To Lenin and Nadia

ASSESSMENT OF REVERBERANCE PERCEPTION AND PREFERENTIAL ACOUSTICAL CONDITIONS IN EDUCATIONAL ATRIUMS

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By

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ASSESSMENT OF REVERBERANCE PERCEPTION AND PREFERENTIAL ACOUSTICAL CONDITIONS IN EDUCATIONAL ATRIUMS

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July 2022

We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

ASSESSMENT OF REVERBERANCE PERCEPTION AND PREFERENTIAL ACOUSTICAL CONDITIONS IN EDUCATIONAL ATRIUMS

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M.S. in Architecture

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July 2022

Atriums, with their large spans and superior voids, in modern life have changed their patterns of use from being only circulation zones to multi-functional gathering spaces. One solution to the challenge of transforming atriums to function as multifunctional spaces is optimizing the reverberation time. However, the optimum criteria of reverberation time for atriums have not yet well been set. This causes unnecessary intent of acoustical material applications within contemporary atriums. This study aims to provide a ground for such discussion on the optimum criteria, which can in the future lead to changes in standards and codes. With an aim of defining a proper range for reverberation per function and volume of the space, this research investigates the perception and preference of reverberation metrics (T30, EDT) within the context of educational atriums. The methodology starts with field tests and field surveys within four atriums of different departments at Bilkent University. Acoustical models of the atriums are tuned according to the field tests. Next, interior surface materials are modified for obtaining different sound energy decay rates and auralizations are applied to be used in subjective testing to seek preferential listening conditions. Produced audio clips by auralizations reflect different reverberation settings by the systemically increased amount of absorption, which is grouped for different intervals. An online listening test and questionnaire are held over a sample group of 67 students. Based on the analysis, the audio clips from groups G2 ($1.00 \text{ s}<EDT\leq 1.40 \text{ s}$) and G3 ($1.40<EDT\leq 1.95$) are mostly preferred by the participants with the highest scores in the paired comparison tests. And the groups G6 ($3.75 \text{ s}<EDT\leq 5.17 \text{ s}$) (too live) and G1 ($0.50<EDT\leq 1.00$) (too dry) are least preferred by the participants. Additionally, no significant correlation is found between participants' perceptions and preferences with activity patterns and gender. The results highlight that the students who are the current users of the assessed educational atriums do not prefer a very dead or a very live acoustical environment. For EDT an interval of 1.00 s – 1.95 s is found to be optimum for a volumetric space ranging from 3500 m^3 to 8500 m^3. This outcome can guide the acoustical design process of either to be renovated or newly designed atriums.

Keywords: Atriums, Reverberation, Early Decay Time, Subjective Testing, Room Acoustics

ÖZET

EĞİTİM YAPILARINA AİT ATRİUMLARDA ÇINLAMA ALGISININ VE YEĞLENEN AKUSTİK KOŞULLARIN DEĞERLENDİRİLMESİ

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Geniş açıklıkları ve büyük hacimleri ile atriumlar zamanımızda sadece sirkülasyon alanları değil aynı zamanda çok işlevli toplanma mekanları olarak kullanılmaktadır. Çok amaçlı mekanlarda akustik konforu sağlamak çınlama süresini en iyileştirme ile sağlanabilir. Fakat, literatürde atrium mahalleri için çınlama süresi kriterleri çok net tanımlanmamaktadır. Bu durum yeni tasarlanan atriumlarda gereksiz miktarda akustik malzeme kullanımına sebebiyet vermektedir. Bu çalışmada lokal veya ulusal kod, yönetmelik ve standartlara yön verebilecek uygun aralıklarda akustik kriter değerlerin tartışması sunulmaktadır. Bu araştırmada eğitim yapılarındaki atriumlar çerçevesinde işleve ve hacme uygun çınlama süresi aralıkları, kullanıcı algısı ve tercihleri dikkate alınarak, ilgili metrikler üzerinden (T30, EDT) sistematik bir çalışma ile değerlendirilmektedir. Çalışma Bilkent Üniversitesi'nin dört farklı atriumunda sahada akustik testler ile başlar. Daha sonra mevcut atriumlarda kullanıcı konforunu değerlendirmek üzere öğrencilerle yerinde röportajlar gerçekleştirilir. Deneysel çalışmaları yürütebilmek üzre mahallerin akustik modelleri oluşturulur ve bu modellerin akustik özellikleri saha ölçümleri değerlerine göre uyumlanır. Farklı sönümleme eğrileri elde edebilmek ve dolayısıyla mekan içindeki akustik koşulları değiştirebilmek üzere iç bitirme malzemelerinin ses yutma katsayıları ve ses yutucu uygulama alanları sistematik olarak değiştirilir. Farklı koşullar için sanal seslendirme yöntemi ile öznel testlerde kullanmak üzere ses kayıtları toplanır. Sanal seslendirmeler sonucu elde edilen kayıtlar farklı çınlama süresi (T30) ve erken sönümleme süresi (EDT) aralıklarında gruplanır. Çevrimiçi dinleme testleri ve anket çalışması 67 öğrenci ile gerçekleştirilir. Analiz sonuçlarına göre, kayıtlardan G2 (1.00 s<EDT≤1.40 s) ve G3 (1.40<EDT≤1.95) grupları en çok tercih edilirken (testelerde en yüksek skoru alarak) G6 (3.75 s<EDT≤5.17 s) (çok canlı) ve G1 (0.50<EDT≤1.00) (çok kuru/ölü) grupları ise en az tercih edilmiştir. Ek olarak, mekanda yürütülen aktiviteler ve cinsiyet ile kullanıcı algısı arasında önemli bir korelasyon bulunmamıştır. Elde edilen sonuçlara göre değerlendirilen atriumların mevcut kullanıcıları olan öğrenciler akustik açıdan çok canlı veya çok kuru bir ortamı uygun bulmamıştır. EDT parametresi üzerinden 1.00 s – 1.95 s aralığı 3500 m^3 ile 8500 m^3 arasında değişen atrium hacimleri için uygun aralık olarak tespit edilmiştir. Bu değerler bundan sonraki atrium tasarımlarında veya yenilenecek atriumlarda akustik tasarım sürecine yön vermek üzere kullanılabilir.

Anahtar Kelimeler: Atriyum, Çınlama Süresi, Erken Sönümleme Süresi, Öznel Test, Oda Akustiği

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LIST OF ABBREVIATIONS

EDT	Early decay time
JND	Just noticeable difference
RIR	Room impulse response
RT	Reverberation time
STI	Sound transmission index
S	Absorption area Sabine
T30	Decay time, based on the impulse decay curve, -5 dB to -35 dB
T20	Decay time, based on the impulse decay curve, -5 dB to -25 dB
V	Room volume in m^3
α	Sound absorption coefficient

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Thermal, lighting, and acoustic design of a place all have a substantial influence on an individual's comfort, performance, and quality of life. As a result, one of the first tasks in designing a building is to examine and research ways to increase the quality of these comfort parameters. Even though the sound is an element not visible, it is nonetheless unconsciously perceived by the users of the space (Nowicka, 2020). The sound in architecture is a feature impacting the space both functionally and aesthetically. In terms of functionality, it refers to meeting the requirement of a specific room for auditory comfort and health when noise control is essential. The aural aesthetic refers to the indoor soundscape of a concert hall (Sü Gül and Çalışkan, 2022). As such, the topic of architectural acoustics has become one of the significant fields of research concentrating on both the optimization/embellishment of sound and noise control.

