Aural Architecture as Affect: Understanding the Impact of Acoustic Environments on Human Experience

by

Alaa Salman Algargoosh

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Doctoral Committee:

Associate Professor Mojtaba Navvab, Chair
Assistant Professor John Granzow
Associate Professor Sile O'Modhrain
Professor Peter von Bülow
Professor Michael Vorländer, RWTH Aachen University

Alaa Algargoosh

alaas@umich.edu

ORCID iD: 0000-0003-4288-8581

DEDICATION

To my family.

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ABSTRACT

Architectural design plays a significant role in shaping human experience in buildings through the perception of space. However, architectural characteristics not only result in visual attributes that affect how the occupants see the space, but they also create auditory environments that impact what the occupants hear based on sound propagation and reflections from surfaces. Yet, architectural acoustics' physical measurements do not precisely reflect the human acoustical experience because other perceptual and cultural aspects contribute to it, as the aural architecture approach suggests. The perceptual aspect deals with the psychological and physiological effects of sound and its relation to human cognition and emotions, while the cultural aspect focuses on the role of cultural background in sound perception.

This research offers a comprehensive approach that allows for a deeper understanding of such experience by studying the interaction between the physical, perceptual, and cultural aspects of acoustics. Since worship spaces offer an example in which the spiritual experience is dependent on the acoustic environment, this study adopts them as case studies aiming to answer the following questions: how does an acoustic environment influence human experience and emotions? What are the acoustic characteristics and parameters related to that emotional impact? What are the links between the acoustic characteristics and the emotional impact?

This research analyzes the experience by recreating acoustics using virtual reality technology and subjective methods that include self-report in addition to objective methods that include physiological measurements (i.e., heart rate and skin conductance), to validate the results. The results demonstrated that the acoustic environment amplifies the intensity of the emotional impact depending on the building's architectural design and that familiarity with sound and acoustic characteristics can increase this impact.

Then, the research proposes a method to investigate the response of the room to the excitation by the sound source considering its architectural characteristics through frequency-domain analysis based on auralization. The auralization-based method named (multiple convolutions) proved its ability to identify room modes that create resonance for spaces with complex geometries, such as worship spaces, taking into account the architectural surfaces' materials and the source location.

Finally, the study analyzes the room acoustics' parameters and includes a correlational analysis to develop indicators for studying the auditory experience and to establish guidelines for designing spaces that enhance it. The correlation between the emotional impact of spaces and their acoustic parameters illustrated the significance of low frequencies in the emotional impact of worship spaces and raised the issue of considering these frequencies when analyzing and designing such spaces. Consequently, the research calls for further studies on the architectural characteristics of acoustic environments that impact emotions and enhance well-being.

Chapter 1

Introduction

1.1 Background

Architectural design is a complex process that involves considering multiple factors at once. Architects try to come up with an aesthetically appealing space design that fulfills the needs of the end-users and the goals of the project owners, while at the same time considering building codes. The architectural characteristics of the space shape the occupants' experience not only visually but also aurally, and the field that studies how the architectural features impact sound is architectural acoustics.

Architectural acoustics is the science that deals with sound inside buildings; while it has some roots in ancient constructions, the foundation of this field was established in the nineteenth century (Long, 2005). Most of the studies in architectural acoustics focus on the physical aspects of sound propagation in a space, particularly when sound plays an essential role in the occupants' main activities, such as concert halls, worship spaces, classrooms, recording studios, and so on. However, the architectural characteristics create spatial attributes that are then experienced through the cultural background lens; thus, based on the occupants' background, the same space will result in a different sensory experience, which influences their mood.

The integration between the physical, perceptual, and cultural aspects of acoustics is at the core of aural architecture (Blesser and Salter, 2007). According to the aural architecture approach, the physical aspect deals with sound propagation in a space; the perceptual focuses on the psychological and physiological effects, and the cultural addresses the influence of the cultural background on interpreting acoustic stimuli. Although the cultural aspect can shape sound perception, it is given less attention. Considering the role of cultural background in the acoustic environment is especially crucial in places such as worship spaces, such buildings provide an excellent opportunity to explore the integration between the physical, perceptual, and cultural aspects. The researcher discussed the role played by these aspects in shaping the aural experience in worship spaces (Algargoosh, 2016).

Worship spaces involve spiritual needs that enhance faith, and thus require complex acoustic environments (Kleiner et al., 2010). Hale defines the sacred space as “an enclosure that makes it possible to enter into a relationship with a greater reality” (Hale, 2007). Then, how can spaces support spiritual needs through acoustics?

Unlike concert halls, where achieving more homogenous acoustics is preferred, attaining diverse acoustic characteristics in different parts of worship spaces can be favored. The acoustic variety produces aural esthetics, forms auditory symbols, and creates emotional experiences (Blesser and Salter, 2007). The variety in the acoustic characteristic can be a result of space’s geometry. For example, worship spaces with a primary space and sub-volumes will have double slope sound decay curves (Sü Gül et al., 2016), resulting in strong early reflections and long reverberation time. Such acoustic characteristics can become auditory symbols parallel to the visual architectural icons associated with specific worship spaces. For example, long reverberation was associated with grand spaces; thus, it has become a symbol of grand worship spaces. Reverberation also adds to the esthetic qualities of the acoustic environment contributing to the emotional impact, as Kleiner et al. explained: “Without reverberation, the sound quality of speech and music would be dependent on the directivity of the sound source and would lose beauty and emotional power" (Kleiner et al., 2010). Reverberation increases the perceived size of the space, providing a dramatic effect, and destroys the localization cues of the sound source, creating a sense of mystery that can support the ritual (Hale, 2007). Such a multi-directional effect may not be as immersive when using sound-reinforcing systems that add artificial reverberation.

In addition to the reverberation time, the sound harmonization created by blending musical notes (Pentcheva, 2011) can influence the occupant’s emotions. Fig. 1.1 shows a sequence of six musical notes and their intensity levels as well as the intensity of reverberation for the first note C. The reverberation of note C blends with the other notes; depending on the intensity of the reverberation, if it is higher than the masking threshold, it can dominate by masking the direct sound of the following note by creating a different perceived sound. The balance in blending direct and reflected sound creates an esthetically appealing aural experience that enhances the emotional effect (Blesser and Salter, 2007).

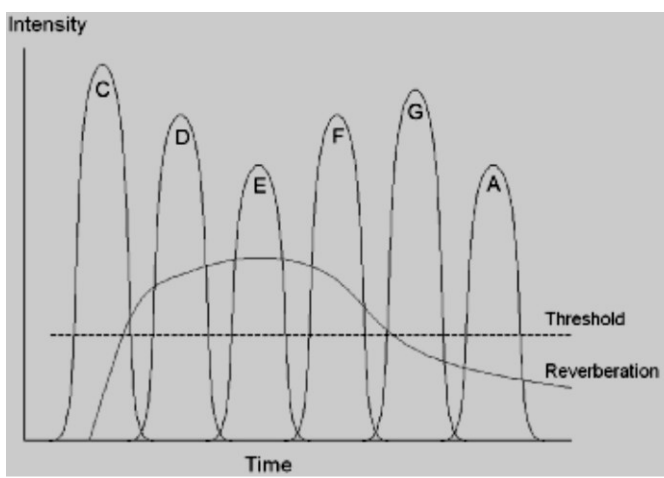


Fig. 1.1 A graph of the intensity of six musical notes and the intensity of the reverberation of the first note (Blesser & Salter, 2007).

Fig. 1.2 & Fig. 1.3 show how the acoustic environment changes the spectrum of the original sound (dry recording) by enriching it in both the frequency and time domains, creating a harmonized sound. It also demonstrates how the acoustic environment amplifies the original sound.

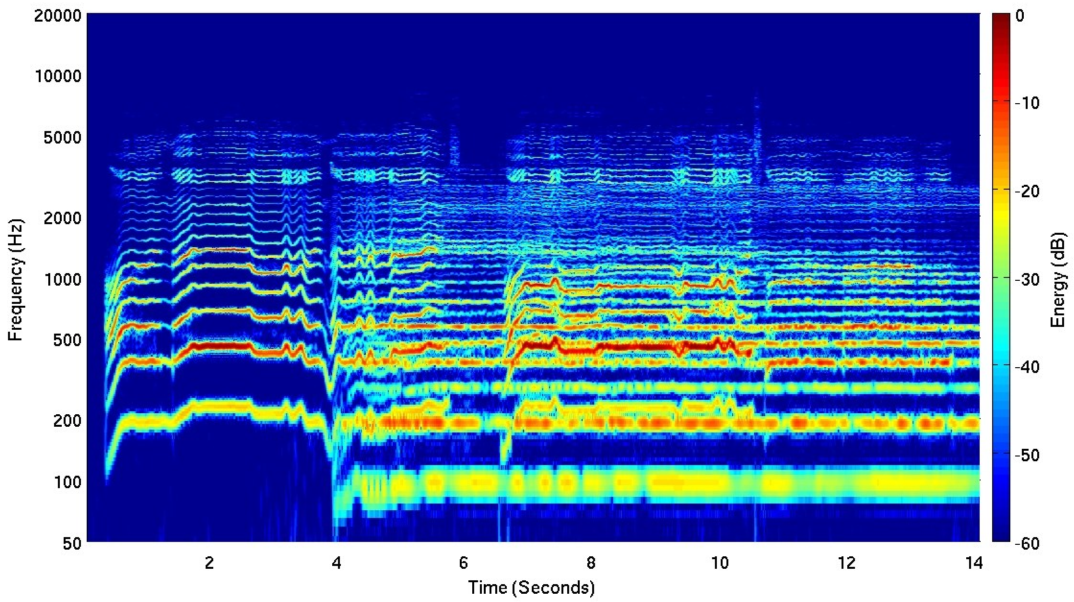


Fig. 1.2 Spectrogram of a dry recording of religious chant (BV Pentcheva, 2017) ©Jonathan Abel

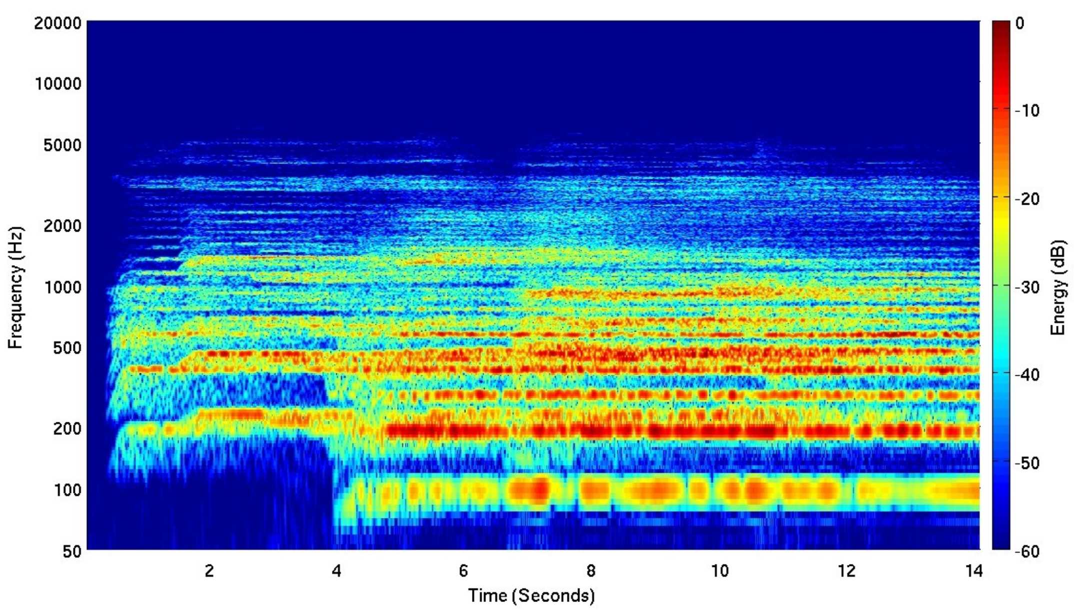


Fig. 1.3 Spectrogram of the same recording of religious chant in a worship space (Hagia Sophia) (BV Pentcheva, 2017) ©Jonathan Abel

Sound amplification is another factor that may enhance the emotional effect of worship spaces. This amplification can be the result of certain architectural elements, such as domes in churches (Fig. 1.4) and mosques (Fig. 1.5), and the reflected sound can be stronger than the direct sound (Kleiner et al., 2010).

Fig. 1.4 The dome in the Church of San Luis de los Franceses (Alberdi et al., 2019)

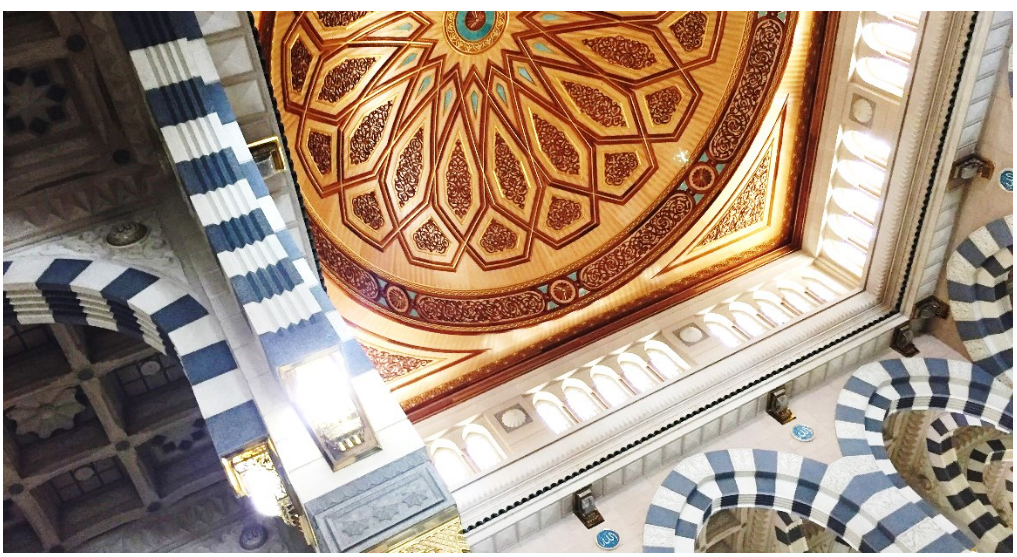


Fig. 1.5 A dome in the Holy Mosque in Medina, Saudi Arabia.

This amplification is nonuniform and does not necessarily cover all frequency ranges. For example, the recesses in Chester Cathedral in England reinforce vocalization with a strong resonance at 125 Hz, which amplifies the sound at this frequency by 25 dB and enhances the emotional effect (Lubman, 2004).

A similar effect has been reported for some ancient structures. Despite the difference in their geometries, they have a resonance frequency of 110 Hz. Since this frequency is within the range of the male human voice, researchers have implied that such resonance supports the chanting during rituals (Devereux and Antiquity, 1996).

There are also many prehistoric caves with strong resonances at specific frequencies that represent musical notes. In a Paleolithic cave in France (Font-de-Gaume and Lascaux), researchers found drawings of animals such as bulls at the locations with strong resonance (Waller, 1993). This example, in addition to other caves, led researchers to suggest that those spaces were used for rituals (Lubman, 2017). In a megalithic structure in England, researchers reported strong resonances at low frequencies 95–120 Hz and implied that acoustics might have played a role in supporting rituals (Cook et al., 2008). Although not enough evidence exists to determine whether it was intentional, many other examples of ancient spaces with acoustic characteristics support auditory performances (Hamilakis, 2014), with some having a selective amplification that produces sound similar to that produced by musical instruments (Dauvois and Ariégeoise, 1990).

The selective amplification effect of resonance impacts not only the frequency domain but also the time domain, creating a temporal spreading; moreover, even when thousands of room modes that create resonances blend in large spaces without a single characteristic frequency, it still changes the source's dominant frequency by amplifying some ranges or damping others (Blesser and Salter, 2007). An example is the seat dip effect, which occurs in low and mid frequencies when the direct and reflected sounds cancel each other due to destructive interference (Pätynen et al., 2013).

The previous acoustic characteristics may have an essential role in shaping the auditory experience through the emotional impact. However, further research is needed to provide evidence on the link between them.

1.2 Problem statement

When architects design a building, they also create a space with acoustic characteristics shaping the occupants' experience. Architects use guidelines to make decisions on the architectural features that fulfill the acoustic requirements. Although general guidelines that assist in designing spaces with good acoustic qualities are available, specific guidelines are essential to account for the variety of acoustic needs based on space activity and acoustic performance to obtain an acoustic environment that enhances the occupant's experience.

This experience is shaped by our perception of the acoustic environment, and a large body of research in architectural acoustics is dedicated to connecting acoustic parameters and perception, with a large focus on concert halls. However, less research has considered how the cultural background influences our perception of the acoustic environment, especially in places where culture plays a critical role, such as worship spaces.

Blesser et al. claim that most scholarly work in aural architecture focuses on Western culture (Blesser and Salter, 2007); thus, worship space acoustics would benefit from including examples of worship spaces from nonwestern cultures.

While acoustic research is more developed in certain types of worship spaces (e.g., churches), it is at the preliminary stages for others. For example, many mosques suffer from major acoustic issues, as stated by Abdou, who studied 90 mosques (Abdou, 2003). Considering that each of the two types of worship spaces has special acoustic requirements based on the undergone worship activities, understanding the acoustic requirements that support the spiritual experience is essential.

The lack of design guidelines based on the acoustic requirements may lead architects to replicate historic mosques with excellent acoustics; however, this limits creativity in designing contemporary mosques. Instead, researchers recommend analyzing the factors that shaped the acoustics to recreate a similar spiritual experience for contemporary designs. Abada stated that, although collective memory links certain architectural features with specific emotions in mosques, architecture should not be limited to those features (Fig. 1.6 & Fig. 1.7 show an example of a contemporary mosque that shares many of the architectural features of a historic mosque). Instead, the spiritual experience can be enhanced by studying both the physical and physiological aspects that can result from environmental factors, such as acoustics and daylighting, utilizing these as inspiration for creative architectural designs (Abada, 2016).

Thus, by studying the characteristics of the acoustic environments that enhance the occupant's experience and its link to the cultural background, this research may allow for recreating such supportive experience while also encouraging design creativity.

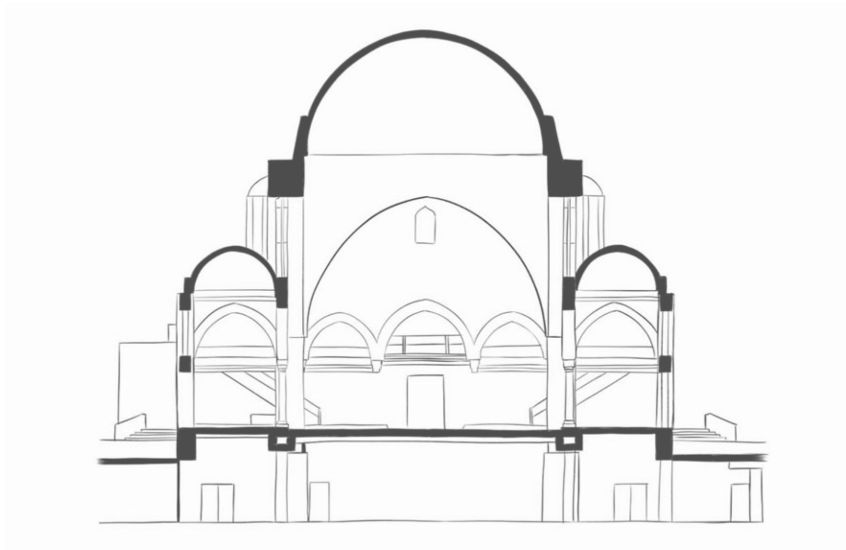


Fig. 1.6 Section sketch of the Diyanet Center of America in Maryland, The United States of America (Founded in 2013).

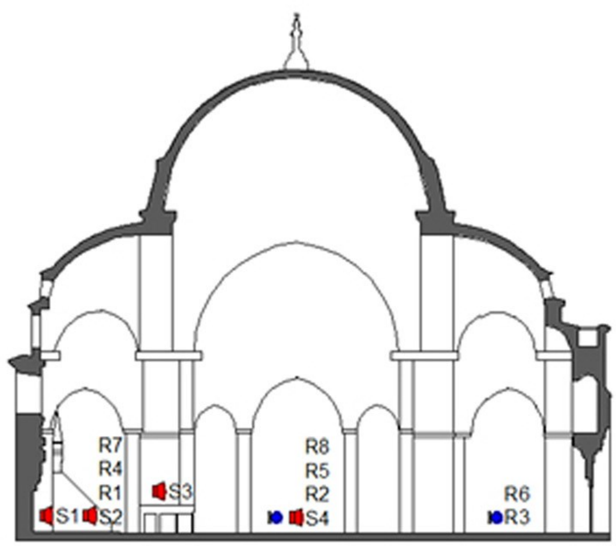


Fig. 1.7 Section drawing of the Süleymaniye Mosque—a historic mosque in İstanbul, Turkey (Sü Gül et al., 2016).

1.3 Research purpose

This research aims to develop methods to both evaluate and design acoustic environments based on their effect on human experience.

To achieve this aim, it analyzes the impact of the acoustic environment on human experience by studying worship spaces as primary case studies. The focus on such buildings in this study is due to the acoustics' essential role in shaping the spiritual experience. Considering the cultural context in which the individuals' backgrounds influences their experience, this study examines the links between the physical characteristics of the acoustic environment and the occupant's experience.

1.4 Research questions

Considering that architectural acoustics' physical measurements do not fully reflect the auditory experience (Blesser and Salter, 2007), this research adopts aural architecture—an emerging field integrating the physical, perceptual, and cultural aspects of architectural acoustics. The physical aspect focuses on analyzing sound propagation in spaces; the perceptual aspect deals with the physiological effects of sound that result in emotional impact (referred to in psychology as an "affect"); and the cultural aspect studies the role of cultural background and familiarity in shaping the sense of place. To explore the role of architectural features in enhancing the spiritual experience through sound reflections, this research provides a comprehensive approach, using both qualitative and quantitative methods when analyzing auditory experience by answering the following questions:

1. How does the acoustic environment influence human experience and impact emotions?
2. What are the acoustic characteristics and parameters related to that emotional impact?
3. What are the links between the acoustic characteristics and the emotional impact?

1.5 Methodology

As shown in Fig. 1.8, this study includes three phases that incorporate field measurements and simulation. Phase 1 focuses on studying the perceptual aspects and the emotional impact of the acoustic environments, and Phase 2 focuses on some physical aspects related to analyzing the acoustic characteristics. Since resonance which is created by room modes have been repeatedly mentioned when describing spaces associated with spiritual experiences, this section proposes a method for studying room modes using auralization. Phase 3 connects the physical, perceptual, and cultural aspects to provide indicators for analyzing the acoustic environment that can enhance the spiritual experience.

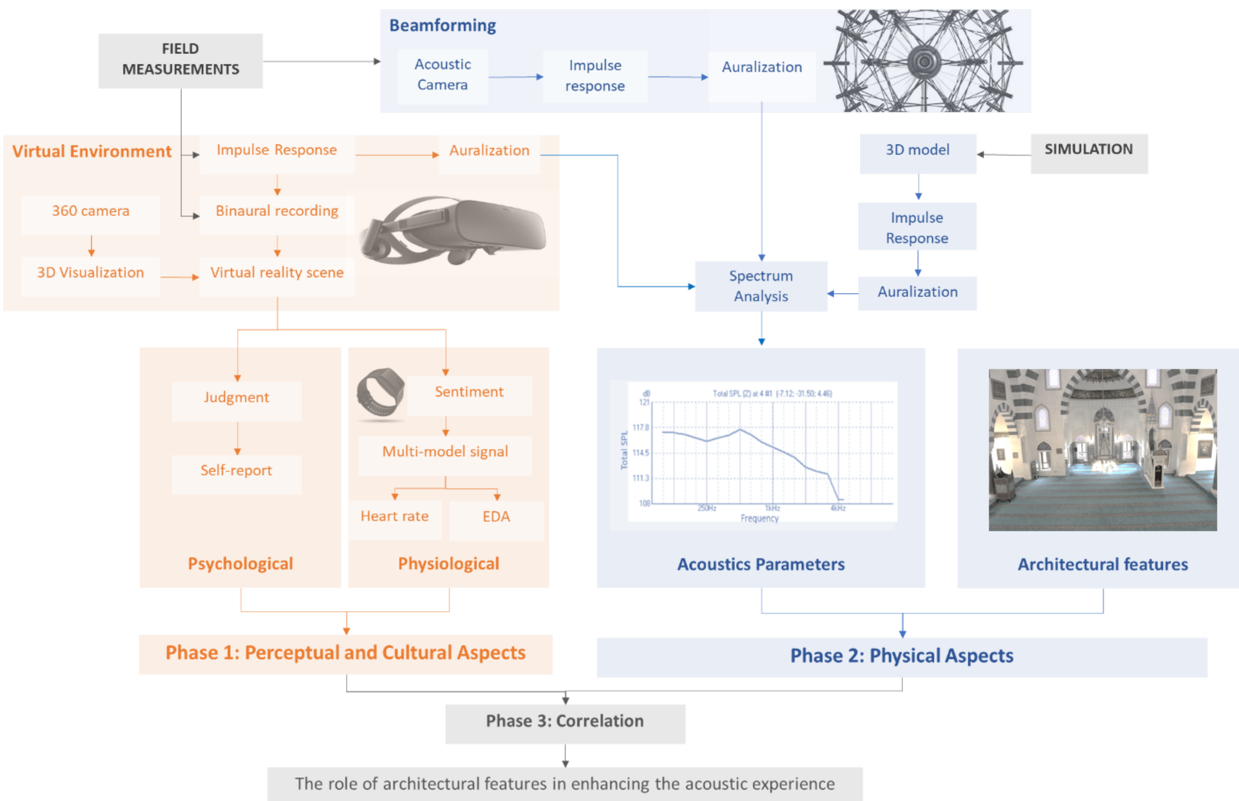


Fig. 1.8 Research Methodology Flowchart

In summary, Phase 1 allows for understanding the emotional impact of the acoustic environments and how it shapes the auditory experience and examines links to intangible cultural heritage. In contrast, Phase 2 allows for analyzing some physical characteristics of acoustic environments. Finally, Phase 3 connects the results of the first two phases, determining acoustic indicators that can be used to analyze and design spaces that can enhance the auditory experience.

Fig. 1.9 shows a flowchart of the research questions, how they are related, and how they integrate the perceptual, cultural, and physical aspects of acoustics.

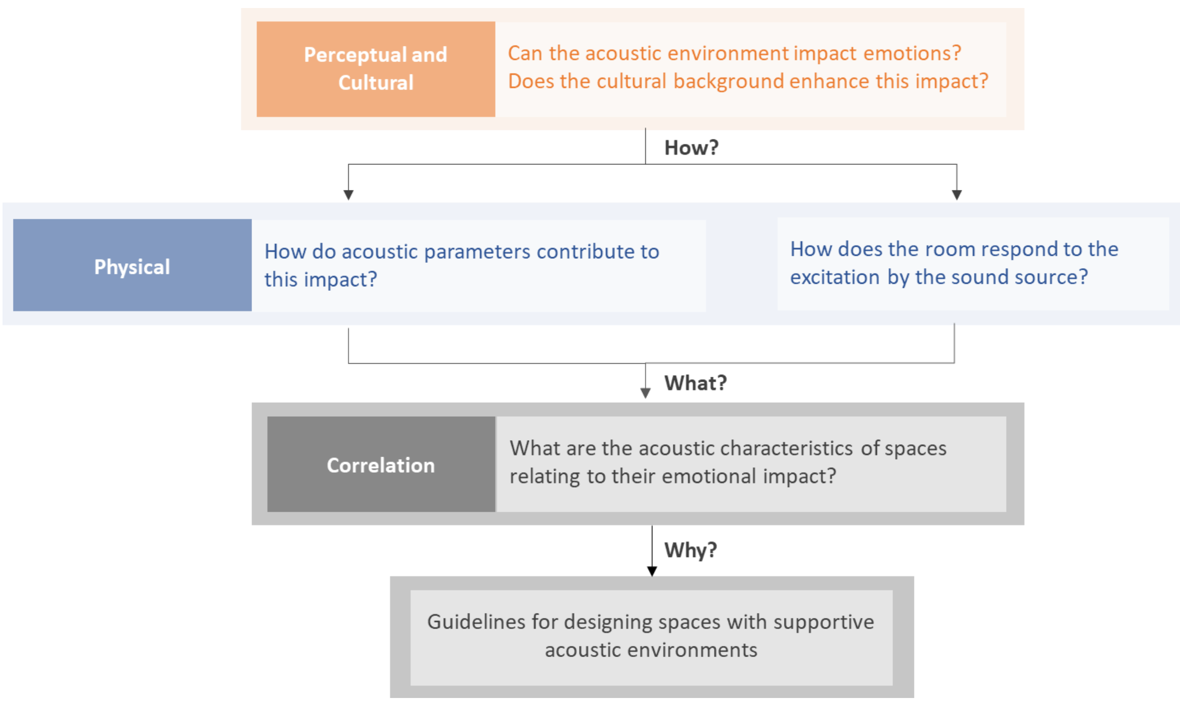


Fig. 1.9 A flowchart of the research questions

1.6 Research Contribution

This dissertation makes three major contributions in that (1) it explains how sound can enhance the occupant's experience and connects experience and emotional impact with the cultural background; (2) it provides a method for analyzing resonance created by room modes in spaces of complex geometries; (3) it links the characteristics of the acoustic environments with the emotional indicators, and it lays the foundation for future research on the sound characteristics of emotionally supportive environments.

1.7 Outline of Chapters

This chapter served as the introduction. It included background information about architectural acoustics and explained why aural architecture was adopted in this research. It also discussed related studies that laid a foundation for this research, highlighting the importance of integrating the physical, perceptual, and cultural aspects when studying architectural acoustics, and outlined the research questions and methods developed to answer them. As shown in Fig. 1.10, Chapter 2 deals with the perceptual and cultural aspects through an experimental study that examines the impact of the acoustic environment on the occupant's experience. Chapter 3 focuses on the physical aspects by developing a method for studying room acoustics, with a focus on frequency domain to analyze room modes and resonance. Then, Chapter 4 links all the aspects of aural architecture together through a correlation analysis aimed at identifying the acoustic characteristics of spaces that impact emotions and enhance the occupant's experience.

Finally, Chapter 5 provides a summary of the findings for each research phase, discusses the impact and application of the research, and proposes a direction for future studies that utilize the results of this dissertation to inform designing spaces that enhance human experience and well-being.

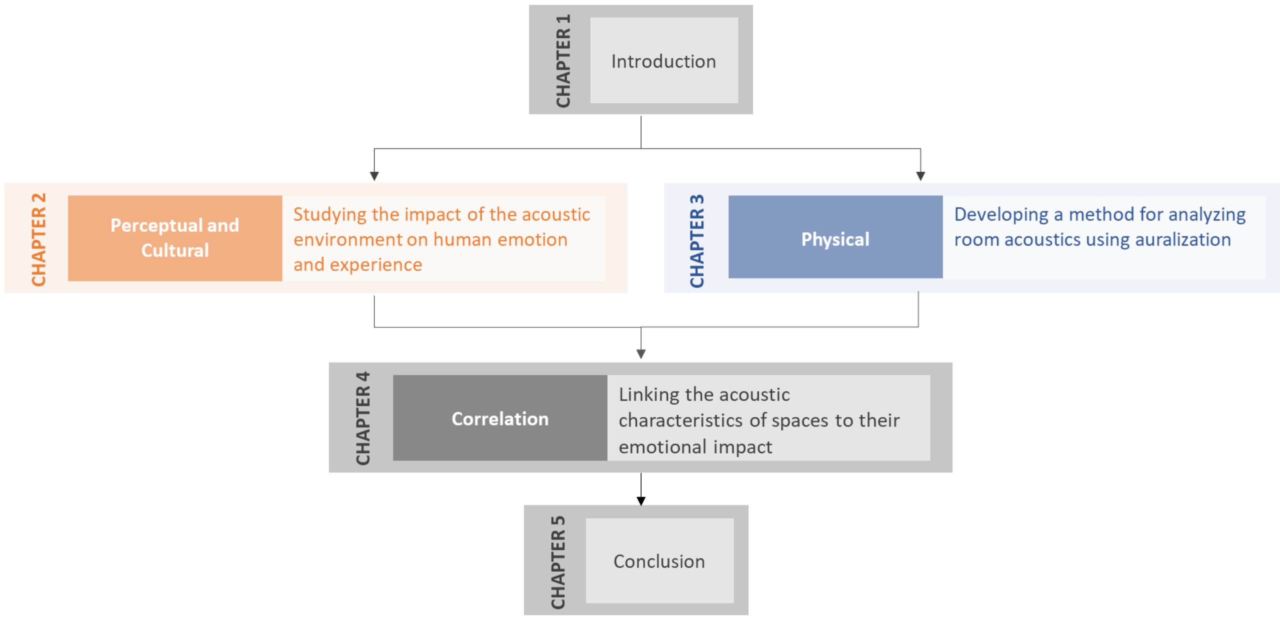


Fig. 1.10 Dissertation structure

Chapter 2

Studying the Impact of the Acoustic Environment on Human Emotion and Experience[1]

Abstract

People's interactions with the environment shape their experience. Thus, understanding these interactions is critical when it comes to enhancing the overall wellbeing of humans. Visual attributes play a significant role in shaping the perception of space; however, aural attributes are also crucial. It is well known that sounds evoke an emotional response, but less is known about how the acoustic characteristics of environments reinforce such an emotional impact. By adopting virtual reality as a platform for recreating 360-degree visuals and 3D sounds of built environments of worship spaces as case studies, the study reported here aims to investigate the influence of the acoustic environment on enhancing the experience of space users through self-report and physiological response analysis. It also examines the role of cultural background in terms of familiarity with a sound and acoustic environment in amplifying the intensity of the emotional impact. The convergent mixed-methods approach, merging both quantitative and qualitative analysis, provides a deep understanding of the role of architectural features to enhance the auditory experience through sound reflections. The results show that the acoustic environment amplifies the intensity of the emotional impact, and the amplification of the impact can vary depending on

1 The abstract has been published in: Algargoosh, A. ; S. B. (2019). "The impact of the acoustic environments on the emotional experience of worship spaces," J. Acoust. Soc. Am., doi: 10.1121/1.5137477. doi:10.1121/1.5137477.

the architectural design of the building. They also reveal that familiarity with sound and acoustic characteristics can increase this impact. Thus, this research provides a method for assessing the potential emotional impact of acoustic environments and demonstrates the role of evaluating aural aspects in designing buildings, especially when sound is an integral component of activities in the space.

2.1 Introduction and related research

The design of the built environment plays a significant role in shaping the human experience (Bower et al., 2019; Kaplan and Kaplan, 1982; Marchand et al., 2014; Scopelliti and Vittoria Giuliani, 2004). Blesser et al. stated that the human experience is shaped by interaction with the environment: "As human beings, we interact with both our social and our physical environment by using all our senses…. Each of our senses plays a unique and complementary role in creating our internal experience of the external world" (Blesser and Salter, 2007). However, architectural characteristics in a building not only result in visual attributes that affect how the occupants see the space, but also create auditory environments that impact what those occupants hear based on sound propagation and reflections from surfaces. Nevertheless, the physical measurements of architectural acoustics do not precisely reflect the human auditory experience (Giménez et al., 2014); other perceptual and cultural aspects contribute to it, as the aural architecture approach suggests (Blesser and Salter, 2007). The perceptual aspect of auditory experience deals with the psychological and physiological effects of sound and its relation to human cognition and emotions, while the cultural aspect focuses on the role of cultural background in sound perception (Álvarez-Morales et al., 2014).

2.1.1 Acoustic environments and perceptual aspects

Research in architectural acoustics has significantly improved, but the area continues to face some challenges, and further studies are required to answer questions beyond the physical aspects of acoustics, including the perceptual and cultural aspects (Blesser and Salter, 2007). While researchers such as Beranek have studied audience responses to acoustics to analyze how acoustic attributes contribute to sound perception in concert halls, there are still questions that require answering to understand how the architectural features of the space create certain auditory experiences (Beranek, 2004). Therefore, Pätynen et al. took a further step by investigating the connection between acoustic perception and what concert hall shape is ranked as the most preferred based on Beranek's analysis. The result of the study showed that rectangular halls were the most preferred and that they created a more intense emotional effect based on physiological measures (Pätynen and Lokki, 2016). Other researchers have argued that the study of sound preference needs to consider personal and group tastes, which can be influenced by culture (Ando, 2011). Thus, researchers have recognized the need to re-evaluate the acoustic parameters used to develop subjective measures, to account for cultural aspects (Ando, 2015).

2.1.2 Acoustic environments and cultural aspects

The experience of acoustic environments is linked to culture, as stated by Blesser et al.—"Cultural values convert physical phenomenon to experiential phenomenon" (Blesser and Salter, 2007)—and aural architectural analysis, which includes perceptual and cultural aspects in addition to the physical aspects, provides a more holistic approach to understanding the auditory experience. Since worship spaces require acoustic environments that support spiritual needs and enhance faith (Kleiner et al., 2010), such spaces offer an example in which the human experience is dependent on the acoustic environment. A detailed review of the aspects of aural architecture that shape such experience in worship spaces has been discussed (Algargoosh, 2016) including the physical, perceptual, and cultural aspects. In addition, worship spaces are buildings in which cultural aspects are highly influential in space design and usage. Researchers claim that the design of worship spaces has responded to the acoustic needs of the worship activity; the architecture of Catholic churches, as an example, has changed on grounds of change in liturgy, while the design of Orthodox churches changed very little because liturgy that is practiced in those spaces did not undergo similar changes (Pentcheva, 2011). The above reasons make worship spaces an ideal building type to adopt as a case study to investigate how acoustic environment influences human experience and emotions.

Many worship activities involve musical performance, and music has always been associated with emotion. Emotion is a complex topic that has been defined differently by several researchers; however, scholars agree that the emotional response is usually associated with physiological actions such as sweat, flush, muscle tension or relaxation, and change in heart rate (Dawson et al., 2007).

