ODEON Room Acoustics Software v16.07. The calculation method of the software relies on a hybrid process combining image source and ray tracing methods. It is a reliable method for acoustical analysis as it is widely used for almost 50 years, applied for estimating both early and late part of sound energy decay (Adeeb and Sü Gül 2022; Ciaburro et al. 2020; Iannace et al. 2019; Naylor 1993; Sü Gül 2019).

There are various room acoustic simulation and modeling techniques, which can be grouped under wave-based and geometric acoustics simulations (Savioja and Xiang 2020). Wave-based techniques are computationally not efficient for mid to high frequencies and especially challenging for simulating real-case structures. Geometrical acoustics (GA) simulations assume the sound waves as rays, neglecting mostly wave-based phenomena, so less accurate but computationally much more efficient and plausible to be used in both research and practice. In recent years, scale models as well have started to be replaced by geometric acoustics software, which is constantly under development. In this context, hybrid models including image source and ray-tracing have been applied most frequently both in theoretical research and in practice. GA models are capable of estimating variations within the sound field due to different source and receiver configurations. In order to obtain realistic results from ray-tracing, absorption coefficient values of interior finishing materials should be well defined into a virtual model. Detailed information on simulation setup is presented in Table 2.

Acoustical models are calibrated by assigning the sound absorption coefficient values for each surface. Afterward, source and receiver locations are placed within the model. As a next step, T30 values are tuned in accordance with the field test parameter results, in order to create the simulated acoustical environments as similar to the measured environments as possible. The calibration process continued until calculated and measured T30 values proximately match in 1/1 octave band frequency (125 Hz-4000 Hz). In the model tuning process, just noticeable differences (JND) for T30 values are kept under 5%.

Interior finish materials in all four caldaria are similar; marble floors, marble wall cladding, plastered walls,

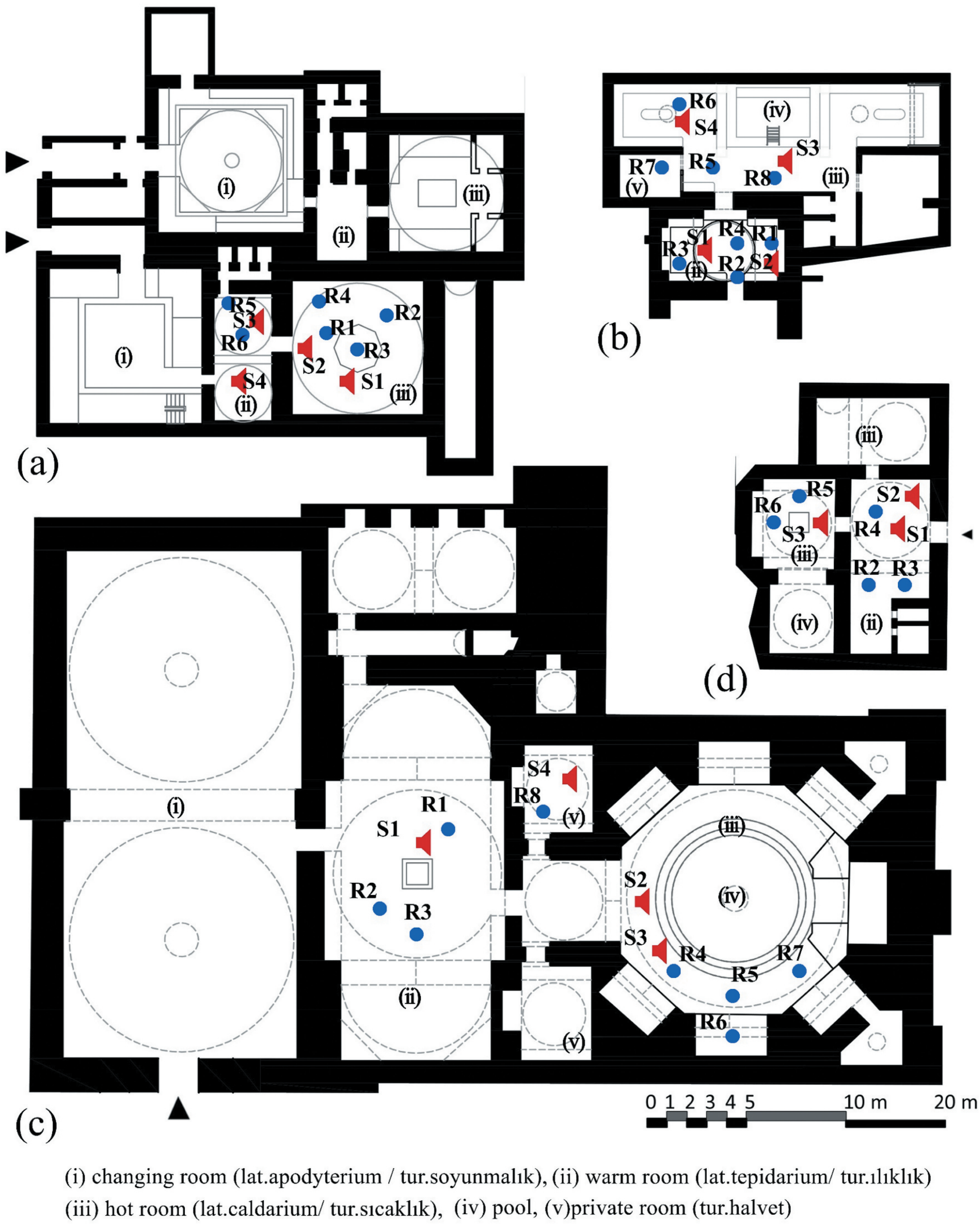

Figure 7. Source (blue, •) and receiver (red, 🔈) positions of measurement points (a= TA, b=KM, c=YK, d=KY) (drawn by the authors based on ; 1983; Gabriel 1958).

dome and arches, and glazed skylights (elephant eyes) (Table 3). Sound absorption coefficients of marble and glass materials are generic and almost identical values can be obtained from the literature. Plastered brick covers the largest surface area within the caldaria, as it is used in dome and wall surfaces. During the interviews with the operators, it was recorded that, recently, repairs to the baths are made every few years with cement plasters. The sound absorption coefficients of plastered brick surfaces, may vary greatly according to the plaster composition and the size and density of aggregate particles. After the tuning process, the sound absorption coefficients over octave bands are noted separately for all four spaces (Table 3). The average sound absorption

Table 1. Background noise levels, relative humidity, and average temperature during field tests.