The architectural acoustic studies with the objective of noise control concentrate on enclosed public spaces where acoustical quality can directly impact the users' performance or users' experience resulting in discomforts, such as hospitals and healthcare centers (Aletta et al., 2018; Okcu et al., 2011), metro stations (Sü Gül and Çalışkan, 2007; Sü Gül et al., 2020; Yilmazer and Bora, 2017), museums (Orhan and

Yilmazer, 2021; Yang and Kang, 2020), libraries (Dokmeci & Kang, 2017), dining spaces (Chen & Kang, 2017), offices (Acun and Yilmazer, 2018; Mei and Kang, 2012), and shopping malls (Chen & Kang, 2004; Meng et al., 2013; Nowicka, 2020). However, these are not the only spaces with acoustical discomfort issues; there still exist other large interior spaces such as atriums, lobbies, or spacious entrances where different activities are conducted by the users. Due to the volume and variety of typologies of these large interior spaces, assigning particular criteria for these spaces is challenging and requires more comprehensive studies and attention (Rychtarikova et al., 2017; Sü Gül et al., 2020).

Atriums as enclosed and mostly glazed indoor spaces have been utilized for over two thousand years, and they still remain an essential part of modern architecture (Saxon, 1986). They are a particular form of courtyards from ancient Greek and Roman architecture that is developed and modernized in harmony with today's requirements. Because of their inseparability from the overall architectural design, they are considered the building's core. They create spatial coherence in the main building by connecting different spaces and subspaces in addition to bringing social and functional unity to the overall design.

During the 19th century, the era of iron and glass, atriums shaped their new forms with longer spans and superior voids, covering the courtyard, while managing climate, and benefiting from natural light and sky view (Bednar, 1986; Hung and Chow, 2001). The new atrium design gained popularity and was utilized in a wide range of building types, including public buildings, offices, hotels, shopping malls, and recreational facilities. These new alterations in their shapes, on the other hand, resulted in uncontrolled acoustic characteristics and longer reverberations (Chen & Kang, 2004; Çalışkan, 2010; Zhao et al., 2017).

Furthermore, one other issue dramatically impacting public spaces in recent years is a shift toward more flexible designs serving multifunctional purposes (Rychtarikova et al., 2017, Gul et al., 2020). Changes to the function of Atriums, similar to other public spaces, consequently resulted in changes in the activity patterns. Thus, atriums are no longer only used as circulation spaces but also for social events, gatherings, receptions, exhibitions, and even seminars. Since they no longer fulfill a single function, proposing an appropriate acoustical criterion has become a design challenge (Pyper et al., 2021). According to literature, one solution to the challenge of transforming atriums to function as multifunctional spaces is altering the reverberation time (Barron, 2009). Since reverberation is dependent on the volume of the space and sound absorption area, it leaves the designers with the option of altering the amount of applied absorptive material in already built atriums. However, one complication of this solution is the excessive use of these materials. The overuse of sound absorptive is not only unsustainable, but it may also conflict with the spirit of space in circumstances when the atrium is utilized for active functions (Pyper et al., 2021). Consequently, there is an increasing interest in researchers on the acoustics of atrium spaces in recent years.

There are majorly two groups of studies that the researchers focused on: subjective impact and assessment of objective acoustical properties of atriums. The studies focusing on subjective characteristics investigate noise annoyance and acoustic comfort utilizing soundscape methodology, sound-walk, and questionnaires (Yang and Kang, 2020). The studies on objective acoustic characteristics of atriums mostly assess sound pressure level

(SPL), early decay time (EDT), sound transmission index (STI), and reverberation time (T30), analyzing their relation to the source-receiver distance (Mei and Kang, 2012). The literature also examines the effect of atrium geometry on their objective acoustical properties (Zhao et al., 2015).

Nonetheless, while recent studies have focused on subjective soundscape assessment or objective evaluation of atriums acoustics features such as SPL, STI, RT, and EDT, a comprehensive study that compares objective parameter results to preferential listening conditions, is missing. Additionally, Chen and Ma (2004) suggest that large interior spaces such as atriums have complicated acoustical characteristics, which can result in a diverse perception of objective parameters for each individual. As such, it is essential to assess how reverberation is perceived by the users of the space since altering the reverberation time is one of the solutions to the acoustical challenges of these multifunctional atrium spaces. Due to these complexities, an in-depth study of atriums taking into account different activity patterns in relation to perception and preference of acoustical characteristics of spaces is found necessary.

1.2. Aim and Scope of the Thesis

This thesis intends to add new insights to the literature on reverberance perception for the specific case of educational atriums. According to the literature, altering the reverberation time can significantly impact the comfort of large atriums and can be a solution to the challenge of transforming atriums to function as multifunctional spaces (Barron, 2009; Chen & Kang, 2004). As such, the primary goal of this thesis is to assess the subjective perception and preference of reverberance within the context of educational atriums by the actual users (the students) of spaces. In previous studies, EDT is suggested to provide a more accurate understanding of reverberation perception (Barron, 2009; Kang, 2002) and thus it is employed in the scope of this study, T30 in the pilot study and EDT in the thesis are investigated. The study aims to propose proper T30 and EDT criteria regarding the volume and function of the atriums for optimization of acoustical material used in newly designed or renovated atriums. This will serve for the minimization of unnecessary use of acoustical materials for the sustainability of materials in buildings. Another objective of the study is to investigate the impact of duration of stay or activities performed by individuals on their perception and preference of the acoustics of these spaces.

In the scope of this thesis, the methodology starts with field tests and field surveys within four frequently used educational atriums of Bilkent University. Acoustical models of all four atriums are generated and tuned according to the field tests. Next, interior surface materials are modified for obtaining different sound energy decay rates and auralizations are applied to be used in subjective testing. Lastly, an online questionnaire is held over a sample group of 67 undergraduate students who are real users of the space. The results of the study are then analyzed and discussed in the thesis.

1.2.1. Research Questions

- What should be the EDT design criteria specific to the volume and usage of a large atrium in accordance with individuals' subjective preferences and perceptions?
- How do different contexts (activity patterns) affect the way individuals perceive reverberation in large atriums?
- How do occupancy and the duration of use affect the perceived reverberation and preference in large atriums?

1.2.2. Objectives

- Add new insight to acoustical quality in large enclosed educational atriums.
- To investigate the subjective perception and preference of EDT within the context of educational atriums.
- To identify whether the duration of stay or activities impacts individuals' preferences.
- To propose appropriate EDT and T30 criteria for large enclosed multipurpose atriums according to their volume and function.

1.2.3. Hypotheses

- The EDT characteristics of a space influence the perception and preference of individuals.
- The participants do not prefer a room that is too dry (extreme ratio of applied absorption) or too live (no applied abruption).
- The duration of stay has a negative correlation with the preferred EDT values; the more time individuals spend at the atriums, the more critical the early decay time values.
- The activities conducted by individuals at the atriums impact the preferred EDT values; the more active functions, the longer the preferred early decay time.