Researchers have extensively studied the emotional impact of music and developed methods including psychological and physiological measures to assess it (Jaimovich, 2013; Jaimovich et al., 2013; Zenter and Eerola, 2010). Since it is well established that sound can create an emotional effect, and since buildings' interiors manipulate sounds through architectural design, is it possible for spaces to enhance the emotional impact created by the sounds performed in them?

While spaces cannot create an emotional experience, their architectural features can affect the physical acoustic aspects of space—such as sound amplification, filtering, enveloping, note blending, and source location manipulation. Such influences enhance the emotional experience, and in many cases, increase the intensity of the emotional impact (Blesser and Salter, 2007; Lubman, 2004). For example, Hale stated that the resonance effect of some historic buildings influences both the state of mind and the emotions; this can appear as a physiological effect (e.g., change in heart rate, breathing rhythm) (Hale, 2007). Another example of this relationship is how the physical environment can influence the characteristics of sound by creating an echo. The echo, which contains multiple sound reflections from the architectural surfaces, makes identifying the sound source difficult—the sound source may appear to be invisible, which influences listeners' emotions (Pentcheva, 2011) (Hale, 2007).

Thus, understanding the impact of architectural design on experience and emotions is essential to improve the conventional method of acoustic design in worship spaces, which tends to focus on the physical measurements of acoustics, neglecting the critical role cultural aspects play in impacting occupants' spiritual experience.

By considering the cultural aspects, this research will contribute to efforts that many researchers and governments have started to take to preserve and reconstruct the acoustics of buildings with social or cultural significance. Oral traditions and rituals are included in the domain of intangible cultural heritage by UNESCO (UNESCO, 2003), but preserving such oral traditions cannot be achieved without considering the acoustics of the spaces that shaped the sound. As an example, worship would be experienced in a significantly different way listening to the ritual performance recorded in a studio with minimum sound reflection as compared to a recording made in the same spaces in which the same rituals are performed. Considering that buildings work as extensions of both human voices and musical instruments by creating echoes and reverberations, researchers assert that the acoustic environment produced by architectural design should be considered as part of the intangible cultural heritage (Álvarez-Morales et al., 2016; Elicio and Martellotta, 2015).

There are, thus, a growing number of studies that aim to both preserve and reconstruct the acoustics of historic buildings (Girón et al., 2017), with a large focus on worship spaces due to their significant acoustics. Pentcheva et al., for instance, have evaluated in detail the acoustic characteristics of the Hagia Sophia, in Istanbul—a worship space known for its unique acoustics—recording its sound signature and producing a model which is then applied to a dry recording, whereby chants can be heard as if they were performed within Hagia Sophia itself (Pentcheva, 2011). Other researchers are attempting to produce virtual reconstructions of the acoustics of spaces that no longer exist (Suárez et al., 2016). The research reported here takes these efforts a step further by including visuals of the buildings to enhance their virtual representation, in addition to using binaural recording instead of sound simulation.

While previous research studies some aspects of the impact of the acoustic environment on the occupant's experience, only a few studies investigated possible emotional impact. The previous research was also based on simulated acoustic environments and linked to general emotional impact and did not necessarily explain details about the experience and the type of elicited emotions. The current research offers a comprehensive approach that allows for a deeper understanding of auditory experience by studying the emotional impact of acoustic environments and how it shapes the auditory experience using a mixed-methods approach. Since research on the acoustics of worship spaces from diverse cultures is limited (Guillebaud and Lavandier, 2020), we included two types of worship space in the study to it examine links to the cultural background in terms of familiarity and associations surrounding the sound and acoustic environment.

The present study provides an integrated approach (convergent mixed method research design) merging qualitative and quantitative methods to address the first research question of this dissertation stated in Chapter 1, which aims to study how the acoustic environment influences human experience and impacts emotions, through answering the following sub-questions:

1) Does the acoustic environment enhance the emotional impact created by sound?
2) Does the intensity of the emotional impact differ based on the characteristics of the acoustic environment created by the architectural design?
3) Does the intensity of the emotional impact differ based on the cultural background and familiarity of the sound and acoustic environment?

After analyzing the auditory experience and emotional impact of the studied acoustic environments in this chapter, Chapter 3 will develop a method to analyze the frequency domain of spaces with complex geometries such as worship spaces, and Chapter 4 will focus on applying the developed method to the case studies, studying their acoustic parameters, and analyzing the links between their acoustic characteristics and the reported emotional impact.

2.2 Methodology

2.2.1 Experimental design

2.2.1.1 Stimuli preparation

This study builds on the method developed by Schroeder et al. (Schroeder et al., 1974), who conducted a subjective evaluation to compare the acoustic qualities of different halls and determine the objective parameters associated with preference. Their method has been the foundation for many studies in subjective evaluation of room acoustics. It involved recording an orchestra in an anechoic chamber, then playing the recordings in various concert halls and recording the signals using binaural technology (two microphones installed in a dummy head), and finally playing back the binaural recordings to the subjects and asking them about their preference. We built upon the original method with modifications that address the particular focus of the research questions posed in this study using advanced virtual reality technology including audio and visuals.

Including the visuals is a unique feature of this study that provided a more realistic experience of listening to the sound in a worship space since researchers have demonstrated the connection between visual and audio perception and explained how the conflict between what we hear and what we see can create a sense of discomfort (Blesser and Salter, 2007; Cox, 2014; Hunter et al., 2010; Tajadura-Jiménez et al., 2010), which highlights the importance of including visuals when studying the effect of sound stimuli.

Consequently, the goal of this study was to analyze the acoustic experience with the presence of the visuals because this dissertation deals with understanding the acoustic environment shaped by the architectural features in contrast with audio manipulated by sound systems. To illustrate, there are many examples of contemporary worship spaces that neglect the acoustics in the design process or eliminate sound reflections and depend heavily on sound systems to create artificial reverberation. Thus, this research aims to illustrate the significance of considering the architectural elements and their role in the acoustic experience. Hence, the goal is to study the acoustic experience with the presence of the visuals, and to ensure that the focus was on the acoustics, the questions asked to the participants were related to the acoustics as it will be shown in the questionnaire explanation in section 2.2.1.2. In addition, to control for the impact of the visuals as suggested by (Galiana et al., 2016), the visuals were identical for each dry and wet recording associated with the same building.

For the present research, four religious buildings with historical and social significance to the community in the Detroit metropolitan area were selected, including two mosques and two churches (Fig. 2.1). The selection of two types of worship spaces is due to our interest in investigating the role of the cultural aspect, which is an integral part of aural architecture. The buildings included A1 - the Islamic Center of America (volume ±5500.26 m^3), A2 - the Islamic Center of Detroit (volume ±1888.801 m^3), B1 - New Bethel Baptist Church (volume ±7560 m^3), and B2 - Breakers Covenant Church International (volume ±15114 m^3).

Fig. 2.1 Interior views of the studied buildings. Top-left: Islamic Center of America (A1). Top-right: Islamic Center of Detroit (A2). Bottom-left: New Bethel Baptist Church (B1). Bottom-right: Breakers Covenant Church International (B2).

We played dry recordings of Quran recitations in the mosques and Christian hymns in the churches. Then, we recorded the played sounds again using a binaural dummy head (B1-E with BE-P1 omnidirectional microphones with a sensitivity of -28 ± 3dB at 1kHz and 80 dB signal-to-noise ratio at 1kHz) and collected 360-degree visuals of the buildings' interiors using Samsung Gear 360 4K (Spherical VR Camera with dual 8.4MP CMOS sensors and dual f/2.2 aperture fisheye lenses). The length of each stimulus was ±75 s, and the reverberation time T30 at 1000 Hz was < 0.4 seconds for the dry recordings and ≥ 1.7 seconds for the wet recordings (A1: 2.1 s, A2: 1.7 s, B1: 2.4 s, B2: 2.7 s).

2.2.1.2 Experimental configurations

The flowchart in Fig. 2.2 shows the research design, which is the section perceptual and cultural aspects in the overall research flowchart (Fig. 1.8) in Chapter 1.

We adopted a within-subject experimental approach for playing back the scene both audio and visual, to the participants using headphones and a wireless virtual reality headset (Oculus Go) with LCD Display 1280x1440 Resolution 60 Hz Refresh Rate.

The study was approved by the authors' institution Review Board. It included 20 participants (9 males and 11 females) from diverse cultural backgrounds (i.e. religious affiliation, nationalities, etc.) and aged between 20 and 40 years old. The sample size was calculated using (G*Power 3.1.9.7) software with statistical power $(1-\beta) = 95$, $\alpha = 0.05$ and effect size of 0.8, and was also based on the studies (Guan et al., 2020; Hunter et al., 2010; Luck et al., 2008; Schroeder et al., 1974; Tajadura-Jiménez et al., 2010). Each participant experienced eight scenes: a dry and a wet recording for each of the four buildings. We randomized the order of buildings' recordings as well as the order of the dry and wet recordings for each building.

Data collection included a questionnaire and physiological measurements. After each scene, we asked the participants about their experience, using self-report evaluation as indicator of the emotional impact on the listener of the combined music and space acoustics. The self-report included asking the participants to describe their auditory experience while listening to the recordings and to rate the intensity of the emotional impact (broken down into spiritual and calming) they felt listening to each one (1. None, 2. A little, 3. Moderately, 4. Quite a bit and 5. Highly). We selected spiritual and calming emotion categories because they are both linked to the spiritual experience in the literature, and they represent different levels of emotional arousal (the first is associated with high and the second with low arousal) (Zenter and Eerola, 2010).

We also asked the participants to select words that best represented their experience from the following list: sad, tense, nostalgic, spiritual, inspired, cheerful, and thrilled; the order of the words was randomized.

Next, we asked the participants to report their familiarity with Islamic recitation and with Christian hymns (1. Not familiar, 2. Familiar, 3. Very familiar). We also asked them to report the frequency with which they attended events at which they listened to similar religious chants as an indicator of familiarity with similar acoustic environments by selecting from the following list: (1. Never, 2. Rarely, 3. Occasionally, 4. Frequently).

In addition, since previous research on the emotional effect of music suggests that there are aspects that depend on the cultural background of the individual and their past association with such music alongside some common aspects of human experiences that result from listening to a piece of music (Deutsch, 2013), we included an open-ended question that asked the participants to describe their experience freely in their own words, to collect more details about the individual differences in the experience.

In addition to the questionnaire, we collected physiological measurements using a wristband biometric device (E4-Empatica). It includes two sensors; 1) a photoplethysmography (PPG) sensor that measures blood volume pulse (BVP) to calculate heart rate response (HRR) and 2) an electrodermal activity (EDA) sensor that measures sympathetic nervous system activity, which is linked to psychological arousal. This sensor provides the data for the electrodermal response (EDR), with a range of (.01 to 100) uS. The sampling rate was 1 Hz for HRR and 4 Hz for EDR (Garbarino et al., 2014).

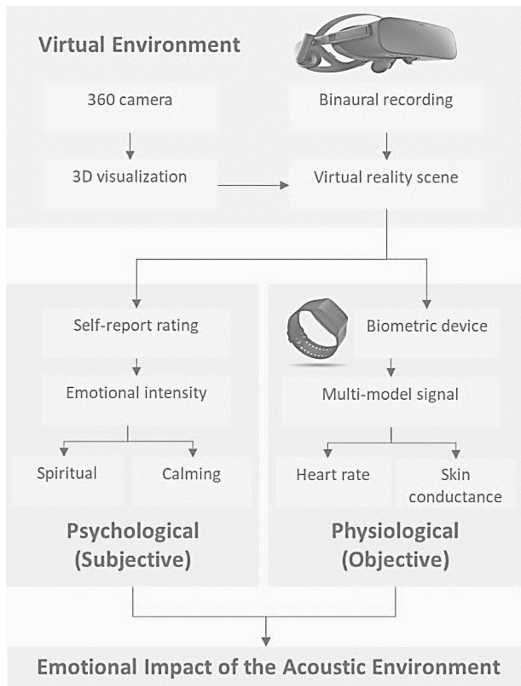


Fig. 2.2 Research design

Using these methods, this research examines the individual aspects of human experience that can result from the acoustic features of a space when using the same piece of music in both cases; dry and wet recordings.

2.2.2 Data analysis

A convergent mixed-methods approach (Creswell and Plano Clark, 2011) was adopted, merging quantitative and qualitative analysis. The quantitative data included the participants' self-report ratings and the physiological responses, while the qualitative data included the participants' self-report descriptions of their experiences while playing the recordings.

2.2.2.1 Data reliability and preparation for the physiological response measurement

1) Heart rate response (HRR)

To determine the most reliable section of the recording during the sessions, which lasted ±75 seconds, in the HRR analysis and to examine heteroskedasticity in the data, we conducted a second-order deviation threshold analysis following Schubert's approach (Schubert, 2007; Zenter and Eerola, 2010). The reliability evaluation involved calculating the first standard deviation (SD1) of sample-by-sample HRR, then calculating the mean of SD1 and SD2 from this mean, which is called the second-order standard deviation. Then, a threshold of significance was calculated based on the following equation:

$$\text{Threshold} = M - [K * SD2], \qquad \text{Eq. (1)}$$

in which M is the mean of SD1; SD2 is the second-order standard deviation; and K is a coefficient that is less than or equal to one. K can be adjusted based on the principle of evaluation conservation: the larger the number, the more conservative the evaluation. For this research, we calculated the reliability threshold considering that K = .5. After calculating the threshold, a sample-by-sample HRR was inspected to determine which section best satisfied the threshold limit. Based on the analysis, we selected a section that starts after 20 seconds from the onset and lasts for 30 seconds. The selected length of time is sufficient to capture possible physiological response, based on previous studies (Park et al., 2018).

Furthermore, we conducted an additional analysis after standardizing the initial heart rate and calculating the increase and decrease of HRR based on the initial measure for each session. To minimize the possible autocorrelation effect, we conducted another analysis after down-sampling the data, similar to the process described in previous research (Luck et al., 2008). For this study, the data were down-sampled by selecting a sample every three seconds.

2) Electrodermal response (EDR)

To assess the reliability of the EDR data, we inspected the results to ensure that there was no value of less than .01 uS, which is the minimum EDR valid value (Garbarino et al., 2014). Accordingly, we excluded the data for participant 19 from the EDR analysis after finding results of 0 uS in one of the sessions, which might have been the result of a movement that caused the electrodermal activity sensor to disconnect for a short period.

Researchers used electrodermal tonic and phasic response as an indicator of the existence and intensity of emotional impact (Braithwaite et al., 2013). The electrodermal response is dependent on many individual variables, which include the basic tonic level (Jaimovich, 2013). We found a significant difference in responses among participants. For example, the responses for the eight sessions within one participant might be different but cluster around a low EDR, while they might cluster around a high EDR level for another. Since EDR is sensitive to the participant's hydration level (Garbarino et al., 2014), this could have been the reason for the vast difference in EDR between subjects. Since this research is a within-subject study, the data were standardized following the guidelines of previous studies (Bradley and Lang, 2007; Braithwaite et al., 2013), using the following equation:

$$EDR_{x2} = [EDR_{x1} - EDR_{min}] / [EDR_{max} - EDR_{min}], \qquad \text{Eq. (2)}$$

where EDR_{x1} is the electrodermal response for the participant at a particular sample, EDR_{x2} is the electrodermal response for the participant after standardization, and EDR_{min} and EDR_{max} are the minimum and maximum electrodermal responses for the same participant over all eight sessions.

2.2.2.2 Quantitative data

The quantitative data for this study component consisted of self-report, heart rate response (HRR), and Electrodermal response (EDR).

The independent variable was represented in the acoustic characteristics added to the base case (dry recording), which resulted in the wet recording. The dependent variables included the ratings in the self-report and the heart rate and electrodermal activity for the physiological response. Using R-studio software, we conducted Shapiro–Wilk normality tests and found that the data did not follow a normal distribution. Thus, we selected non-parametric tests, including Wilcoxon Rank-Sum tests, with paired comparisons because the samples were not independent (since the same participants listened to the dry and wet recordings). Then, we used Kruskal–Wallis tests to compare the self-report ratings for all the buildings and then repeated the same test for the physiological responses. In addition to the statistical analysis, which provided an interpretive approach to the physiological results, we adopted a descriptive approach that included inspection of sample-by-sample central tendency as well as individual response inspection to examine the dynamics and patterns of the physiological response as an indication of emotional impact, as recommended by Schubert (Schubert, 2010).

The study also included thematic analysis of keywords representing selected emotions from the survey. The number of selections of each word was compared between dry and wet recordings and among the four buildings.

2.2.2.3 Qualitative data

We analyzed the qualitative data using thematic analysis (Guest et al., 2012). After reading the participants' descriptions of the dry and wet recordings of all the buildings (160 answers), we identified more than twenty themes emerging and assigned a code for each one. Then, we grouped the themes based on the general concepts that they share, creating three main themes. Next, we gathered the participants' answers within each theme and placed them in two groups; the dry recordings and the wet recordings to examine the respective effects of listening to the dry and wet recordings across all buildings. Later, we analyzed the data within each theme to highlight the most critical factors that the participants explained.

Lastly, we combined quantitative and qualitative data for possible new insights (Table A in the Appendix), and we used the qualitative data to explain some of the results from the quantitative data.

2.3 Results

2.3.1 Quantitative results

2.3.1.1 Self-report

The results from the self-reports showed that the average rating for spiritual emotion category in dry recordings in each of the buildings ranged between 2.4 and 2.6 (with the lowest possible value at one and the highest at five). The average ratings for the wet recordings showed larger variation between the buildings than ratings of the dry recordings. Since the average ratings of the dry recordings of the buildings were very close, this confirms the control of the impact of the visuals in the ratings and indicates that the variation in the ratings of the wet recordings was mostly based on the acoustics.

In general, the ratings of the wet recordings were higher than the dry recordings in all buildings (Fig. 2.3). When investigating each individual rating, we noticed that the number of lower ratings for wet recording for each building was A1: 1, A2: 2, B1: 3, B2: 3, meaning that only (11.25%) of the responses in all buildings rated the wet recording lower than the dry recording.

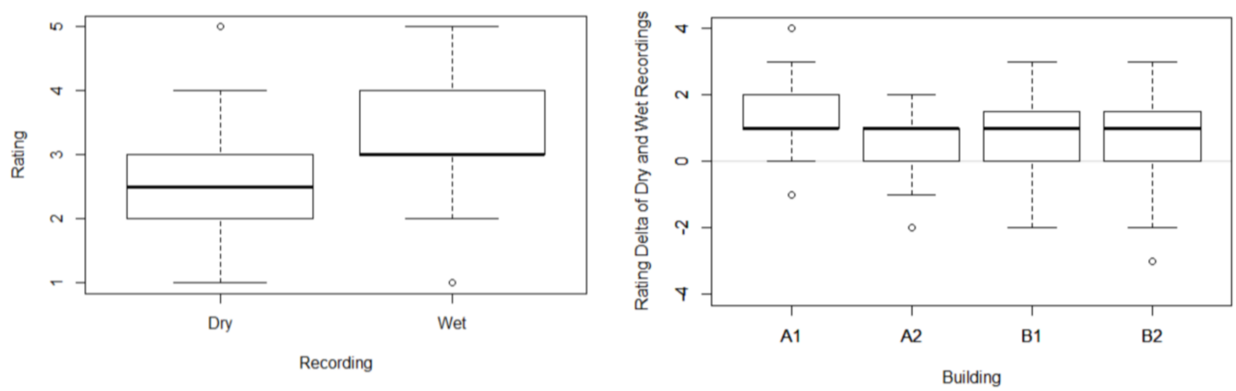


Fig. 2.3 Boxplot of the ratings. Left: the intensity of spiritual emotions for wet recordings for all buildings combined. Right: the delta of ratings of the intensity of calming emotions for each building

Comparing the ratings of the intensity of spiritual emotions while listening to the dry and wet recordings using Wilcoxon Rank-Sum test showed significant differences for all buildings except B2 (A1: p-value < 0.001, A2: p-value < 0.05, B1: p-value < 0.05, B2: p-value > 0.05). However, comparing the ratings of the intensity in the calming emotion category did not show significant differences except for A1 (A1: p-value < 0.01, A2: p-value > 0.05, B1: p-value > 0.05, B2: p-value > 0.05).

The result of comparing the self-report ratings of wet recordings in all buildings using the Kruskal–Wallis test was > 0.05 for spiritual and $p < 0.05$ for calming (Fig. 2.4). A1 received the highest rating for both spiritual and calming emotions.

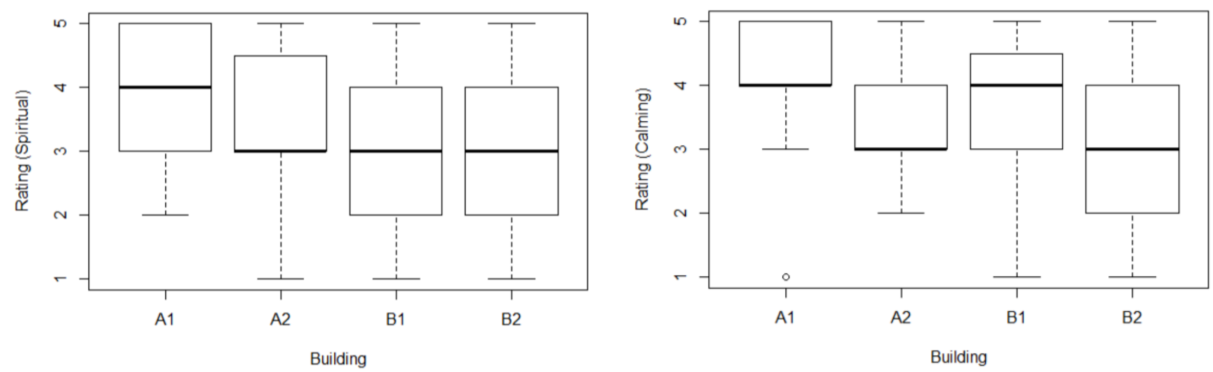


Fig. 2.4 Boxplot of ratings of the intensity of spiritual (left) and calming (right) emotions for the dry and wet recordings for each building

1) Familiarity with the recording and worship space

In terms of familiarity with the recording content, the results for the Islamic recitation were (not familiar = 50%, familiar = 20%, very familiar = 30%), and with the Christian hymn (not familiar = 15%, familiar = 45%, very familiar = 40%). The results for familiarity with the space and acoustic environment showed that the participants' frequency visiting the same kind of worship space for mosques was (never = 50%, rarely = 25%, occasionally = 0%, frequently = 25%), and for churches (never = 35%, rarely = 30%, occasionally = 30%, frequently = 5%). We conducted a correlation analysis to check possible bias in the data, and we did not find any significant correlation between familiarity and demographic information of the participants, including gender and age group.

2) Ratings of wet recordings based on familiarity with space

The results of the familiarity questions, which were intended to address cultural background influence on emotional impact, showed that participants who reported being very familiar with the recorded content (Islamic recitation/Christian hymn) reported a higher level of emotional impact (Fig. 2.5); results were similar for participants familiar with the space/acoustic environment.

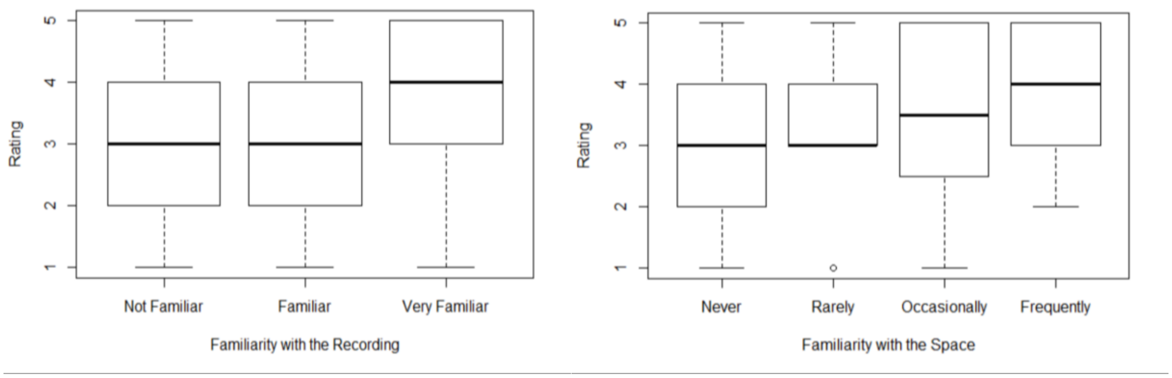


Fig. 2.5 Boxplot of the ratings of the intensity of spiritual emotions based on familiarity with the same kind of religious recording (left), and familiarity with the same kind of worship spaces (right)

3) Emotion keyword results

The results of the keyword self-report showed that participants reported negative emotions such as "sad" and "tense" when listening to dry recordings more often than when listening to wet recordings, as seen in Fig. 2.6. Conversely, positive emotions such as "inspired," "cheerful," and "thrilled" appeared more while listening to the wet recordings. Spiritual emotion showed the most significant difference in number of times reported after listening to dry and wet recordings, respectively with the higher number associated with wet recordings.

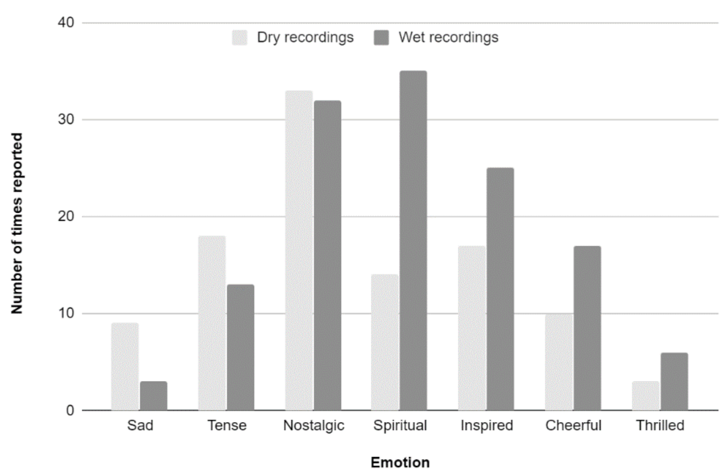


Fig. 2.6 Bar-chart of the cumulative number of times each emotion keyword was reported by participants while listing to the dry and wet recordings in all buildings.

When analyzing the number of times the participants reported the same keyword (spiritual) while listening to the wet recordings of each worship space, the results showed that they reported the spiritual emotion the most significant number of times while listening to the wet recordings of A1 (Fig. 2.7).

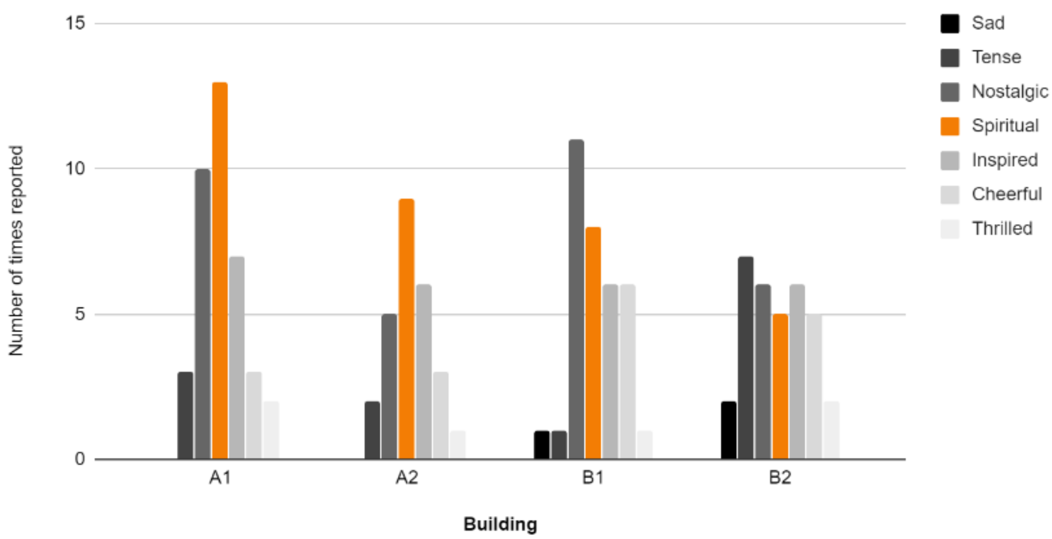


Fig. 2.7 Bar chart of the number of times each emotion keyword was reported by the study participants while listing to the dry and wet recordings in all buildings separated.

2.3.1.2 Physiological response

1) Heart rate response (HRR)

The results for the physiological response sample-by-sample central tendency showed that the average heart rate of the participants while listening to the wet recordings was in general higher than while listening to the dry recordings.

Comparing the participants' heart rates while listening to the dry and wet recordings using Wilcoxon Rank-Sum test showed significant differences for all buildings (A1: p-value < 0.05, A2: p-value < 0.05, B1: p-value < 0.001, B2: p-value < 0.001); approximate median differences in

HRR were A1: 2, A2: -1, B1: 5, B2: 3. These results represent the most reliable section of session time, which starts 20 seconds after the beginning of the session and lasts for 30 seconds.

The results for of the standardized initial start heart rate for the whole session while listening to the dry and wet recordings, analyzed using the Wilcoxon Rank-Sum test, were also significant (A1: p-value < 0.001, A2: p-value < 0.001, B1: p-value < 0.005, B2: p-value < 0.001), and after down-sampling (A1: p-value < 0.005, A2: p-value < 0.05, B1: p-value > 0.05, B2: p-value < 0.05).

When comparing the HRR while listening to the wet recordings of each building for the same selected time section, the Kruskal–Wallis test showed a significant difference (p-value < 0.001), with medians ranged from highest to lowest as follows: B2 > B1 > A2 > A1.

2) Electrodermal response (EDR)

Comparing the participants' mean skin conductance tonic level in each session while listening to the dry and wet recordings using the Wilcoxon Rank-Sum test showed significant differences for A1 and B2 (A1: p-value < 0.001, A2: p-value > 0.05, B1: p-value > 0.05, B2: p-value < 0.001). The results of comparing EDR while listening to the wet recordings of each building using the Kruskal-Wallis test also showed significant difference (p-values < 0.001), with medians ranged from highest to lowest as follows: A2 > B1 > B2 > A1.

3) Familiarity with the recording and the worship space

The results of the familiarity questions, which address the influence of cultural background on emotional impact, showed that participants who reported being very familiar with the recording content or space responded with a higher HRR. Participants who reported being very familiar with the recording content responded with a heart rate median that was ±10 points higher than that of the group who reported being unfamiliar. However, there was no significant difference between the HRR of participants with no and moderate familiarity (Fig. 2.8).

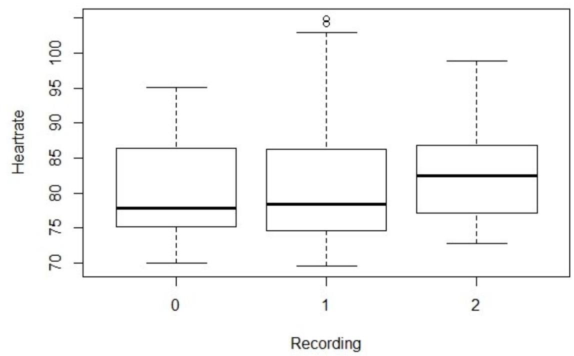
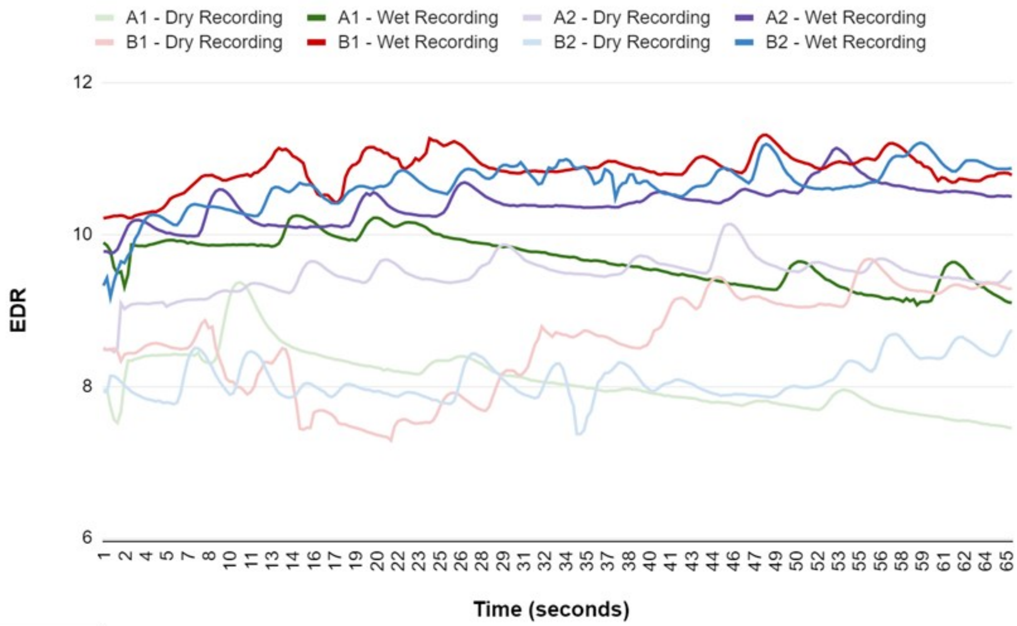


Fig. 2.8 Boxplot of the heartrate response based on familiarity with the same kind of worship spaces

The results on familiarity with the space and acoustic environment showed that participants who reported they never or rarely visited a similar religious space responded with a heart rate that was higher than in those who occasionally visited, by ±4 points. Meanwhile, participants who visited frequently responded with a heart rate close to those who never or rarely visited such a space.

In addition to the previous general interpretations, the results showed particular cases that did not represent all the participants but were still worth investigating in terms of the relationship between familiarity and physiological response. For example, Fig. 2.9 shows the EDR for participant 8, who reported being familiar with both Islamic recitation and Christian hymns but never visited a mosque or a church. The EDR for this participant, while listening to the wet recording of each building, was higher than while listening to the dry recordings. In another case, participant 3 reported to be unfamiliar with Islamic recitation but familiar with Christian hymn, and also never visited a mosque but had been in a church. The EDR of this participant, while listening to the wet recordings of the mosques, was higher than while listening to the recordings of the churches.



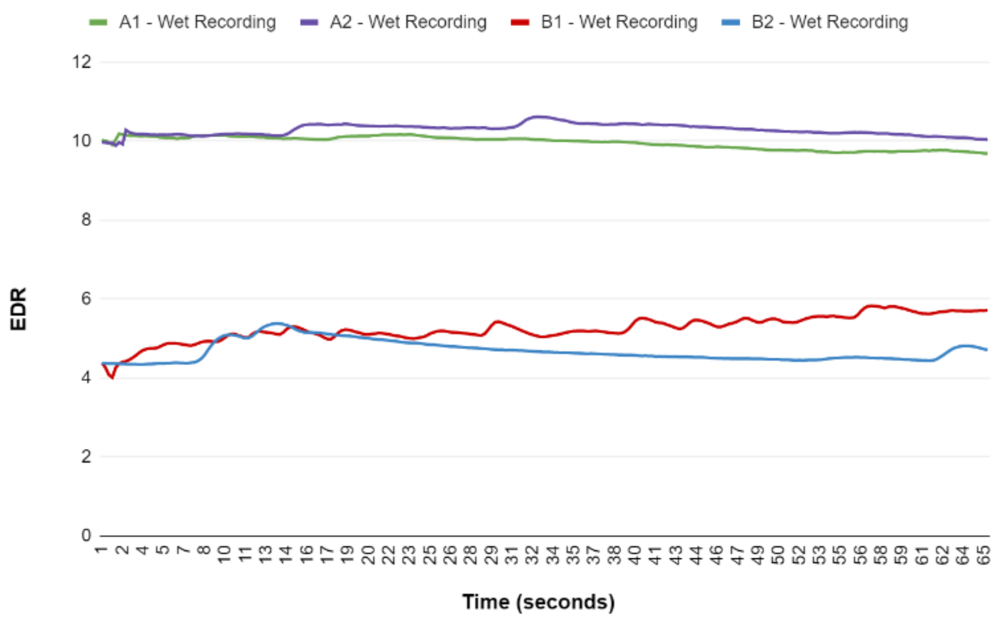


Fig. 2.9 Top: Skin conductance response of participant 8 during the dry and wet recordings of each building. Bottom: Skin conductance response of participant 3 during the wet recordings of each building.

Another observation that can be analyzed further is the similarity in the patterns of HRR while listening to the dry and wet recordings despite the difference in their level (Fig. 2.10 & Fig. 2.11).

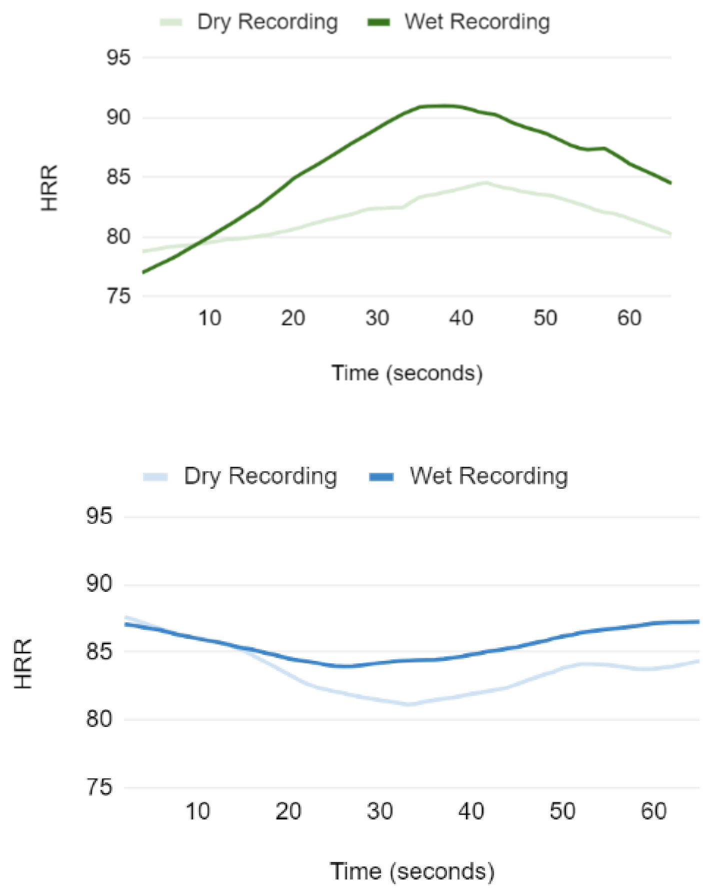


Fig. 2.10 Top: The heart rate response of participant 20 during the dry and wet recordings of A1. Bottom: The heart rate response of participant 4 during the dry and wet recordings of B2

Moreover, analyzing the dynamics of HRR while listening to the dry and wet recordings showed some cases that encourage further investigation. For instance, as shown in Fig. 2.11, the HRRs of participant 10 and participant 7 demonstrate an increase after the initial time while listening to the wet recordings, while there was less or no increase while listening to the dry recordings. Also, the HRR of participant 1 showed a broader dynamic range while listening to the wet recordings, while it was more stable while listening to the dry recordings.