Measured rooms	Temperature (°C)	Relative humidity (%)	Background noise level (LAeq)
YK (caldarium)	29°C	80%	47 dBA
YK (tepidarium)	24°C	60%	46 dBA
KM (caldarium)	25,7°C	49%	46 dBA
KM (tepidarium)	24,7°C	47%	44 dBA
KY (caldarium)	26°C	54%	69 dBA
KY (tepidarium)	25,8°C	50%	60 dBA
TA (caldarium)	31°C	52%	40 dBA
TA (tepidarium)	32°C	43%	38 dBA

coefficients of tuned plasters for low and mid frequencies, respectively, are estimated around 0.05 and 0.02 for YK, 0.12 and 0.06 for KM, 0.04 and 0.02 for KY, and 0.03 and 0.03 for TA (Table 3).

It is known from the literature that during the Ottoman period, brick-lime (horasan) plaster was used as an interior finish to protect the structure from humidity (Aydin, Tavukcuoglu, and Caliskan 2008; Uğurlu and Böke 2009; İpekci, Uğurlu Sağın, and Böke 2019). Therefore, previously measured (Aydin, Tavukcuoglu, and Caliskan 2008) absorption coefficients of horasan plaster (HP) are defined in simulations under 85% relative humidity setup

Subsequently, the effects of different microclimate conditions on room acoustic parameters are investigated with a series of simulations on tuned models. 5%, 15%, 30%, 50% 80%, and 95% relative humidity conditions are simulated while room temperatures are kept as is in-situ. Applied sound absorption and scattering coefficients are given in Table 3.

4. Results and discussion

Within the scope of this study, field measurements are carried out within four bath buildings from different periods. Simplified 3D acoustical models of caldarium sections are developed and tuned according to the measurement results. Acoustical analyses are held under three different scenarios investigating current condition, historical situation (reflecting historical plaster finishes) and the effects of different relative humidity levels. Obtained in-situ measurement results and acoustical simulation results are presented in this section.

Two different types of signals are used during measurements (ESS and MLS) to gain a signal with a peak signal-to-noise ratio (PSNR) of 45–50 dB higher than the background noise in all octave bands for reliable analysis of sound energy decay curves (Sü Gül 2019). The highest PSNR values are provided with ESS signals in all four locations; hence these samples are utilized in post-processing of RIRs (Figure 8).

4.1. *In-situ measurement results*

Reverberation time (T20, T30), early decay time (EDT), clarity (C80), definition (D50), and speech transmission index (STI) parameters are analyzed over collected room impulse responses. RT can be briefly explained as the required time for the decay of sound energy by 60 dB (to one millionth of its original value). The four caldaria have significantly different volumes, so RT is expected to vary. Average T30 and EDT values for all

Table 2. Detailed information on acoustical models and ray tracing simulations of caldarium sections.

ODEON Room Acoustics Software, v. 16.07	Yeni Kaplıca (YK)	Karamustafa Bath (KM)	Kaynarca Bath (KY)	Tahirağa Bath (TA)
Number of late rays (calculated by the software for "*survey*" selection)	13269	15499	7838	12478
Impulse Response Length (ms)	15000 ms	6000 ms	15000 ms	6000 ms
Max. reflection order	10000	10000	10000	10000
Impulse Response Resolution	0.3 ms	0.3 ms	0.3 ms	0.3 ms
Transition Order	2	2	2	2
Number of surfaces in the room	19253	11611	8244	16307
Mean free paths (m)	4.70 m	2.17 m	2.38 m	3.75 m
Acoustical volumes	2,600 m^3	335 m^3	365 m^3	725 m^3

Table 3. Sound absorption and scattering coefficient of materials.

	Frequency (Hz)						
Material	125 Hz	250 Hz	500 Hz	1 KHz	2 KHz	4 KHz	Scattering Coefficient
Marble	0,02	0,02	0,03	0,04	0,05	0,05	0.05/0.15*
Ordinary window, single glazing (elephant eyes)	0,35	0,25	0,18	0,12	0,07	0,04	0.10
Pool water surface	0.01	0.01	0.01	0.02	0.02	0.03	0.05
Plaster, tuned, YK	0.06	0.04	0.03	0.02	0.03	0.04	0.10
Plaster, tuned, KM	0.12	0.12	0.07	0.04	0.04	0.03	0.10
Plaster, tuned, KY	0.05	0.03	0.03	0.02	0.03	0.03	0.10
Plaster, tuned, TA	0.03	0.03	0.03	0.02	0.02	0.02	0.10
Plaster, measured, HP (Aydin, Tavukcuoglu, and Caliskan 2008)	0.12	0.18	0.15	0.27	0.34	0.34	0.01

Note: *Hand-painted tiles.