1.3. Structure of the Thesis

The main goal of this study is to understand and assess the perception and preference of reverberation by individuals in atrium spaces. In order to achieve the goal of the study, the thesis is organized into five chapters. Chapter 1 introduces the problem by highlighting the gap in the literature and the limited studies on subjective perception and preferential listening conditions in the specific field of atrium acoustics. The chapter also discusses how atrium spaces have changed their usage pattern to multifunctional spaces. Resulting in a more complex challenge to provide one specific criteria for these atrium spaces.

Chapter 2 consists of four sections; the first of which covers the acoustical parameters employed in the study of the atriums. The presented parameters are defined, and their significance for the purpose of this study is underlined. In the second section, the room acoustic assessment tools for the subjective parts of the thesis are presented. The section that follows is a summary of literature carried out in the field of large public indoor acoustics. It refers to some of the prominent studies and their findings in relation to acoustic comfort. The aim of this section is to lay the groundwork for the acoustical analysis of atrium spaces. The last section concentrates on the topic of atriums and deliberates on the architectural uniqueness of atriums, atriums typology, and the impact of atriums' architectural elements on acoustical parameters. It further highlights the unique acoustical characteristics of atrium shapes and summarizes the recent research. They are discussed to help with a profound understanding of the current knowledge in the field and the need for further assessment.

Chapter 3 is a description of the methodologies and steps in the assessment of the atriums that have been used in the thesis. It starts by describing the case studies, four Bilkent University atriums, their architectural forms, used materials, and purpose of use. The chapter then discusses the field test and surveys and the way they are carried out in accordance with room acoustic standards and other similar studies in the literature. Then acoustical simulations and auralisations that are conducted for the base/present condition of all four atriums are presented. Lastly, the online listening test conducted over a sample group of undergraduate students is described. This part of the study aims to help with understanding participants' auditory perceptions and preferences.

Chapter 4, results and discussions, includes the main findings of the study. The result of site measurements, field surveys, acoustical simulations, and listening tests and their relation and possible correlation with each other are analyzed and discussed in this chapter. First, the site data gathered from all four atriums' site measurements are compared with one another. It is then used for computer simulations and auralisations, which are required for the listening test. Finally, the results of the listening test are individually assessed to understand the participant's perception and preference. They are then correlated with site measurements for further assessment.

Chapter 5 summarizes the whole thesis. It brings the study to a close by emphasizing the most important findings and outcomes. This chapter also explores potential future research and paths based on the issues excluded by the thesis's scope.

CHAPTER 2

STATE OF THE ART

2.1. Acoustical Parameters

This chapter begins by defining the acoustical parameters that are used in the acoustical analysis of atrium spaces such as; reverberation time, early decay time, and speech intelligibility. The chapter then provides background information on the acoustical assessment methods and introduces the concept of atriums and their typologies based on previous literature.

2.1.1. Reverberation Time (RT)

During the 19th century, Sabine was the first who studied the concept of reverberation time and defined it as the amount of time required for the sound level to drop by 60db after the initial sound source has stopped (Egan, 2007). That is the amount of time in which the initial sound becomes inaudible after the original sound source has stopped (Barron, 2009). This phenomenon has been one of the fundamental parameters in studying room acoustics due to the fact that it can be calculated in a straightforward manner with adequate accuracy, it demonstrates the characteristics of the space, and its numerical values are easily understandable (Barron, 2009). Figure 1 uses a sample decay to define Reverberation Time.

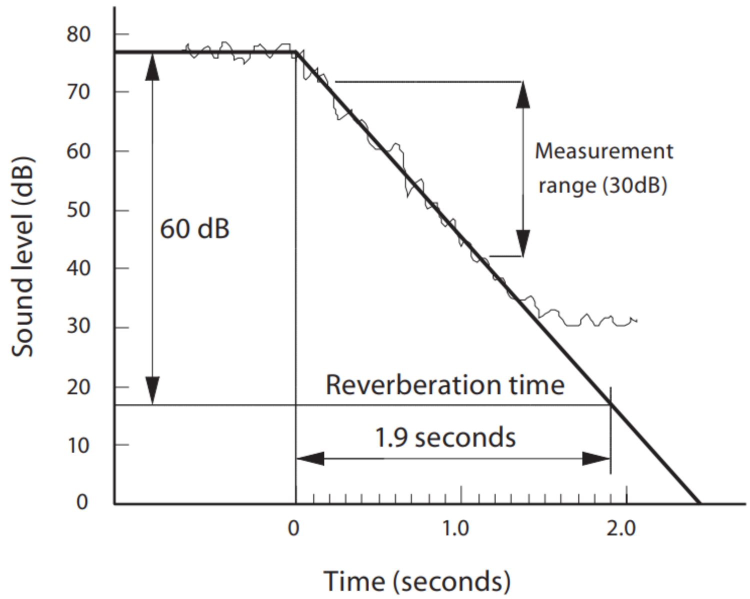


Fig. 1. Reverberation Time definition with a sample decay (Barron, 2009, p. 28)

In practice, while measuring the Reverberation Time, dropping the initial sound level by 60db can be challenging due to the uncontrolled background noise. As such, Parameters T20 and T30 are used to evaluate the Reverberation Time in a smaller range than 60dB. According to ISO 3382-1, T20 refers to the time when decay curves reach 5dB and 25dB while T30 is when the decay values are 5dB and 35dB below the initial sound level.

W.C. Sabine discovered that the Reverberation time is dependent on two parameters: the Volume of the room (V) and the total acoustic absorption ($A = \sum S\alpha_{av}$). The total absorption area can be calculated by adding all the sound-absorbing areas in a room which is the multiplication of the overall area of absorptive surfaces (S) with the absorption coefficient (α) of the materials (Barron, 2009). The Reverberation Time can be calculated using three formulas; Sabine's Formula, Eyring's, and Millington-Sette's formulas. Sabine's formula is generally used in most architectural spaces when the sound field is diffused (Yap et al., 2007) and the room dimensions' variations are not extreme. Sabine's equation is as follows:

$$T = 0.161\ V / A$$

Where,

T = Reverberation Time

V = Volume of the room in m^3

A = Equivalent sound absorption area in m^2 ($= \sum S\alpha_{av}$) (Egan, 2007).

2.1.2. Early Decay Time (EDT)

Early Decay Time (EDT) is another fundamental parameter employed in this study. EDT can be defined as similar to RT, as the amount of time for the rate of sound decay to decrease by 10dB (Barron, 2009). Unlike the Reverberation Time which is independent of position and nearly stays constant across the room, the early decay time varies with the location of measuring positions (Peters, 2013). In the cases where the room is highly diffused that is when the decay curve is linear, the values of RT and EDT will be equal. According to ISO 3382-1, EDT has been proven to be more accurate in the judgment of perceived reverberation in comparison to RT which refers to the physical properties of a room. As such, EDT is mostly used for subjective assessment of reverberation in a space (Barron, 2009; Chen and Kang, 2004; Kang, 2002).