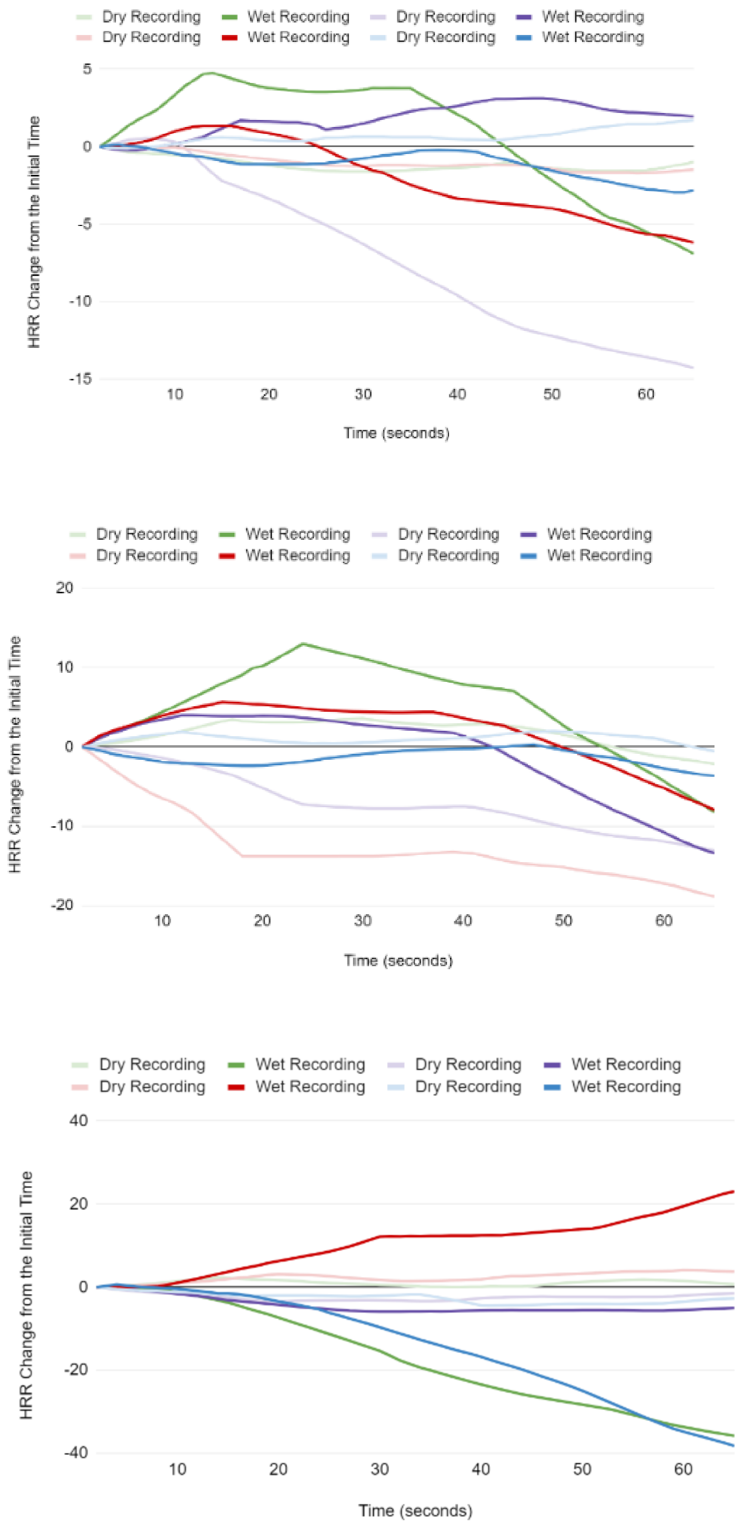


Fig. 2.11 The dynamics of heart rate response of during the dry and wet recordings of all the buildings. Top: participant 10. Middle: participant 7. Bottom: participant 1

2.3.2 Qualitative results

2.3.2.1 Thematic analysis

Table 2.1 shows the themes that emerged from the analysis—"acoustics," "perception," and "emotions"—and their content.

Table 2.1Comparison of the experience described by the participants while listening to each of the dry and wet recordings

Theme	Dry recording	Wet recording
Acoustics	Flat Too close/ inside the head/intimate Puts focus on the musicality	Amplified Echoey
Perception	The sound does not fit the space Seems to come from a sound system Unreal Disconnected from the visual	Fits the space Inviting to participate Hard to locate Surrounding Immersive Spacious
Emotions	Annoying Sad Calming Less relaxing Lonely Uncomfortable	Contented Emotional Peaceful/ relaxing/calming Happy/cheerful/uplifting Tense Nostalgic Spiritual/holy/sacred Mysterious Awe-inspiring Hopeful

In general, the analysis showed that the participants focused more on describing emotions (i.e., spiritual, calming, nostalgic) when listening to the wet recordings, and more on describing acoustics and perception while listening to the dry recordings (e.g. disconnection between audio and visual). The following provides more details about each of the themes that appeared, based on the participants' descriptions:

1) Acoustics

Reflecting the absence of influence of space acoustics in the dry recordings, the participants described their experience as flat, inside the head, and too close and intimate, which made many of them uncomfortable. Many of the participants focused on the musicality of the piece and the performance errors, which they did not notice while listening to the wet recordings. In the wet recordings, they described the sound as echoey and amplified. Some also mentioned that the echo added more harmony to the piece; as participant 17 described it, "because of the echo—although they are not very good singers—I felt more harmonized about the songs." In one case, the subject thought that there was a musical instrument in the wet recording. Others thought that the speed of the performance was different, as participant 5 mentioned: "This singer was slower and he was taking time while praying while the first was more rushed. I felt I was praying with him. I felt very spiritual." In some cases, the participants thought that the dry and wet recordings included different pieces, which calls for further research on the possible effects on musical pieces of reflection-based sound illusions.

2) Perception

The participants described their experience during listening to the dry recordings as unreal, in addition to mentioning the disconnection between audio and visuals. Some felt that the dry sound was coming from a loudspeaker and that it did not fit the space. In contrast, when they listened to the wet recordings, they described the sound as surrounding them, which made it hard to localize the sound source, as it seemed to be coming from everywhere. They also mentioned that the echo made it feel spacious, and described the experience as immersive, providing a sense of belonging and inviting to participate. However, some mentioned that the wet recording of A2 did not fit in with the visuals and felt fake. They explained that the interior of A2 does not represent what that they would expect a mosque to look like, as it does not have the traditional architectural features; as participant 13 mentioned: “it felt fake because of the lower ceiling, and it had the echo effect.”

3) Emotions

While listening to the dry recordings, the participants expressed feeling lonely and sad, and in some cases, uncomfortable and annoyed, although some found it calming. Conversely, the majority described their experience with the wet recording as more calming and spiritual, and in many cases, nostalgic. Although the participants had diverse cultural backgrounds, they mentioned that listing to the wet recording brought memories of religious events even when listening to unfamiliar chanting from a different religion. Some of the participants expressed intense although varied emotions (uplifting, awe-inspiring, mysterious, and in one case, horrific).

In addition to the previously analyzed quantitative and qualitative results, Table A in the Appendix shows additional quantitative and qualitative results for each building, providing more details and insights about the participants’ experiences.

2.4 Discussion

This study has adopted an integrated, mixed-methods approach that included collecting self-report and physiological responses to investigate the emotional impact of acoustic environments, using worship spaces as a case study as they allow for additional exploration of the role of cultural background in the intensity of the emotional impact.

2.4.1 Self-report and Physiological Response

Self-report is a post-performance evaluation, while physiological measurement is considered a continuous (time-dependent) response. Both self-report and physiological data have advantages and disadvantages; combining them allows us to take advantage of the strengths of each method to provide a robust understanding. Although physiological measurements can be complicated to analyze due to potential effects of other factors, unrelated to the stimulus, they allow emotions to be captured that might not be evident to the participant or might be difficult to express. In addition, a physiological response is an unconscious process that can limit the bias that might accompany self-report evaluation (Hodges, 2010). In any case, it provides rich information about dynamic changes in emotional state during the listening session. Heart rate and skin conductance signals are the most commonly used physiological measurements to study emotional impact in response to music (Hodges, 2010). For more reliable results, researchers recommend a multi-signal approach that combines more than one physiological response (Bradley and Lang, 2007; Hodges, 2010). A combination of heart rate and electrodermal responses has previously been used by researchers to study the human perception of built environment characteristics such as façade and sunlight pattern geometry (Chamilothori et al., 2019), noise (Park et al., 2018), and thermal-acoustic comfort (Guan et al., 2020). Thus, a multi-signal approach using HRR and EDR was selected for this study. The increase in heart rate and electrodermal activity is an indicator of an increase of emotional arousal, however, additional factors need to be considered to understand the type of elicited emotion (Hodges, 2010). To illustrate, changes in the tonic level of EDR is an indicator of strong emotional response regardless whether it was positive or negative (Dawson et al., 2007), which is another reason for the importance of combining physiological measurements with self-report.

The results summary in Table B shows that wet recordings were generally rated higher in terms of intensity of spiritual emotions than dry recordings. This result was confirmed by the physiological response data, using both HRR and EDR. The average sample-by-sample HRR for the wet recordings was higher than for the dry, in general. Additionally, studying the dynamics of the HRR showed that heart rate continues to increase above the initial point for at least the first 20 seconds with the wet recording, to levels larger than with the dry recordings. The statistical analysis also showed a significant difference between HRR during the dry and wet recordings. However, as previous researchers have stated, care should be taken when interpreting such results due to possible auto-correlation because the selected statistical analysis assumes independence of the data points (McAdams, 2004). Although using a single value, like the mean of each session in the statistical analysis, will eliminate auto-correlation, it might not be ideal for analyzing HRR in this study, as it will result in loss of dynamic changes in response during the session and might cause misleading results. Therefore, this research adopted the down-sampling approach (Luck et al., 2008) to minimize the possible impact of auto-correlation, and even after this modification, the results showed a significant difference in HRR while listening to the dry vs. the wet recordings.

Furthermore, the comparison of wet recordings of the four buildings showed a statistically significant difference in physiological response and self-reported rating of the emotion “spiritual,” but was less significant for the emotion “calming.” Since the acoustic environment of each building caused a different response, this result encourages further exploration of the contribution of architectural design in creating acoustic environments that impact the intensity and possibly the type of emotional impact created by sound. For example, considering that each of the buildings has a specific reverberation time based on its architectural design, and given that researchers stated that varying the length of the reverberation time using simulation models is shown to evoke different emotional responses (Västfjäll et al., 2002), studying the architectural elements associated with specific emotional responses will provide guidance for designing spaces that enhance the occupants' experience.

2.4.2 Emotion Keyword analysis

In addition, the analysis of keywords showed that wet recordings evoked more positive emotions than dry recordings. This result was confirmed by the participants' descriptions of their experiences in the qualitative analysis. Positive emotions mentioned, such as calming, uplifting, awe-inspiring, and, mostly, spiritual dominated while listening to the wet recordings. Conversely, a large number of participants described a sense of disconnection between the sound and space when listening to the dry recordings; this conflict between visual and aural cues causes a sense of discomfort (Blesser and Salter, 2007). Looking at the visuals of a grand space and listening to a sound recorded in an anechoic chamber, without reflection, can create confusion. The opposite can also create a similar effect. Two participants mentioned while listening to the wet recording of A2, which was a mosque with rectangular plan and flat low ceiling, that they felt the sound did not match the space, although it had been recorded in that space. They explained that the sound was echoey, which is what they would expect from a grand mosque with typical architectural designs. This point draws attention to the possibility of a similar effect that can result from neglecting the acoustics in the architectural design process and using artificial reverberation excessively or depending on sound systems to fix acoustic defects in a renovated space. Thus, even if the sound might be improved, it might not match the expected acoustic environment based on the visual attributes of the architectural characteristics.

Furthermore, the keyword analysis revealed that participants reported multiple emotions for the same session. For example, although the word "spiritual" was reported alone in many cases, it was also accompanied by "inspired" in some cases and by "tense" in others, which may provide insight into some variations in the reported intensity of emotion and the level of the physiological response. To illustrate, the building for which the highest intensity of spiritual emotional impact was reported was A1; however, the one that showed the most significant results for physiological response was B2. When looking at the keyword analysis, we notice that for A1, the word "spiritual" was reported 13 times while it was reported only 5 times for B2. Also, when we look at Table A, we notice that the combination of emotions reported for each of these two buildings is vastly different. We mentioned earlier that physiological response provides an indicator of emotional arousal (Hodges, 2010) without giving detailed information on the relevant emotional categories. Emotional arousal includes emotions such as excitement, inspiration, and even tension in addition to spirituality, and these emotions vary in terms of their level of arousal, with spiritual emotions generally lower than excitement. Physiological response might be an indication of such a combination of emotions, and the level of physiological response to B2 might be explained by other high arousal emotions, as shown in Table A. This also calls for consideration of the impact of acoustics to amplify the intensity of the emotion based on the background and memory related to it. For example, the participant who had a feeling of horror mentioned that the echo was similar to (one in) horror movies. In contrast, another participant mentioned that the wet recording brings back memories of worship places.

2.4.3 Familiarity with the recording and the worship space

The analysis of the impact of the cultural background revealed that high familiarity increases the intensity of the emotional impact based on the participants' self-report and the heart rate response.

The self-report showed that participants who were very familiar with the recording and space rated spiritual emotion intensity higher than all others. On the other hand, the physiological response also showed that participants unfamiliar with the recording responded similarly to those who said they were “very familiar” with the material, and both responded higher than those who said they were “moderately familiar”. This result can also be explained: the high physiological response could be a result of high arousal emotions other than the spiritual emotions mentioned above, such as excitement caused by surprise, or tension caused by unfamiliarity.

The additional analysis of the individual responses provides more details regarding the dynamics of the emotional impact during the session. For instance, comparing the range of HRR change and the level of EDR while listening to the dry and wet recordings showed that the wet recordings resulted in a more significant physiological response in the cases presented. Also, the similarity in the patterns of HRR response during listening to the dry and wet recordings despite the difference in their level calls for further research to study the dynamics of change in the physiological responses based on the characteristics of the recording in each session, such as its frequency component.

Future research can take another step forward by investigating the impact of the frequency component in the two types of recordings and its relation to the intensity and type of emotional impact. For example, some of the participants compared dry and wet recordings and mentioned that the sound reflections in the wet recording made the chant seem more harmonized. Thus, analyzing the contribution of design and architectural features in reinforcing different ranges of frequencies may result in the creation of a sound illusion or reduction of sound defects that can also allow for the achievement of better acoustic environments, based on the improvement of the space design.

2.5 Conclusion

This study has investigated the emotional impact of the acoustic environment and how it shapes the auditory experience in addition to examining its links to its cultural background. The findings show that the acoustic characteristics of the space can increase the intensity of the emotional impact and enhance the listener's experience. The intensity of this impact can be further increased based on the listener's familiarity with a similar acoustic environment.

The study also demonstrates the role of the architectural features in shaping the acoustic environments that support the emotional experience in buildings such as worship spaces. Many worship spaces include reinforcement sound systems that, in some cases, are used excessively. The dependence on the sound system creates an acoustic environment that does not match the expected sound reflections based on the architectural design. More details about the differences between the acoustic characteristics of sounds generated through artificial reverberation and natural reverberation in real spaces will be discussed in Chapter 5.

Since the intensity of the emotional impact varied in the studied acoustic environments, further research with detailed analysis of the acoustic characteristics highlighted through the case studies will be discussed in Chapter 3 and Chapter 4, and their contribution to emotional impact will be analyzed in Chapter 4 to provide insight to determine which acoustic parameter is correlated with which particular emotional impact.

Future studies of the architectural characteristics that created such an acoustic environment, resulting in supportive emotional impact, will help architects design better spaces in which acoustics is an essential contributor to the experience, such as worship spaces, performance spaces, meditative spaces, and museums.

The next chapter aims to develop a method for analyzing the acoustic characteristics of spaces focusing on the frequency domain, given that resonance has been mentioned frequently in the literature as a possible factor linked to the emotional impact.

Chapter 3

Developing a Method for Analyzing Room Acoustics Using Auralization[2]

Abstract

Room modes are the resonances that result from generating a sound in a room. They are formed by the constructive and destructive interferences caused by sound reflections from the room surfaces. They result in amplifying some frequencies and suppressing others and therefore changing the tonal characteristics of the sound and causing what is referred to as sound coloration. The sound coloration produced by these modes is often deemed problematic. Research in room acoustics continues to refine our means to control this coloration for reconciling visual and aural variables in architectural design. Alvin Lucier demonstrated the resonant frequencies of a room in his sound art piece "I am sitting in a room" by recording his speech in a space, then playing the recording and rerecording it in the same room multiple times, until the resonant frequencies of the room became dominant. Inspired by Lucier's work, this research explores the possibilities that can emerge from replicating the same iterative process within a simulated framework. Accordingly, a room is modeled, an impulse response (IR) is generated, and an auralization is created by

2 The abstract has been published in: Algargoosh, Alaa; Granzow, John. 2019a. "Developing a New Method for Analyzing Room Acoustics Based on Auralization." *The Journal of the Acoustical Society of America*. Furthermore, part of the method has been published in a short article: Algargoosh, Alaa; Granzow, John. 2019b. "Developing A New Method for Analyzing Room Acoustics Based on Auralization 'How Can a Room Shape Your Voice?'" Retrieved June 24, 2020 (https://acoustics.org/2aaa-developing-a-new-method-for-analyzing-room-acoustics-based-on-auralization-how-can-a-room-shape-your-voice/).

convolving an anechoic recording with the IR. The output is then used as an input that is convolved again with the same IR. This chapter discusses the potential of the developed method in identifying the room modes and therefore the frequency bands that the room will amplify based on the room's response to the excitation by a continuous sound source and its frequency characteristics. The results show that the method allows for analyzing room modes for rooms with complex geometries—such as worship spaces—by considering the room materials and the location of the sound source.

3.1 Introduction and related studies

The acoustic environment results from the room's response to the excitation by the sound source depending on the characteristics of the room in which the sound/music is propagating, including the room volume, geometry, and the materials present in the space.

One of the phenomena that some researchers pointed out as a significant contributor in shaping the auditory experience in worship spaces is the resonance that results from the room modes formed by generating a sound in a room. The sound coloration produced by these room modes is often considered problematic in other spaces (Bonello, 1979; Toyoda et al., 2009). However, in worship spaces, the resonance resulting from the reinforcement of specific frequency bands can provoke an emotional response that enhances the spiritual experience (Algargoosh, Alaa; Granzow, 2019a).

Examples of room resonance may extend into prehistory (Watson and Keating, 1999); researchers in archeoacoustics, for instance, have found that many of the paintings in ancient caves were located in areas with strong resonances that may have played a role in rituals (Lubman, 2017).

They suggested that such resonance in ancient structures served in supporting rituals because it is within the range of human voice (Cook et al., 2008; Devereux and Antiquity, 1996).

In the Hagia Sophia, an architectural wonder that was historically used as a worship space in Turkey, specific frequencies are also amplified by the accumulation of the sound energy interacting with the architectural geometry and materials. Resonances at low frequencies cause the sound level to increase above the original sound source level after the onset (Pentcheva, 2017). Given the long reverberation time (T30= ±11 seconds at low frequencies), this amplification can be explained by the constructive interferences formed after the multiple sound reflections. Similar results have been reported in the Imam Mosque in Iran—another worship space known for its remarkable acoustics (Farzaneh and Braasch, 2020).

Among the complex factors that give rise to these acoustic qualities in worship spaces, this study examines the contribution of architectural geometries and materials and analyzes how they reinforce specific ranges of frequencies within a cultural context in which such phenomena might be desirable or serve a musical function (Algargoosh, Alaa; Granzow, 2019b).

The sound amplification caused by resonance is not uniform among different frequency bands; the resonance strength at different frequencies can be affected by the location and distribution of the sound energy in the sound source (Heller, 2013). This can change the characteristics of the original sound; in some cases, for example, the reflected sound is one octave higher as some frequencies will be enhanced, and others suppressed (Heller, 2013). As Pencheva explained, "sustained notes cause gradual build-up," which amplifies the sound due to the accumulated sound energy while the source is still producing higher energy in some frequency bands (Pentcheva, 2017). Thus, it is essential to study the room modes while considering the type and frequency characteristics of the sound source.

Most of the studies that addressed the frequency domain of concert halls focused on the first few milliseconds of the reflected sound, which does not include the time in which the sound energy accumulated and caused the sound level to build up (Pätynen et al., 2013). Thus, a method to take this into account must be developed. How do we study the sound amplification and resonance that results from room modes?

Room modes can be calculated using the following formula:

$$f_{n_x n_y n_z} = \frac{c_0}{2}\sqrt{\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2} \quad \text{Eq. (3)}$$

Where $f_{n_x n_y n_z}$ are the natural frequencies, L_x, L_y, L_z are the dimensions of the rectangular room, n_x, n_y, n_z are the modal numbers, and c0 is the speed of sound (Petrolli et al., 2020). W web-based eb-based room mode calculators that provide room modes using room dimensions also exist, although neither of the previous methods can be used in rooms with complex geometry. Moreover, they do not allow to calculate room modes based on the location or the frequency content of the sound source.

Some researchers thus developed a method that considers the different source and receiver locations to calculate room modes based on the Finite Element Method (Petrolli et al., 2020), while others developed one that depends on time-frequency analysis of the IR to study the sound energy build-up at different frequencies (Pätynen et al., 2013). While the previous method above allowed for a more advanced analysis of room modes, neither of these methods consider the room's response to the excitation by a continuous (contrary to impulsive) sound source and its frequency characteristics. Hence, this research proposes a new method that utilizes auralization to study this response.

Auralization is “the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data” (Vorländer, 2008). It is usually used for the subjective evaluation of an acoustic environment and can be created by the convolution between a dry recording of a sound source and the room’s IR. In this research, auralization is used as a diagnostic tool for room modes through studying the room’s response to the excitation by a continuous sound source and utilizing the time and frequency domains for objective analysis. Thus, the purpose of the developed method is to identify the frequency bands that the room will amplify by considering the room geometry and materials in addition to the sound source location and frequency characteristics.

The frequency characteristics of a sound source determine its pitch, and studies have connected pitch in music with its emotional impact (Juslin and Sloboda, 2010). Further, recent work has included pitch features of environmental sounds (Yang and Kang, 2016). Since the room’s response to the excitation by a continuous sound source results in a change in the frequency domain of the original sound, this may influence the emotional impact based on how the sound is perceived. In small rooms, strong individual modes exist; in large rooms, however, several modes exist within the same frequency. Hence, in this research, less focus will be given to single modes, and more focus will be given to the frequency range that the room amplifies, given their potential of impacting the aural experience and emotions of the space occupants.

3.2 Methods

This research analyzes the frequency and time domains of room acoustics based on the room’s response to the excitation by a continuous sound source and its frequency characteristics. The response is studied through auralization (convolution), which shows the frequency domain that the room amplifies more based on the room modes and the sound source’s dominant frequencies. The convolution is then repeated multiple times as a visualizing tool that makes the amplified frequencies more distinguishable.

To listen to such cumulative effects of these room modes, we developed a novel technique as part of this work; inspired by Alvin Lucier's famous piece ("I Am Sitting in a Room") (Lucier, 1970), where the composer records his voice, plays it back into the room, and rerecords the playback iteratively. Over time, Lucier's process amplifies the frequencies within his voice that correspond to the room modes and cause resonance; by the end of the piece, his words have transformed into a prosodic ringing of room modes. A similar approach is used in the testing of live-sound systems: feedback loops are created to identify frequencies that will cause ringing within a given space. Hence, this research explores the possibilities that can emerge from replicating the same iterative process within a simulated framework (Algargoosh, Alaa; Granzow, 2019b). It is worth mentioning that a similar method (multiple convolutions) has been used in previous research by (Abel, Jonathan s. and Wilson, 2012); however, the method's purpose and application were different from what is proposed in this research.

3.2.1 Parametric analysis

First, we conducted a parametric analysis to explore how this method would allow us to identify and localize the room modes and study the room's response to the excitation by a continuous sound source considering architectural characteristics (geometry and materials). A room with the dimensions of 30 x 30 x 30 ft, which equals 9.14 x 9.14 x 9.14 m and has a volume of 764.55 m^3, was modeled (Fig. 3.1). We selected the cubic shape intentionally to generate strong room modes. The RAVEN software (Schröder, D., & Vorländer, 2011) generates an impulse response (IR) and creates an auralization by convolving an anechoic recording with the IR. The output is then used as an input that is convolved again with the same IR.

The parametric analysis included the following factors: (1) sound source and its frequency characteristics; (2) room geometry; (3) room materials. The spectra of the IRs and convolutions were analyzed to study the room's response to the excitation by a continuous sound source and understand how different frequency bands are amplified by the room.

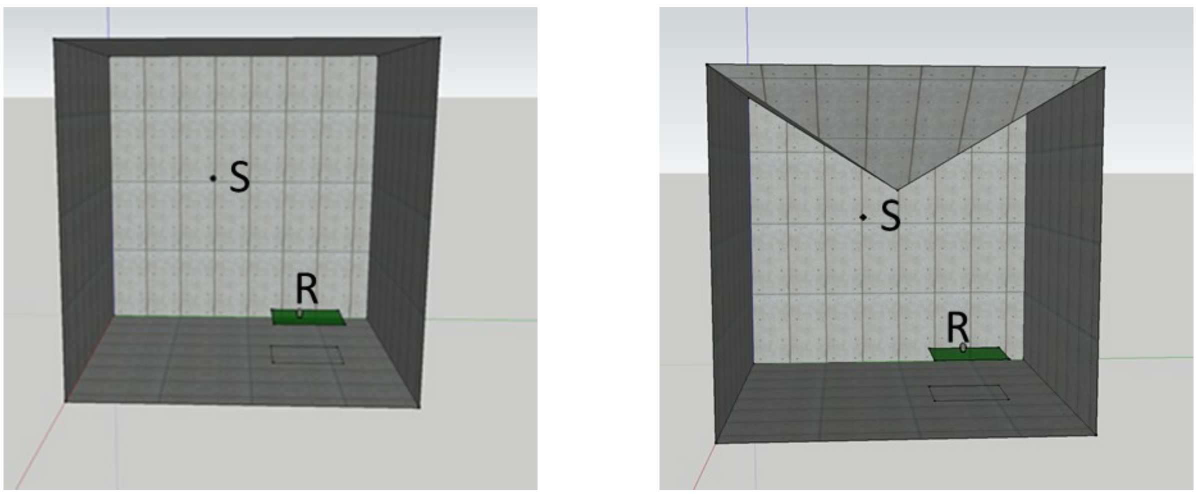


Fig. 3.1 3D models of the room used in the parametric analysis (S: sound source, R: sound receiver). Left: Room 1 (base case). Right: Room 2 (modified geometry)

3.2.2 Method validation

To validate the developed method, it was applied to the data collected through field measurements of a small room with simple geometry, and the outcome was compared with the results of the traditional method for calculating room modes. The AMROC room mode calculator (Melcher, n.d.), a web-based calculator, was used to estimate the room modes using the room dimensions (length, width, and height). The studied room (Fig. 3.2) was 4.27 x 3.35 x 2.29 m and had a volume of 32.76 m^3.

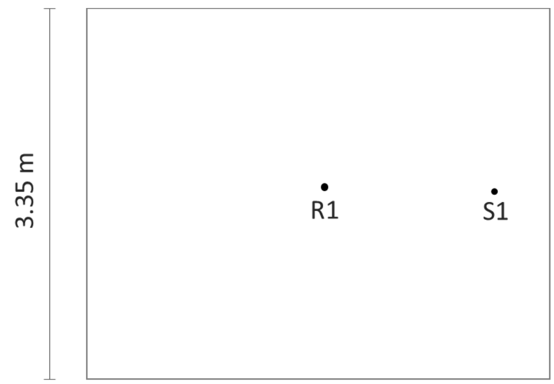


Fig. 3.2 Plan of the studied room with the source and receiver locations (S1: sound source, R1: sound receiver)

To examine the possibility of using the previous method as a diagnostic tool for the impact of room modes considering the room materials, absorptive panels (± 30 x 60 cm) have been added to three walls of the same room. When comparing the spectra of both scenarios, the IR of the test room was recorded in two scenarios: (1) without absorptive panels; (2) with absorptive panels on the walls. The IRs were recorded using an Acoustic Camera, which utilizes beamforming technology, as a receiver. The Acoustic Camera includes 120-channel spherical and acoustically transparent omni directional microphone array (Heilmann et al., 2008), and acoustic beamforming is "an instrumental tool applied to the localization and quantification of acoustic sources." (De Santana, 2017). More information about the technical details of the acoustic camera and beamforming can be found in the following references (Navvab et al., 2012; De Santana, 2017).

After recording the IRs, they were convolved with a dry recording using GratisVolver™ software by CATT-Acoustic. The convolution was repeated four times to explore the possibility of providing a more distinguishable visualization of the frequencies, amplified because of the room modes.

The spectra of the IRs and convolutions were analyzed using the ITA-Toolbox (Bomhardt et al., 2017) to understand how the room amplifies different frequency bands and how its surface materials modify this amplification across different frequency bands.

3.2.3 Method application

Field measurements of a worship space with complex geometry (Diyanet Center of America, a mosque in Lanham, Maryland) with a volume of ± 8305 m^3 (Fig. 3.3 & Fig. 3.4) were used to apply the developed method. The goal was to explore the potential of using the method for large spaces with complex geometries to serve the purpose of this research, namely to study the impact of the architectural features in amplifying specific ranges of frequencies of worship spaces.

The IR was recorded using an acoustic camera at eight locations in the mosque (Fig. 3.3), and the IRs were convolved with a dry recording using GratisVolver™. The convolution was also repeated four times, as explained in the previous section. Finally, the spectra and spectrograms of the IRs and convolutions were analyzed using the ITA-Toolbox.

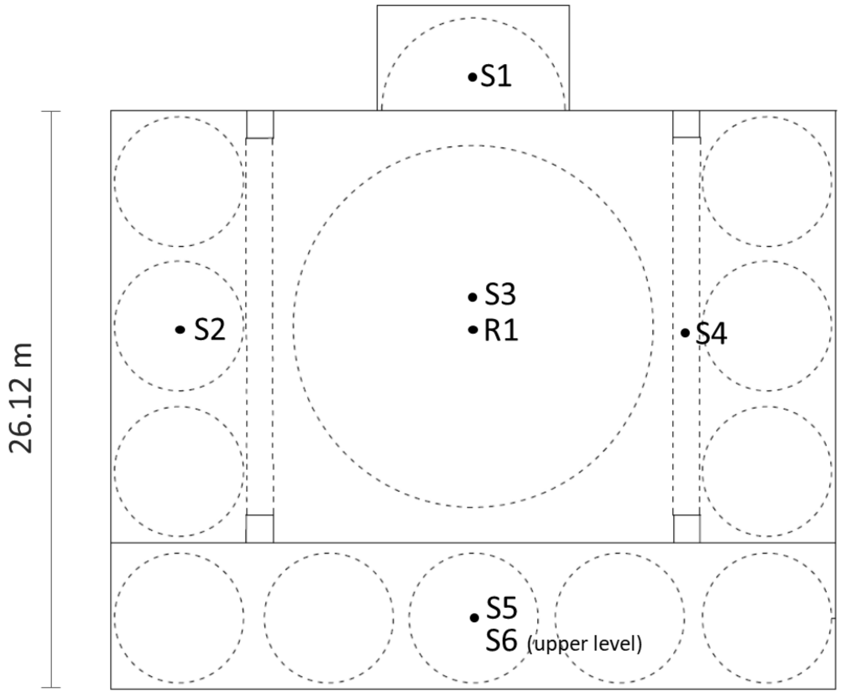


Fig. 3.3 Plan of the Diyanet Center of America in (Lanham, Maryland) with the source (S) and receiver (R) locations.

Fig. 3.4 Interior view showing the architectural features and the field measurement method (acoustic camera) at the Diyanet Center of America in Lanham, Maryland.

3.3 Results and discussion

Analyzing the IR provides information about the sound level at different frequency bands, as shown in Fig. 3.5 (left). The peaks in sound level (resonant peaks) indicate the frequencies that represent the room modes. These room modes contribute to amplifying the sound level of a signal within the associated frequency bands when a sound is played in that room. Depending on the sound source, the sound level of the original source will have peaks within specific frequency bands; these may or may not be the same frequencies in which the room modes occur. Fig. 3.5 shows the frequency domain of the base case room's IR and the dry recording of the vocal sound source used in the study (sound source 1).

Therefore, studying the the room's response to the excitation by a continuous sound source through analyzing the spectrum of the convolved (auralized) sound provides an understanding of how the room will amplify or dampen different frequencies, as shown in Fig. 3.6 (left). Those peaks and dips become more distinguishable when the convolution is repeated multiple times (Fig. 3.6; right). We can see that frequencies <1000 Hz were more amplified than frequencies >1000 Hz, and the room mode at ±30 Hz became more visually distinguishable.

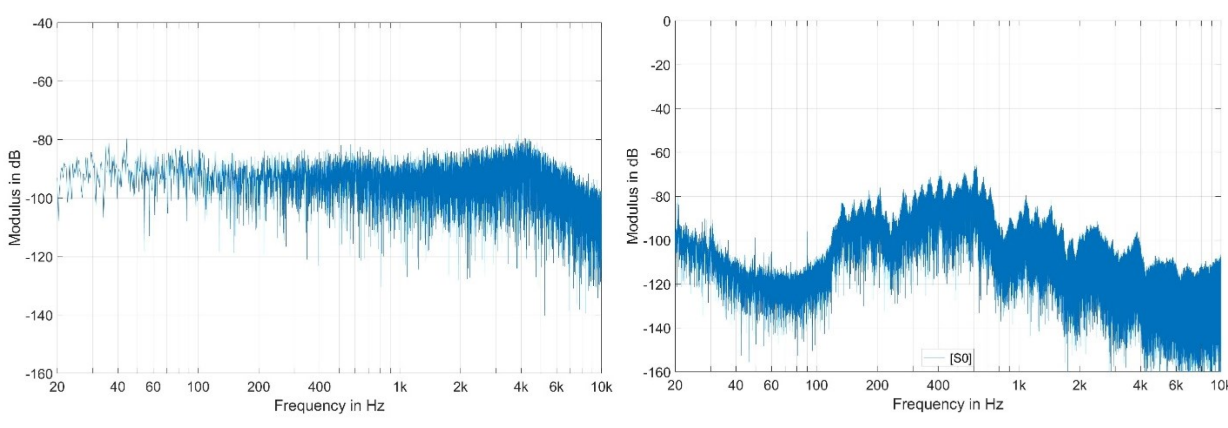


Fig. 3.5 Left: Spectrum showing the frequency-domain response of the base case room (room 1). Right: Spectrum of a vocal dry recording (Sound source 1)

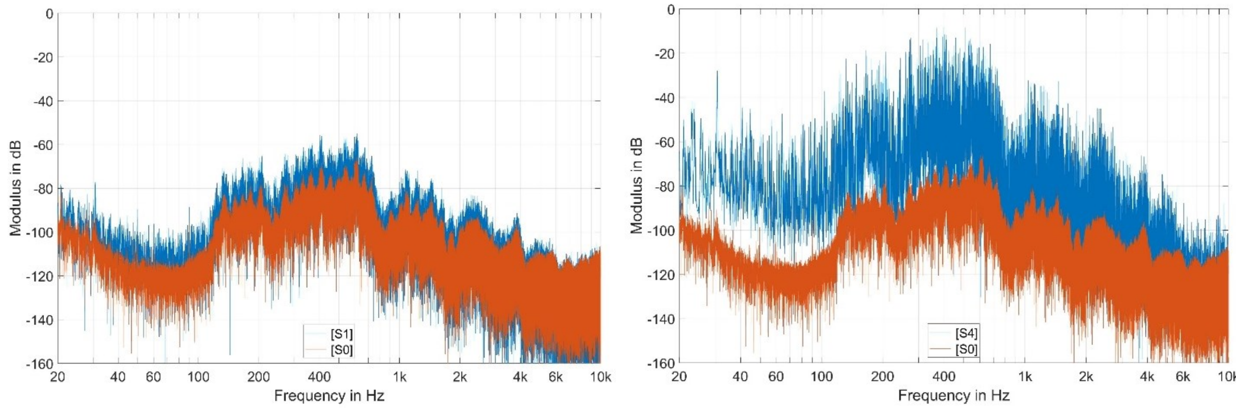


Fig. 3.6 Left: Spectrum of the convolution of the IR of the base case room (room 1) and (sound source 1) [S0: dry recording, S1: first convolution]. Right: Spectrum of the convolution of the same IR and the dry recording after repeating four times [S0: dry recording, S4: fourth convolution].

The method described in the previous section considers the room's response to the excitation by a continuous sound source, making it possible to determine the impact of the room modes based on the dominant frequencies of the sound source. However, what if we have different sound sources, room geometry, or materials?

The parametric analysis results below will explain how to analyze the effect of the room modes in amplifying the sound by considering the previous factors.

3.3.1 Parametric analysis results

The following explains the potential of the developed method in identifying the amplification of different frequency bands with different sound sources, room geometry, and materials.