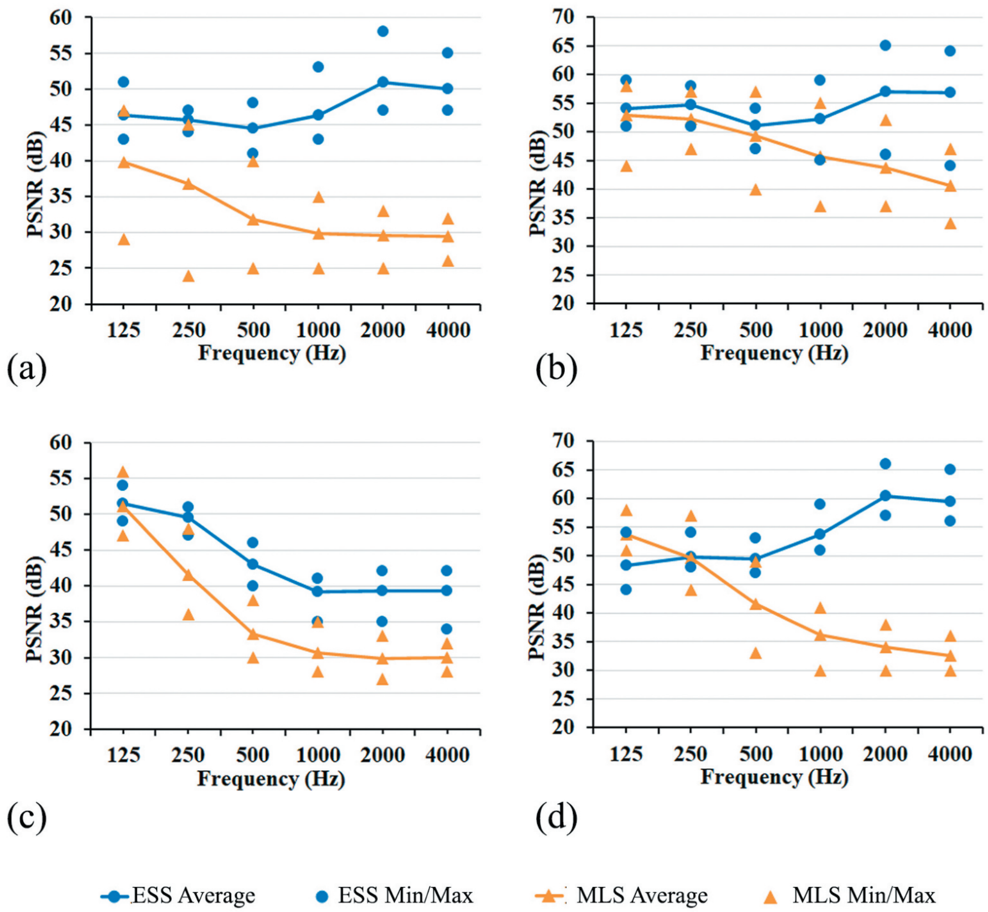

Figure 8. Comparison of INR over 1/1 octave bands in Hz (a:YK, b:KM, c:KY, d:TA).

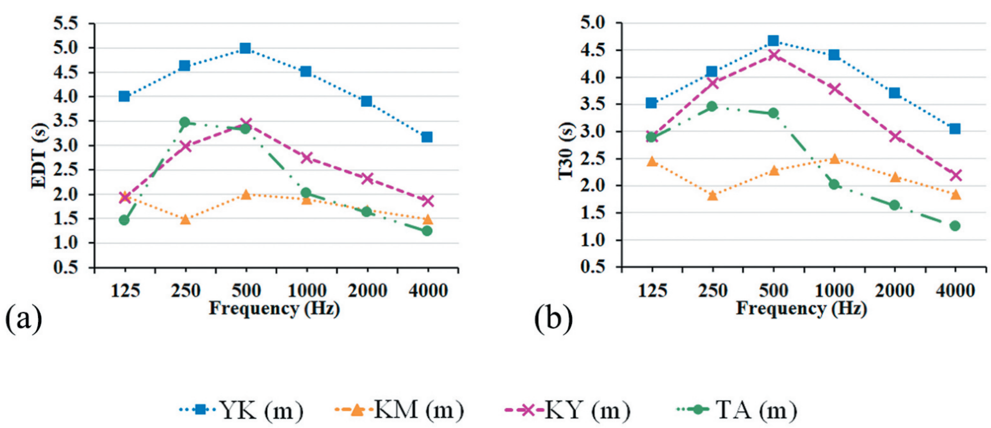

Figure 9. Measurement (m) results over 1/1 octave bands, a: mean T30 values (m) for all four tepidarium, b: mean EDT values (m) for all four tepidarium.

four tepidariums are given in Figure 9 and average T30 values for all four caldaria are given in Figure 10. Due to the nature of hard and reflective finish materials within caldaria, T30 values are measured longest at low-mid frequencies and decrease as the frequency ascents due to the air absorption. T30 values in average mid-frequencies (500 Hz and 1000 Hz) of YK, KM, KY, and TA are 7.82 s, 2.98 s, 4.10 s, and 5.60 s respectively (Figure 9). The longest T30 values are measured in YK, which is also the largest caldarium among all four. T30 values in low and mid-frequencies are measured as sequential as expected considering the room volumes.

However, although the room volumes of KY and KM baths are almost similar, approximately a 1.5s

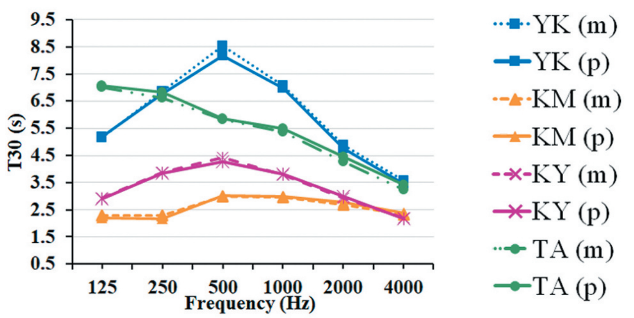

Figure 10. Measurement (m) and post-tuning (p) results for all four caldaria, over 1/1 octave bands.

difference is observed in 250 Hz-500 Hz frequencies. Considering the almost identical finishing materials and application areas, this difference is believed to occur due to room geometries (Table 1). While RH values recorded during measurements in KM, KY and TA are almost similar (49–52%), while in YK it is measured as 80%.

Regarding Ottoman baths, live musical activities with instruments and chorus are a big part of the bathing tradition as well as verbal communication. Hence, the evaluation of STI, D50, and C80 parameters can provide essential information on the acoustic environment. Speech Transmission Index (STI) is a parameter to measure the quality of the intelligibility of speech (Beranek 1988). Table 5displays average female and male STI results of measured caldaria. No considerable difference is obtained between female and male STI values.