2.1.3. Speech Intelligibility

Speech intelligibility can be defined as how well speech is perceived in a given space. It refers to both a speaker's ability to be understood and a listener's capacity to hear and accurately decipher verbal signals (Peters et al., 2013). The quality of speech intelligibility can be improved by a high level of early energy and a low level of late energy (Barron, 2009). There are other factors influencing speech intelligibility such as speech levels, background noise, reverberation times, and the room shape. Additionally, the quality of acoustic privacy between rooms is assessed using speech intelligibility as a criterion. There is a negative correlation between speech intelligibility and speech privacy in a room; good speech intelligibility results in poor speech privacy (Peters et al., 2013). Therefore, it is important to be able to assess speech intelligibility within a space.

There are different methods to assess speech intelligibility; one of the most commonly used metrics is the speech transmission index. The speech transmission index (STI) is used to demonstrate speech quality while considering the loss of speech articulation caused by reverberation (Peters et al., 2013). Long reverberation time results in poor speech intelligibility. The values of STI vary between 0 to 1, 1 referring to perfect speech intelligibility (Table 1).

Table 1. Relation between STI values and speech intelligibility quality (Beranek, 1988, p. 623)

Quality Score	Bad	Poor	Fair	Good	Excellent
STI Value	0 to 0.32	0.32 to 0.45	0.45 to 0.60	0.60 to 0.75	0.75 to 1.00

2.2. Room Acoustics Assessment Methods

The behavior and propagation of sound in enclosed or partially enclosed environments is the main subject of room acoustics studies. The idea of modern room acoustics as we know it today was developed by Sabine in the 19th century. Sabine emphasized the significance of reverberation in room acoustics, which is now considered the most critical objective characteristic (Kuttruff, 2016) and needs to be studied further. There are various methods to assess objective acoustical metrics in room acoustics studies, especially during the design process or further experimenting with existing spaces. The major methods used in the field are; geometric (ray tracing) acoustics, wave theory (room modes), statistical (e.g. Sabine's) approaches (Peters, 2013), and diffusion equation modeling. On the other hand, scientifically real-size field measurements are the most reliable tool for data collection if the space under study exists. Acoustical simulations can still be utilized for testing different architectural parameters in the effect of acoustical outcomes.

However, ultimately it is the listeners (individuals) that use the space and it is also important to analyze how they perceive the sound field and to match their desired expectations of a specific sound field as well (Fig.2). As such, to assess sound field perceptions, systematic listening tests are used to explore the relationship between objective (physical) parameters and individuals' subjective perceptions (Kuttruff, 2016).

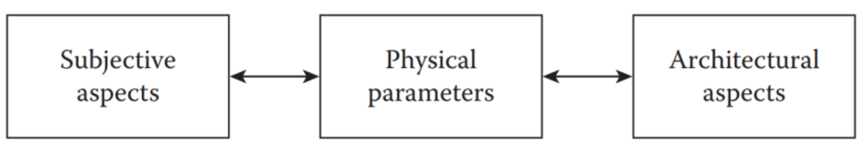


Fig. 2. Relationship between architectural, objective, and subjective features of room acoustic (Kuttruff, 2016, p. 158)

In room acoustics studies, the concept of evaluating the relationship between physical (objective) parameters and the subjective perception of the users of the spaces has been a key theme. And so far, the “listening test” is one of the highly utilized scientific approaches of assessment to analyze their relationship (Kuttruff, 2016). An individual's perception and preference of each of the aforementioned objective factors can be determined with the aid of systematic listening tests. In order to have a systematic listening test; the test must be conducted in a way that allows for the changing of one objective parameter at a time, such that, for example, only RT values are altered while everything else remains the same (Kuttruff, 2016).

The studies that employ listening tests mostly focus on the subjective perception or preferred listening condition in acoustically treated spaces such as; concert halls (Bradley and Wang 2010; Ermann, 2007), cathedrals (Girón et al., 2020), and churches (Martellotta, 2008). Moreover, the listening tests are also used as a method to assess the perceptual thresholds and just the noticeable difference (JND; defined as the smallest perceivable change) of individuals (Luizard et al., 2015; Martellotta, 2010).

2.3. Acoustic Comfort in Large Indoor Public Spaces

The sound in architecture is a feature impacting the space both functionally and aesthetically. In terms of functionality, it refers to meeting the requirement of a specific room for auditory comfort and health when noise control is essential. The aural aesthetic refers to the indoor soundscape of a concert hall (Sü Gül and Çalışkan, 2022). In order to offer a specific space with the proper and right level of auditory comfort, extensive research in the field of acoustic comfort in that specific space is required (Dökmeci, 2009). The studies focusing on the acoustic comfort analyze the impact of objective parameters of a space on the overall comfort of the users. In order to assess these relationships, scholars apply sound-walk, field measurements, and questionnaires (Yang & Kang, 2020).

Large indoor public spaces are constructed and used in numerous public buildings worldwide serving more diverse functions such as gathering, circulation, exhibitions, or simply just waiting. Thus, the acoustical comfort in large indoor spaces plays a more significant role in user satisfaction resulting in many studies concentrating on the topic. The results of these studies revealed that the level of background noise, reverberation time, and intelligibility of speech is proven to have the highest impact on the individual's acoustic comfort level (Dökmeci et al. 2008; Nowicka, 2020). Short reverberation time and low level of noise are specified by Chen and Kang (2004) as critical for the acoustic comfort of the users. Additionally, studies even argued that the duration of stay in large indoor spaces can impact the comfort level. Consequently, the employees of the spaces (people who use the spaces on daily basis) are less sensitive toward communication comfort compared to visitors of the space (Chen and Kang, 2004). People's sensitivity to the acoustical discomfort might vary depending on how long they spend in that specific space. Atriums, as an example of one of these large indoor public spaces, are reported to suffer from acoustical discomfort and low level of user satisfaction due to the absence of acoustical consideration and treatment (Shi and Zhou, 2008). Similar to the other large indoor spaces, atriums are also in need of comprehensive studies for auditory comfort enhancements.

2.4. Architectural Definition of Atriums

Atriums are defined as “a centroidal, interior, daylit space, which organizes the building” by Bednar (1986, P.63). According to Saxon (1986), atriums are not a new concept in architecture design; indeed, they have been used for the last two thousand years and still developed and remained an integral part of modern architecture in large-scale public buildings, creating spatial cohesiveness. In recent years, there has been an increase in the popularity of these spacious spaces in a large variety of building types such as; public buildings, offices, universities, hotels, shopping malls, and leisure spaces. This increase in popularity is explained by three key factors; architectural, environmental, and economical aspects of atriums (Hung and Chow, 2001) which are further explored in the following.

From an architectural perspective, atriums offer a practical solution for the revitalization of old buildings by conveying new social and functional areas to the old planning. This can be achievable by adding an atrium to an existing building or adding a roof and establishing a new atrium in between a couple of buildings. Atriums also give the building a chance to merge different spaces and subspaces while maintaining a visual connection, vertically in particular. Environmentally speaking, covering the atrium’s roof with skylights allows for controlling the climate and benefiting from natural light, a vital factor in public buildings (Hung and Chow, 2001). With the help of a glazed roof, natural light is transmitted to the atrium void and to adjacent floors of the interior space reducing the need for artificial lighting. The transmission of natural light is further aided by the addition of highly reflecting surfaces and materials, which are frequently utilized in atrium spaces.