3.3.1.1 Sound source

Studying the room's response to the excitation by the sound source provides a customized estimation of the sound amplification resulting from the room modes and the sound source's dominant frequencies. Fig. 3.7 shows the frequency domain of the dry recordings of two different sound sources (sound source 1: vocal; sound source 2: cello). When comparing the spectra of the sound signal generated from convolving the IR of the base case room four times with two different sound sources (Fig. 3.8), the spectrum shows different peaks resulted from the room modes and the dominant frequencies of the sound source. For example, the sound level peaked at 100 Hz when the cello (sound source 2) was auralized in room 1, while it dropped at the same frequency when using a dry vocal recording (sound source 1) in the same room. The frequency bands that are more amplified based on the room modes and the sound source’s dominant frequencies become more evident when the convolution is repeated multiple times (Fig. 3.9).

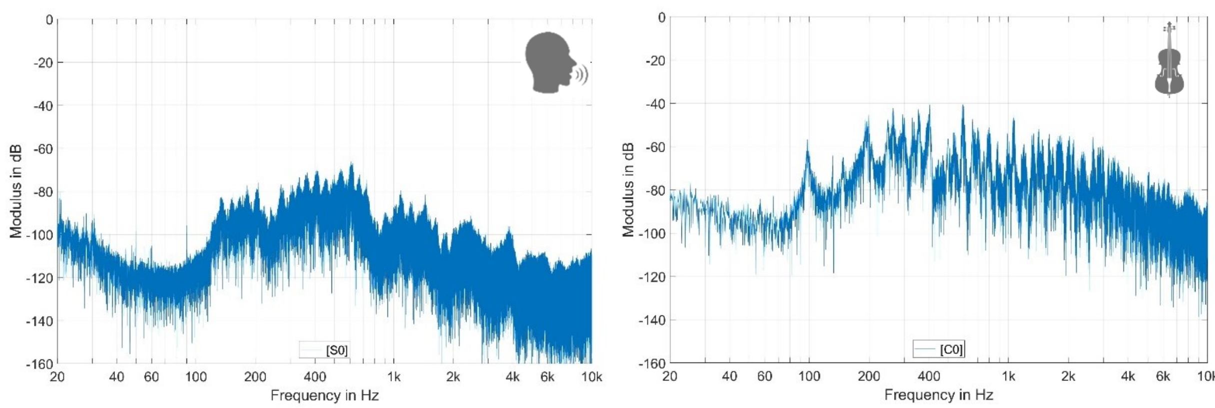


Fig. 3.7 Left: Spectrum of a vocal dry recording (sound source 1). Right: Spectrum of a cello dry recording (sound source 2)

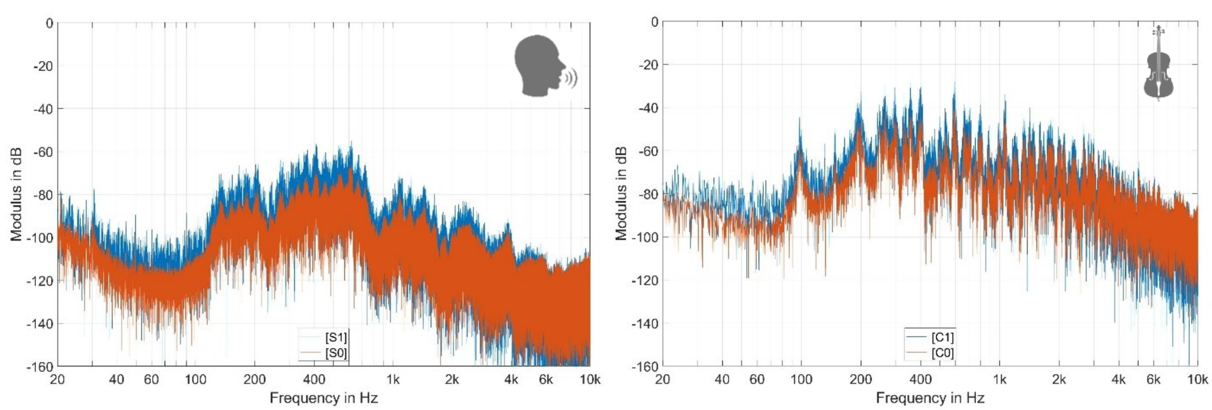


Fig. 3.8 Left: Spectrum of the convolution of the IR of the base case room (room 1) and (sound source 1) [S0: dry recording, S1: first convolution]. Right: Spectrum of the convolution of the IR of the base case room (room 1) and (sound source 2) [C0: dry recording, C1: first convolution].

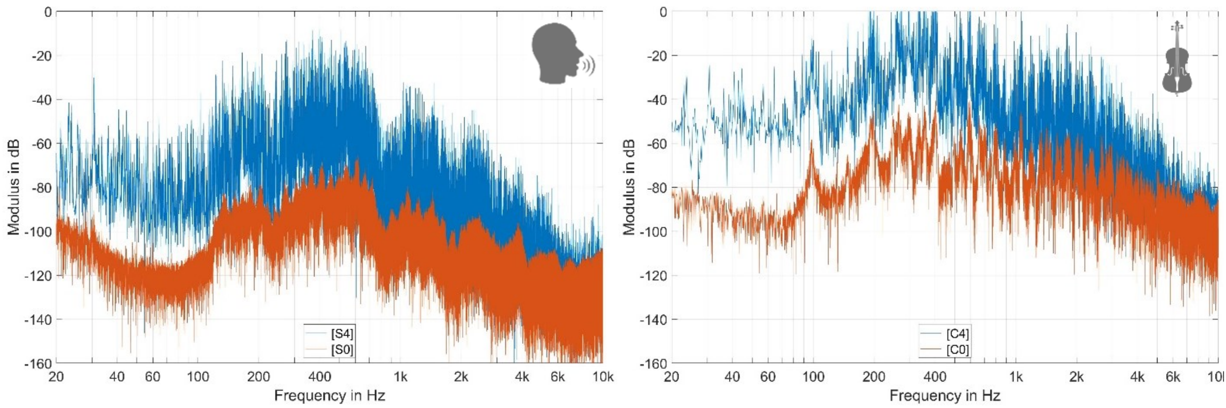


Fig. 3.9 Left: Spectrum of the multiple convolutions of the IR of the base case room (room 1) and (sound source 1) [S0: dry recording, S4: fourth convolution]. Right: Spectrum of the multiple convolutions of the IR of the base case room (room 1) and (sound source 2) [C0: dry recording, C4: fourth convolution].

3.3.1.2 Room geometry

Comparing the frequency domain of IRs of both the base case room (room 1) and the room with modified geometry (room 2) in Fig. 3.10 shows that room 2 has a lower amplitude by ±3 dB at the frequency range 100–1000 Hz. However, analyzing the impact of the geometry difference in room modes visually is challenging in this case given that the spectra are remarkably similar. Moreover, predicting the way each of the two rooms responds to a sound source can be challenging.

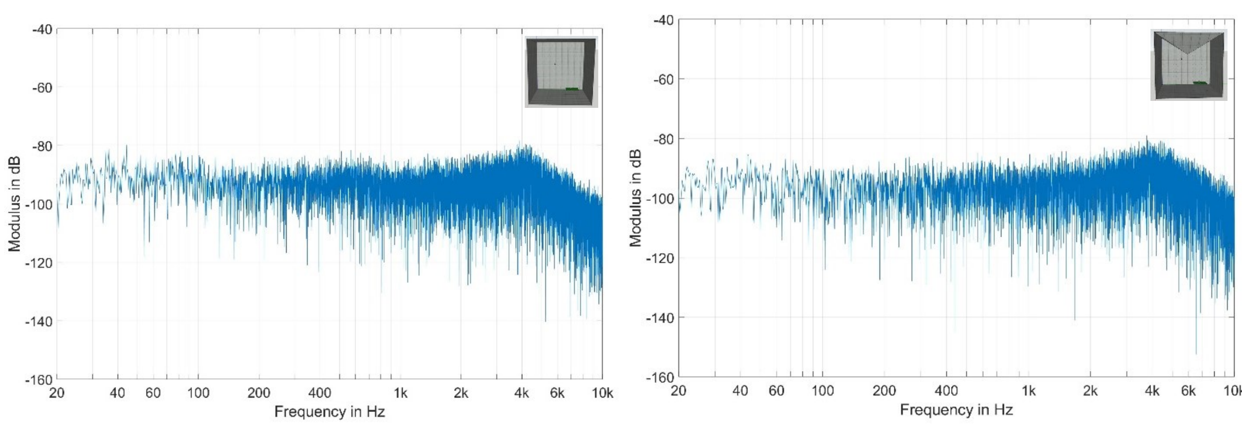


Fig. 3.10 Left: Spectrum showing the frequency-domain response of the base case room (room 1). Right: Spectrum showing the frequency domain response of the modified room (room 2).

Conversely, when the auralization was generated using (sound source 1) in each room (Fig. 3.11), room 1 resulted in a higher level of amplification at the frequency range 100–1000 Hz. The range of the amplified frequency band became more distinguishable when repeating the convolution (Fig. 3.12). The individual modes at low frequencies <100 Hz in (room 2) became more visually identifiable (Fig. 3.12; right).

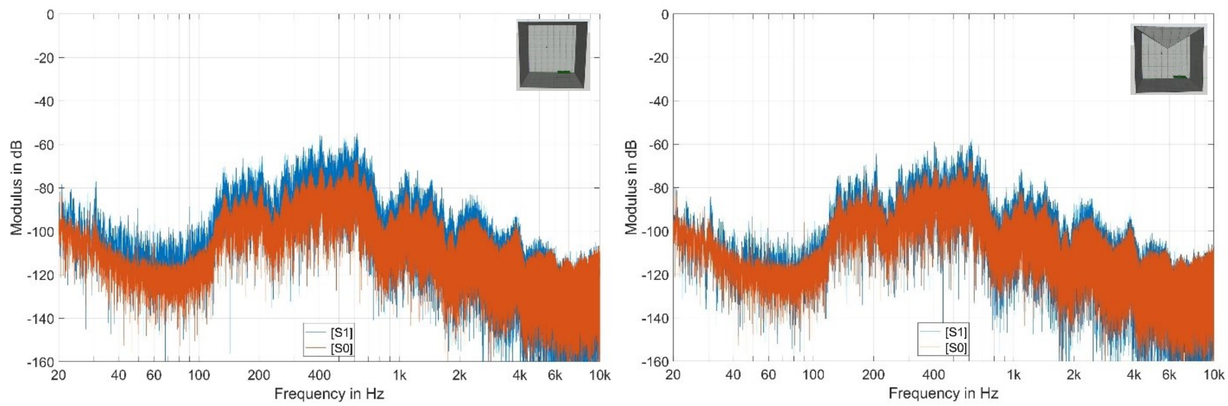


Fig. 3.11 Left: Spectrum of the convolution of the IR of the base case room (room 1) and (sound source 1). Right: Spectrum of the convolution of the IR of the base case room (room 2) and (sound source 1). [S0: dry recording, S1: first convolution]

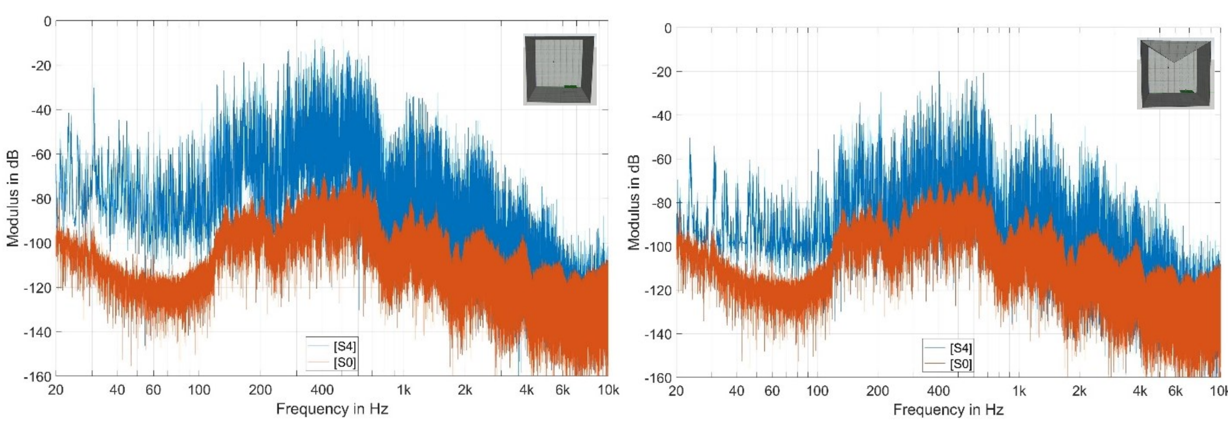


Fig. 3.12 Left: Spectrum of the multiple convolutions of the IR of the base case room (room 1) and (sound source 1). Right: Spectrum of the multiple convolutions of the IR of the base case room (room 2) and (sound source 1). [S0: dry recording, S4: fourth convolution]

When sound source 2, which generated higher peaks in room 1, was auralized with the IR of room 2, the level of amplification of low frequencies <100 Hz decreased, and some of the peaks (room modes) changed, as shown in (Fig. 3.13 & Fig. 3.14). This demonstrates one of the strengths of the proposed method as it provides a means to study the impact of room modes in spaces with irregular geometry, which is not possible with traditional room-mode calculation methods.

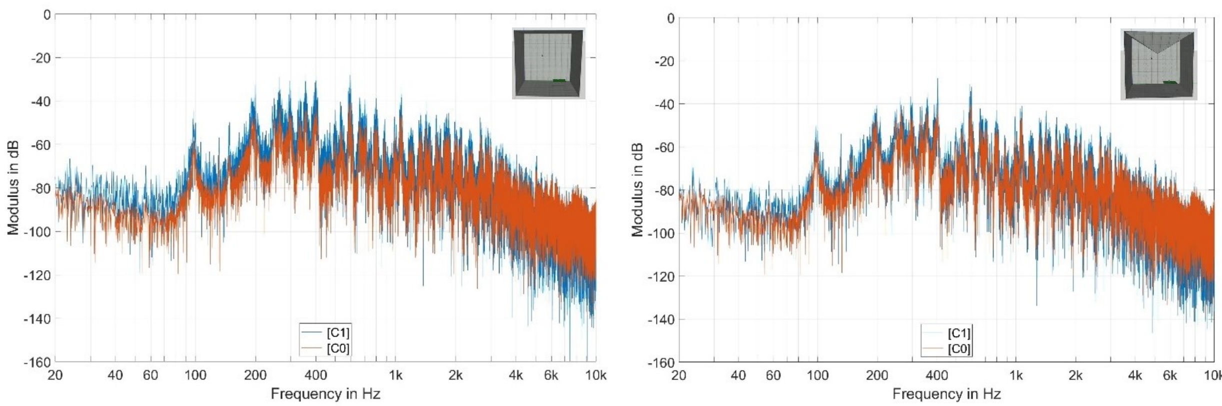


Fig. 3.13 Left: Spectrum of the convolution of the IR of the base case room (room 1) and (source 2) [C0: dry recording, C1: first convolution]. Right: Spectrum of the convolution of the IR of the base case room (room 2) and (sound source 2) [C0: dry recording, C1: first convolution].

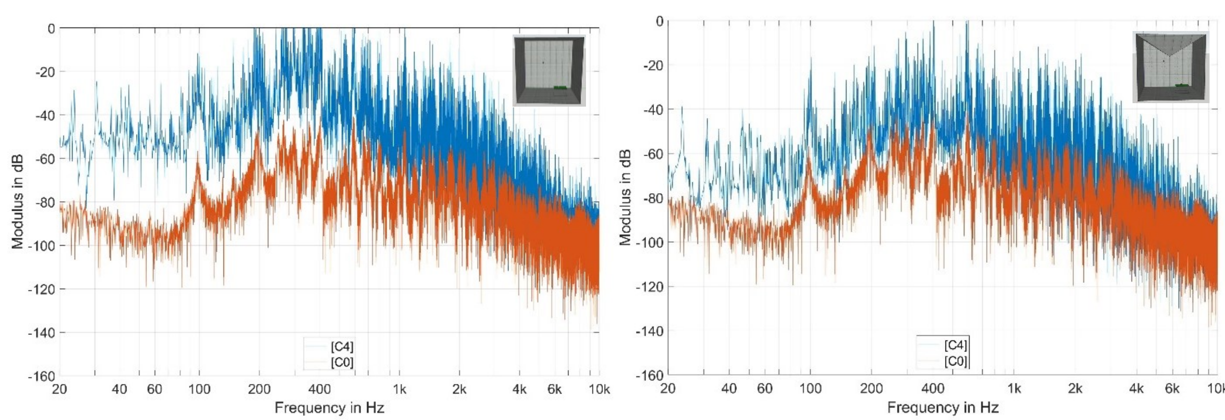


Fig. 3.14 Left: Spectrum of the multiple convolutions of the IR of the base case room (room 1) and (sound source 2) [C0: dry recording, C4: fourth convolution]. Right: Spectrum of the multiple convolutions of the IR of the base case room (room 2) and (sound source 2) [C0: dry recording, C4: fourth convolution].

3.3.1.3 Room materials

When testing the potential of the method in studying the room modes' impact depending on the surface materials, the results showed that using highly absorptive materials caused the sound level to decrease (Fig. 3.15; left). In contrast, the room with reflective surfaces caused an amplification of the sound level—especially at low frequencies—and a reduction at high frequencies (Fig. 3.15; right). Repeating the convolution (Fig. 3.16) shows that the amplification and dampening are not equal in all frequency bands. It also shows that the room modes became more distinguishable, such as the mode at 30 Hz (Fig. 3.16; right).

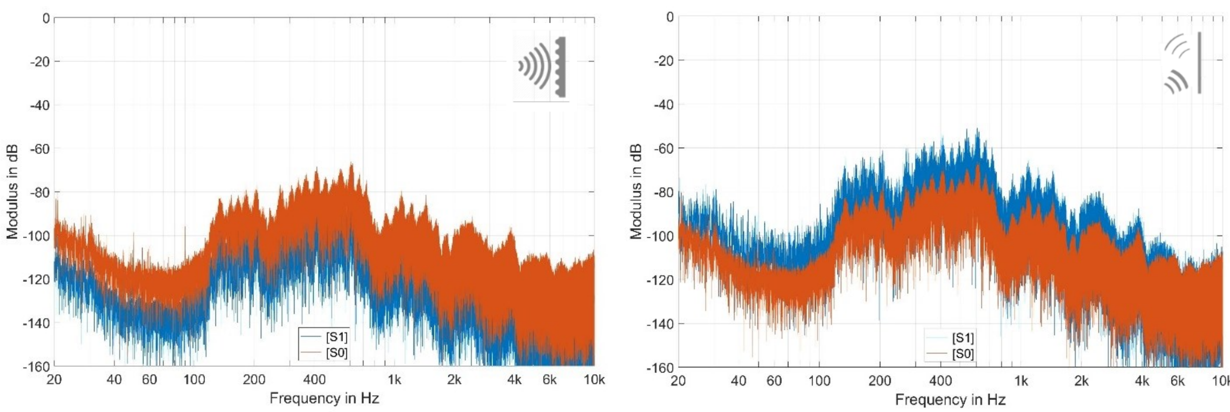


Fig. 3.15 Left: Spectrum of the convolution of the IR of the base case room (room 1) with highly absorptive walls and (sound source 1). Right: Spectrum of the convolution of the IR of the base case room (room 1) with highly reflective walls and (sound source 1). [S0: dry recording, S1: first convolution]

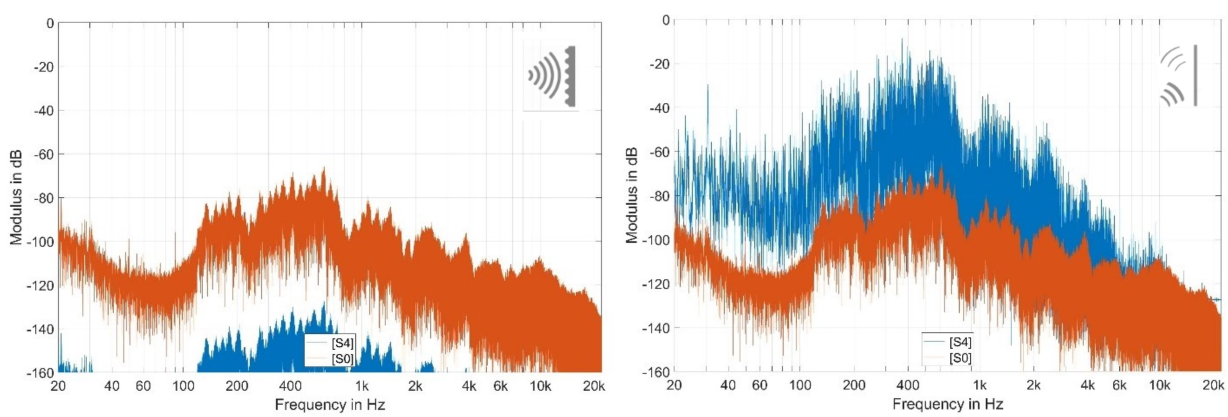


Fig. 3.16 Left: Spectrum of the multiple convolutions of the IR of the base case room (room 1) with highly absorptive walls and (sound source 1). Right: Spectrum of the multiple convolutions of the IR of the base case room (room 1) with highly reflective walls and (sound source 1). [S0: dry recording, S4: fourth convolution]

The parametric analysis results demonstrate that unlike traditional room mode calculation method, the proposed method allows for considering both surface materials and the room's irregular geometry in addition to considering the frequency characteristics of the sound source.

3.3.2 Method validation results

The results of the room modes obtained by the AMROC room mode calculator (Fig. 3.17; top) and the room modes identified by the developed multiple convolution method are in good agreement, as shown in Fig. 3.17 (bottom left). However, the developed method allows for analyzing the strength of the mode in each frequency rather than only identifying the frequency where the room modes occur.

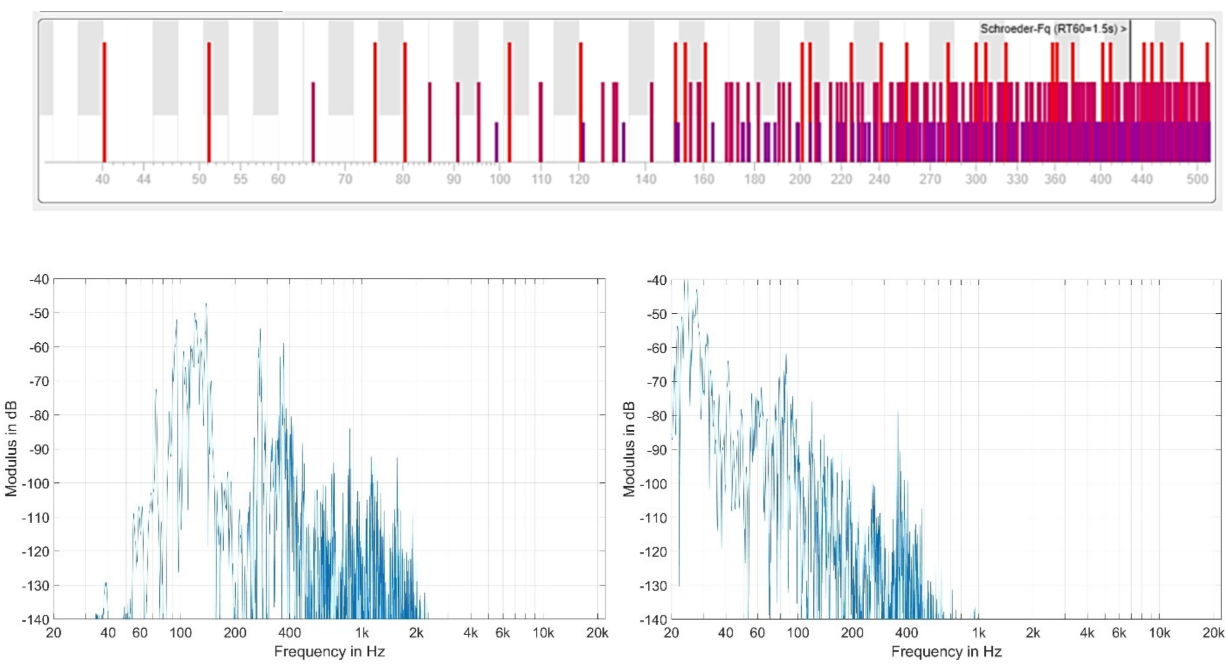


Fig. 3.17 Top: Room modes of the studied example using AMROC online calculator. Bottom left: Spectrum of the multiple convolutions of the IR of the tested room (without absorbers). Bottom right: Spectrum of the multiple convolutions of the IR of the tested room (with absorbers).

Furthermore, the results show that the developed method takes a step forward by allowing to calculate the room modes after modifying the room materials (adding absorbers) (Fig. 3.17; bottom right). The result of analyzing a recorded IR in a small room with simple geometry showed that adding absorbers reduced the amplification at high frequencies above 1000 Hz and increased it at low frequencies below 100 Hz.

In addition, the method allows for studying the sound amplification results from the room's response to the excitation by a continuous sound source considering the room's materials and the sound source's frequency characteristics. When a dry recording (sound source 1) was convolved with the IRs of the studied room with and without absorbers, amplification occurred in both cases. In the first case (without absorbers), the amplification was at the frequencies <4000 Hz; however, the amplification in the second case (with absorbers) was limited to frequencies <1000 Hz with strong amplification at low frequencies (Fig. 3.18). When repeating the convolution multiple times, the frequencies with the strongest room modes became more distinguishable (Fig. 3.19).

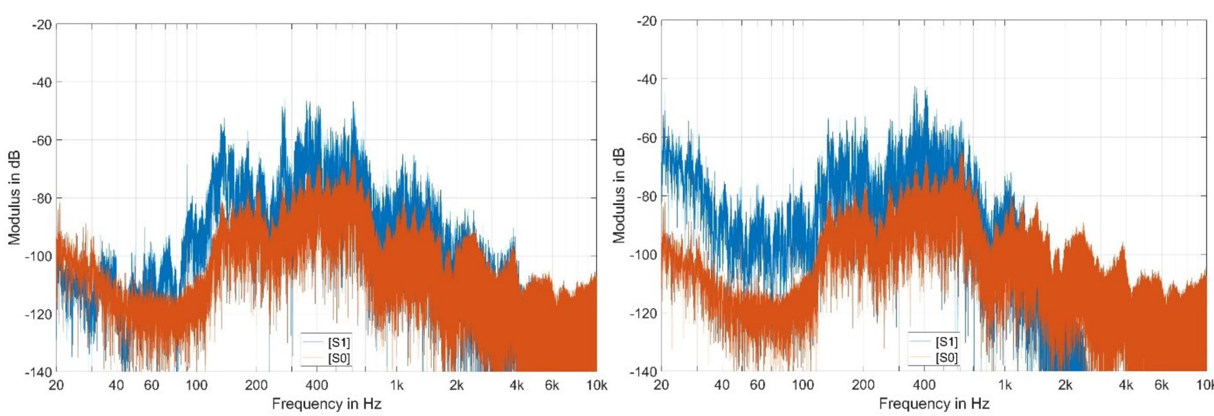


Fig. 3.18 Left: Spectrum of the convolution of the IR of the tested room (without absorbers) and (sound source 1). Right: Spectrum of the convolution of the IR of the tested room (with absorbers) and (sound source 1). [S0: dry recording, S1: first convolution].

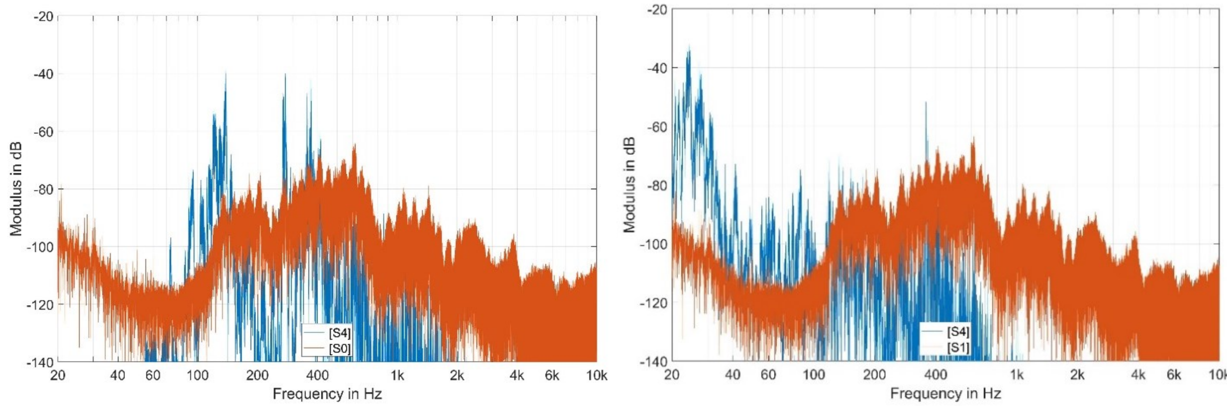


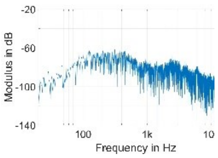
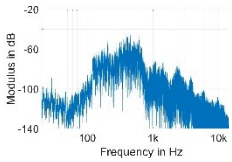
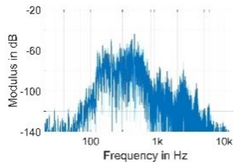
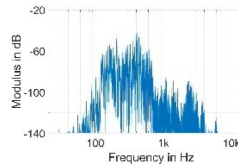
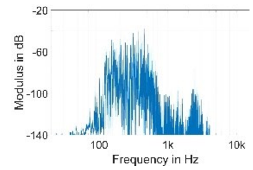
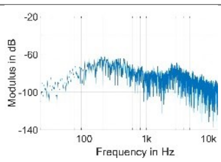
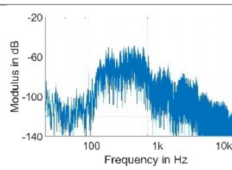
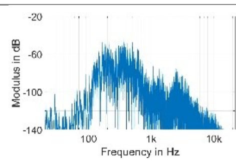
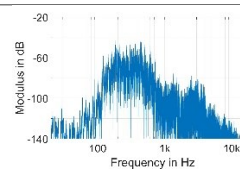
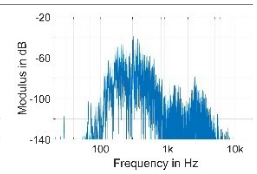
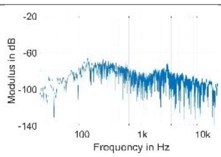
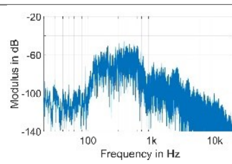
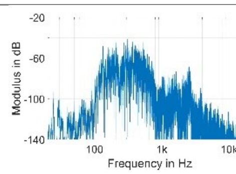
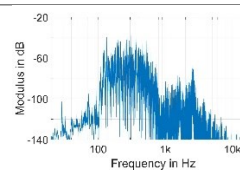
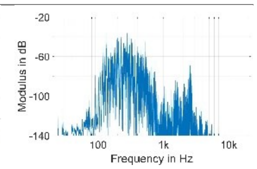
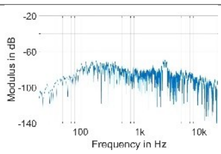
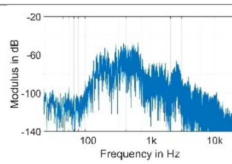
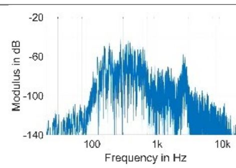
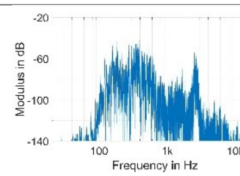
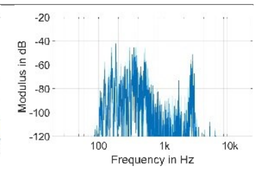
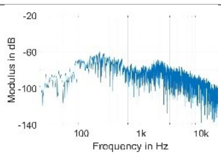
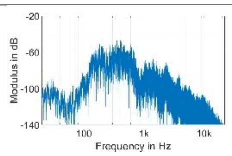
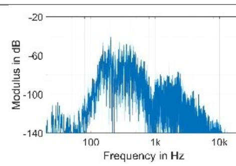
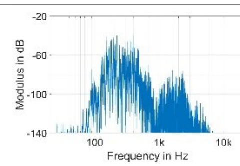
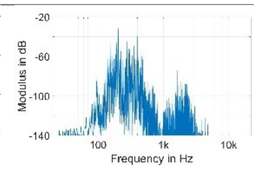
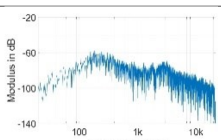
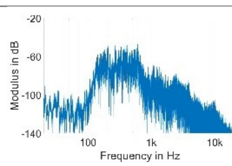
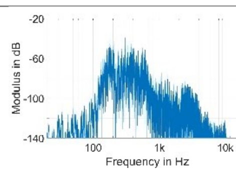
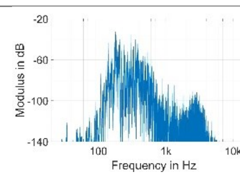
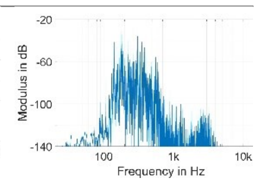
Fig. 3.19 Left: Spectrum of the multiple convolutions of the IR of the tested room (without absorbers) and (sound source 1). Right: Spectrum of the multiple convolutions of the IR of the tested room (with absorbers) and (sound source 1). [S0: dry recording, S4: fourth convolution].

3.3.3 Method application results

The following table (Table 3.1) shows the results of analyzing the spectra of the IRs and convolutions at different locations of the studied building, namely the Diyanet Center of America (DCA). In all locations, the frequency band that was amplified the most was similar (100–500 Hz—the dominant frequency range of the sound source). However, modes at high frequencies were more sensitive to location, which is evident in the results of the multiple convolutions (fourth convolution column in Table 3.1).

Since general trends in modes at low frequencies are, unlike modes at high frequencies, not significantly affected by location (Table 3.1), when the same mode appears at different locations, it can be an isolated resonance. However, if it changes based on locations, then it is generated by the overlap of many modes (Heller, 2013), which occurs after the Schroeder frequency—the frequency after which the isolated modes transition to overlapping ones (Schroeder, 1996).

Table 3.1: The Spectra of the convolutions of the impulse response of the selected case study (DCA) and a sound source (sound source 1) at different locations (see Fig. 3.3).

S	IR Spectrum	First convolution	Second convolution	Third convolution	Fourth convolution
1					
2					
3					
4					
5					
6					

Furthermore, in addition to the location of the sound source, the amplification depends on the resonance strength (peaks of the modes) and the distribution of the sound energy in the sound source (Heller, 2013). This also confirms that considering the source's dominant frequencies when studying the room resonant frequencies is essential.

To explain this further, we can take a closer look at the results of IR2 (Fig. 3.20: left), which shows two frequencies (150, 400 Hz) which have similar amplitude level. However, since the sound source has a higher amplitude at 400 Hz (Fig. 3.20; right), the latter was amplified more when convolved with the IR of the room, and the difference in amplification becomes clearer when repeating the convolution (Fig. 3.21).

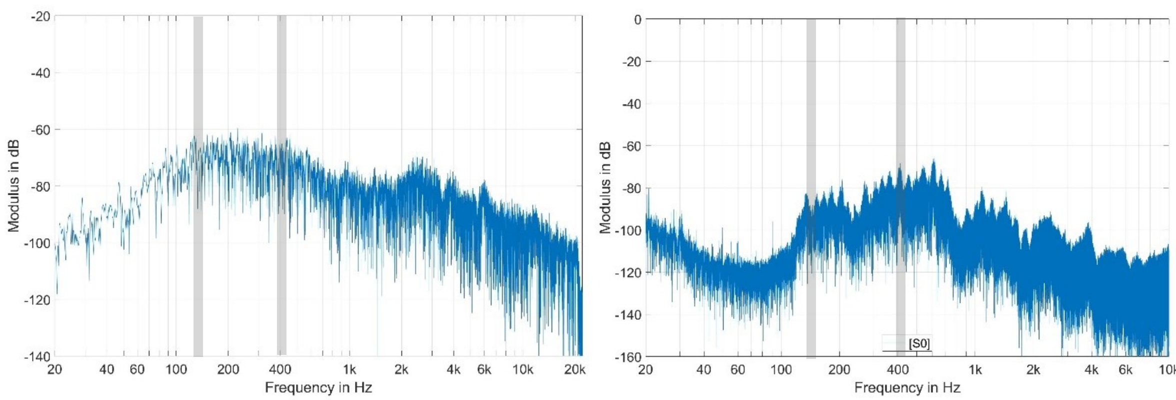


Fig. 3.20 Left: Spectrum of the IR of the studied room. Right: Spectrum of a vocal dry recording (sound source 1).

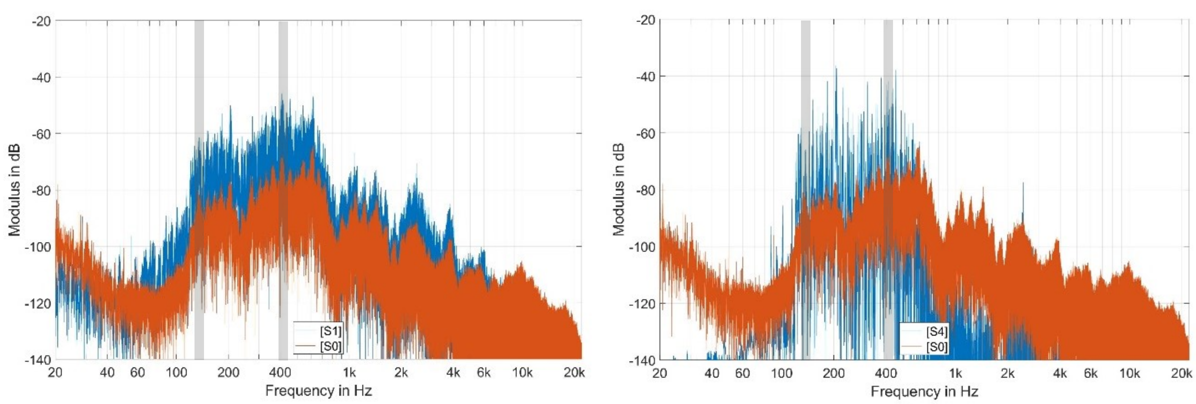


Fig. 3.21 Left: Spectrum of the convolutions of the IR of the studied room and (sound source 1). Right: Spectrum of the multiple convolutions of the IR of the studied room and (sound source 1). [S0: dry recording, S1: first convolution, S4: fourth convolution].