Clarity(C80) and Definition (D50) are the ratio of early arriving sound energy (within 80 ms and 50 ms, respectively), generally used for describing the subjective characteristics of space to understand whether musical content (correlated with C80) and speech (correlated with D50) can be received clearly (Kuttruff 2009). Optimum values vary according to the distance from the source (Sü Gül 2019). In addition, a minor time delay of a strong reflection can cause a noticeable difference in both parameters (Kuttruff 2009). The optimum range recommended for both music and speech activities are given in Table 4. Measured C80 and D50 values are presented in Table 5.

C80 is a parameter known to trend in opposite directions to T30, and it is expected for spaces with high T30 values to have low values of C80. In addition, in smaller-sized spaces, C80 values tend to increase with the attributes of early reflections. For speech-related activities, positive values of C80 are desirable as it signifies a crisp acoustical environment (Templeton 1998).

In YK, KM, and TA, the average C80 values are lower than 0 dB over the frequency spectrum. The lowest C80 values are observed in YK and TA; both within a range of −8 to −3.3 dB. The average D50 values in YK and TA are almost the same with the lowest values among all four baths. D50 is a useful descriptor of the intelligibility of speech; higher values indicate good intelligibility (Kuttruff 2009). Thus, the results given in Table 4 signify that the YK and TA are highly reverberant and crisp not practically well-suited for the intelligibility of speech on their current conditions, but responsive more to music. In KM, both C80 and D50 values are higher than YK and TA. D50 values in KM are at their highest at 250 Hz, 500 Hz, and 4000 Hz. The highest C80 and D50 values are obtained in KY These results signify a more suitable acoustical environment for both speech and music-related activities.

As expected, within YK and TA, high reverberation times in the overall frequency spectrum cause low values

Table 4. Acoustical parameters and optimum ranges.

Parameter	Optimum Ranges for Music and Speech Purposes	Just Noticeable Difference
Clarity (C80)	>0 for speech (Templeton 1998) −5 to + 5 for concert or multipurpose halls (ISO 2009) *	1 dB
Definition (D50)	0.3 to 0.7 (ISO 2009)	0,05
Speech Transmission Index (STI)	>0.60 (Beranek 1988)	0,05

Note: * The average of 500 Hz and 1000 Hz.

Table 5. Measured STI, C80, and D50 over octave bands; spatial averages for all caldaria, mean values.

Caldarium	Parameter	125 Hz	250 Hz	500 Hz	1 KHz	2 KHz	4 KHz	STI	
YK	C80 (dB)	−4.5	−7.2	−8.0	−7.4	−5.7	−4.0	Female	0.29
	D50	0.2	0.1	0.1	0.1	0.1	0.2	Male	0.28
KM	C80 (dB)	−3.5	−1.8	−2.6	−3.1	−2.7	−1.7	Female	0.41
	D50	0.2	0.3	0.3	0.2	0.2	0.3	Male	0.41
KY	C80 (dB)	1.0	−1.0	−2.5	−2.1	−1.2	0.1	Female	0.45
	D50	0.4	0.3	0.3	0.3	0.3	0.4	Male	0.45
TA	C80 (dB)	−5.4	−6.7	−6.9	−6.0	−5.4	−3.3	Female	0.31
	D50	0.2	0.1	0.1	0.1	0.1	0.2	Male	0.31

of clarity, as compared to the other baths. In addition, the difference in the C80 and D50 values is considered mainly due to the geometric attributes. In smaller-sized volumes, (KY, KM) where surfaces are much closer to the receiver positions; the early reflected energy is greater. Whereas, higher late energy pattern within some baths is mostly due to the domical upper structures causing additional height and volume, as in the cases of YK and TA baths (Sü Gül 2019).

4.2. Acoustical simulation results

Simulations are conducted within three different setups for all four caldaria; current condition (p), historical plaster (hp), and different relative humidity levels (RH). T30 values obtained from in-situ measurements (m) and post-tuning (p) simulations are presented in Figure 10. The post-tuning stands for the simulation results obtained via tuned acoustical models, which are reflecting the current field measurements. In Figure 11, T30 and STI distribution maps of post-tuning (p) and historical plaster (hp) scenarios for 500 Hz of YK are presented in sequence.

4.2.1. Effect of plaster on T30

T30 and EDT results with post-tuning (current state, p) and historical plaster (hp) are given in Figure 12. The T30 values obtained with hp in mid-frequencies (500 Hz and 1000 Hz) are reduced to around 1.67 s, 1.42 s, 0.88 s, and 1.55 s in YK, KM, KY, and TA, respectively (Table 5).

Obtained results are consistent with the literature. Previous studies (Aydin, Tavukcuoglu, and Caliskan 2008) show that the sound absorption coefficient (α) of the damp samples (saturated at 85% RH) and dry samples are measured as 0.27 and 0.29 at 1 kHz, whereas cement-based plasters have α 0.03 for 1 kHz. In addition, measured α values of wet (100%) conditions of hp are lower than dry and damp (saturated at 85% RH)