One of the other advantages of the unique architecture of the atrium is the void. The atrium's void connects various levels together, providing stack ventilation for the building making the overall design of a building more environmentally friendly. Atriums can also economically benefit the building. They also help with energy cost reduction, by one-half or two-thirds, by controlling the thermal, light, and ventilation comfort of the building (Hung and Chow, 2001). The development of the atrium typologies and the effect of their architectural features on their acoustical properties are further discussed in the following sections.

2.4.1. Architectural History and Typologies of Atriums

Roman houses were the first place that atriums appeared. "Roman atriums" were described as a large courtyard in the center of the house, open to the sky with grand entrances (Hung and Chow, 2001; Kent, 1989). However, the concept of the atrium has evolved over time. In the 19th century, the phrase "modern atrium" first appeared. In the era of iron and glass technology, modern atriums shaped their new forms with longer spans, superior voids, and glazed roofs covering the same courtyard and social spaces (Bednar, 1986; Hung and Chow, 2001).

The atriums as we are familiarized with them today emerged during the second wave of evaluation of atriums in the 20th century. Architects such as Frank Lloyd Wright introduced two to three-story height gallery spaces at the entrance lobby connecting different levels to one another (Hung and Chow, 2001; Saxon, 1986). As such, the idea of vertical visual connection between different levels of the building by the use of stacked gallery spaces was initiated. As indicated in Figure 3, there are three ways that the stacked galleries of the atrium spaces relate to the rest of the building: a. enclosed entity, b. adjoining, and c. open atrium. Furthermore, the void generated by this spatial relation can also be categorized in d. vertical, e. A form and f. V form (Fig. 3) (Zhao et al., 2015).

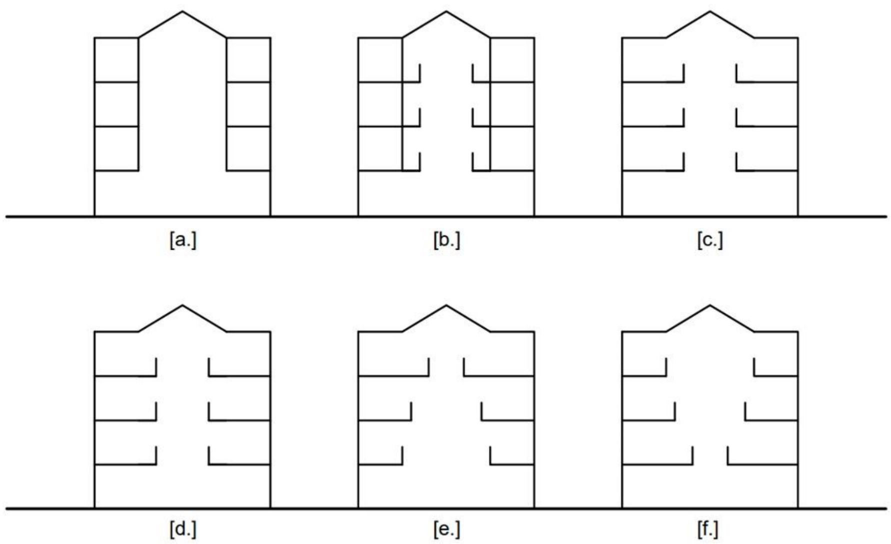


Fig. 3. The relationship between the void of the stacked galleries and the building in the section (Zhao et al., 2015, p.393)

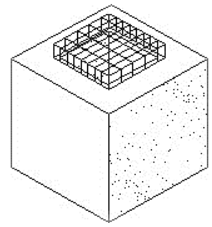
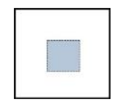
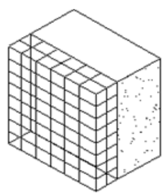
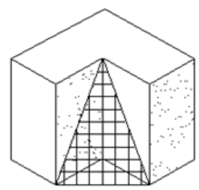
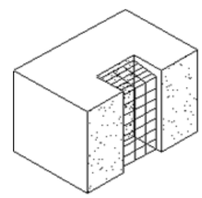
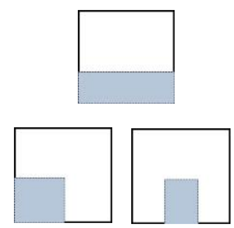
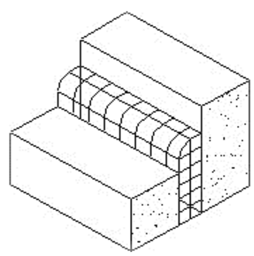
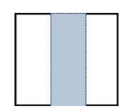
The connection of the atrium void with other sub-spaces through corridors and circulation paths makes defining the architectural borders and forms harder resulting in many different atrium typologies (Sü Gül et al., 2020). Bednar (1986) characterized atriums as "Centroid" spaces, however, modern atriums can have a wide range of different typologies and are not necessarily always located at the center of the main building. Indeed Saxon (1986), categorizes the generic form of atriums into two groups; simple forms and complex forms each having its own subcategories. The following are the simple atria's subcategories:

i. Closed Atrium / Four-sided Atrium: these atriums are closed and surrounded on all sides by other areas, leaving the only source of natural light and view to be the roof (Bendar, 1986). They can be generated in any form of the plan as long as the atrium is located at the center of the main building connecting to the horizontal levels (Table 2).

ii. Open-Sided Atrium: these atriums can be one, two, or three-sided atriums. They can be adjoined by one, two, or three occupied spaces relatively (see Table 2). They receive natural light and view from a fully or partially glazed side (Bendar, 1986).

iii. Linear Atrium: According to Bendar (1986), a linear atrium is surrounded by elongated circulation and occupied spaces from both sides. The plan of this type of atrium is usually in a rectangular form ending with possible glazed façades at both ends (Table 2). Linear atrium benefits from skylight for natural light in most cases.

Table 2. The generic form of simple atriums and their plans' diagrams (Saxon, 1986)

Type (Generic forms)			Plans Diagram
Closed Atrium / Four sided Atrium 			
Open Sided Atrium			
Single sided atrium; Adjoins 1 occupied side 	Two sided atrium; Adjoins 2 occupied sides 	Three sided atrium ; Adjoins 3 occupied sides 	
Linear atrium 			

The complex atriums are categorized by Saxon (1986) into four groups as followed:

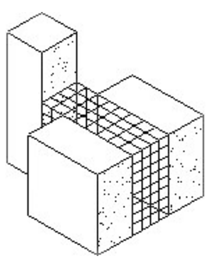
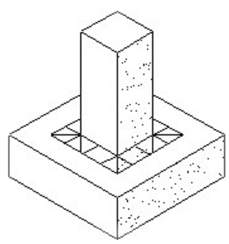
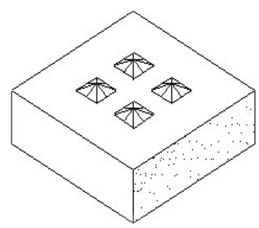
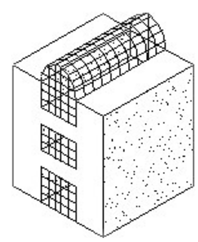
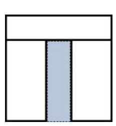
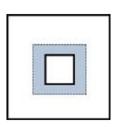
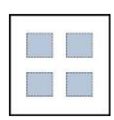
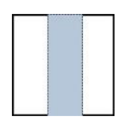
iv. Bridging atrium: These types of atriums are located between multiple buildings. They not only connect the occupied spaces in the main building, but also connect them to other buildings (Saxon, 1986). This type of atrium can benefit from a glazed roof and glazed façade (see Table 3).