Another factor that is linked to the level of amplification is the reverberation time (T30), which, at this building, is 4.5 seconds at 250 Hz and 1.8 seconds at 2000 Hz. To illustrate this, we can take a look at the spectrogram of the same IR (IR2) in Fig. 3.22, which shows that the room allows some frequencies to last longer than others. As a result, when a dry recording is played in the room or auralized, the sound length extends through the reverberation from ± 1.5 seconds in the dry recording (Fig. 3.23; left) to ± 4 seconds in the auralized recording covering the few seconds of silence (Fig. 3.23; right). Since reverberation time is positively correlated with resonance quality (Heller, 2013), and since 250 Hz falls within the dominant frequency band of the sound source, the latter was amplified more, as seen in Fig. 3.23.

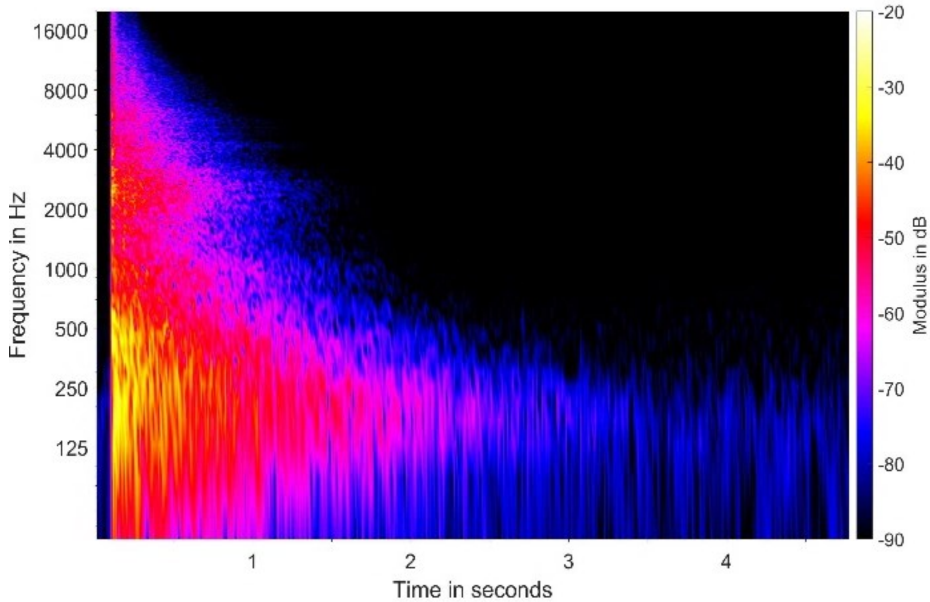


Fig. 3.22 Spectrogram of the IR of the studied room.

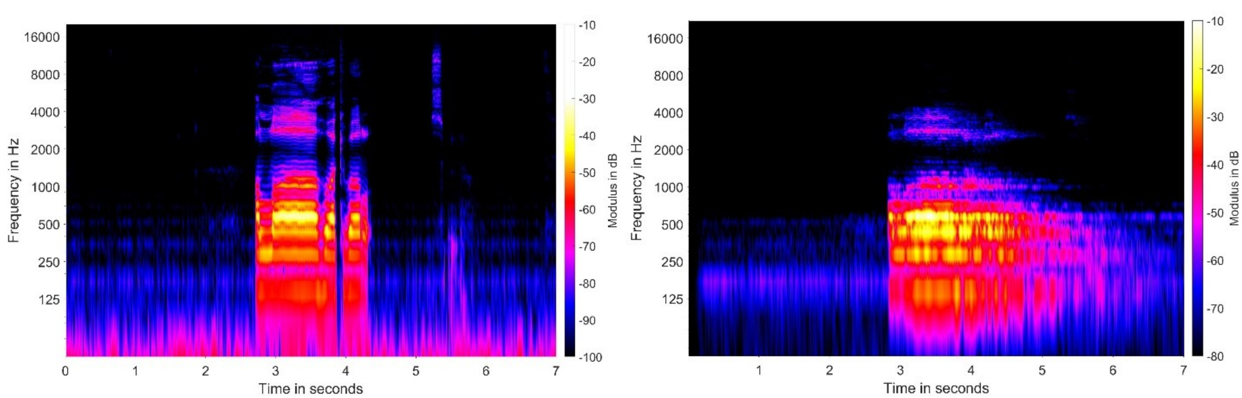


Fig. 3.23 Left: Spectrogram of a vocal dry recording (sound source 1). Right: Spectrum of a vocal dry recording (sound source 1). Spectrogram of the convolutions of the IR of the studied room and sound source 1.

The spectrogram in (Fig. 3.24; left) also shows that the low frequencies lasted longer than the high frequencies. Thus, in the event of no silence and continued sound source (Fig. 3.24; right), the frequency range that is reinforced by the room through the longer reverberation time (Fig. 3.25; left) will continue to build up and dominate. The mix between the original note and the reverberation from the previous notes produces a different perceived sound and may possibly change the dominant frequencies of the sound source (Fig. 3.26). To apply this to the studied room, we can see that in the auralized recording (Fig. 3.25; left) the amplitude of the frequency ± 300 Hz is higher than in the dry recording (Fig. 3.24; right). Conversely, the amplitude of ± 1000 Hz is lower. Repeating the convolution multiple times shows the frequencies amplified the most by the room (Fig. 3.25; right).

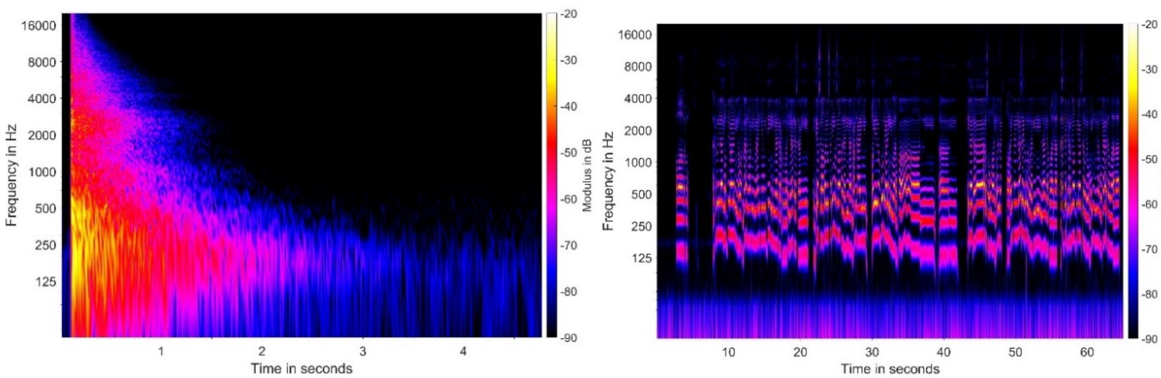


Fig. 3.24 Left: Spectrogram of the IR of the studied room. Right: Spectrogram of a vocal dry recording (sound source 1).

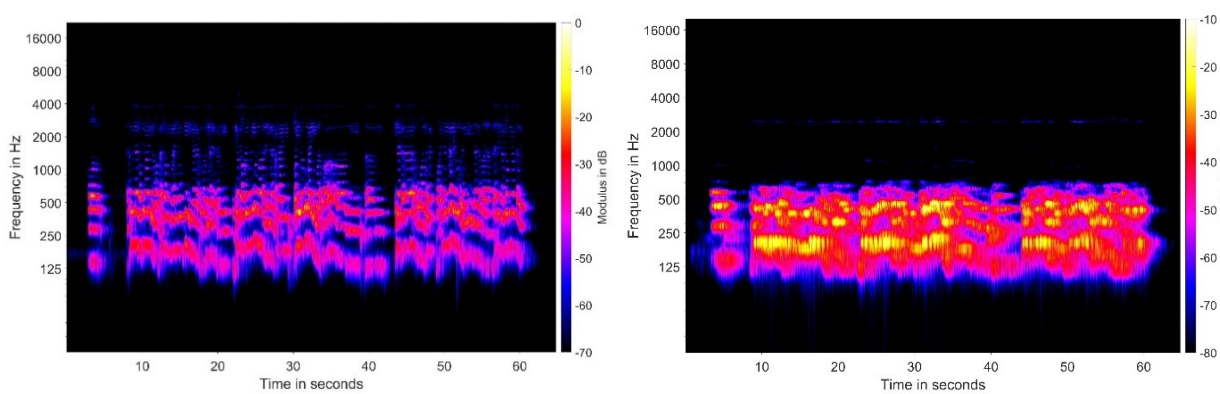


Fig. 3.25 Left: Spectrogram of the convolutions of the IR of the studied room and sound source 1. Right: Spectrogram of the multiple convolutions of the IR of the studied room and sound source 1.

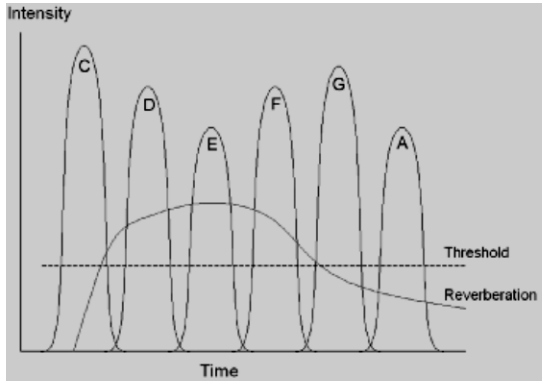


Fig. 3.26 The sound intensity of multiple notes played in a sequence and the reverberation of the first note added and mixed with the following notes.

To explain the reason for amplification and damping of different frequencies, when a sound with a dominant frequency is joined by its few milliseconds-delayed reflection in a large room, they will either cancel each other if they were out of phase (considering they have the same amplitude) (Blesser and Salter, 2007), or they will reinforce each other if they were in phase, resulting in a more amplified sound at that frequency. Such nonuniform frequency response may impact the auditory experience, even though it is not as strong in large rooms, and the listeners are unaware of the acoustic characteristics (Blesser and Salter, 2007).

3.4 Conclusion

This research introduced a method for analyzing room acoustics using auralization, which allows for studying the amplification of frequency bands based on the room's response to the excitation by a continuous sound source. The parametric analysis showed its ability to consider room geometry and materials to identify room modes, which is not possible when using the traditional room modes calculators. It also allows for analyzing the strength of the modes in addition to identifying the frequencies in which they occur.

The results of the developed method were validated by comparing the room modes of a simple cubical room, and the method was then applied to a worship space with a complex geometry. The method showed its ability to determine the frequency bands that the room will amplify most based on the room modes and the dominant frequency bands of the sound source. The next chapter will investigate possible links between the amplified frequency bands and the emotional impact on the listeners.

Future research can study the role of the architectural features in amplifying certain frequency bands to inform design decision-making based on the desired auditory experience.

Chapter 4

Linking the Acoustic Characteristics of Spaces to their Emotional Impact[3]

Abstract

The link between sound and emotions has been widely studied in music. However, when sound propagates through space during a performance, the architectural features of the space impact how sound reflects, causing an alteration in some of the original sound characteristics. Therefore, it is essential to study how the acoustic environment contributes to the emotional impact. For instance, researchers of worship spaces have reported the significance of the acoustic environment in impacting emotions and enhancing spiritual experience. Nevertheless, further research is required to understand the acoustic parameters that contribute to that effect. In Chapter 2, we analyzed the emotional response to the acoustic environments of worship spaces using self-report and physiological indicators. This chapter builds on the earlier results by analyzing the acoustic characteristics of such spaces and their relationship with emotional impact. Establishing such a link between room acoustics' parameters and emotions provides a guide for designing spaces that enhance the occupant's experience.

3 The abstract has been published in: Algargoosh, A. (2020). "Analysis of the Acoustic Characteristics of Spaces Relating to their Emotional Impact," Acoust. Virtually Everywhere.

4.1 Introduction and related studies

The emotional impact of music has been widely studied (Juslin and Sloboda, 2010). Since musical performances are impacted by the acoustical features of the venues in which they are played (Martellotta, 2008), researchers started to explore the emotional impact of the acoustics of concert halls to understand the reason behind the most preferred choices (Ando, 2011; Beranek, 2009; Pätynen and Lokki, 2016). As with concert halls, the psychological and emotional effect of worship spaces' room acoustics is essential as it is considered to support spiritual needs (Kleiner et al., 2010). While buildings cannot create a spiritual experience, the architectural features of such places create sound effects that can enhance the room's auditory experience and evoke specific emotions (Algargoosh, 2019). Researchers in worship spaces have reported a similar emotional impact due to the acoustic environment (Hale, 2007); however, further research is required to understand the acoustic and architectural characteristics that contribute to that effect. In Phase 1, we conducted a subjective analysis to understand the emotional impact of the acoustics of worship spaces. This study builds on the earlier results by analyzing the acoustic characteristics of such spaces and their relationship with emotional impact. It aims to (1) establish a correlation between the acoustic parameters and the spiritual experience, and (2) analyze the frequency and time domains to identify the characteristics of the acoustic environments of worship spaces and their contribution to spiritual experience. Both will allow for a better understanding of the physical factors that contribute to the aural experience in worship spaces.

4.1.1 Correlation between the acoustic parameters and the indicators of emotional response

To understand the acoustic factors that contribute to the perception of music in concert halls, many researchers developed links between the physical aspects and the perceptual aspects of sound.

Beranek linked musical factors with acoustic factors that impact music quality, as shown in Fig. 4.1 (Beranek, 2004). Ando connected the acoustic parameters in Fig. 4.2 with temporal and spatial sound sensations (Ando, 2015).

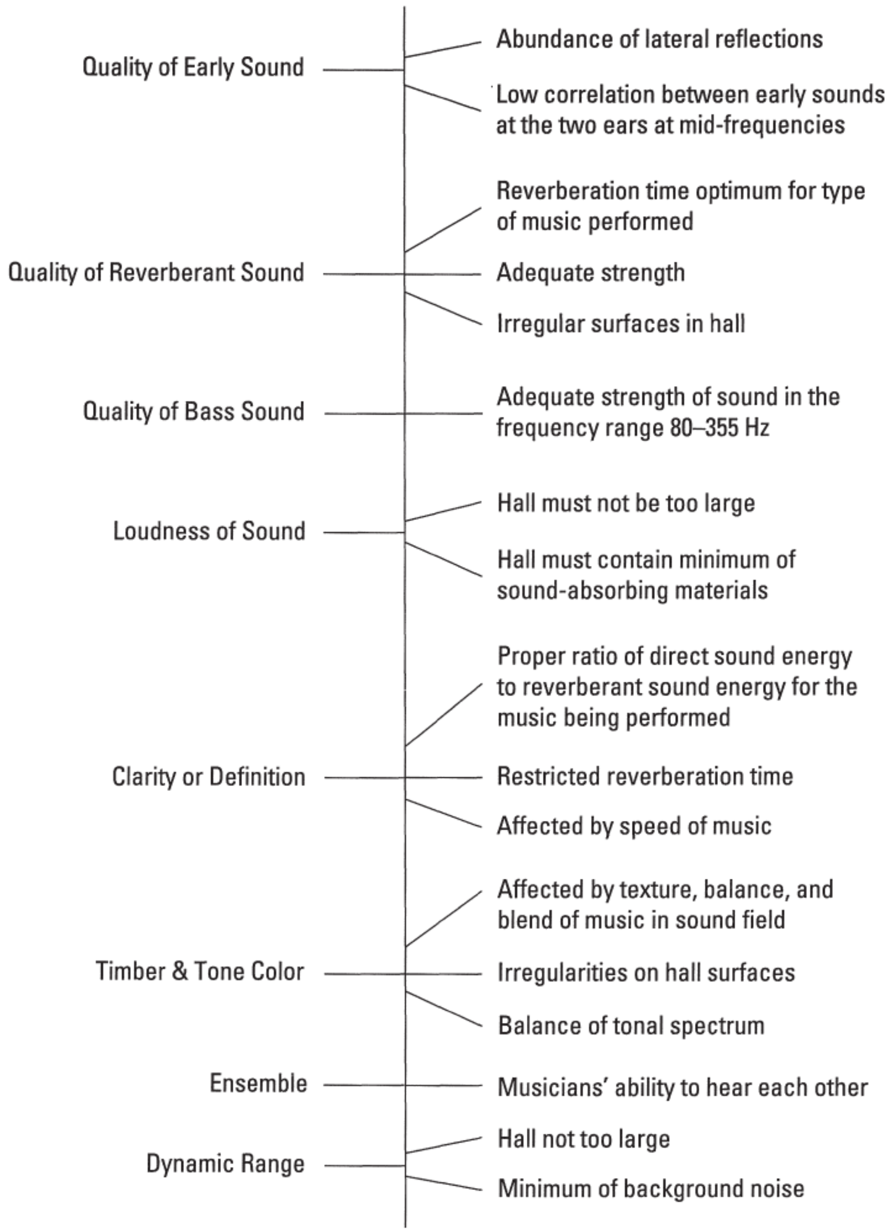


Fig. 4.1. Linking musical qualities with acoustic parameters (Beranek, 2004)

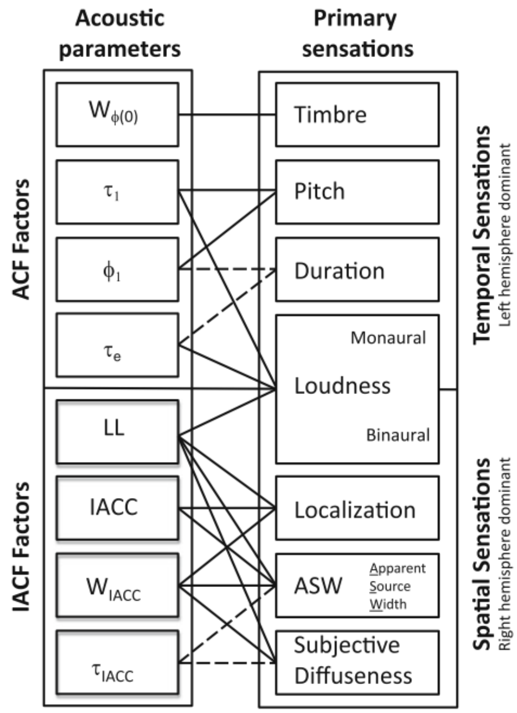


Fig. 4.2. Linking sound subjective qualities with acoustic parameters (Ando, 2015)

Pätynen and Lokki studied the emotional response in concert halls using self-report & physiological indicators (skin conductance response). The results demonstrated that sound strength and envelopment play a critical role in the emotional impact; more specifically, strength at low and mid-frequency strongly correlated with skin conductance response (Pätynen and Lokki, 2016). Although the study provides a link between the acoustic environment and emotional impact, its applicability to other types of buildings—such as worship spaces, with their unique experience requirements—must be evaluated. To illustrate the importance of considering the type of sound performance, many of the links established between acoustic parameters and musical qualities for concert halls in Fig. 4.1 apply to opera houses; however, they need to be reevaluated to consider some differences in performances (Beranek, 2004).

Martellotta studied the role of performance type in subjective rating, analyzing the acoustic parameters in worship spaces by considering different musical motifs. The result showed that the listeners' preference depends on the musical motif and that the parameter of early decay time (EDT) is correlated with the preference for vocal music. The study found that the optimum EDT value is within the range of 1.7–3.6 seconds for vocal music and suggested that longer reverberation time is preferred in comparison with concert halls due to the associations with the sacred character of the sound (Martellotta, 2008). Although this study shows that preference depends on the type of the performance (sound source's musical characteristics) and that the spectra of different musical motifs vary considerably (Fig. 4.3), it does not address how the room amplifies each musical motif depending on the dominant frequency of the sound source.

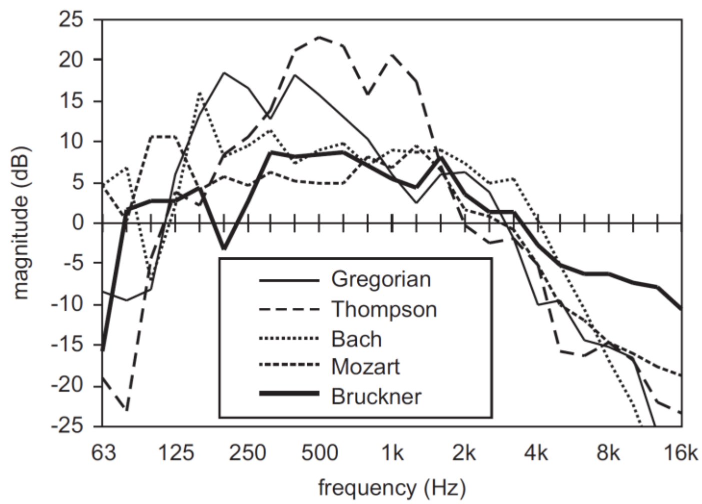


Fig. 4.3. Spectra of different sound motifs (Martellotta, 2008)

This study builds upon previous research in establishing links between the room's acoustic characteristic and emotional impact in concert halls. It examines the specifications of such links in worship spaces while considering the the room's response to the excitation by the sound source and its characteristics by analyzing the time and frequency domains.

4.1.2 Frequency and time domains

Rooms can act as passive amplifiers of the sound generated by a source (Heller, 2013); however, this amplification is not equal across all frequencies (Pätynen et al., 2013). As noted earlier, researchers studying the acoustics of Hagia Sophia reported that specific frequency bands are also amplified by the accumulation of the sound energy interacting with the architectural surfaces of the space. Specifically, the room modes at low frequencies cause the sound level to increase above the original sound source (Pentcheva, 2017).

Researchers studied how certain frequency bands build up after multiple reflections from the room surfaces through analyzing short time frames of the impulse response ranging between 20 milliseconds (ms) and 200 ms (Pätynen et al., 2013). The suggested method provides details of the frequency responses of the halls as they progress over time, showing how the amplitude of specific frequency bands build up based on the geometry of the space and the receiver location. Although the method was applied as a tool to understand the seat dip effect, this study does not consider the amplification of the frequency bands after interacting with the sound source, and how the dominant frequencies in the source reinforce the amplification created by the sound reflections.

For example, the highest amplitude value in Fig. 4.3 is within the range 125–500 Hz for Gregorian chants and within 300–1500 Hz for Thompson music (polyphonic choral music). Thus, if the room amplifies the magnitude at 200 Hz higher than other frequencies, the impact of sound amplification resulting from the room's response to the excitation by the sound source can be more substantial when the Gregorian chant is performed, in comparison to Thompson music.

Previous research asserted that specific spaces are known to acoustically perform better with a certain type of music (Kuusinen and Lokki, 2020; Martellotta, 2008) and demonstrated that the emotional impact of an acoustic environment depends on the sound source, as seen in Fig. 4.4 (Västfjäll et al., 2002).

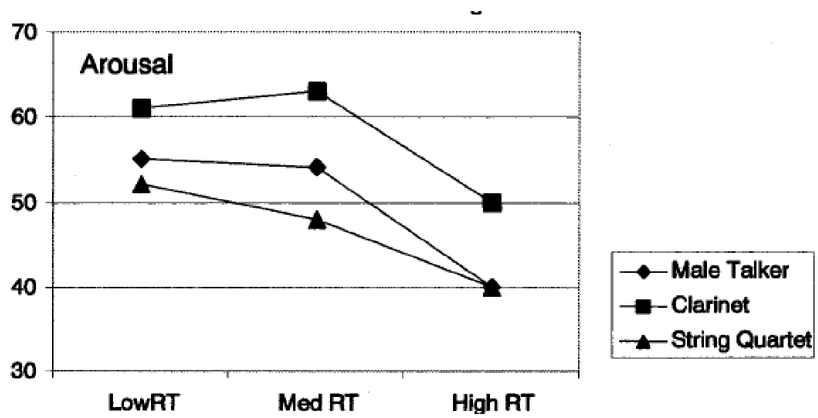


Fig. 4.4 Emotional arousal (mean value) response using three levels of reverberation and music types (Västfjäll et al., 2002)

Hence, this study examines the room's response to the excitation by the sound source considering its frequency characteristics by analyzing the spectra and spectrograms of the case study buildings of Phase 1. This analysis will allow for understanding how the room acoustic characteristics can amplify some frequency bands more than others depending on the dominant frequencies of the sound source.

4.2 Methods

The room acoustics of the case studies in Phase 1 were analyzed based on the parameters that have been reported as the most significant in worship spaces: reverberation time (T30), early decay time (EDT), clarity (C80), and sound strength (G) (Kleiner et al., 2010). Given that T30 is the time that the sound takes to decay by 30 dB, EDT is the time to decay by 10 dB, C80 is the ratio of the early sound to the reflected sound at 80 milliseconds, and G is the level of sound at a distance of 10 m from the source.

Subsequently, the emotional response to the acoustic environments of the same buildings (including self-report and physiological responses) was studied to examine the possible correlations with the acoustic parameters mentioned above.

Later, the characteristics of both the frequency and time domains of the studied buildings were analyzed to investigate patterns in spectra and spectrograms, in addition to identifying the unique attributes of the building's acoustic environment that resulted in the highest emotional response.

4.2.1 Acoustic parameters

To obtain the acoustic parameters for the studied buildings, the IR of each building was recorded based on the standard ISO 3382-1:2009 (E). An impulse sound was generated using a wooden clapper at the front of the space (which is the typical location of the sound source in such worship spaces) at the height of 1.5 m above the floor (ISO 3382-1, 2009). The sound receiver (microphone) was located at the center of the worship space, and the spaces were unoccupied during the measurements.

The IR was recorded, and the acoustic parameters (including T30, EDT, and C80) were calculated using SMAART software. Sound strength (G) was calculated according to the (ISO 3382-1:2009(E)) as follows:

$$G = L_1 - L_2 \qquad \text{Eq. (4)}$$

Where L_1 is the measured sound pressure level at the selected location for calculating G, and L_2 is the measured sound pressure level at a 10 m distance in a free field. The sound pressure was calculated using ITA MATLAB Toolbox (at octave bands).

In addition, the bass was analyzed using bass gain (G_{Bass}), which is the strength of the bass sound, and bass ratio (BR), which is the ratio of T30 at low to mid frequencies (Beranek, 2004). The formulas below show the methods of calculating each:

$$G_{Bass} = G_{Low} (G_{125 Hz} + G_{250 Hz}) - G_{Mid} (G_{500 Hz} + G_{1000 Hz}) \quad \text{Eq. (5)}$$

Where G_{Low} is the total sound strength at 125 Hz and 250 Hz, and G_{Mid} is the total sound strength at 500 Hz and 1000 Hz.

$$BR = (T30_{125 Hz} + T30_{250 Hz} / (T30_{500 Hz} + T30_{1000 Hz}) \quad \text{Eq. (6)}$$

4.2.2 Correlation between the acoustic parameters and the indicators of emotional response

After analyzing the acoustic parameters of the studied buildings, we conducted a Pearson correlation using R-Studio software to explore the acoustic parameters correlated with the emotional response indicators discussed in Chapter 2, including the self-report and physiological response. Furthermore, we performed a Pearson correlation analysis between the volume and the emotional response indicators.

4.2.3 Frequency and time domain analysis

To further explore the acoustic characteristics of the studied buildings and understand the unique features for the building that received the highest rating for emotional impact, the frequency and time domains of the IR were studied using spectra and spectrograms analysis. Then, to explain some of the main differences in the results, we analyzed resonance in terms of quality (Q), which is a quality factor defined by the number of oscillations before the amplitude decays to 4% or the energy decreased to 0.19% of the original value, and width (Δf), which is the distance between the occurring resonances in frequency (Heller, 2013). In other words, resonance quality is the ratio of mode frequency to its bandwidth (Tooley, 2006). We calculated resonance quality and width based on the following equations:

$$Q(f)= 0.227 \times f \times T30 \qquad \text{Eq. (7)}$$

$$\Delta f= 4.4/ T30 \qquad \text{Eq. (8)}$$

Given that Q(f) is the resonance quality for frequency (f), T30 is the reverberation time at the same frequency, Δf is the resonance width (Heller, 2013).

Later, two of the buildings that showed the most significant differences in resonance were selected to compare the spectra and spectrogram of the recorded sound for the same religious recitation in the buildings.

Next, since previous research demonstrated that acoustical preference and emotional impact depend on the frequency component of the source (Martellotta, 2008), the room's response to the excitation by the sound source (with consideration to its frequency characteristics) was studied by analyzing the spectra resulting from playing a sound source in two of the studied buildings and playing two different sound sources in the same building.

Lastly, the multiple auralization method developed in Chapter 3 was applied as a tool to identify the dominant frequency bands that the room amplifies.

4.3 Results and discussion

The results of the acoustic environments' emotional impact for the studied cases in Chapter 2 indicated that the acoustic environment enhanced spiritual emotions and that the intensity of the emotional impact was different among the buildings. The results below show the acoustic characteristics of each building with links to the results of the emotional responses previously explained.

4.3.1 Acoustic parameters

The results of EDT of the studied buildings (A1, A2, B1, and B2) in (Fig. 4.5) show that all the buildings (except A2) have longer EDT at frequencies <1000 Hz. Fig. 4.6 indicates that the reverberation time for all the buildings (except A2) follows the same pattern in having the longest T30 values (2–3 seconds) between 250 Hz and 1000 Hz and showing a drop at high frequencies >1000 Hz to the range (.5–1 second). Such a pattern that contains long reverberation time values at low frequencies is preferred in choral music (Rational Acoustics, 2018). On the other hand, T30 values for A2 are significantly lower at frequencies <1000 Hz, and in general, all buildings showed a peak in T30 at 250 Hz.

The results of C80 in Fig. 4.7 show that, in general, the buildings (except A2) had lower C80 values at low frequencies <1000 Hz and higher values for mid and high frequencies ≥1000 Hz (except B2). It is noted that A1 had the highest contrast, with the lowest C80 values at frequencies <1000 Hz and the highest values >1000 Hz. This may have contributed to preserving the speech intelligibility at the critical frequency range (500–4000 Hz) while still adding aesthetics to the sound at low frequencies.

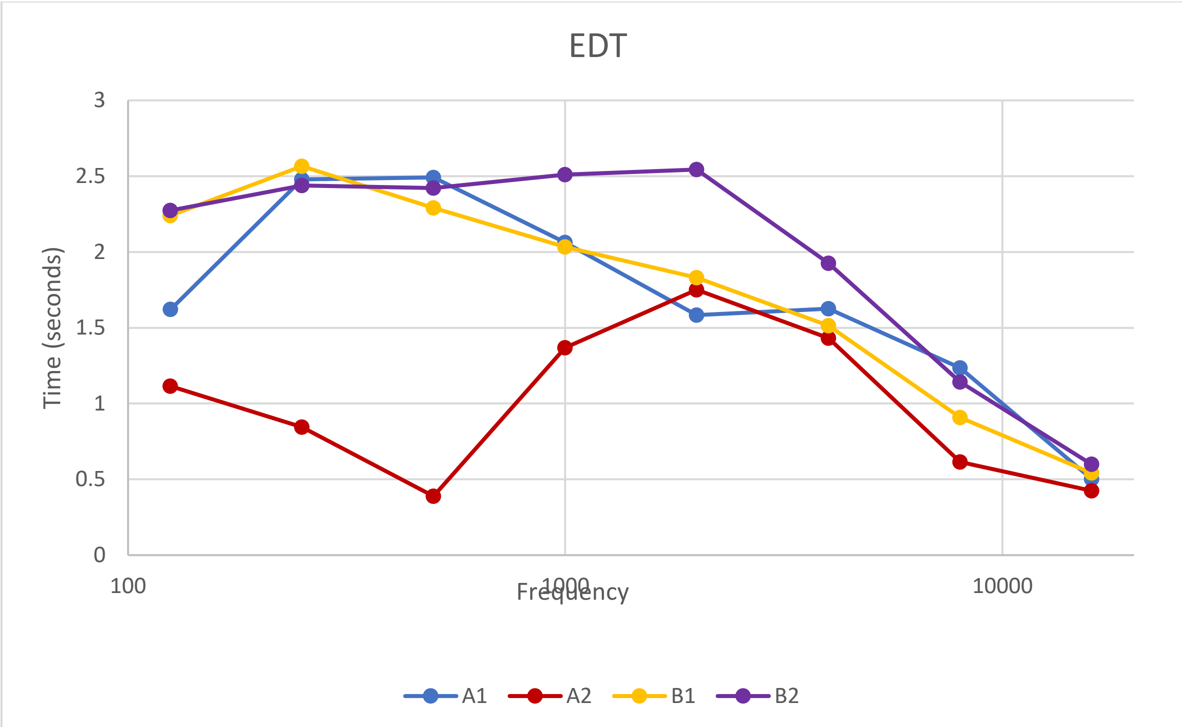


Fig. 4.5 EDT values for the studied building

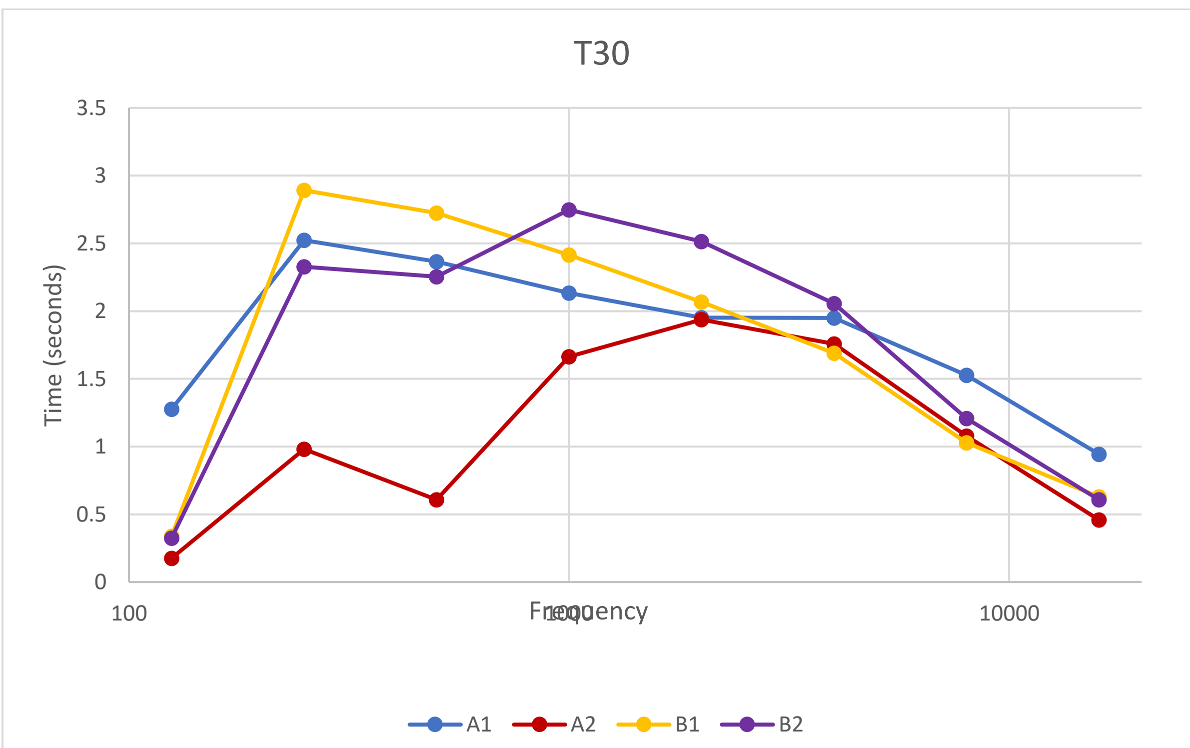


Fig. 4.6 T30 values for the studied buildings

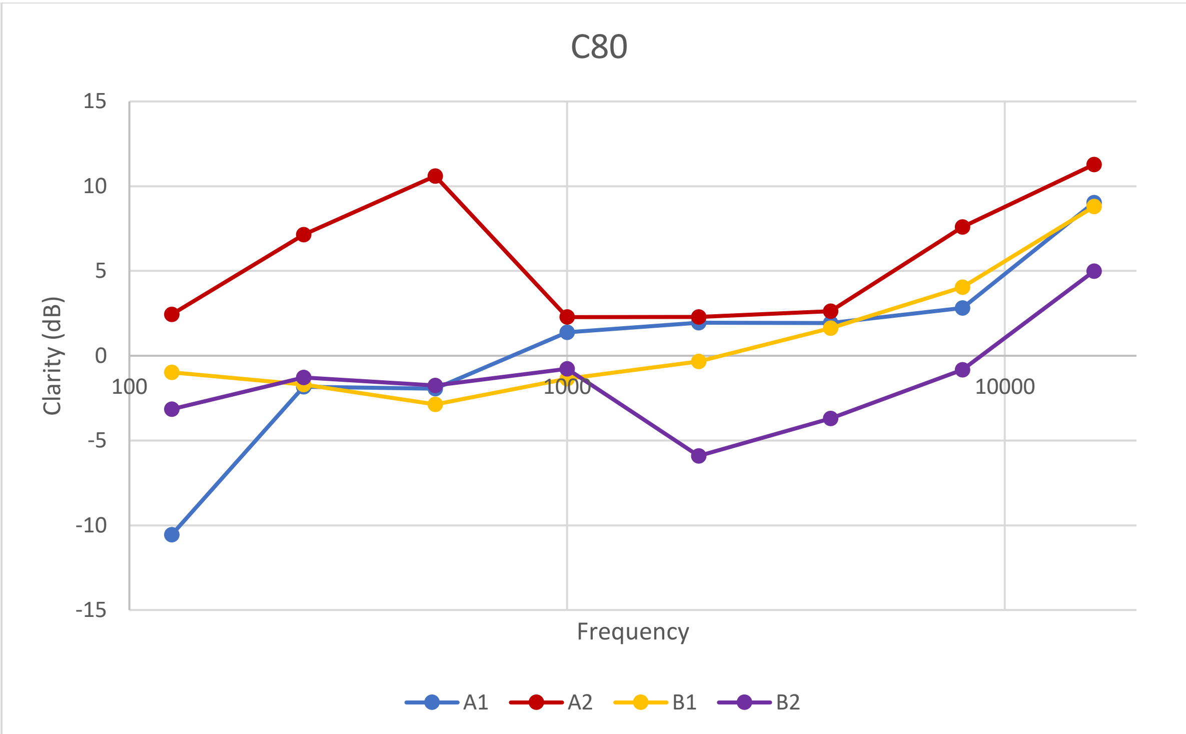


Fig. 4.7 C80 values for the studied buildings

In all parameters, the EDT, T30, and C80 values of all the buildings became close at 1000 Hz and varied significantly, especially at frequencies <1000 Hz. This indicates that only reporting T30 at 1000 Hz, which is a standard followed by many researchers, might cause overlooking important acoustic features that can contribute to the impact of sound perception and its impact on emotions.