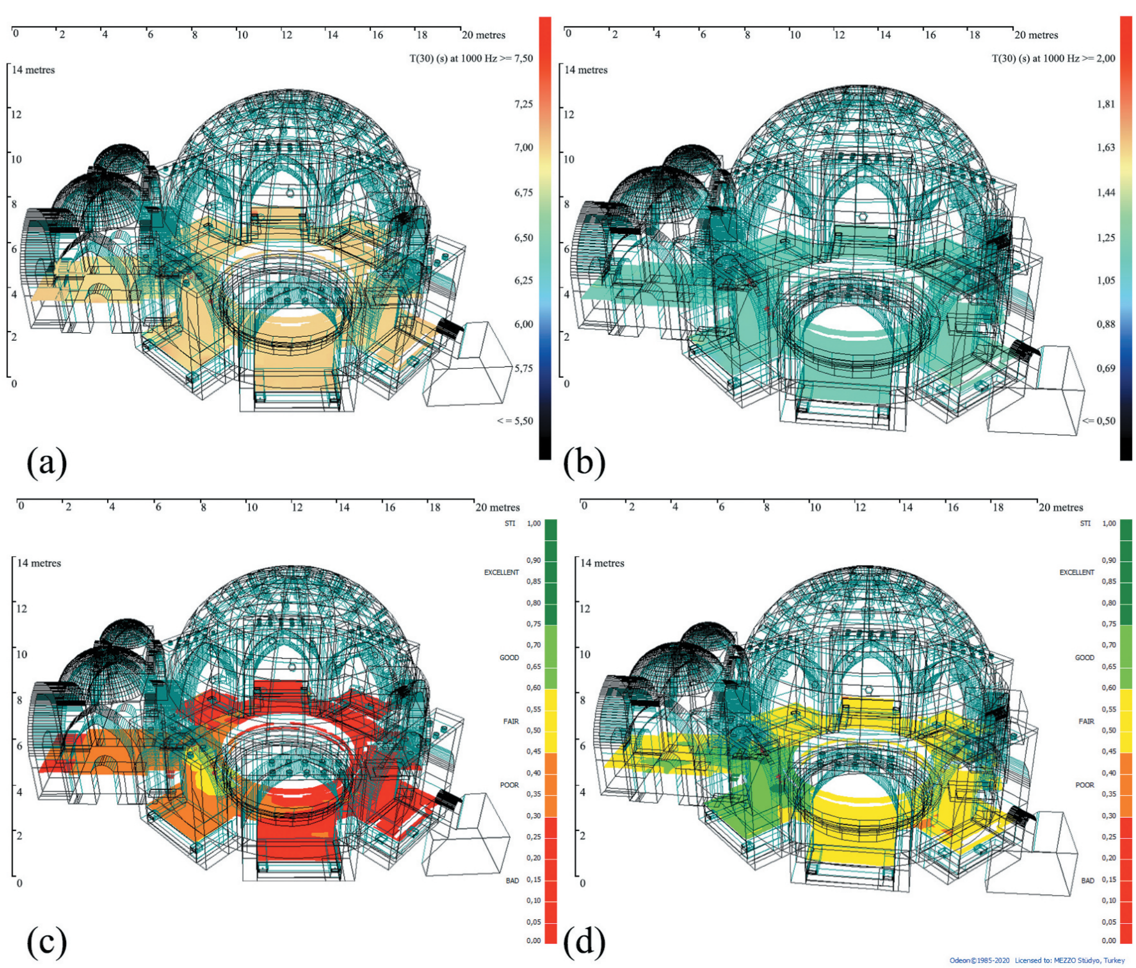

Figure 11. T30 and STI Distribution maps for Yeni Kaplıca (YK) caldarium section: (a) post-tuning (p) scenario T30 distribution map for 1000 Hz; (b) historical plaster (hp) scenario T30 distribution map for 1000 Hz; (c) post-tuning scenario (p) STI distribution map; and (d) historical plaster scenario (hp) STI distribution map.

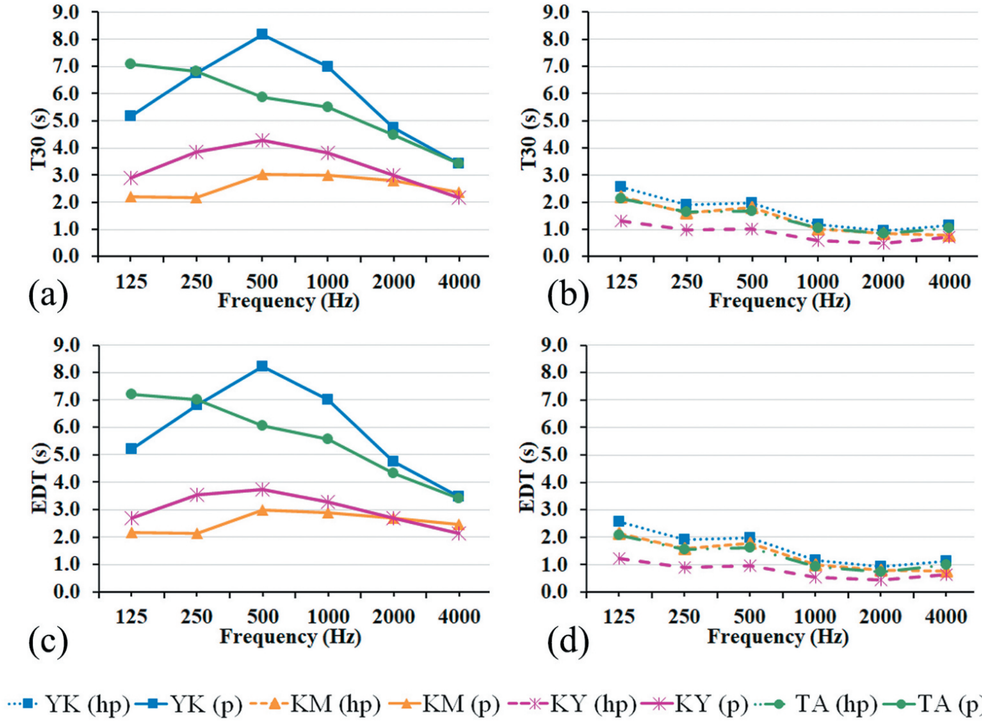

Figure 12. Post-tuning (p) and historical plaster (hp) results over 1/1 octave bands for all four caldaria: (a) mean T30 values (p); (b) mean T30 values (hp); (c) mean EDT values (p); and (d) mean EDT values (hp).