v. Podium atrium: similar to bridging atriums, podium atriums connect the occupied spaces of two separate buildings. However in this case it mainly connects the bottom occupied space (foundation building) to the tower (Saxon, 1986) (see Table 3).

vi. Multiple Lateral Atrium: Bendar (1986) defines a multiple lateral atrium as a number of atriums distributed in the main building. Each of the scattered atrium may have its own type, organizing a separate section with circulation in between them as shown in Table 3.

vii. Multiple Vertical Atrium: According to Saxon (1986), multiple Vertical atriums are similar to multiple lateral atriums with the repetition done throughout the vertical levels, the tower, of the building as shown in Table 3.

Table 3. The generic form of complex atriums and their plans' diagrams (Saxon, 1986)

Type (Generic forms)			
Bridging Atrium	Podium atrium	Multiple Lateral Atrium	Multiple Vertical Atrium
			
Plans Diagram			
			

2.4.2. Acoustical Characteristics of Atrium Spaces

The acoustical characteristics of atriums are influenced by their unique features, the connections between spaces and subspaces, their volume, shape, and utilized materials (Meissner, 2007). As such, there have been studies that searched for the influences of the physical environment of atriums on their acoustical characteristics. Some exact atriums' borders are hard to define, due to the coupling of many subspaces such as corridors and pathways with main spaces vertically and horizontally. As a result, it is suggested that the relation between source-receiver distances is much more complicated. With an increase in the distance, the reverberation time and sound pressure level differ continuously as well (Mei and Kang, 2012). Non-diffuse characteristics are also suggested at this type of atriums as a result of non-linear decay curves (Nowicka, 2020). Additionally, the changes employed by atriums in 19th century; longer spans and superior voids resulted in larger uninterrupted volumes. Since one element affecting RT is the volume of the space, larger volumes led to longer reverberation times at atriums (Çalışkan, 2010; Mahdavi et al., 2007; Nowicka, 2020; Zhao et al., 2015). One other feature causing longer RT is hard reflective material which is most commonly used at typical atriums due to the maintenance of materials.

Researchers such as Zhao et al., (2017) study the impact of lengths, heights, aspect ratios, skylight form, and slope of atriums on their acoustical characteristics. The results show that an increase in length causes SPL to decrease and T30 to increase sharply in small spaces at atriums. When the height of the atrium increased, the average SPL is decreased however, the changes in T30 are dependent on the scattering effect and absorption ratio. When different skylight forms are compared the largest value of SPL and T30 are obtained for flat skylights. Whereas, the sloped and double-pitch skylights have the shortest T30. In addition, one other commonly used roof type at atriums is concave roofs such as barrel-vaulted ceilings. The concave ceilings focus reflected sound, they can reduce the intelligibility of direct sound by poor distribution (Barron, 2009; Egan, 2007) and convex surfaces diffuse the reflected sound (Maekawa & Lord, 1994). In some other atriums, the barrel-vaulted ceiling is partially glazed which absorbs low frequencies and reflects middle and high frequencies resulting in longer RT at mid frequencies and shorter RT at low frequencies (Chen & Kang, 2004).

In some other studies, the impact of the plan geometry is assessed. The results suggest a lower value of average sound pressure level (SPL) at all frequencies in a rectangular plan form by 1 to 1.5 dB in comparison to circular and square-shaped plans, although it is not noticeable. It also suggests that RT is the shortest at rectangular plan atriums and longest at squared plans (Zhao et al., 2015). Nonetheless, while recent studies have covered the impact of the atrium's geometry and form on objective parameters, a comprehensive study that compares objective parameter results to preferential listening conditions has not yet been held.

CHAPTER 3

METHODOLOGY

The data in this study has been collected initially by real-size field measurements. Later, acoustical models that are tuned according to the field test data are used to further process auralizations. The recordings from auralizations are applied for perception and preference surveys through listening tests. They are carried out with the intention of gathering information about the respective objective and subjective attributes of the selected atriums. This chapter provides further details on each of the methods and introduces the case studies.

3.1.Description of Atrium Case Studies

For the scope of this study, four educational atriums of Bilkent University; FC, A, FF, and SA have been selected for objective and subjective acoustical assessments. All four atriums are classified as four-story height atrium buildings that are being used as multifunctional spaces on daily basis. The first atrium, FC, belongs to the faculty of Fine Art and is favoured by many students as a study and gathering space. The FC building houses a commercial chain café, where many students and academicians visit and spend time, particularly during the breaks. The FC atrium has a rectangular floor plan and can be categorized as a closed atrium. The ceiling of the atrium is flat with no skylights. The main circulation is located at the center of the atrium void with four main columns supporting the staircases (Fig.4). Since the FC atrium belongs to the department of Fine Arts, there are a number of student paintings in different sizes hung from the walls.

Fig. 4. Interior views from FC atrium, (top left) an overall view of FC and the central staircase, (bottom left) the study area, (right) the chain café in the field tests

The next atrium, A/H, is located in the Department of Economics, Administrative, and Social Sciences. Likewise, this atrium's central stairway serves as both a platform for final juries and defences as well as an open study space, circulation, and a café. The atrium void is surrounded by circulation paths and corridors on all four sides linking the secondary spaces to the main volume (Fig.5). This atrium, similar to the FC atrium, is a closed atrium in a rectangular floor plan. The volume of the atrium of the A/H building is comparably bigger than the FC atrium with a flat roof and no skylights.

Fig. 5. Interior views of A/H atrium, (top left) the right side of the main central staircase, (bottom left) the main atrium void, (right) one of the corridors leading to classes and offices

The other atrium, FF, belongs to the department of Architecture and functions as a circulation space, an exhibition, and on the second floor serves as an open study area. The FF atrium is covered by a solid barrel-vault ceiling and can be categorized as a linear atrium. The atrium void of the FF building is surrounded by three sides with circulations connecting different levels to one another (Fig. 6). Similar to the two previous atriums, FF atrium is also shaped in a rectangular plan.

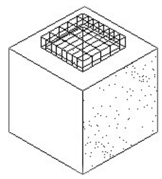
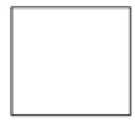
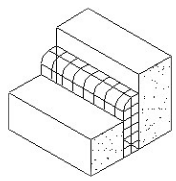
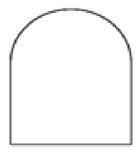
Fig. 6. Interior views of FF atrium, (left) the main atrium space showing barrel-vault ceiling, (right) the offices at the right side of the atrium under the bridge during the field test

The last atrium, SA, belongs to the Faculty of Science and is used as an open study area, for seating, and circulation. It is also additionally used for various events such as the New Year Party. A glass barrel vault covers the atrium and a small fountain is located in the middle, this atrium also houses a great number of indoor plants as seen in Figure 5. The SA atrium has a linear typology as well, however, its floor plan has a more complex shape on the ground floor (Fig. 6).