The same observation can be seen in Fig. 4.8, where G values of all the buildings are also close at 1000 Hz and vastly different at low and high frequencies. Although Beranek only used G at mid frequencies in analyzing the loudness in music halls and mentioned that it had proved not to be useful due to the variation that might result from measuring unoccupied and occupied concert halls (Beranek, 2004), researchers have recently found that reporting G at mid frequencies (G mid) is not sufficient (Lokki and Pätynen, 2020).

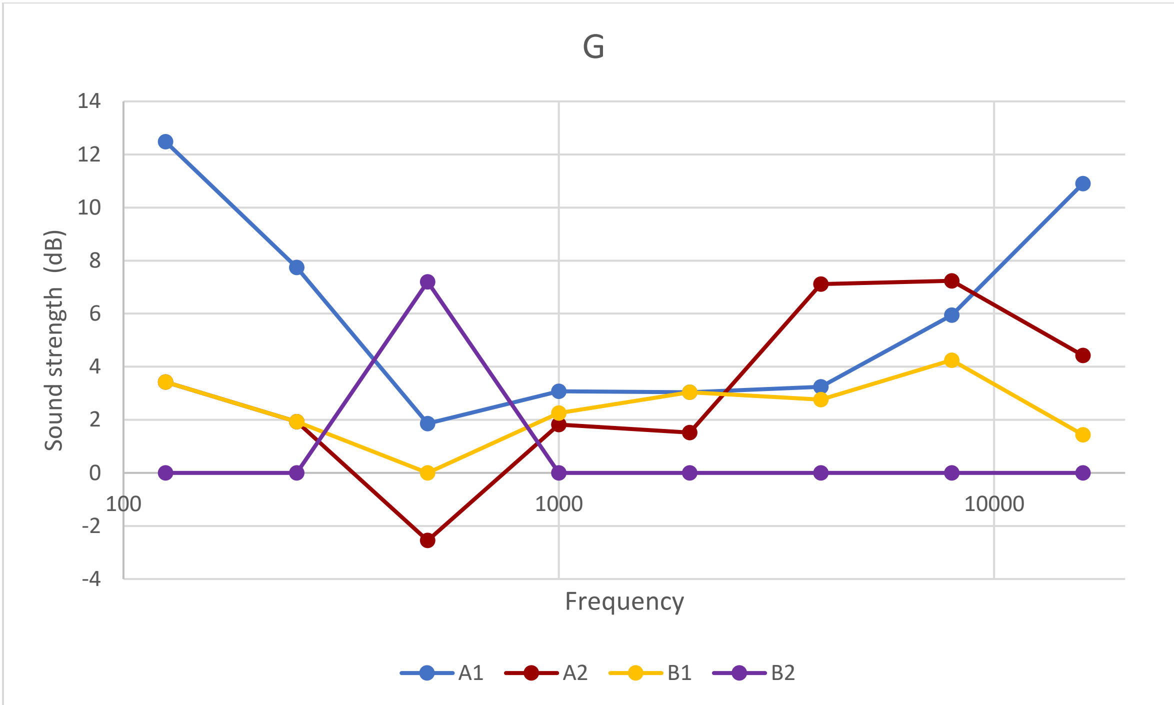


Fig. 4.8 G values for the studied buildings

Table 4.1 shows the detailed results of the strength of the bass sound at low and mid frequencies (G_{Low} and G_{Mid}), and the bass gain (G_{Bass}) in the studied cases. A1 showed the highest G_{Bass} value, and it was the building that received the highest rating for spiritual emotions in Phase 1 (Fig. 4.9). The high (G_{Bass}) in A1, A2, and B1 can be a result of having higher absorption at mid frequencies rather than low frequency because of the carpet flooring in these building.

Table 4.1: G low, G mid, and bass gain of the studied buildings

Strength	**A1**	**A2**	**B1**	**B2**
G_{Low}	20.22	5.35	5.35	0
G_{Mid}	4.93	-0.73	2.25	7.2
Bass gain (G_{Low} - G_{Mid})	**15.29**	**6.08**	**3.1**	**-7.2**

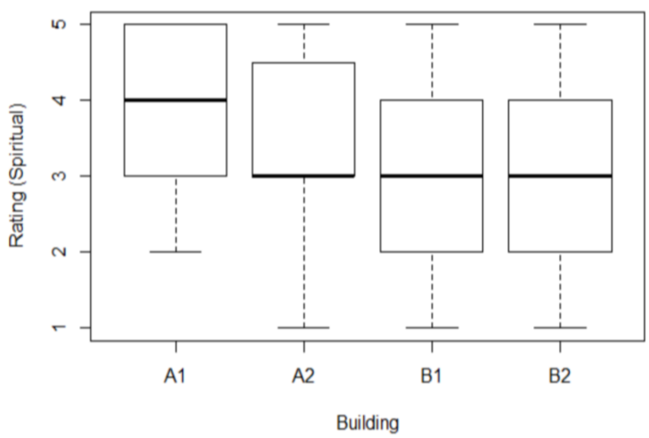


Fig. 4.9 Self-report rating for spiritual emotions for the studied buildings.

Bass gain is an objective indicator of sound warmth (the subjective feeling of the strength of the bass), and both bass gain and BR contribute to the richness of the bass (Beranek, 2004). The following table shows the BR for the studied buildings. It also shows that A1 has the highest BR. Previous research indicated a significant increase in BR when adding carpet to a worship space resulting in sound amplification of the frequencies in the male voice and adding warmth to the sound (Sü Gül, 2021)

Table 4.2: Bass ratio for the studied buildings

Building	**A1**	**A2**	**B1**	**B2**
Bass ratio	0.84	0.51	0.63	0.53

4.3.2 Correlation between the acoustic parameters and the indicators of emotional response

The result of the Pearson correlation analysis between volume and emotional response showed a negative correlation with HRR (-0.99, p-value < .01), and EDR (-0.45, p-value < .05). This aligns with the results of a previous study on the emotional impact of concert halls, which demonstrated that the halls with the most significant impact (the first three halls in Table 4.3) had smaller volumes than the other ones (Pätynen and Lokki, 2016). This was supported by another study, which indicated that halls with a large volume were associated with less emotional arousal because of the extensively long reverberation time (Västfjäll et al., 2002).

Table 4.3: Volumes of concert halls studied for their emotional impact (Pätynen and Lokki, 2016)

Id	Hall	Shape	V (m^3)	N	G (dB)	EDT (s)
VM	Vienna Musikverein	Rect.	15 000	1680	3.7	3.0
AC	Amsterdam Concertgebouw	Rect.	18 780	2040	2.7	2.5
BK	Berlin Konzerthaus	Rect.	15 000	1575	2.2	2.2
BP	Berlin Philharmonie	Vineyard	21 000	2220	1.9	1.9
HM	Helsinki Music Centre	Vineyard	24 000	1700	1.9	2.1
CP	Cologne Philharmonie	Fan	19 000[a]	2000	1.9	1.7

The result of the Pearson correlation coefficients between the acoustic parameters in the studied cases and the emotional impact indicators are shown in Table 4.4.

The correlation result for octave band frequencies between 125–8000 Hz showed the following:

1) At 125 Hz, G had a significant correlation with SRR (p-value < .01). EDT and T30 had significant correlation with HRR and SRR respectively (p-value < .05).

2) At 250 Hz, G had a significant correlation with SRR (p-value < .01).

3) At 1000 Hz, T30 had a significant correlation with HRR (p-value < .05).

4) At 8000 Hz, EDT had significant correlation with EDR (p-value < .05), and G had significant correlation with HRR (p-value < .05).

Additionally, the result of the Pearson correlation between G_{Bass} and SSR was 0.82 (p-value < .01), as shown in Fig. 4.10.

Table 4.4: Pearson correlation coefficients between mean self-report and physiological emotional response (SRR, HRR, and EDR) and selected acoustic parameters in octave bands for frequencies 125–8000 Hz separated.

Freq.	Response	EDT	T30	C80	G
125	***SRR***	-0.30	**0.95** [b]	-0.81	**0.99** [a]
	HRR	**-0.96** [b]	0.22	0.07	0.54
	EDR	-0.29	-0.80	0.93	-0.55
250	***SRR***	0.25	0.26	-0.29	**0.99** [a]
	HRR	-0.71	-0.65	0.69	0.53
	EDR	-0.64	-0.50	0.68	-0.55
500	***SRR***	0.29	0.30	-0.24	-0.19
	HRR	-0.70	-0.69	0.72	-0.81
	EDR	-0.74	-0.54	0.63	-0.69
1000	***SRR***	-0.07	-0.30	0.42	0.82
	HRR	-0.89	**-0.98** [b]	0.91	0.65
	EDR	-0.69	-0.46	0.07	-0.04
2000	***SRR***	-0.72	-0.60	0.61	0.7
	HRR	-0.81	-0.88	0.92	0.42
	EDR	-0.15	-0.30	0.27	0.02
4000	***SRR***	-0.23	0.10	0.51	0.16
	HRR	-0.78	-0.41	0.84	0.92
	EDR	-0.66	-0.83	0.41	0.62
8000	***SRR***	0.47	0.83	0.09	0.51
	HRR	-0.50	0.17	0.84	**0.95** [b]
	EDR	**-0.95** [b]	-0.90	0.73	0.36

[a] Correlation with p-value < .01
[b] Correlation with p-value < .05

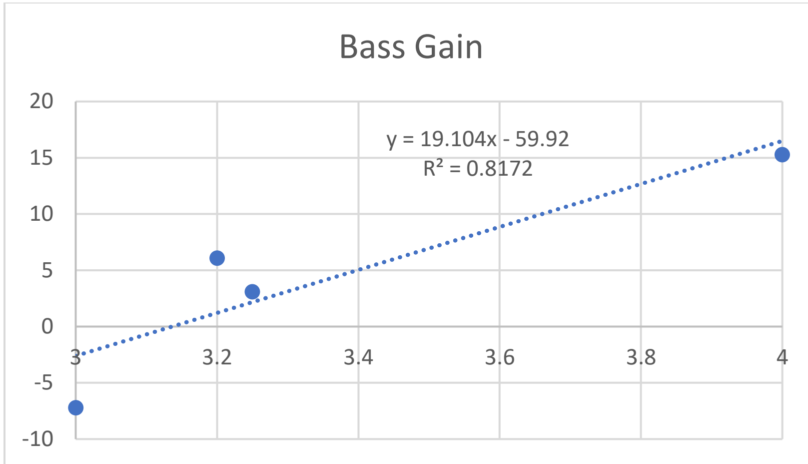


Fig. 4.10 Correlation between bass gain and SSR

The previous results indicate that the frequency showing the most significant correlation between the acoustic parameters (EDT, T30, and G) and the emotional response SRR was 125 Hz, which is in the low-frequency range. Thus, reporting acoustic parameters only at mid frequencies (500, 1000 Hz) may result in missing critical information related to the subjective evaluation of an acoustic environment, and more specifically, related to the emotional impact.

Researchers mentioned identifying resonance resulted from room modes in frequencies at the ranges 95–120 Hz in prehistoric megalithic structures (Cook et al., 2008; Hale, 2007; Miguel Gaona et al., 2014). They also demonstrated that listening to low frequencies, such as 110 Hz, is associated with asymmetrical brain activity that is related to an emotional response. This result suggests that resonance at the low frequencies may have played a role in supporting rituals, given that such low frequencies fall within the human vocal range (Cook et al., 2008) and the drive frequency average for the vocal tract for males (100–125 Hz) (Heller, 2013). Further, other researchers reported resonance at low frequencies in worship spaces known for their unique acoustic qualities, such as the Hagia Sophia (a worship space in Turkey) (Pentcheva, 2017).

In addition to worship spaces, previous studies in concert halls showed that low frequencies within the range (125–250 Hz) showed a significant correlation between the acoustic parameters (strength and reverberation time) and the emotional response (self-report), as seen in Table 4.5. However, the correlation with strength was also significant at other frequency bands, which may be explained using musical instruments as a sound source in the study (Pätynen & Lokki, 2016).

Table 4.5: Pearson's correlation coefficients between mean self-report and selected room acoustic parameters in frequency bands (Pätynen and Lokki, 2016).

	Room acoustic parameter							
Hz	G	C80	EDT	T	LJ	LEF	BQI	BDR
				Position R1 only				
63–125	0.63	0.28	−0.24	0.36	0.80	−0.15	–	–
125–250	**0.90**[a]	−0.64	0.45	**0.43**[a]	0.91	0.23	0.80	–
250–500	**0.78**[a]	−0.82	**0.53**[a]	0.39	0.84	0.66	0.93	0.65
500–1 k	**0.63**[a]	−0.80	0.57	0.37	0.78	0.72	0.98	0.22
1 k–2 k	**0.80**[b]	−0.76	0.54	0.40	0.83	0.69	**0.97**[a]	0.75
2 k–4 k	**0.92**[a]	−0.53	0.40	0.31	0.85	0.68	**0.99**[b]	0.73
4 k–8 k	0.76	−0.49	0.35	0.13	0.81	0.68	**0.98**[a]	0.84
				Position R2 only				
63–125	0.52	0.41	−0.13	0.63	0.54	0.09	–	–
125–250	**0.63**[a]	−0.25	0.60	0.70	**0.72**[a]	0.55	0.82	–
250–500	0.54	**−0.63**[a]	0.69	0.62	**0.72**[a]	0.69	**0.76**[a]	0.53
500–1 k	0.46	−0.66	0.67	0.58	0.68	0.64	**0.67**[b]	0.01
1 k–2 k	0.50	−0.62	0.67	0.61	**0.72**[a]	0.58	**0.72**[b]	0.39
2 k–4 k	**0.42**[b]	−0.50	0.58	0.53	**0.70**[a]	0.58	**0.84**[b]	0.54
4 k–8 k	0.16	−0.40	0.40	0.32	0.54	0.60	**0.81**[b]	0.59

[a]Statistically significant correlations at the $p < 0.05$ level.
[b]Statistically significant correlations at the $p < 0.01$ level.

4.3.3 Frequency and time domain results

4.3.3.1 Spectra and spectrogram

The following figures show the frequency domain of the IR for the studied buildings. Fig. 4.11 represents the spectra for all the buildings together, and Fig.12–15 represents the spectrum of each building. Fig. 4.12 indicates that A1 has the highest magnitude at frequencies <200 Hz compared to the other buildings. Besides, Fig. 4.12 & Fig. 4.13 show that A1 and A2 have strong individual modes at 108, 123 Hz for A1 and 120 Hz for A2, with magnitude levels that are 10–15 dB higher than the neighboring frequencies.

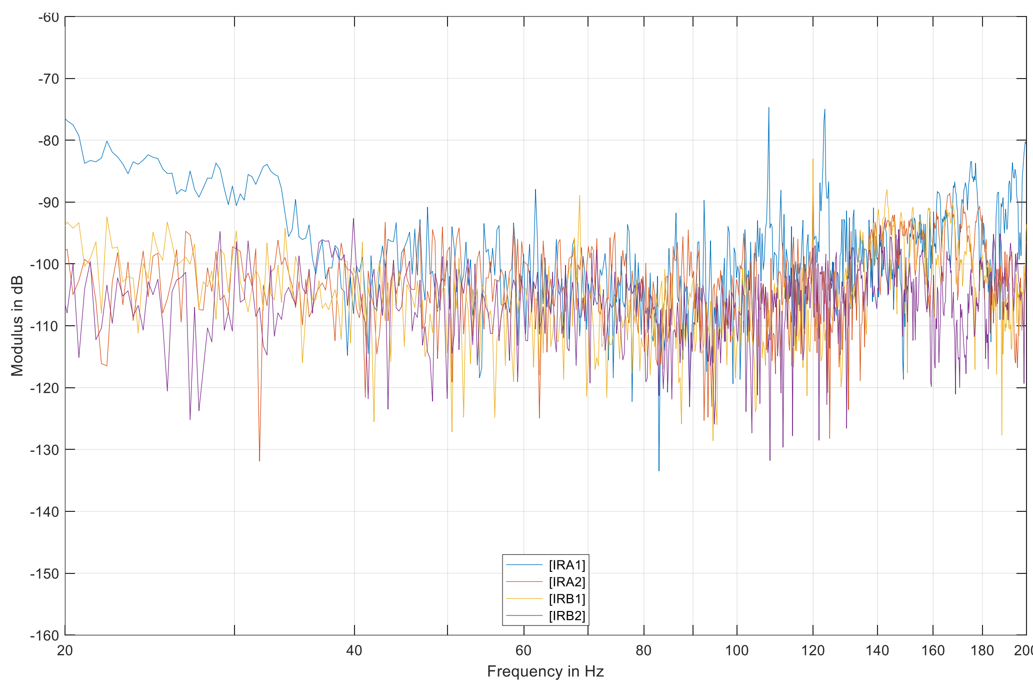


Fig. 4.11 Frequency-domain plot of the impulse responses of the studied buildings

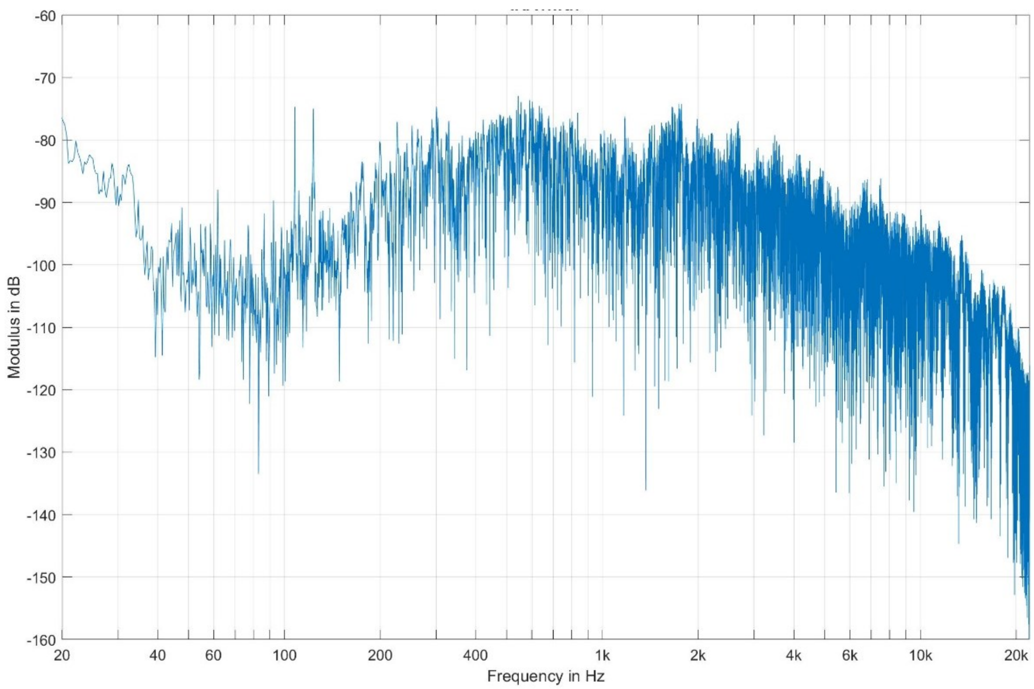


Fig. 4.12 Frequency-domain plot of the impulse response of A1

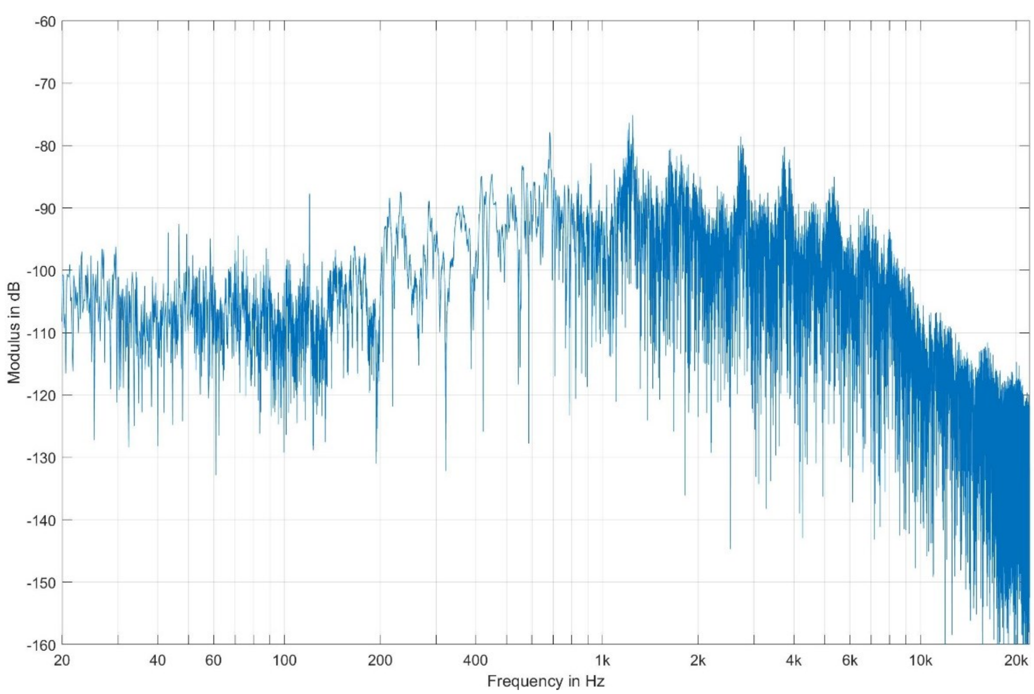


Fig. 4.13 Frequency-domain plot of the impulse response of A2

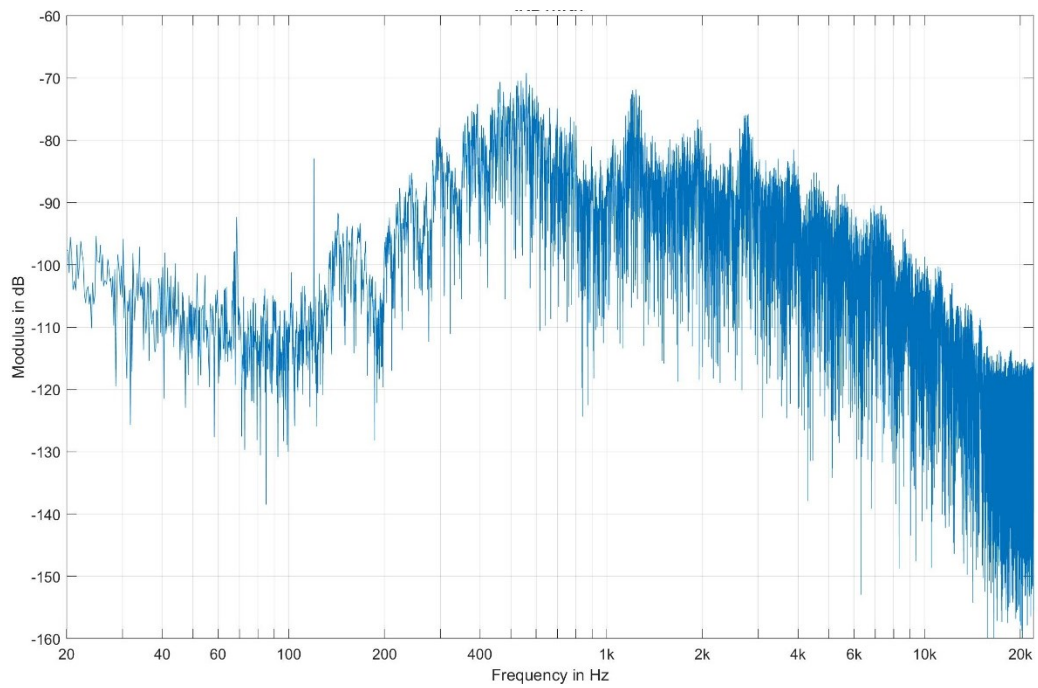


Fig. 4.14 Frequency-domain plot of the impulse response of B1

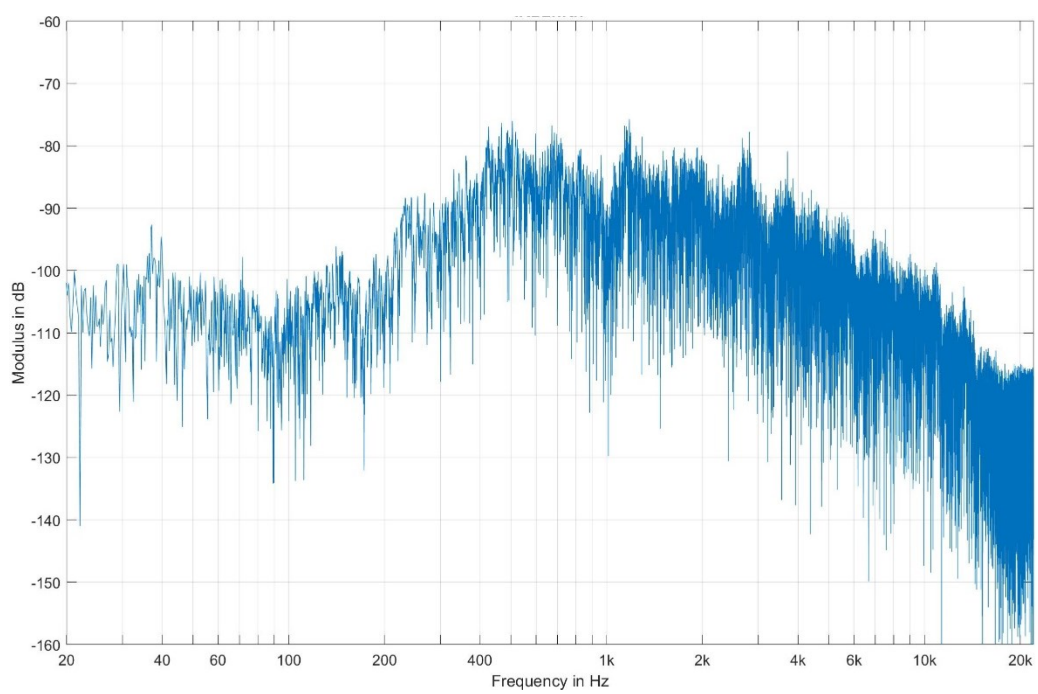


Fig. 4.15 Frequency-domain plot of the impulse response of B2

The following figures represent the spectrogram of each building. Fig. 4.16 shows that sound between 125 Hz and 1000 Hz lasts around 0.5 seconds in A2, while it extends up to 1.5 s in A1, B1, and B2, as shown in Fig. 17–19.

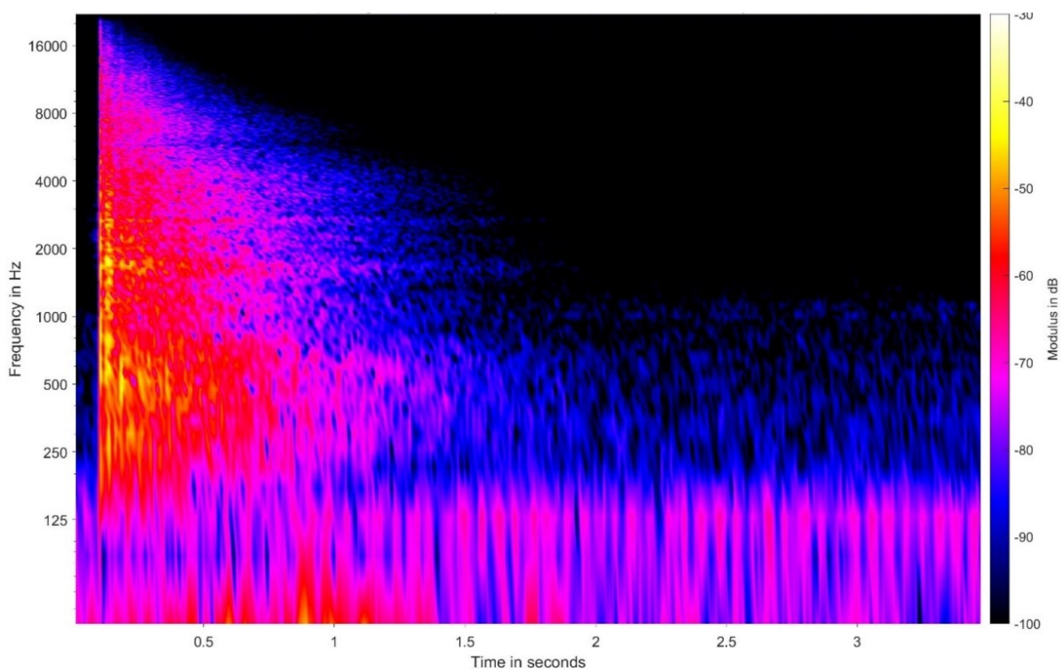


Fig. 4.16 Spectrogram of the impulse response of A1

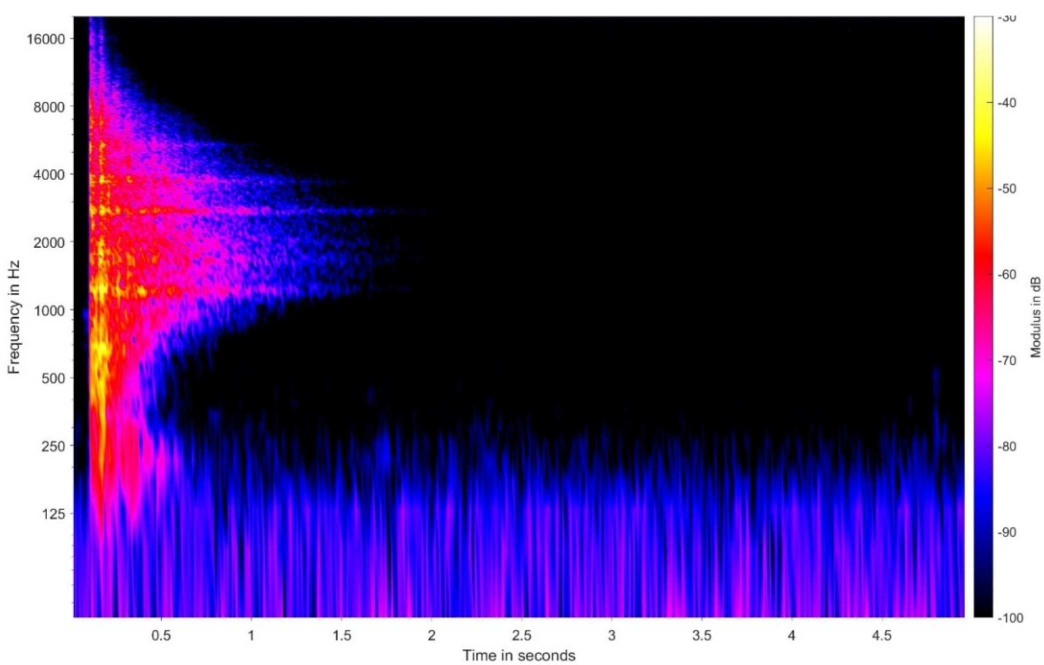


Fig. 4.17 Spectrogram of the impulse response of A2

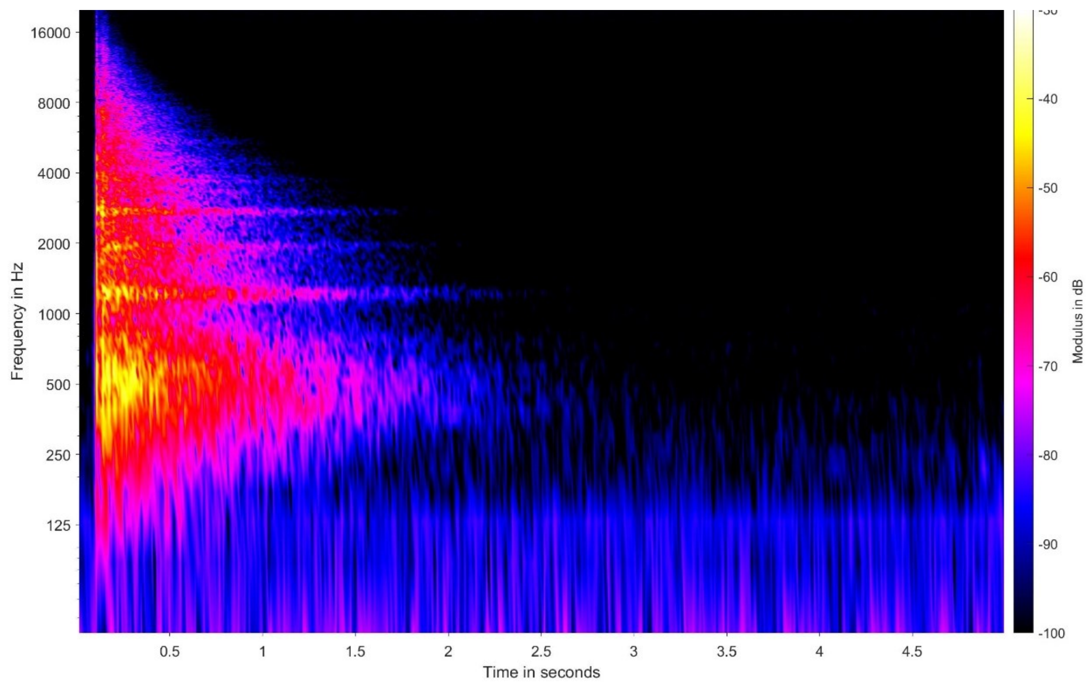


Fig. 4.18 Spectrogram of the impulse response of B1

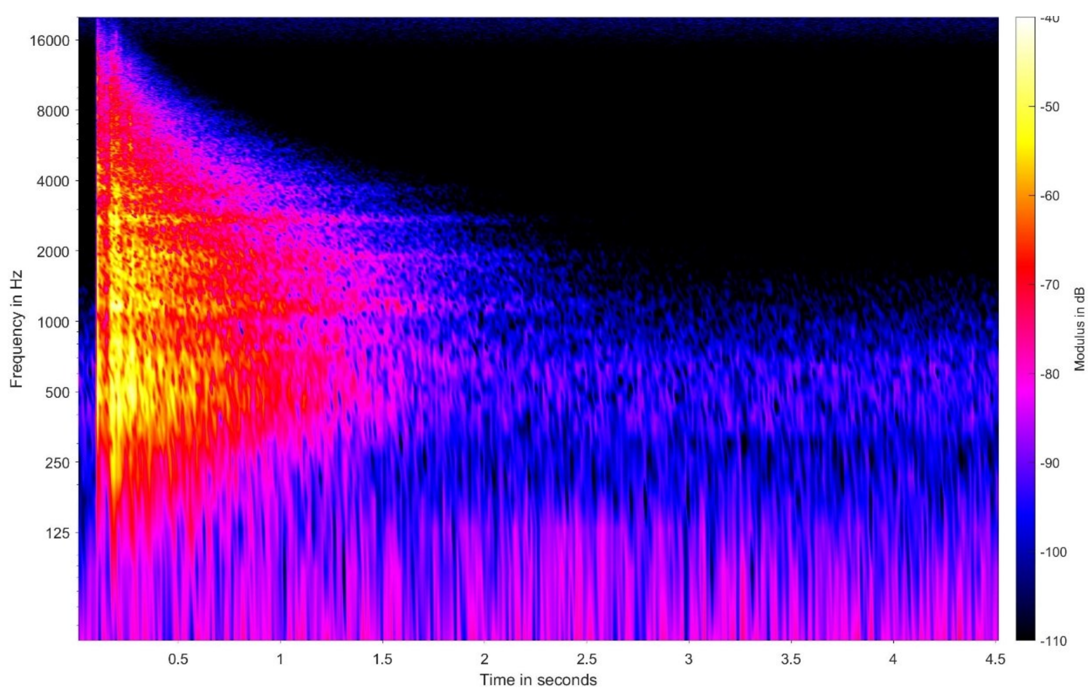


Fig. 4.19 Spectrogram of the impulse response of B2

1) Resonance

The dramatic difference between A2 and the other buildings can be explained by the resonance analysis results, including resonance quality and width.

Resonance Quality (Q): Table 4.6 shows that A2 has the smallest Q valueS below 1000 Hz. It is also worth mentioning that at 125 Hz, A1 has the largest Q value, and A2 the lowest.

Table 4.6: The resonance quality of the selected buildings in octave bands from 125 to 8000 Hz

Frequency	**Resonance Quality (Q)**			
Hz	A1	A2	B1	B2
125	**36.23**	**4.99**	9.59	9.22
250	143.18	**55.73**	164.12	132.11
500	268.54	**68.89**	309.17	255.83
1000	484.42	377.73	548.21	623.80
2000	885.75	879.40	938.87	1141.81
4000	1770.60	1595.36	1533.61	1865.94
8000	2771.22	1957.65	1868.66	2191.91

Resonance width (Δf): Fig. 4.20 demonstrates that A1 and A2 have the most distinguished resonance widths at 125 Hz. Table 4.7 shows more details, indicating that A1 has the smallest width (3.45 Hz), and A2 has the largest (25 Hz), while B1 and B2 have a resonance width of (± 13 Hz). The large resonance width in A2 can be explained by its small volume in comparison to the other buildings since room-mode density increases with volume (Heller, 2013).

Above 125 Hz, the resonance widths for all buildings are similar expect A1, which has a higher width at 250 Hz and 500 Hz (4.48 and 7.25 Hz), respectively.