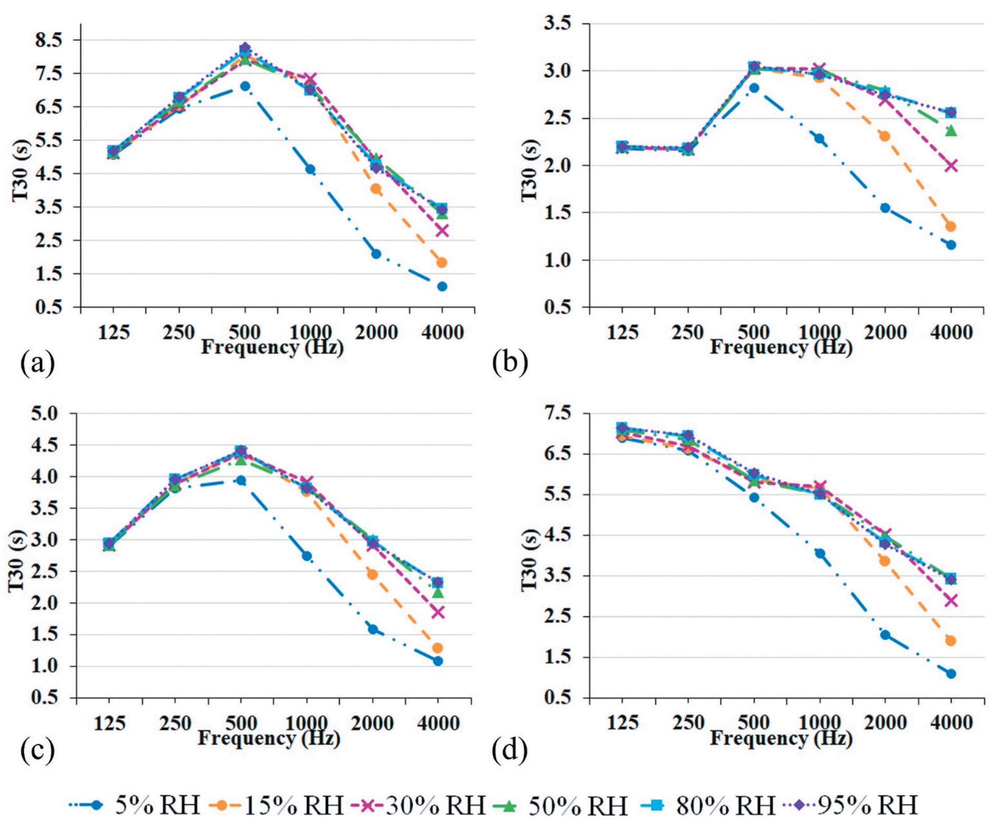

Figure 13. Post-tuning (p) T30 results under different relative humidity levels (RH) (a: YK, b: KM, c: KY, d: TA).

samples. These results reveal the decreasing sound-absorbing capacity of plasters as the humidity level increases.

4.2.2. Effect of different relative humidity levels on T30

The effect of different relative humidity levels on T30 is investigated through simulations (Figure 13). 5%, 15%, 30%, and 95% humidity levels are defined for all four caldaria. Room temperatures in acoustical models are kept as it is in-situ (Table 1). No noticeable difference is observed between 80% and 95% humidity levels. However, considerable differences are observed between 5% and 50% RH levels. As the RH level within the rooms decreases, a falling trend occurs in T20 and T30 values when compared for the same frequency range or octave band. In addition, T20 and T30 values decrease as the frequency increases when RT levels are kept constant, due to air absorption.

Obtained values indicate two possible factors reasoning these outcomes. Air absorption is considered the first factor. It is known that air absorption increases as the frequency ascents, especially for above 4 kHz. Harris (1966) investigates the sound absorption capacity of air under different humidity revels on 1/3 octave band frequency range. The results show that the air attenuation is greater at higher frequencies and lower humidity levels.

Supportive results are discussed by Gomez-Agustina, Dance, and Shield (2014), where the effect of humidity and temperature on air absorption of underground stations are investigated through acoustical/ray-tracing simulations. T30, EDT, D50, STI, and SPL parameters are estimated under varying air humidity levels of 20%, 40%, 60%, and 80% and a constant 20°C. Results show that, as RH level increases, T30 and SPL levels increase at higher frequencies, whereas D50 and STI are reduced. Similarly in this study, the acoustical sound field of bath interiors are investigated under different RH levels. Findings signify that as the RH level increases up to 95%, which simulates the true nature of baths, T20 and T30 values in high frequencies tend to increase as well. Similarly, Nowoświat (2022) investigates the effect of relative humidity on T30 values through reverberation room measurements and simulations. It is found that as RH levels increase, T30 values also increase on average, however, tendency is found to be different in different frequency bands. Tronchin (2021) investigates the relationship between common room acoustics parameters such as C80, D50, EDT, T30 with thermo-hygrometric variables (temperature, humidity, and air velocity) through experimental analysis. The most influenced parameters by the variety of thermos-hygrometric variables are found as C80 and T30. However, since the humidity and temperature parameters are closely related to each other, it could not be evaluated separately within this study.

The second factor may be the clogging of open pores of surface materials with water. Zhang et al. (2020) investigate the effect of humidity and temperature levels on the sound absorption coefficient of concrete through measurements. It is found that the dry and wet conditions at 20°C have a significant difference in their acoustical properties; absorption values reduce in wet conditions as water fills the pores and changes the first and second dominant frequency. Similarly, Aydin, Tavukcuoglu, and Caliskan (2008) reveal that measured sound absorption coefficients of wet (100%) conditions of historical (horasan) plaster are lower than dry samples. Yılmazer and Özdeniz (2005) investigate the effect of humidity on the sound absorption capabilities of expended perlite plates through impedance tube measurements. A significant difference is found between 50%-95% RH levels, whereas dry and 50% RH conditions showed no significant difference. It is found that samples kept under an equilibrium state (98%) lose their absorption capacity and behave like a sound reflector.

4.2.3. Effect of plaster and humidity on speech intelligibility

As discussed in section 4.2.2., a decrease in the humidity levels changes RT values. Thus, STI values are expected to be higher in non-humid environments with similar geometric attributes. Accordingly, Figure 14 shows STI results obtained with the application of tuned-model current plaster (p) and historical plaster (hp) scenarios, and the corresponding intelligibility rating scale (Beranek 1988). The distribution maps are given in Figure 11. The differences between the female and male STI values are rather small in all four caldaria within the same scenarios. Among scenario "p", the lowest STI value is 0.27 (YK, male), whereas the highest STI value is 0.41 (KY, female). A drastic increase, on the other hand, is observed between "hp" and "p" scenarios. The lowest STI value increased to 0.53 in scenario "hp" (YK, male), while the highest value is 0.68 (KY, female). While intelligibility rating within scenario "p" is "poor" and "bad", results improve to "fair" and "good" with the "hp" scenario (Figure 11). Meaning that historical plaster absorbs more as discussed in Section 4.2.1, and increases STI values.