Fig. 7. Interior views of SA atrium, (left) view of the main atrium space from entrance, (top right) a view towards the studying areas with lower ceiling, (bottom right) the study area during field test

Table 4 summarizes the primary information of all four atriums, their geometries, typologies, and dimensions. Painted plaster on brick walls and ceramic tiles are the main materials used at all four of these atriums. One other similarity between the overall space characteristics of all these atriums is the continuous circulation path of all floors that surrounds the atrium voids which allows sound to be transmitted through different subspaces. As a result, any receiver in these atriums will record sound from sources on all other levels in addition to sources at the same level (Çalışkan, 2010).

Table 4. General data of the atriums

Atriums	Atrium Typology	Roof form	Volume (m³)	L × W (m × m)	Heights (m)	T30 (s)
FC	Closed atrium 	Flat roof 	3,585	28 × 10	12.8	2.96
A			8,482	45 × 13	14.5	2.92
FF	Linear atrium 	Barrel Vault roof 	3,850	30 × 8	16	4.51
SA			5,450	26 × 10	17.5	3.05

3.2. Acoustical Field Measurements

Acoustical measurements were carried out in unoccupied atrium spaces during the winter mid-semester break on 21 January at 9 AM when there was minimum background noise, which is recorded to be 45 dB on average. The measurements were held according to the ISO 3382-1 standards (ISO, 2009). Due to the pandemic conditions, a limited number of students were on campus; Figure 4-7 show photos from each atrium during the field test. The room impulse responses were collected using a dodecahedron omni-directional sound source set at 1.50 m height for acoustic excitation, a B&K (Type 2734-A) power amplifier, a B&K microphone (Type 4190ZC-0032) fixed at 1.2 m height, and a portable PC. The DIRAC Room Acoustics Software Type 7841 v.4.1 is used to generate e-sweep noise signals. The range of frequency covers the octave bands from 63 to 8,000 Hz and the impulse response length is kept at 10s. Different sound source and receiver positions are selected for each atrium to collect impulse responses and later to estimate the fundamental acoustical parameter, particularly T30 and EDT, to be utilized in this research. Based on ISO standards, to record the impulse response, a minimum of two distinct sound source positions must be utilized (ISO, 2009). Therefore, 3 source and 7 receiver positions in FC atrium, 2 source and 9 receiver positions in A/H atrium, 2 source and 7 receiver positions in FF, and 3 source and 9 receiver positions in SA atrium are used to record the impulse responses (Fig. 8-11). T30 and EDT results obtained from field measurements are used later on to tune acoustical models in simulations by adjusting sound absorption coefficient data of specific materials.

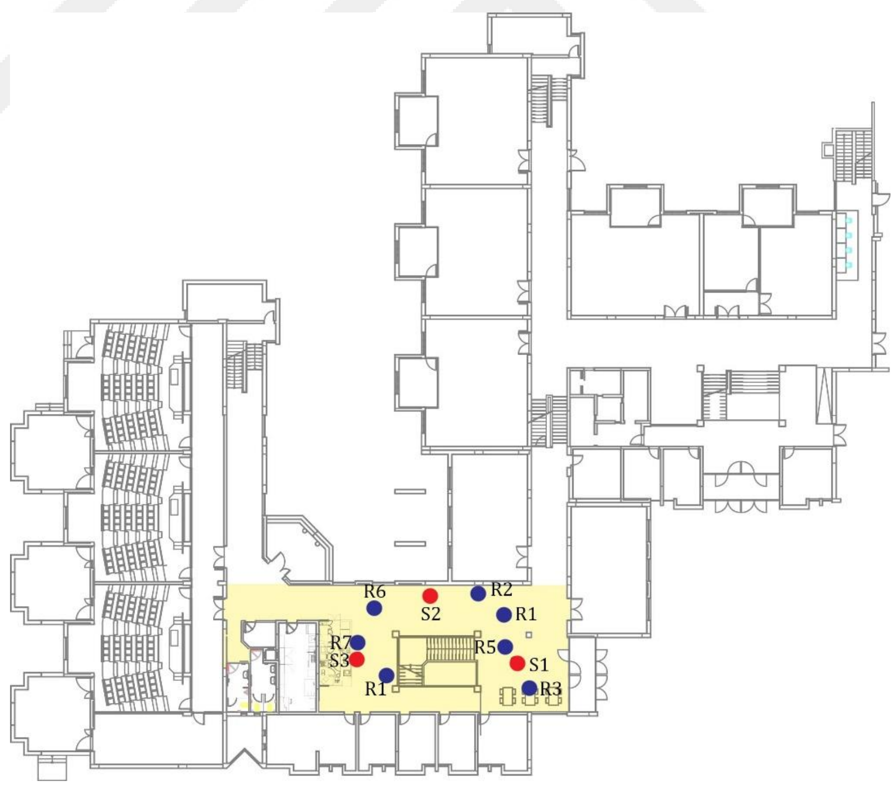


Fig. 8. The plan of FC atrium with 3 Sources (S) and 7 receivers (R) locations for field measurements

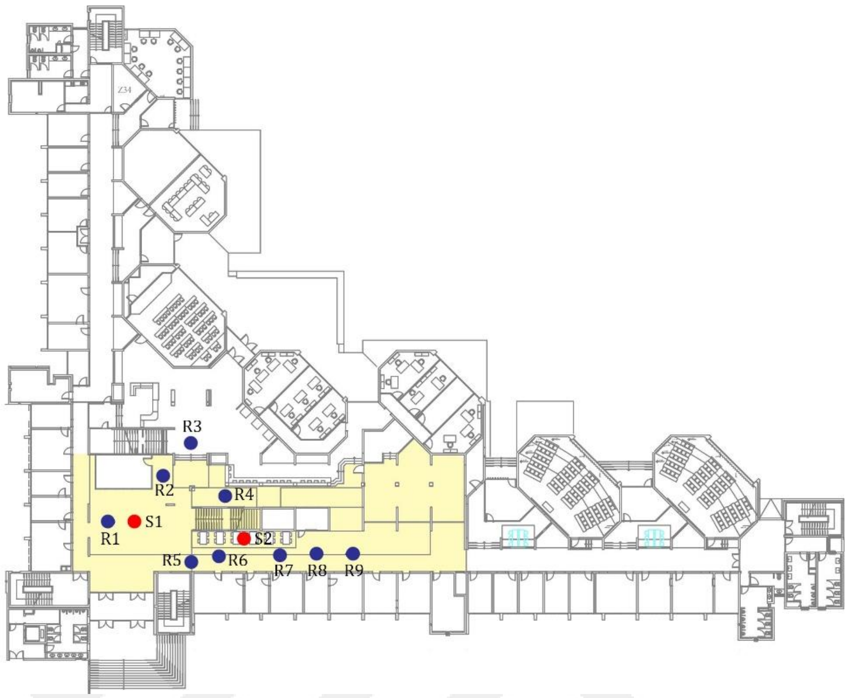


Fig. 9. The plan of A/H atrium with the location of 2 Sources (S) and 9 receivers (R) for field measurements