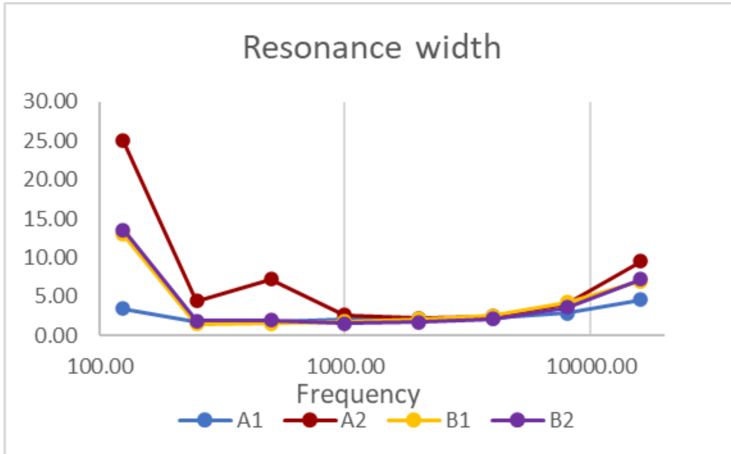


Fig. 4.20 Resonance width for the studied buildings

Table 4.7: The resonance width of the selected buildings in octave bands from 125 to 8000 Hz

Frequency Hz	Resonance Width (Δf)			
	A1	A2	B1	B2
125	3.45	25.00	13.02	13.54
250	1.74	4.48	1.52	1.89
500	1.86	7.25	1.62	1.95
1000	2.06	2.64	1.82	1.60
2000	2.26	2.27	2.13	1.75
4000	2.26	2.50	2.61	2.14
8000	2.88	4.08	4.28	3.65

2) Comparison between the selected cases

Considering that A1 and A2 presented dramatic differences in the resonance results, the following section will include the results of the room's response to the excitation by the sound source depending on the dominant frequencies of the sound source and acoustic characteristics of the room.

The figure below shows the spectra and spectrograms of the selected two buildings, displayed together for easier comparison.

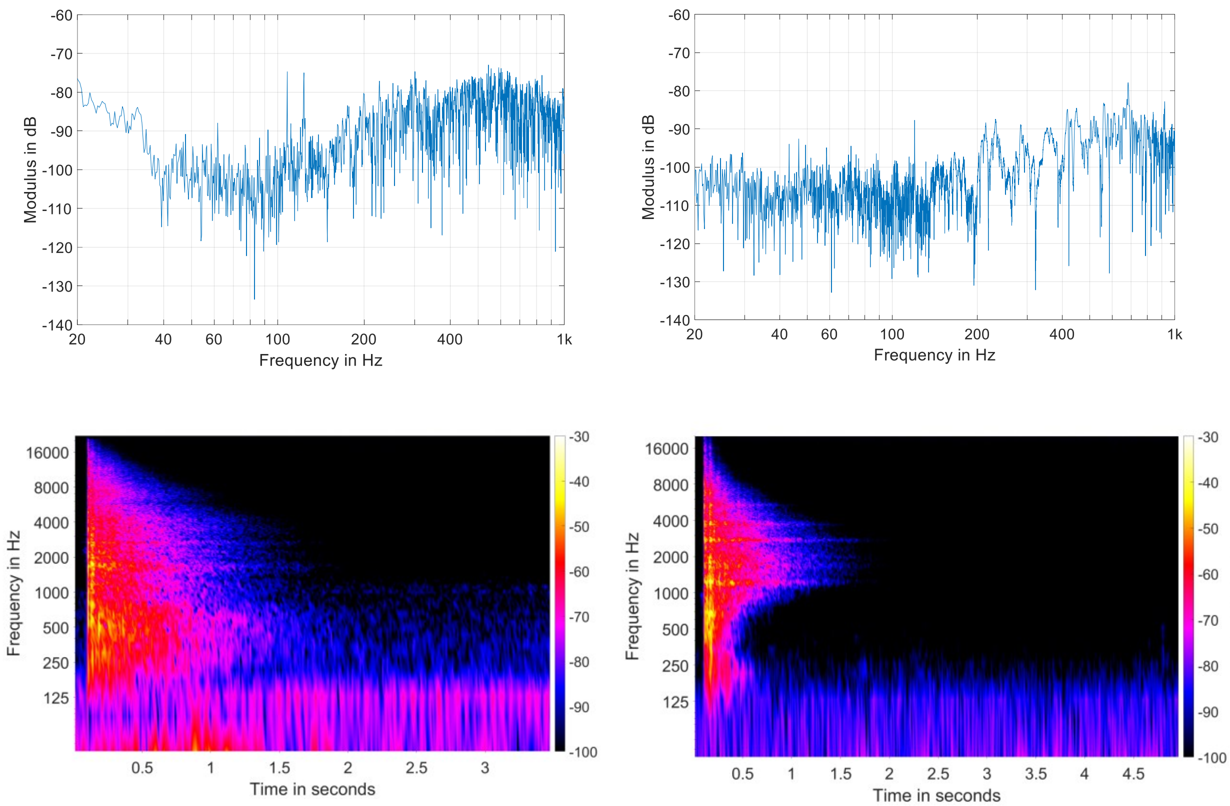


Fig. 4.21 Spectra and spectrograms of IR for the two selected buildings. Top left: spectrum of IR for A1. Top right: spectrum of IR for A2. Bottom left: spectrogram of IR for A1. Bottom right: spectrogram of IR for A2.

Fig. 4.22 & Fig. 4.23 show the spectrum and the spectrogram of the dry recording of the religious recitation (sound source 1) used in both A1 and A2. Both graphs indicate that the dominant frequencies are within the range (120–800 Hz).

Fig. 4.24 shows the spectrograms of the wet recordings of A1 and A2 using (sound source 1). The result shows that the dominant frequency in A1 remained within the range (120–800 Hz), similar to the dry recording, while A2 reinforced other high-frequency ranges that were not dominant in the dry recording, such as 4000 Hz. Both extended the sound in the time domain, with A1 having a larger effect than A2 due to its longer reverberation time.

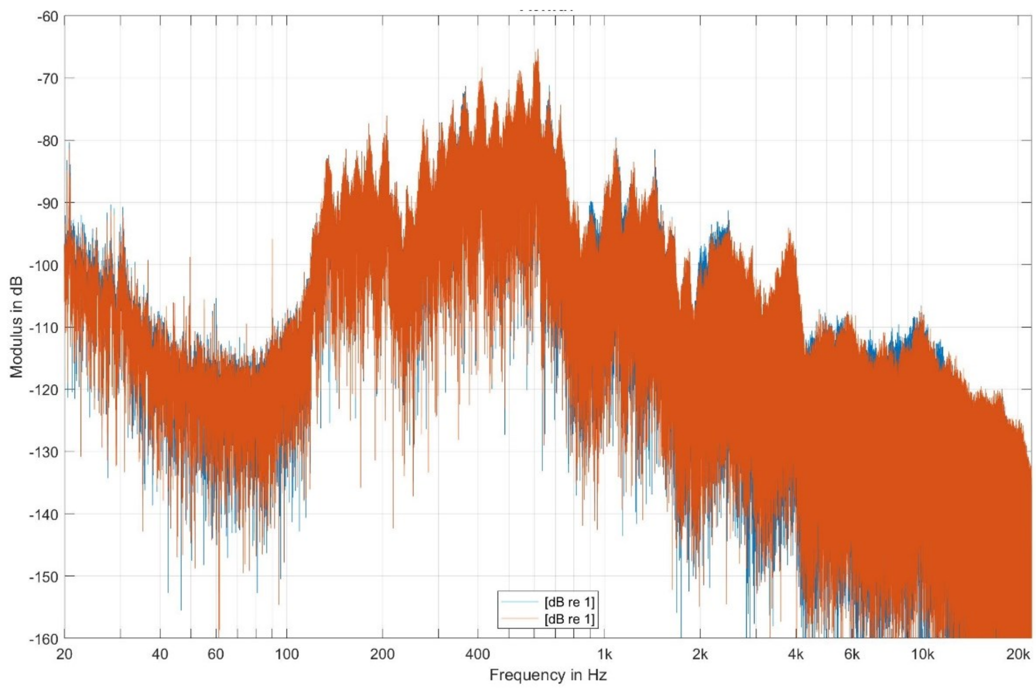


Fig. 4.22 Spectrum of the dry recording for religious recitation (sound source 1)

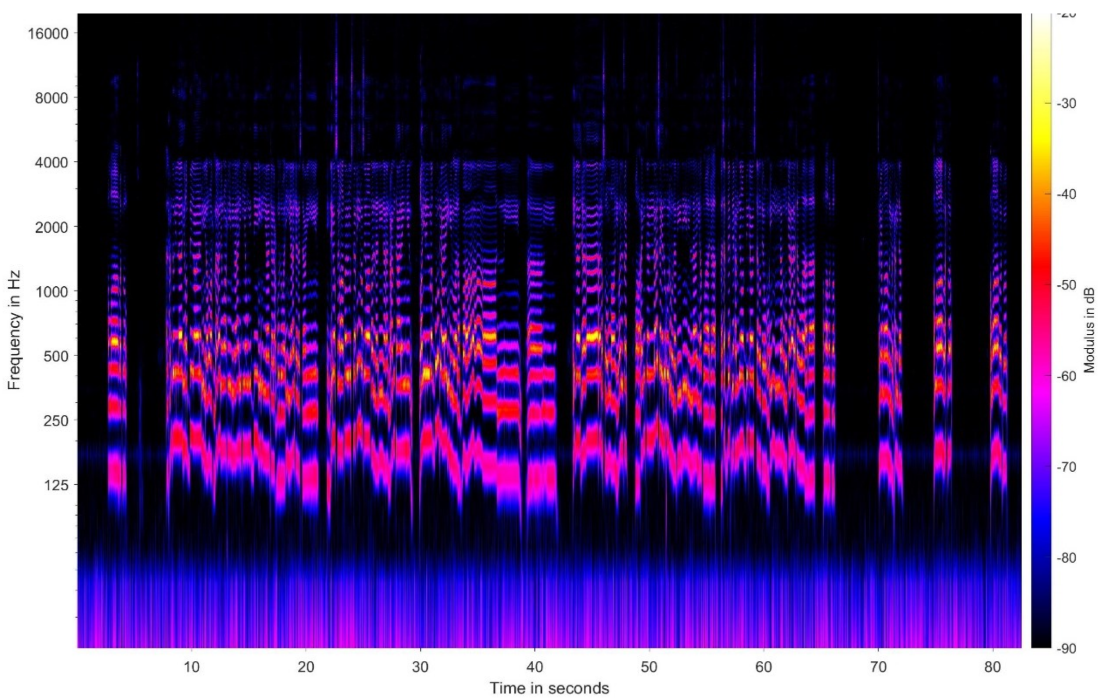


Fig. 4.23 Spectrogram of the dry recording for religious recitation (sound source 1)

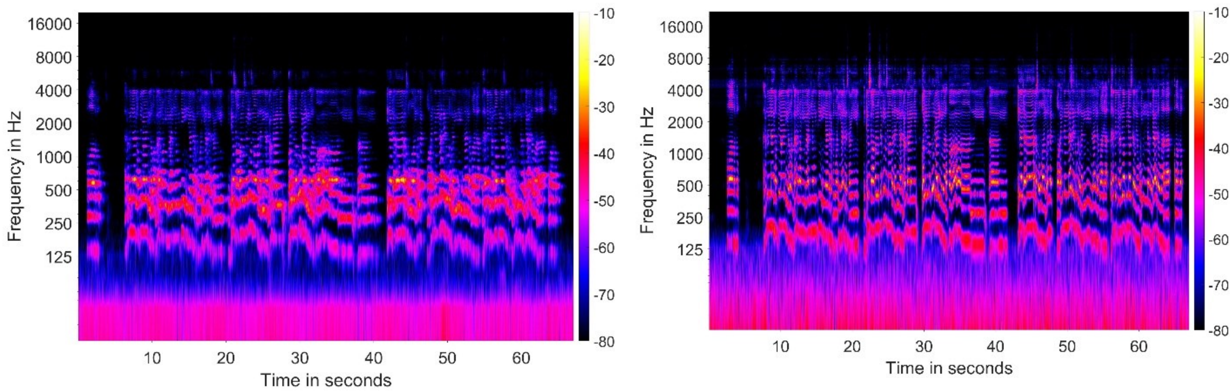


Fig. 4.24 Spectrograms of the wet recordings of the selected buildings A1 (left) and A2 (right).

Since reverberation can cause sound masking (Pätynen and Lokki, 2016), the previous results call for further investigation of the possibility of time and frequency masking in enhancing emotional impact.

In addition, given that A1 reinforced the low and mid frequencies, which are the dominant ones of the sound source, and given that A1 was rated significantly higher for the emotional impact (spiritual) than A2 (Fig. 4.25), the results provide additional support to the link between spiritual emotions and acoustic environments that reinforces low and mid frequencies.

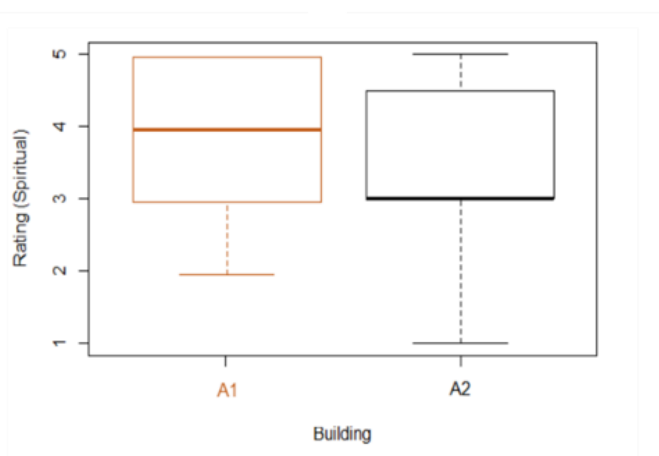


Fig. 4.25 Self-report rating for spiritual emotions for the wet recordings of A1 and A2

3) The room's response to the excitation by the sound source

The room's response to the excitation by the sound source showed considerable differences, mainly at low frequencies.

In the first case, comparing the spectra of A1 and B1 when using the same source (sound source 1) showed that frequencies emphasized by each building are not the same, as seen in in Fig. 4.26 & Fig. 4.27. For example, compared to B1, the magnitudes of the frequencies <100 Hz in A1 is higher by ± 30 dB and lower at 10,000 Hz by ± 20 dB. Moreover, the magnitudes of the frequencies <100 Hz in both buildings were dependent on the direction (more emphasized in A1), which may have contributed to the sense of immersion and envelopment described by the participants in Phase 1.

In the second case, when two sound sources (sound sources 1 and 2) were used in the same building B2, the magnitudes were different depending on the sound source, especially at the range between 100–1000 Hz, as seen in Fig. 4.27 & Fig. 4.28. In addition, a significant magnitude difference (± 20 dB) was detected at 100 Hz with source 2 because the dry recording peaked in that frequency (Fig. 4.29).

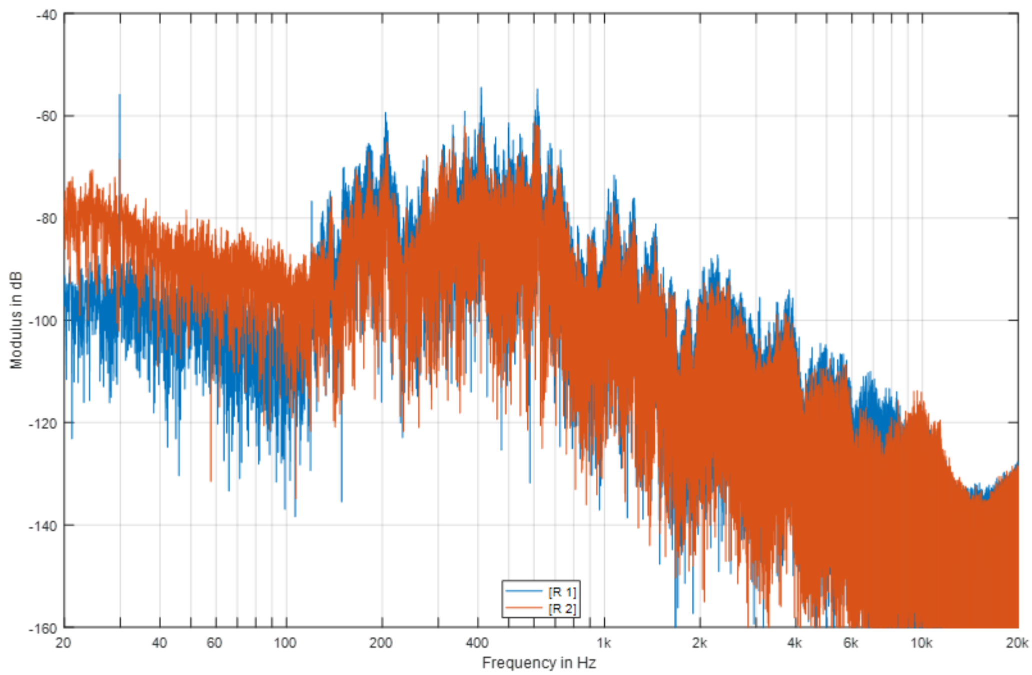


Fig. 4.26 Spectrum of the wet recording for religious recitation (source 1) in A1 (2 channels)

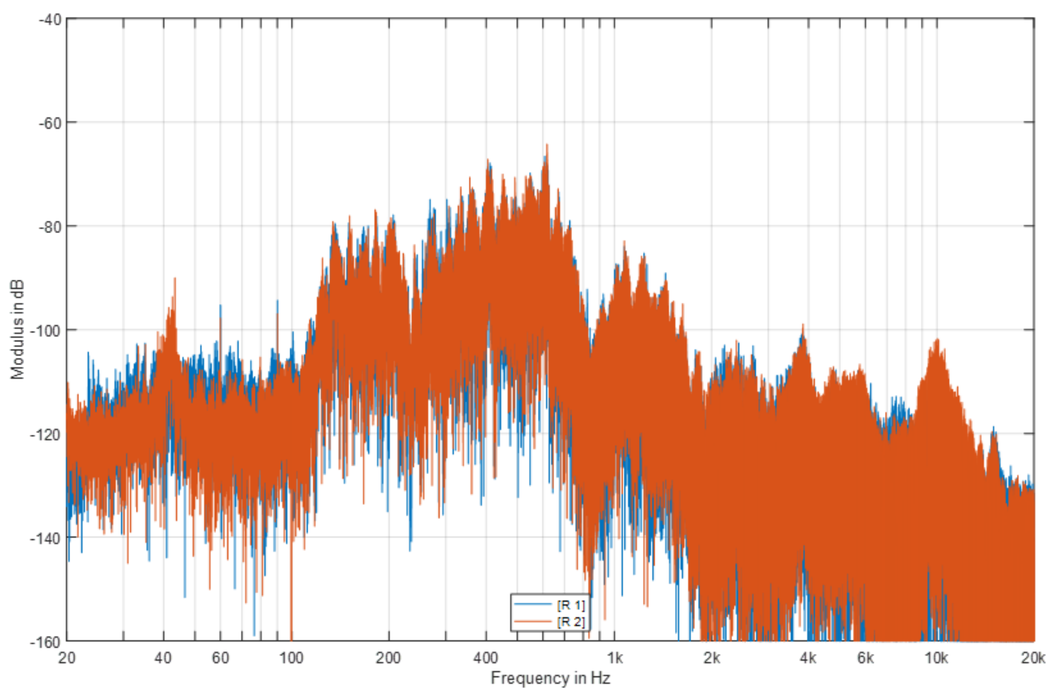


Fig. 4.27 Spectrum of the wet recording for religious recitation (source 1) in B2 (2 channels)

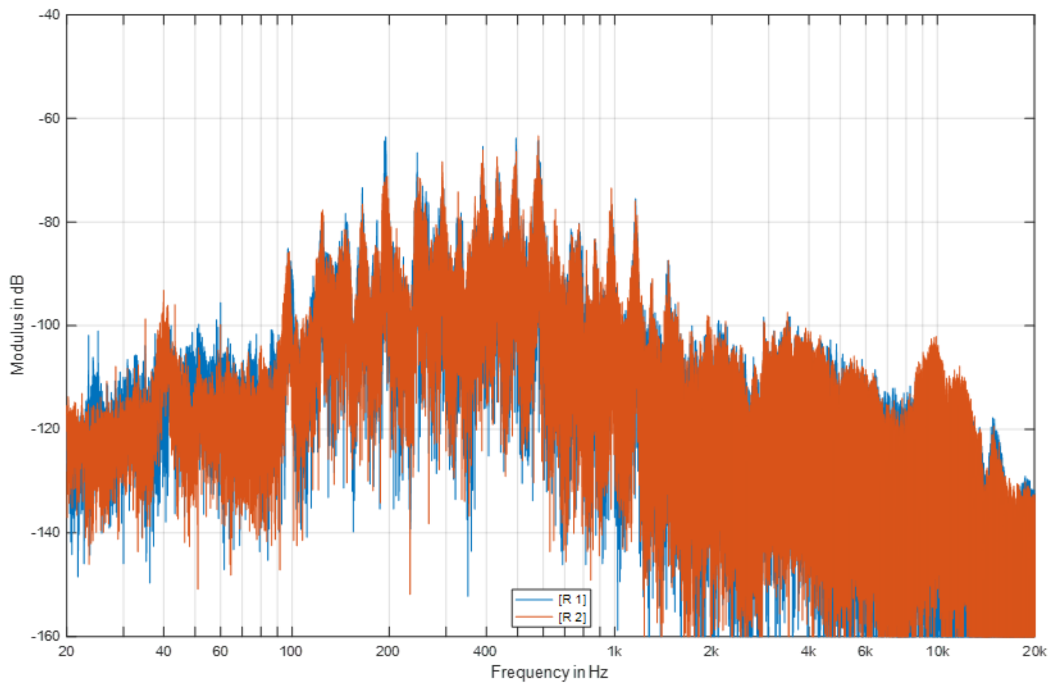


Fig. 4.28 Spectrum of the wet recording for religious hymn (source 2) in B2 (2 channels)

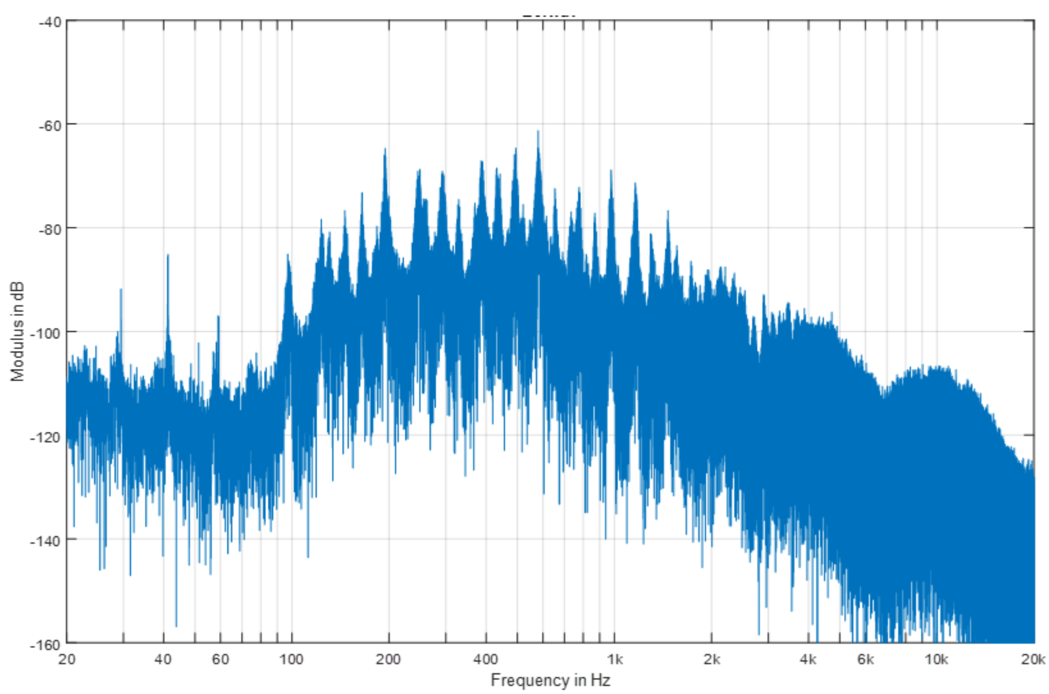


Fig. 4.29 Spectrum of the dry recording for the religious hymn (source 2)

The previous results demonstrate that considering the room's response to the excitation by the sound source depending on its the frequency characteristics is essential when designing spaces in which the emotional impact is part of the space user's experience.

4) Application of the multiple auralization method

The following spectrograms of A1 and A2 are a visual demonstration for the frequency range amplified by the room as an application of the multiple auralization method to identify the dominant frequency range reinforced by the room. Fig. 4.30 shows the spectrogram of the auralizations (wet recordings) achieved by convolving the dry recording and the impulse response of A1 and A2.

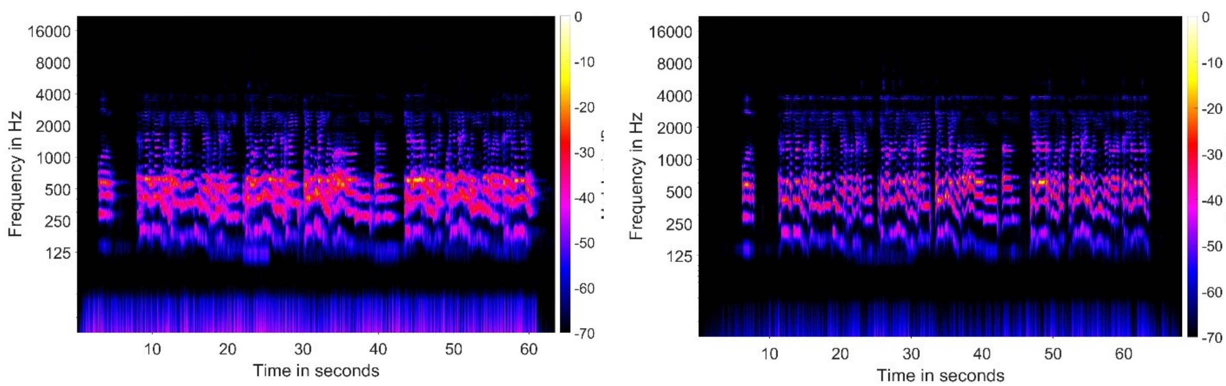


Fig. 4.30 Spectrograms of the auralization of the selected buildings A1 (left) and A2 (right).

Fig. 4.31 shows the spectrograms of the wet recordings after repeating the auralization four times. The multiple auralization makes it visually easier to distinguish the dominant frequencies reinforced by the room. For example, the figures below show that A1 has strong modes around 125 Hz.

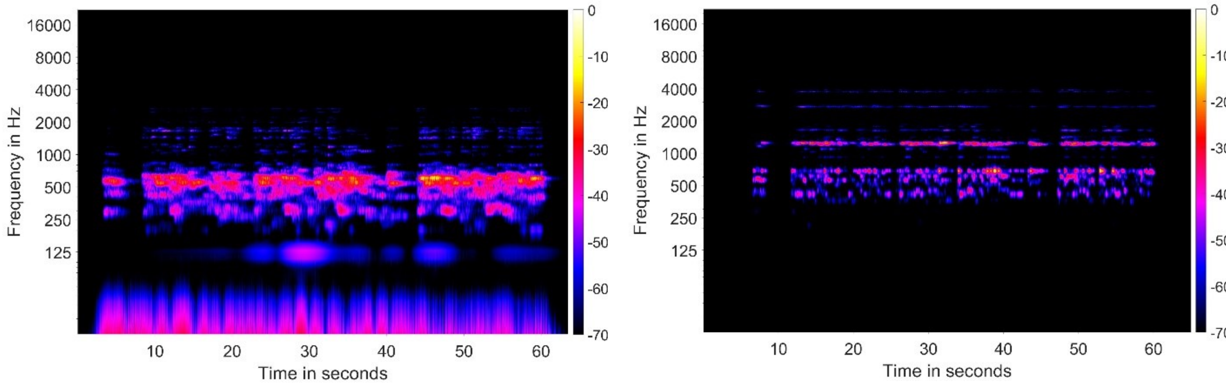


Fig. 4.31 Spectrograms of the auralization (repeated four times) of the selected buildings A1 (left) and A2 (right).

The following section shows the application of the same method for all buildings using the spectra of the auralizations resulting from convolving the IR with the dry recording (Fig. 4.32), and the auralizations resulting from repeating the convolution four times (Fig. 4.33).

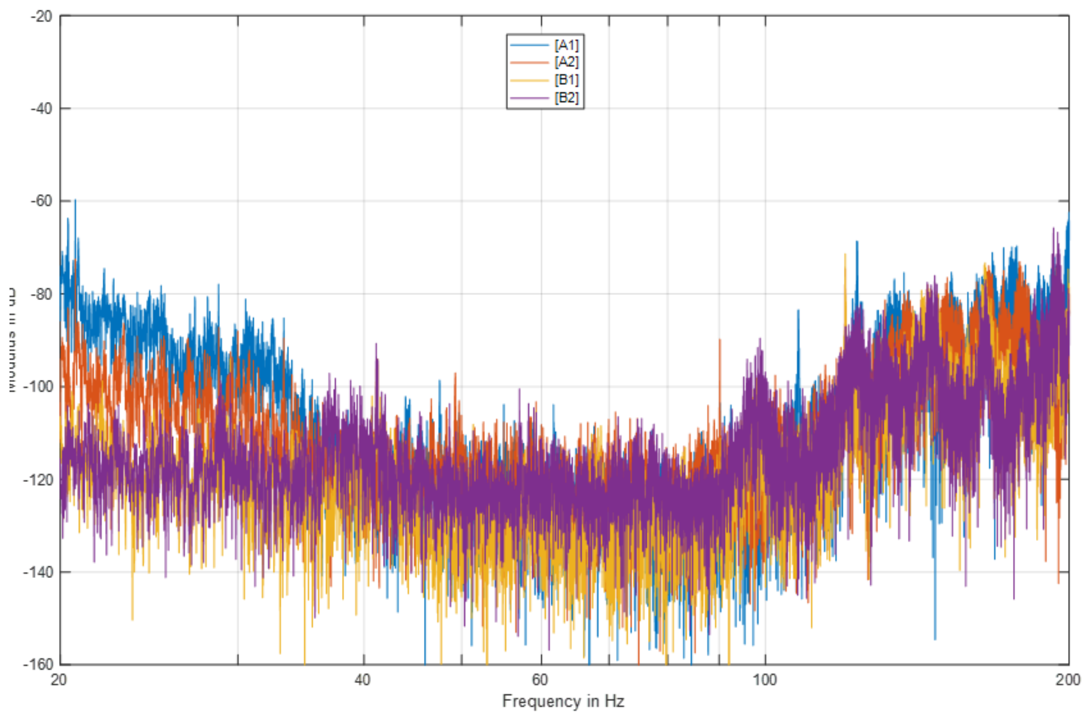


Fig. 4.32 Frequency-domain plot of the auralizations of the studied buildings for the range (20–200 Hz)

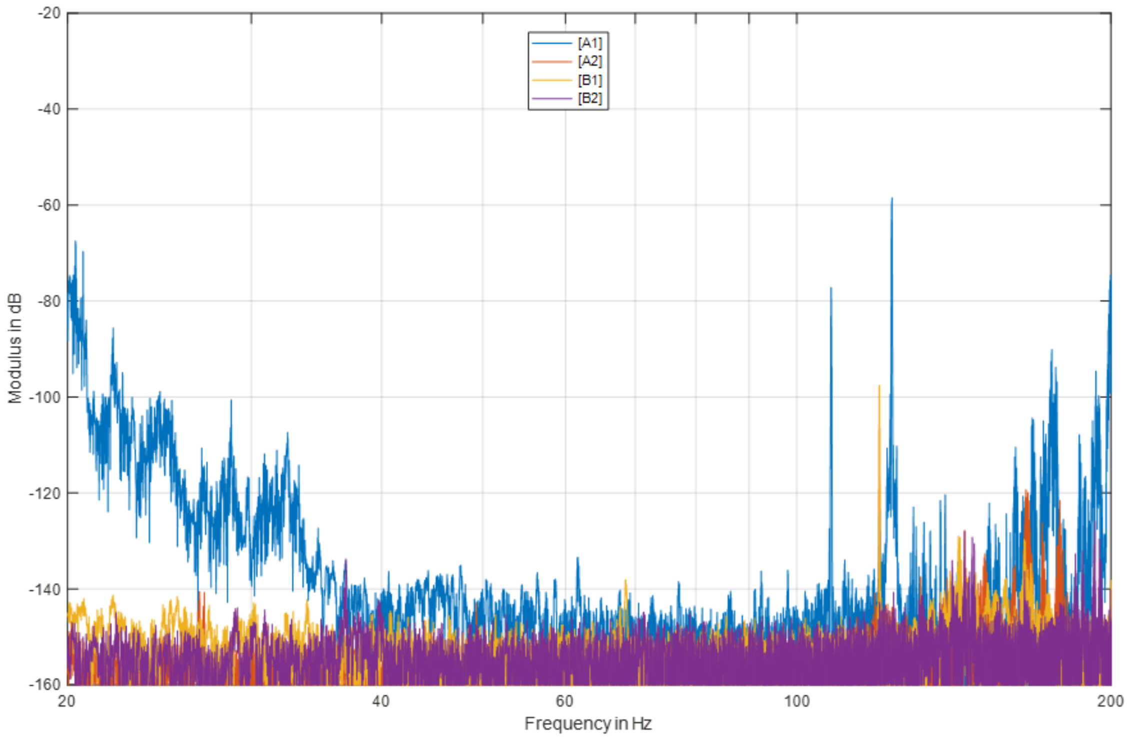


Fig. 4.33 Frequency-domain plot of the auralizations (repeated four times) of the studied buildings for the range (20–200 Hz)

The graphs show a peak at 125 Hz in all buildings except B2, with A1 showing the highest peak. Since A1 was rated the highest and B2 the lowest in spiritual emotions, this outcome, in addition to the previous results, confirms the critical role that low frequencies play in enhancing the spiritual emotional impact in worship spaces. It also demonstrates the potential of the multiple auralization method in detecting room modes and analyzing how they reinforce the dominant frequencies of the sound source.

It is also worth mentioning that the auralization results show a significant drop in the magnitude value at frequencies <200 Hz. This can be seen when comparing the spectra of the first auralization in Fig. 4.32and the wet recording (recorded in the building) in Fig. 4.34.

Thus, if the low frequencies such as 125 Hz are essential in the aural experience and emotional impact, caution should be exercised when using auralization for the subjective evaluation of worship spaces as those frequencies might not be represented realistically using the auralization algorithm.

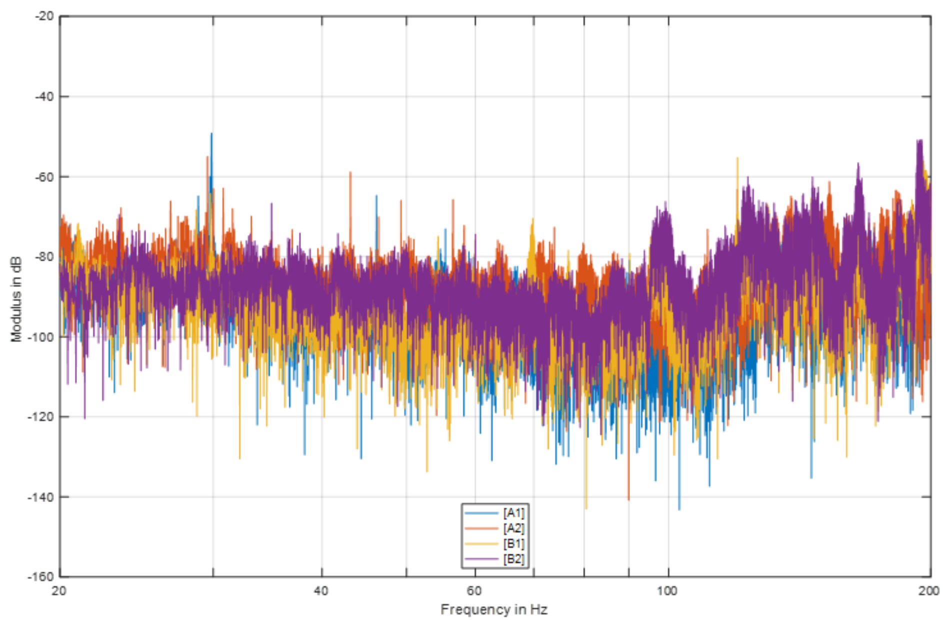


Fig. 4.34 Frequency-domain plot of the wet recordings of the studied buildings for the range (20–200 Hz)

4.4 Conclusion

This chapter explored the links between the acoustic characteristics of spaces and their emotional impact through (1) acoustic parameter analysis for the buildings studied in Chapter 2, (2) correlation analysis between the acoustic parameters and the emotional response results obtained in Chapter 2, and (3) frequency and time domain analysis of the same worship spaces to understand the room’s response to the excitation by the sound source depending on its frequency characteristics.

The acoustic parameter analysis showed similar pattern at mid and high frequencies but varied considerably at low frequencies, with A1 having the most distinct values, including long EDT and high G values at 125 Hz.

The correlation analysis showed that low frequencies <250 Hz strongly correlated with the emotional impact in worship spaces (spiritual emotions), with 125 Hz showing the most significant correlation.

The frequency and time domain analysis showed that three of the buildings had strong room modes at the frequency range between 100–125 Hz. It also emphasized the importance of studying the room's response to the excitation by the sound source as it can result in amplifying the dominant frequencies of the sound source.

Future studies should explore the architectural features that create an environment with the acoustic characteristics that reinforce low frequencies shown here to be linked with enhancing the spiritual emotions in worship spaces. Another possible direction is studying the role of architectural features in reinforcing different bands of frequencies to provide design guidelines depending on the space activity and the required frequency enhancement.