Warmth in enclosed spaces is expressed with Bass Ratio (BR), which is the average of low to mid-frequencies. For musical performances, BR is expected to be greater than 1.20 (Egan 1988). For YK, KM, and

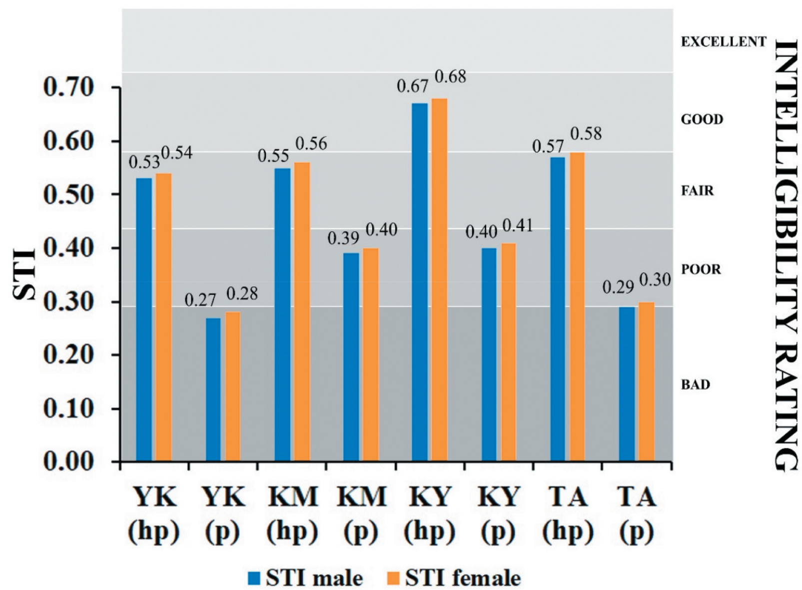

Figure 14. Male and female STI results for all four caldaria, post-tuning scenario (p) vs. historical plaster scenario (hp).

KY in scenario "p", the calculated BR range is 0.73–0.84, whereas results improve to the optimum range for musical performances in scenario "hp".

The frequency spectrum (dynamic range) of the sound is different by nature in men's and women's baths. The men's section hosts collective and private bathing with ceremonies such as the bathing before marriage or before/after military services. Thus, the activity of male speech is prominent. On the other hand, musical activities mainly take place in the women's section and ceremonies are more colorful. For mothers, getting to know potential bride candidates in the bath is one of the oldest and most well-known bath traditions. The bridal bath is a ceremony in which all the female relatives, neighbors, and friends come together. The military bath is a tradition started by women; after sending their children to the military service, mothers invite their relatives and neighbors to celebrate their son's enlistment, with prayers and wishes to return home safely. The postpartum bath is a ceremony held 40 days after birth to give baby's first bath. All of these ceremonies contain food and gift servings, along with the musical performances from attendees with instruments such as tambourine/mandolin and singing accompaniments. Thus, the main activity becomes speech and music related within the women's bath.

The longest T30 values are measured in the largest bath (YK). Differences in T30 values between similar room sizes, points out the effect of geometrical differences. Neither flutter echo nor echo is detected in measured source-receiver configurations. This is mostly due to the fact that the acoustically effective zones under the domes are mostly higher than the user zone for all baths in warm areas (tepidariums) in all four cases (Figure 15). In caldarium (hot area) sections, the affected range covers the pool and/or central navel stone (raised marble platform for massage), in which the hearing height of users (sitting/lying positions) fall outside of the impact area of domes, due to the nature of functions occur at the center. Acoustically effective zone for dome geometry, similarly, is discussed in some other studies but for the mosque typology (Sü Gül and Çalışkan 2013). In addition to this, the presence of skylight holes (filgözü) aids the sound scattering, disturbs the acoustical symmetry and so minimizes focusing effects of the geometry of upper structure in Turkish baths. Similar applications are observed in other building typologies in Ottoman architecture in form of Sebu (clay pots). These applications disrupt the symmetrical form of dome surfaces and minimize acoustic defects (Atay and Sü Gül 2020; Sü Gül 2019).

Relative humidity is shown to be another factor of T30 values; a decrease on RH values can lower T30 values and consequently enhance speech intelligibility. Higher C80 and D50 values are obtained in smaller sized baths, due to increased early reflections. And lastly, the application of historical *horasan* plaster within baths, in comparison to current cement-based plasters, resulted