Chapter 5 Conclusion

5.1 Summary of the findings

This dissertation aimed to provide an understanding of the impact of the aural environment on the occupant's experience by (1) analyzing the emotional impact of the acoustic environment using worship spaces as case studies; (2) developing an advanced method to analyze room modes in spaces with complicated geometry (such as worship spaces), given the potential of room resonance, which is formed by room modes, to impact emotions; (3) analyzing room acoustic parameters and resonance quality to explore their links and correlation with the indicators of emotional impact using the case studies

The dissertation findings can be summarized as follows. Chapter 2 focused on examining how the acoustic environment shapes the occupants' experiences by studying its emotional impact through quantitative and qualitative measures. The mixed-methods study aimed to investigate the influence of acoustic environments in enhancing the experience of space occupants through self-report and physiological response analysis. It also examined the influence of cultural background—in terms of familiarity with a sound and the acoustic environment—on amplifying the intensity of the emotional impact. The integrated method provided a deep understanding of the role of architectural features in enhancing the auditory experience through sound reflections. The results showed that the acoustic environment amplifies the intensity of the emotional impact depending on the building's architectural design. They also revealed that familiarity with sound and acoustic characteristics can increase this impact.

While this research adopted worship spaces as case studies, this approach provides a new insight into the role of cultural aspects in shaping the occupants' experience since sound perception is influenced by the listeners' previous experience of sound events and sound environments (Murphy et al., 2017).

Chapter 3 explored the possibilities that can emerge from auralization (convolution) as a tool to analyze how the room amplifies sounds through room modes. The goal was to identify the frequency bands that the room will amplify the most and the ones it will dampen. In addition to determining the room modes, the auralization allowed for studying the possible amplification outcome based on the frequency characteristics of the sound source. When the room has modes that amplify a frequency within the range of the dominant frequencies of the sound source, this band of frequency gets amplified more than others.

Chapter 4 investigated the correlation between the emotional impact results from Chapter 2 and the acoustic parameters of the studied buildings. It also analyzed the frequency and time domains by applying the method developed in Chapter 3 to identify the room modes and study the room's response to the excitation by the sound source depending on the dominant frequencies of the sound sources.

The results clearly illustrated the significant connection between low frequencies and emotional impact in worship spaces and raised the question of considering these frequencies when analyzing and designing such spaces. Such findings align with the call by researchers to pay more attention to low frequencies when analyzing the acoustic characteristics of concert halls, given that sound strength (G) highly impacts the perception of loudness at low frequencies (Lokki and Pätynen, 2020).

Since the results showed a significant link between the emotional impact and the amplification of low frequencies in the case studies. This nonuniform amplification across frequency bands is a critical factor to consider when using artificial reverberation since researchers stated that many artificial reverberators have resonance densities that are constant at all frequency bands compared to natural reverberation in real spaces, which is proportional to the square of the frequency (Blesser and Salter, 2007).

To illustrate, we can compare the spectra of a dry recording, a wet recording generated through artificial reverberation, and a wet recording captured at building A1. The result in Fig. 5.1 shows that resonances that resulted from the sound reflections in a real space (Building A1) are more nonuniform than the ones generated by artificial reverberation, especially at low frequencies.

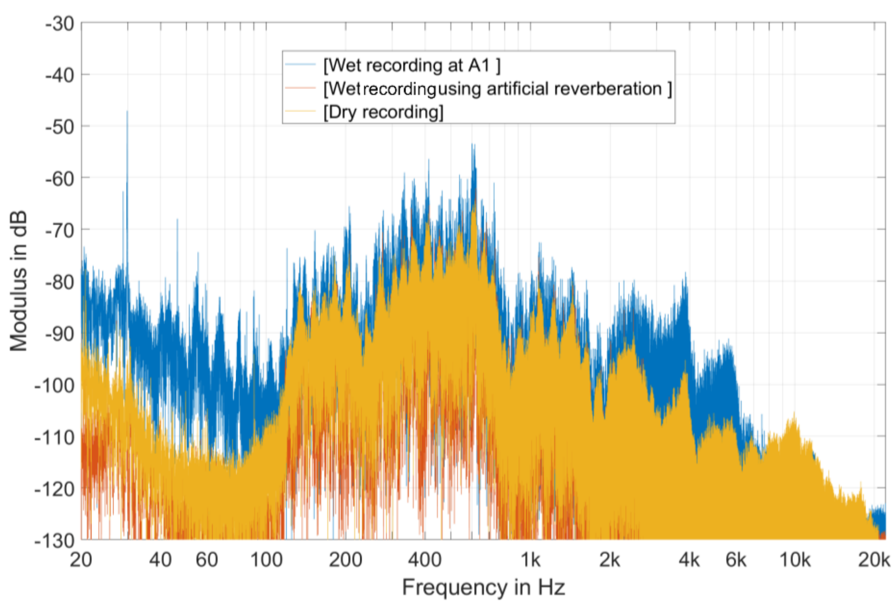


Fig. 5.1 Spectra of a dry recording, wet recording generated by artificial reverberation, and a wet recording captured at building A1

Since resonance (formed by room modes) contributes to the sound's amplification, the constant resonance densities in some artificial reverberators may explain the uniform amplification of such systems. Thus, this shortcoming of such artificial reverberators can influence how they may impact emotions compared to real spaces that can add more reinforcement to the frequency domains linked to the emotional impact, such as low frequencies.

Advancement in signal processing technology such as auralization allows for generating wet recording with nonuniform amplification that mimics real spaces' acoustic characteristics. However, the results in Chapter 4 revealed an issue that should be considered when using auralization in spaces where low frequencies are critical, as some software programs may produce an auralization that does not provide a realistic representation of the acoustic environment at low frequencies. Hence, the auralization technology will benefit from future research that addresses more realistic representation, especially at low frequencies, given its potential to enhance the experience and the emotional impact.

5.2 Research impact and contribution

This research addressed issues extending beyond treating acoustic problems and optimizing sound. The integration between the physical, perceptual, and cultural aspects allows for a more comprehensive understanding of the factors that shape the aural environment and impact the experience of the space occupants.

5.2.1 Understanding the impact of the acoustic environment on the occupant's experience

The study provides a method for assessing the potential emotional impact of acoustic environments and demonstrates the role of evaluating aural aspects while designing buildings—especially when sound is an integral component of activities in the space. Thus, this study expands on the knowledge from recent research, which has focused on the impact of other built environment characteristics on the occupants' experience. The research also examines the role of the cultural background in amplifying the emotional impact of a space. In addition, it provides a method that utilizes virtual reality (360-degree visuals combined with binaural sound) to evaluate the auditory experience.

Although this study adopted binaural recording and did not consider the impact of head movement on the characteristics of the acoustic environment, we conducted ambisonic recording in the studied buildings and tested a method that allows for ambisonic playback with head tracking when the Oculus VR headset is used. This allows for analyzing the impact of the directionality of sound reflections—especially at low frequencies, where the loudness in some of the case studies was highly impacted. Fig. 5.2 illustrates a magnitude difference >10 dB at frequencies lower than 250 Hz in A1 (using two channels of the ambisonic microphone). This difference is above the just-noticeable difference (JND) (Pätynen et al., 2014). In addition to head tracking, this can be taken a step further by including a walkthrough ambisonic recording, which will represent the 3D sound accompanying the 360-walkthrough video.

Thus, the visual and aural documentation and playback methods applied in this study and suggested in the previous paragraph can be used in designing multisensory VR representations of cultural heritage in museums, given that the acoustic heritage is an integral component, as suggested by (Hamilakis, 2014; Murphy et al., 2017). Besides, multisensory VR representations can also be utilized for educational purposes, specifically to teach architectural acoustics (Hall et al., 2012).

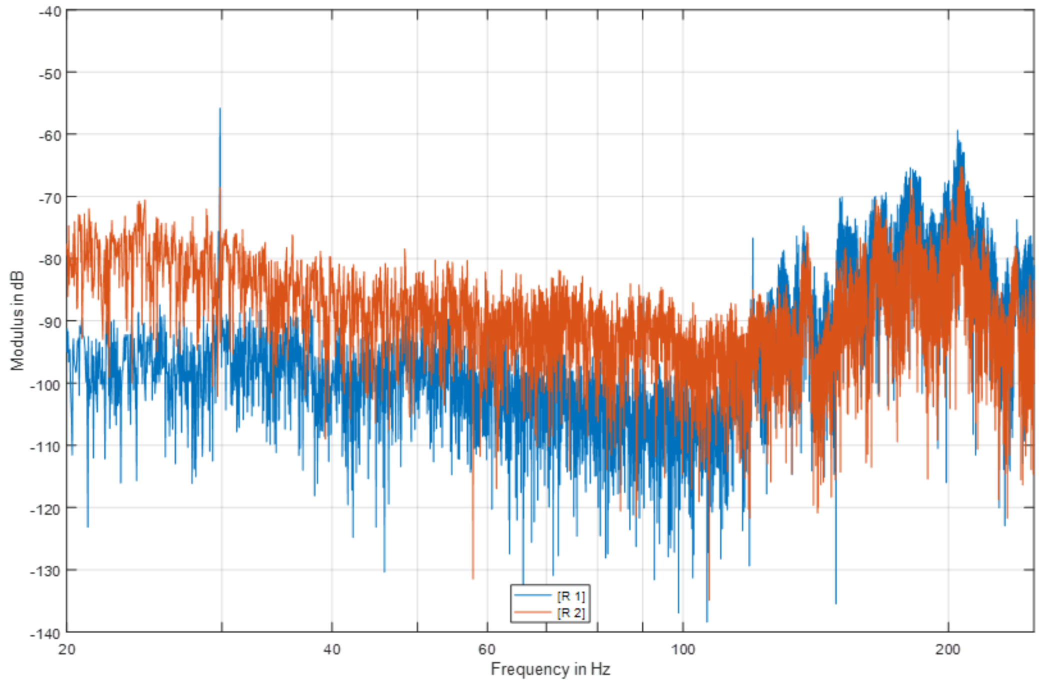


Fig. 5.2 Spectrum of the wet recording for religious recitation (sound source 1) in A1 (2 channels)

5.2.2 Developing a method for analyzing room acoustics based on auralization

The developed method will allow to analyze the room modes of spaces with complex geometry, various materials, and source locations, exceeding the outcome of traditional room-mode calculators.

It also allows for understanding the effect of room modes based on the sound source, providing a tool for evaluating existing rooms to determine the location of the sound source and the location of sound absorbers (if needed).

Furthermore, it can be used as a tool to inform design decisions of modifying the room's geometry, volume, and materials, depending on the acoustic amplification needs across frequency bands by applying the method using a recorded IR in an existing space. It can also be applied in a parametric analysis using simulation to study the role of different architectural features in forming the room modes that reinforce specific frequency bands, considering that a room mode in the simulation does not necessarily represent the absolute mode, but instead provides an estimation of the frequency band where the mode will occur and shows the impact of geometry, volume, and materials on that frequency band.

5.2.3 Establishing links between emotional impact and acoustic parameters

Linking emotional impact with acoustic parameters allows for a better understanding of the way in which our perception of an acoustic environment is shaped by the physical aspects of sound propagation in a space.

Moreover, since researchers highlighted that room acoustics can enhance musical dynamics (Pätynen et al., 2014), studying the room's response to the excitation by the sound source, identifying the frequency bands that will be amplified, and determining the architectural characteristics that create such an effect is essential. For example, in the church of San Luis de los Franceses, the dome results in a higher amplification of frequencies <500 Hz when the sound source is located under the dome, compared to other locations (Alberdi et al., 2019).

The findings that linked acoustic characteristics at low frequencies and emotional impact in worship spaces may allow for predicting the impact of the acoustic environment on the occupants' emotions and experiences. To illustrate these, we consider the DCA, which was used to apply the auralization method in Chapter 3, analyzing its acoustic characteristics and comparing them to those of A1 (the building rated the highest for spiritual emotion impact in Chapter 2). We include the acoustic parameters (EDT and BR), resonance quality, and the frequency and time domains to explore the potential emotional impact of the building's acoustic environment.

As shown in (Fig. 5.3), the EDT values in DCA and A1 are very close at frequencies >250 Hz. The values differ at frequencies <250 Hz, but they follow a similar pattern to A1. Similarly, the resonance width values of DCA are very close to A1 across the different frequencies > 250 Hz (Fig. 5.4).

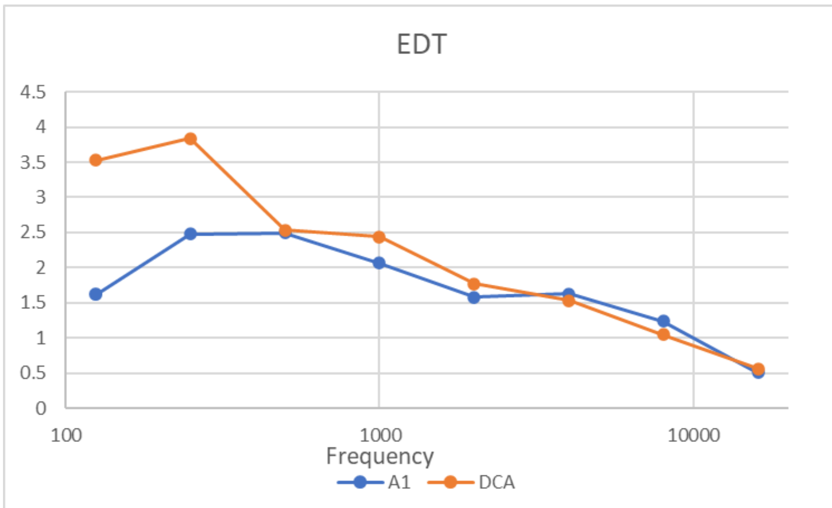


Fig. 5.3 EDT values for DCA and A1

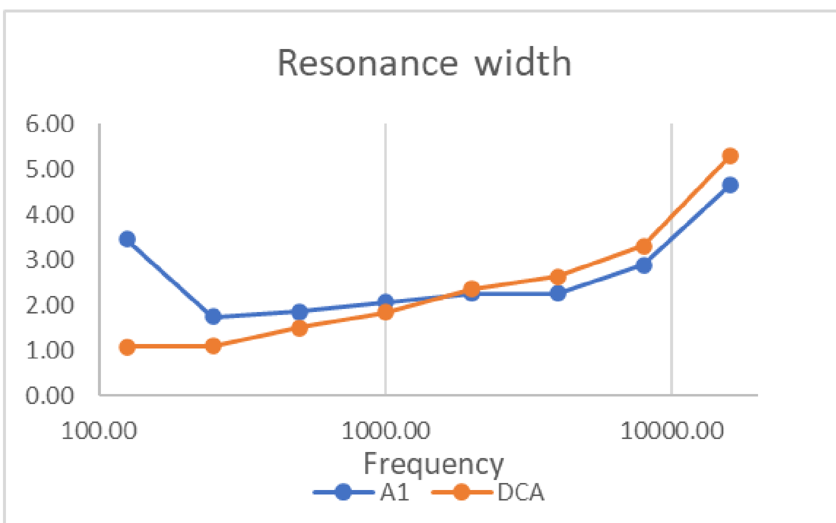


Fig. 5.4 Resonance width values for DCA and A1

The main differences are detected in the low frequencies, resulting in DCA having a BR of 1.51, which is higher than A1 (0.84). The analysis of the case studies showed that the buildings with the highest BR and lower resonance width received a higher rating for emotional impact. Since resonance width is inversely related to resonance quality, this also indicates that the buildings with higher resonance quality resulted in higher emotional impact.

Since the results of the case studies also showed that emotional impact is higher when the building amplifies the sound source's dominant frequencies, we can reconsider the room's response of DCA to the excitation by the religious recitation (sound source 1) using the developed auralization method. The spectra and spectrograms in Fig. 5.5 and Fig. 5.6 show that the sound source's dominant frequency band is between 100–500 Hz, and the auralization (convolution) shows that the DCA amplifies this frequency range more than others. Thus, based on the previous analysis, we can predict that the acoustic characteristics of the DCA may enhance the spiritual emotional impact.

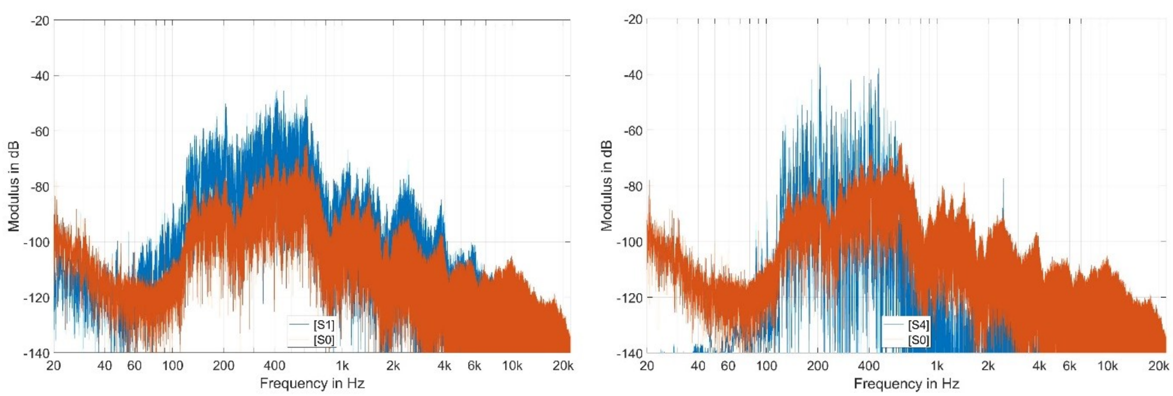


Fig. 5.5 Left: Spectrum of the convolutions of the DCA's IR and sound source 1. Right: Spectrum of the multiple convolutions of the DCA's IR and sound source 1. [S0: dry recording, S1: first convolution, S4: fourth convolution].

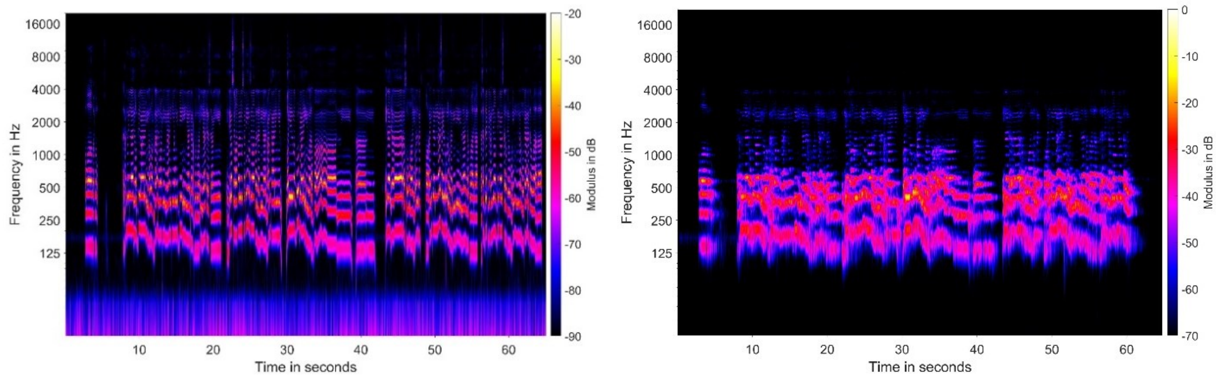


Fig. 5.6 Left: Spectrogram of the religious recitation's dry recording (sound source 1). Right: Spectrogram of the auralization of the DCA's IR and sound source 1.

The next step is analyzing the architectural surfaces that contributed to the amplification of the mentioned frequency band. Fig. 5.7 shows the measured sound level at 315 Hz after reflecting from the DCA's architectural surfaces using the Acoustic Camera, which utilizes beamforming technology (see section 3.2.2 in Chapter 3 for further description of the Acoustic Camera and beamforming) The localization and measurements of sound strength using the Acoustic Camera is based on calculating the difference in time arrival of sound to each microphone. Then the collected data is used to map the sound pressure on the 3D CAD model using NoiseImage software (Navvab et al., 2012)

Such analysis allows for identifying the design features that enhance the auditory experience by reinforcing the desired frequency band and opening new possibilities for creativity in designing spaces that enhance emotions and wellbeing as will be explained in the future research section.

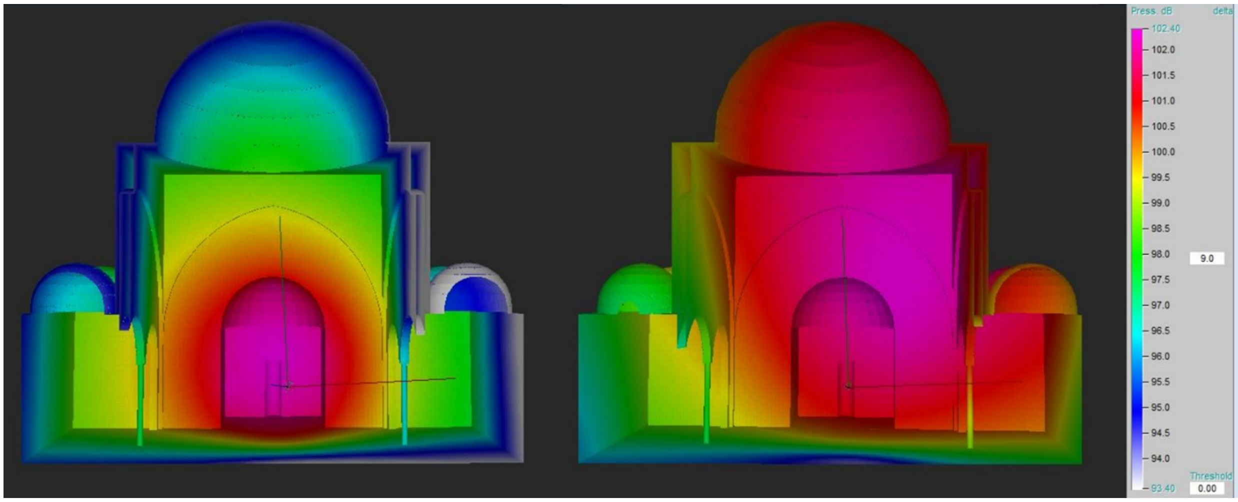


Fig. 5.7 Sound level at 315 Hz measured in DCA using the acoustic camera and NoiseImage software after a few milliseconds of the start of the impulse sound (left), and after two seconds of the impulse sound (right).

Thus, this dissertation contributions include providing an understanding of the impact of acoustic environments on the occupant's emotions and experience with more specific analysis and links between emotion indicators and acoustic characteristics including room modes. In addition to providing a method to analyze room modes in spaces with complex geometries such as worship spaces.

5.3 Research limitation

Although some results of this research can be generalized, some are specific to worship spaces. For example, the effect of acoustic environments in enhancing the occupant's experience and the cultural background's role in enhancing the emotional impact can be generalized. On the other hand, the significance of low frequencies in this study is linked to spiritual emotions. Thus, further studies can examine the possibility of different frequency bands in enhancing other kinds of emotions.

Also, as mentioned in section 5.2.1, the study of the impact of the acoustic environments on the occupant's experience in phase 1 included binaural recording, which provides a three-dimensional sensation that takes into account the sound direction and the acoustic shadow resulted from the head; however, it did not account for head movement. Since the study used the same recording method in all buildings, it is not expected to impact comparing cases in the analysis. Nevertheless, the researchers have collected ambisonic recordings that work with head tracking for future research to provide a more realistic representation of the acoustic environment.

Lastly, the developed multiple convolution method provides information about the frequencies of room modes; however, identifying the modes will be more accurate using a recorded IR. When used in the simulation, the method can estimate a general band where room modes can occur and can be used to examine the effect of modifying the architectural characteristics on the room modes.

5.4 Future research

The impact of built environments on health and well-being has been studied extensively, resulting in the establishment of standards that guide in designing buildings promoting wellness. The WELL standard by the International WELL Building Institute, for instance, identified the acoustic environment as one of the significant contributors to enhancing well-being; in line with this, standards that address sound were included in the latest version (WELL V2 pilot) ("Standard | WELL V2," n.d.). Despite the fact that WELL V2 also includes a section for restorative spaces, the sound standards focus primarily on noise reduction, and the recommendations only refer to using intrusive noise and sound masking.

The impact of music in enhancing well-being by stimulating positive affect (emotions) has been widely studied, and researchers have established links between musical characteristics and affect.

Since acoustic environments can manipulate the characteristics of the original sound by working as sound filters, utilizing the way acoustic environments (real and virtual) modify the frequency domain of sounds can evoke positive affect to enhance well-being and thus create restorative acoustic environments through their esthetics (Algargoosh, 2017).

Depending on their musical characteristics (e.g., tempo), sounds can evoke positive emotions (Deutsch, 2013). Indeed, research on music and emotions demonstrates that listening to music can be effective in transforming one's state of mind (Juslin and Sloboda, 2010), directing it to a positive affect state (Su et al., 2018). Can the acoustic environment reinforce this positive affect?

Although many have studied the analysis of acoustic parameters to optimize room acoustics, few have focused on understanding the factors that contribute to creating an acoustic environment that supports well-being. For example, researchers have extensively studied preference and sound perception in concert hall acoustics and provided guidelines to design better acoustics; yet little is known about designing spaces with restorative and stimulating acoustic environments. Indeed, without such guidelines, architects cannot take advantage of this knowledge and apply it to their designs. Further research is needed to fill this gap by analyzing the ways in which architectural features can impact room acoustics to enhance well-being.

The sound character of a musical instrument is defined by its shape and material, which reinforces some of the harmonics of the instrument's fundamental frequencies (Hale, 2007). Space is considered an extension of the musical instruments played in it (Bradley et al., 2016), and the acoustic environment alters some of the characteristics of the original sound depending on its architectural features. This alteration is not equal in all frequency bands as discussed in this dissertation, and the architecture characteristics of the room can modify the tone of the sound in the real or virtual space—similarly to the way the Sound Equalization (EQ) alters the tone of the music of audio systems. In other words, when sound is reflected from the surfaces of a space, the constructive and destructive interferences of sound waves result in amplifying some frequency bands and damping others. Further, the amplified frequencies will mask other frequencies, and, depending on the length of the reverberation, this masking will result in a different perception of sound (Blesser and Salter, 2007; Kleiner et al., 2010). Then, how do we design spaces that alter sound and enhance emotions and wellbeing?

To better understand the emotional impact of the acoustic environment, this dissertation included the analysis of several case studies, focusing on the emotional effect after listening to acoustic environments of the studied spaces. Yet, further research is needed to progress by identifying the architectural features that can be more effective in enhancing positive affect.

Such research is needed to develop tools for designing supportive acoustic environments with restorative qualities by providing guidelines for architects to design such spaces and for sound engineers to create restorative virtual acoustic environments that enhance general well-being.

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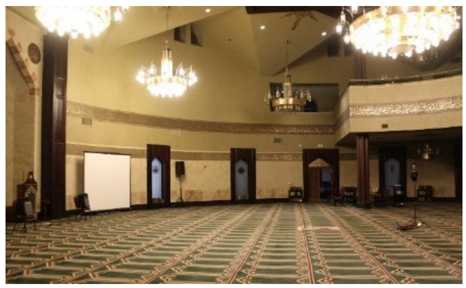
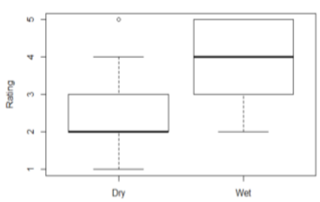
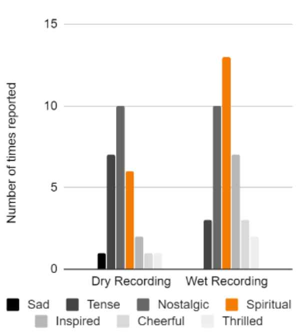
APPENDIX

Appendix Table A: Joint display of some quantitative and qualitative results for each building

<table>
<tr><td colspan="3">A1 - The Islamic Center of America</td></tr>
<tr><td colspan="3">
Interior view of the Islamic Center of America</td></tr>
<tr><td rowspan="2">Quantitative results</td><td colspan="2">Qualitative results</td></tr>
<tr><td>Dry recording</td><td>Wet recording</td></tr>
<tr><td>

Participants' self-reported rating for the intensity of spiritual emotions during the sessions of A1


Participants' self-reported emotions during the sessions of A1</td>
<td>- “Felt disconnected.”

- “Found it a little less relaxing. More pauses in the sound. The sound was different. I felt less surrounded.”

- “Sounded a little more isolated from space. It didn’t echo as much. There seemed to be a disconnect. That made me feel a bit out of place.”

- “Felt out of place because of the flatness of the audio. It was as if someone is singing in front of you. It didn’t match the space with a high ceiling. You expect the echo.”

- “Unreality. Someone is reciting inside my head or behind me.”

- “I feel like I was a little tense with this one because of the disconnection between what you see and what you hear makes you feel weird.”

- “The sound was flat, so it was less interesting to listen to.”</td>
<td>- “Very immersive coming from around me.”

- “This singer was slower, and he was taking time while praying, while the first was more rushed. I felt I was praying with him. I felt very spiritual.’

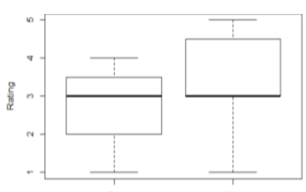
- “Audio was more connected to space.”

- “This felt a lot more peaceful, even though it had the same echo. Because the ceiling is high, it felt more in tune. It’s something that I expect when I enter the mosque. Not the confusion with the office-looking mosque. This one was more echoey. Echo gave me a sense of comfort, knowing my spirit is safe where I am, and there is a sense of belonging where I am.”

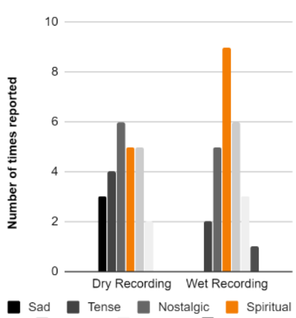
- “It felt more like being in the church. The sound, the echo of the wall. Pretty nice to hear it. I am very ignorant of this culture and good to get a sneak peek of the culture. Felt like entering a hidden place. Awe-inspired.”

- “It reminded me of Ramadhan. Something emotional. Something comfy and relaxing. Good feeling.”</td></tr>
</table>

<table>
<tr><td></td><td></td><td>- “It felt more like I was really in a mosque. I felt better than the first one. It might be because of his voice and combined with the echo you feel you were really surrounded.”

- “The sound was not that different, but the whole experience was more solemn because of the building, which felt more spacious. The sound was all around me.”</td></tr>
<tr><td colspan="3">A2 - The Islamic Center of Detroit</td></tr>
<tr><td colspan="3">
Interior view of the Islamic Center of Detroit</td></tr>
<tr><td rowspan="2">Quantitative results</td><td colspan="2">Qualitative results</td></tr>
<tr><td>Dry recording</td><td>Wet recording</td></tr>
<tr><td>

Participants' self-reported rating for the intensity of spiritual emotions during the sessions of A2



Participants' self-reported emotions during the sessions of A2</td><td>- “I felt lonely after hearing the song.”

- “I felt more focused on the sound from a musical sense rather than the spiritual sense.”

- “I didn’t feel I was in a religious place.”

- “Space felt a little less grand compared to the first. Did not feel as important. The sound was the same. Pauses make it feel jumpy and less relaxing.”

- “Felt flat, it was as if someone was inside my head; lack of acoustic and direction made the experience intimate, as if it was only you and the person.”

- “Weird. I don’t feel like this in a mosque. The sound in my head. Too intimate for the space. It didn’t seem like a sound in the space.”

- “It was a very flat experience.”</td><td>- “It felt wider than the room. I was questioning where the sound was coming from.”

- “This time, I felt a bit more cheerful and more hopeful because the voice was louder than the first time.”

- “It sounded better than I thought for the room but definitely not very full.”

- “The sound takes up more of space. It puts you in space. More echoey. More relaxing. It had a vibrated tone. More relaxing feeling. Still, the first mosque felt grander. This one felt less spiritual compared to the first one.”

- “Were they different tracks? I thought I heard different things in the second one.”

- “It felt a bit mysterious to me only because when you hear this kind of ritual, it usually takes place in a beautiful mosque, not an office looking mosque. It made a disconnect that made me confused.”

- “Definitely nostalgic. The sound had an echo effect. While I felt tense in the</td></tr>
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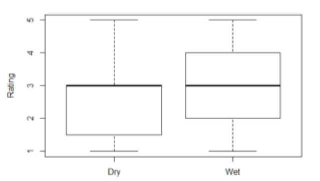
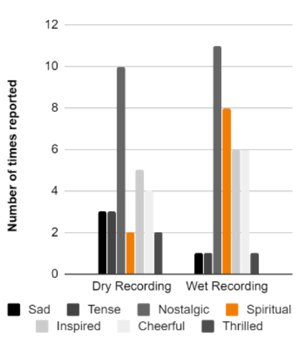
<table>
<tr><td></td><td></td><td>other setting, in here, I felt that I belong there. The sound and space were a lot more fitting.”

- “It felt fake because of the lower ceiling that it had the echo effect.”

- “I felt surrounded by the sound.”

- “You feel like you are part of a religious spiritual event rather than flat experience. That warm feeling in the first one was more present. For me, that echo made it more spiritual.”</td></tr>
<tr><td colspan="3">B1 - New Bethel Baptist Church</td></tr>
<tr><td colspan="3">
Interior view of the Islamic Center of New Bethel Baptist Church</td></tr>
<tr><td rowspan="2">Quantitative results</td><td colspan="2">Qualitative results</td></tr>
<tr><td>Dry recoding</td><td>Wet recording</td></tr>
<tr><td>

Participants' self-reported rating for the intensity of spiritual emotions during the sessions of B1



Participants' self-reported emotions during the sessions of B1</td><td>- “It felt annoying. They were singing at me, and it didn’t fit the space.”

- “This one less surrounded than the first one. It didn’t feel the space. I heard the higher pitch voice, which wasn’t really relaxing.”

- “There was a little discrepancy between the sound, which was too clear, and the space with a high ceiling.”

- “It felt more artificial and closer. I felt I was not in the place I was looking at.”

- “It felt a bit sad.”

- “The sound was quieter than the first one.”

- “When I was listening without the reverb, I was too focused on the performers. In such a small recording, there is no spirituality to it. I could hear all the human errors.”

- “I felt like it is more intimate.”</td><td>- “The sound was more amplified, and it was a bit more upbeat. I was happy. Trying to sing along in my head. I am religious, and I go to church a lot. The first one was not as upbeat and felt slow.”

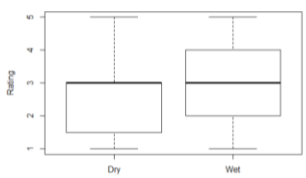
- “Just a room can make something sound so much better. I enjoyed the sound of this church much more. It felt larger and more spiritual.”

- “I felt very uplifted.”

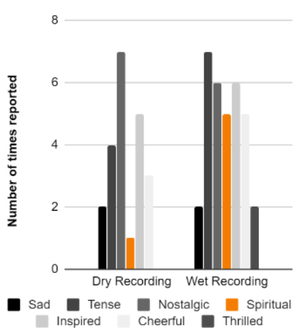
- “The music was a little loud. I am not Christian, but the music was relaxing.”

- “This time I felt more echo. Because of the echo, although they are not very good singers—I felt more harmonized about the songs.”

- “It felt everywhere. It felt surrounding.”</td></tr>
</table>

<table>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">B2- Breakers Covenant Church International</td></tr>
<tr><td colspan="3">
Interior view of the Islamic Center of Breakers Covenant Church</td></tr>
<tr><td rowspan="2">Quantitative results</td><td colspan="2">Qualitative results</td></tr>
<tr><td>Dry recording</td><td>Wet recording</td></tr>
<tr><td>

Participants' self-reported rating for the intensity of spiritual emotions during the sessions of B2



Participants' self-reported emotions during the sessions of B2</td><td>- “When I was listening without the reverb, I was too focused on the performers. In such a small recording, there is no spirituality. I could hear all the human errors. Despise the nostalgic religious song; it felt like I was just listening to performers.”

- “The sound felt disjointed from the space. From looking around the space, I expected the sound to be fuller with more reverb.”

- “The sound was more monotone. I was relaxed but also sad.”

- “It felt like I was not in the space and more focused on the high pitch. So not too relaxing.”

- “It seemed isolated and created a disconnect between the space and the sound.”

- “I was not part of the sound. The building was too big, and the sound was too small.”</td><td>- “This time, the sound was much fuller and more enjoyable. I felt happier. This one fits the space better.”

- “It was amplified. It was very spiritual and uplifting, and I felt I was there singing. This building was bigger, and the sound matched the scenery because of the acoustics.”

- “Felt more like I was actually there and not like a recording. Very filling. You could hear all the voices. The sounds blended well. Both churches had a big grand feel. This one is a bit more soothing because I like the look better.”

- “Felt more connected to space. A little loud. Made me feel more like I was in the space.”

- “The sound felt more holy and sacred. Nostalgic. Reminded me of my own church experience. It was holy because of the ambience and echoing by the wall.”

- “I felt a little more intense. It was a bit more formal. Felt like a ceremony that I have to be more professional and tense about it. I think the echoes of it made it feel so much bigger.”

- “Mixed feelings. I didn’t know if I should be sad or happy.”

- “The sound was similar to a big sound from a Haram.” (Haram is the Holy Mosque in Islam located in Mecca)</td></tr>
</table>

		- "Compared to the previous ones, it was more echoey. It reminded me of Ashura. It made me feel I like to join them." (Ashura is religious commemoration of the martyrdom of the grandson of the Prophet Muhammad that involves mourning rituals for a group of Muslims) - " When you played the one without echo, I felt it was more soothing. But in the mosque, I felt more comfortable listening to all the echo." - "A bit more holy and solemn. The sound was everywhere, but it felt right."

Appendix Table B: The P-values of the Wilcoxon Rank-Sum tests for the self-report and physiological response

			A1	A2	B1	B2
	Response	**Analysis Type**	**P-value**	**P-value**	**P-value**	**P-value**
Self-report	Rating	Spiritual emotions	< 0.001	< 0.05	< 0.05	> 0.05
		Calming emotions	< 0.01	> 0.05	> 0.05	> 0.05
Physiological response	Heart rate response	Selected section (30 seconds)	< 0.05	< 0.05	< 0.001	< 0.001
		Standardized initial	< 0.001	< 0.001	< 0.005	< 0.001
		Standardized initial + down sampling	< 0.005	< 0.05	> 0.05	< 0.05
	Electrodermal response	Standardized + down sampling	< 0.001	> 0.05	> 0.05	< 0.001