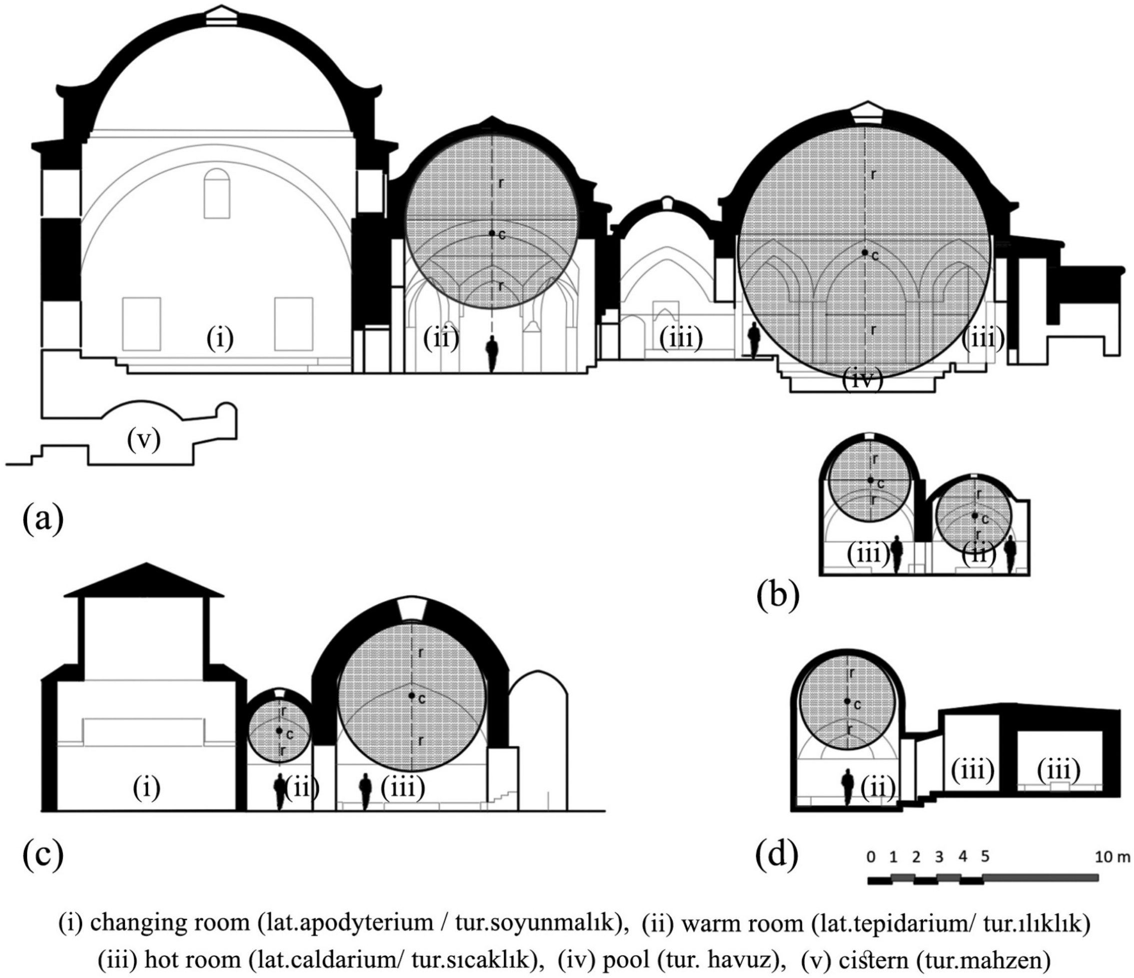

Figure 15. Acoustically effective zones (shaded area) under the domes (a: YK, b: KY, c: TA, d: KM).

in lower T30 and higher STI values, which enables the baths to be acoustically much more comfortable for the held activity patterns in their authentic state.

5. Conclusion

In Anatolian culture, baths play an important role for both bathing and socializing. It has never lost its importance, especially due to its place in ceremonial traditions and still keep their role as a substantial typology in architecture with their effect on social life as they used to be. Whereas there are also many examples of Turkish baths for refurbished uses; such as museums, art galleries, workshops, shopping centers, café/restaurants, etc. In older cases, the original layout within baths was wrongly modified with minor maintenance by the owners, without considering the historical texture. Recently, abandoned or misused baths have been restored and adapted into new functions, mostly by municipalities (Büyükdigan 2003). A full understanding of the historical texture in all aspects is essential towards preservation of Turkish baths.

This paper aims to offer insight into the authentic acoustical characteristics of traditional Turkish baths by field measurements, together with acoustical simulations for experimenting with various scenarios of a historical state as well as up-to-date conditions and different humidity levels during use. Decay rates (EDT, T20, T30), energy ratios (C80, D50), and intelligibility metric (STI) are obtained. YK was found to be the most reverberant space, as expected due to its interior volume. However, approximately a 1.5 s difference at T30 values in 250 Hz-500 Hz frequencies in KY and KM is observed, although the interior volumes of baths are almost similar.

Average C80 values are lower than 0 dB over the frequency spectrum in YK, KM, and TA. The lowest C80 and D50 values are observed in YK and TA, both within a range of −8 to −3.3 dB. The highest C80 and D50 values are obtained in KY at 125 Hz and 4000 Hz frequencies. The greater the domes and heights of the baths the late energy is more dominant in the baths and early reflected energy is surpassed. The values of clarity metrics increase in smaller baths, which become more comfortable for speech use, in the current state of analyzed baths.

As an outcome of this study repair materials used over time has changed the acoustical characteristics of Turkish baths. Contrary to cement-based plasters, which are applied in yearly maintenance of the dome and wall surfaces, originally used Horasan plasters has higher sound absorption performance in overall octave bands. Simulation results obtained with historical plaster have lower T30 (around 4-6 s lower in YK and TA, 2-3s lower in KY and KM) and higher STI values (almost 2 rating scale up in all four baths) than the current (measured) conditions. Humidity is found to be effective on acoustical metrics; as the RH level ascents, an increasing trend is observed at T20 and T30 values in high frequencies. These outcomes are associated with two factors; air absorption decreases with the increase in humidity, and saturated materials become more reflective as water fills into pores.

In brief, this study aims to include Turkish baths in historical archive studies and lead for a more conscious approach in terms of material selection for further repair and restoration works. The obtained objective acoustical parameters through field tests enable to tune the acoustical models and later experimenting with the original materials. As discussed in some other studies on historical structures (Sü Gül 2019), the lime-based multi-layered *horasan* plaster of Ottoman architecture is not only performing well for heat insulation, but also acoustically as they provide a much more comfortable indoor environment. On the other hand, the wise decisions on dome sizes and heights in relation to the usable zones on the floor and activity patterns, are minimizing acoustical defects as of echo or flutter echo, rendering the geometric proportions of the baths very appropriate. Such attributes can be a reference for future designs of structures with dome typology.

To conclude, the results of this study provide the basic yet significant objective acoustical attributes of Turkish baths, which are one key building typology of Anatolian architecture and socio-culture. Examined bath structures within the scope of this study have survived up-today with minor maintenance, keeping their original structural and geometrical characteristics for almost five centuries. However, due to the replacement of historical plasters with contemporary cement-based plasters in repairs, original acoustical characteristics cannot be sustained. The outcomes emphasize the contribution of material characteristics and climatic factors to indoor acoustical quality. There are a bunch of activities that take place in traditional Turkish baths, which include both speech and music, as briefly outlined in this research. Follow-up work to this study, aims to include the aural reconstruction of the traditional use of baths with support of the objective findings of this research for subjective analysis and further discussion in relation to the soundscape.

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