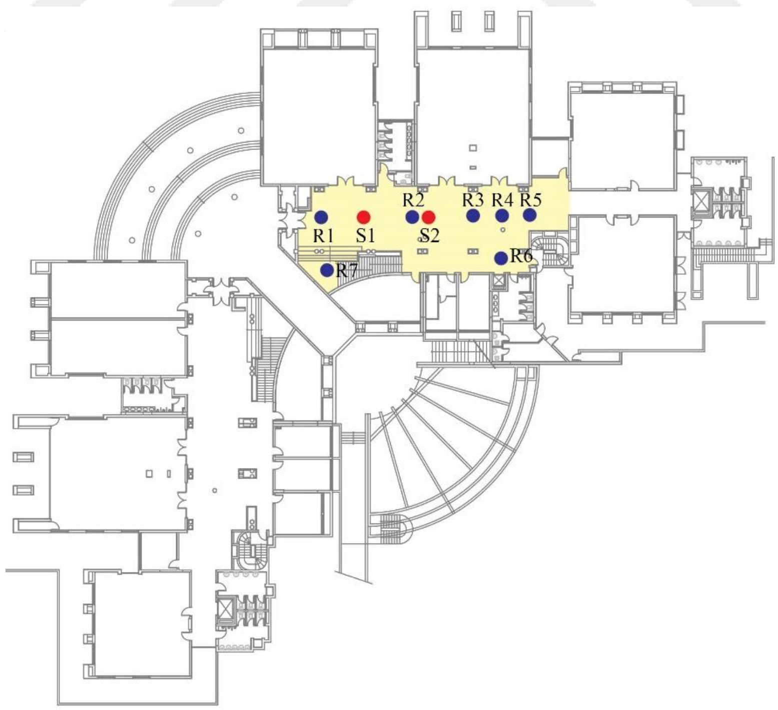


Fig. 10. The plan of FF atrium with the location of 2 Sources (S) and 7 receivers (R) for field measurements

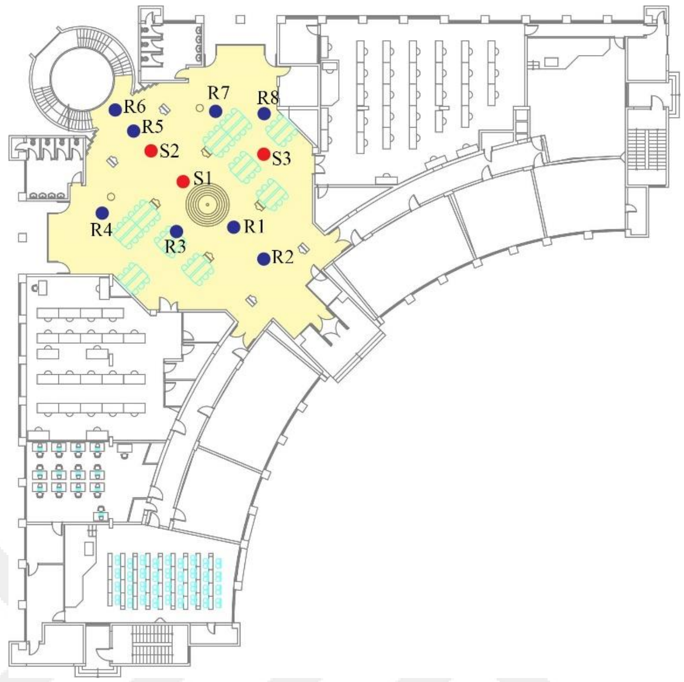


Fig. 11. The plan of SA atrium with the location of 3 Sources (S) and 8 receivers (R) for field measurements

3.3. Field Survey

A survey including ten questions is prepared by careful examination and consideration of the previously recognized subjective perception surveys. The survey consists of two main sections namely; A. user characteristics (age, gender, and profession), B. their auditory perception of these atrium spaces taking into consideration the annoyance, reverberation, appropriateness, and loudness. Part A of the survey intends to help with a better comprehension of the auditory perception by the participants (Chen and Kang, 2004). The survey was conducted at each of these atriums during the fall semester of 2022 on weekdays and lasted for two weeks (22^{nd} November_6^{th} December). During these two weeks, each atrium was visited on weekdays, and surveys were handed to the people who were using the spaces. The main goal of the field survey is to investigate the overall auditory perception of the students, real users of the space. Forty surveys are collected to help with the assessment of auditory perception of these atrium spaces. The questionnaire used in the field survey can be seen in Appendix B.

3.4. Room Acoustic Simulations and Auralizations

For this study, simplified models of all four atriums, are generated in accordance with architectural drawings and site observations. They are later exported to ODEON Room Acoustics Software version 16.10. for auralisations to be held. Later surface materials are assigned based on on-site visual observation and standard materials sound absorption coefficients present in the literature, such as ceramic tile flooring, painted concrete, and a double pane of window glass as demonstrated in Table 5. 3D open GL view of all four atriums can be found in Appendix C. Additionally, the paint over concrete and brick surface is slightly tuned in reference to measured T30 and EDT results for the field-tested source-receiver configurations. The tuning of the model is to ensure the simulated models are behaving as similar as the real atriums. The difference between simulations and the field measurements for EDT at the same source and receiver position is kept around 0.01s to 0.03s, smaller than the Just Noticeable Difference (JND), making the tuned model adequate.

Table 5. Material list and sound absorption coefficients over 1/1 octave bands between 125 Hz to 4000 Hz

Location	Material Names	125	250	500	1000	2000	4000
Wall Surfaces	Painted plaster on brick wall	0.09	0.09	0.09	0.10	0.10	0.15
Ceiling Surfaces	Painted Concrete	0.01	0.01	0.01	0.01	0.02	0.03
Floor Surfaces	Ceramic tiles	0.01	0.01	0.01	0.02	0.02	0.02
Columns	Painted plaster on masonry	0.02	0.02	0.02	0.02	0.02	0.02
Windows	Ordinary window glass	0.35	0.25	0.18	0.12	0.07	0.04
Door	Solid timber door	0.14	0.10	0.06	0.08	0.10	0.10
Stair	Ceramic tiles	0.01	0.01	0.01	0.02	0.02	0.02
Tables	Wood	0.25	0.18	0.11	0.08	0.07	0.06
Painting	Canvas covering	0.90	0.70	0.50	0.35	0.25	0.15

After the models are generated and tuned, using the 3D investigate rays option, the models are tested to make sure there are no holes in the models so that the simulations can be held accurately (See, Fig. 13). The next step is conducting auralisations. Auralisations can be defined as a technique that finds its basis in capturing and/or modeling room impulse responses (RIRs) and combining them with anechoic music and speech signals (Postma and Katz, 2016). The auralisations option in ODEON is based on binaural technologies allowing a room to be audible (Rindel, 2000). For auralisations additional source and receiver positions are used including those that are tested in field measurements. A total of 25 sources and 4 receivers are located within the atriums in a way to present the typical usage of these atriums; people studying, seating, chatting, cafe employees and customers, and people waiting in the line (Fig. 13).

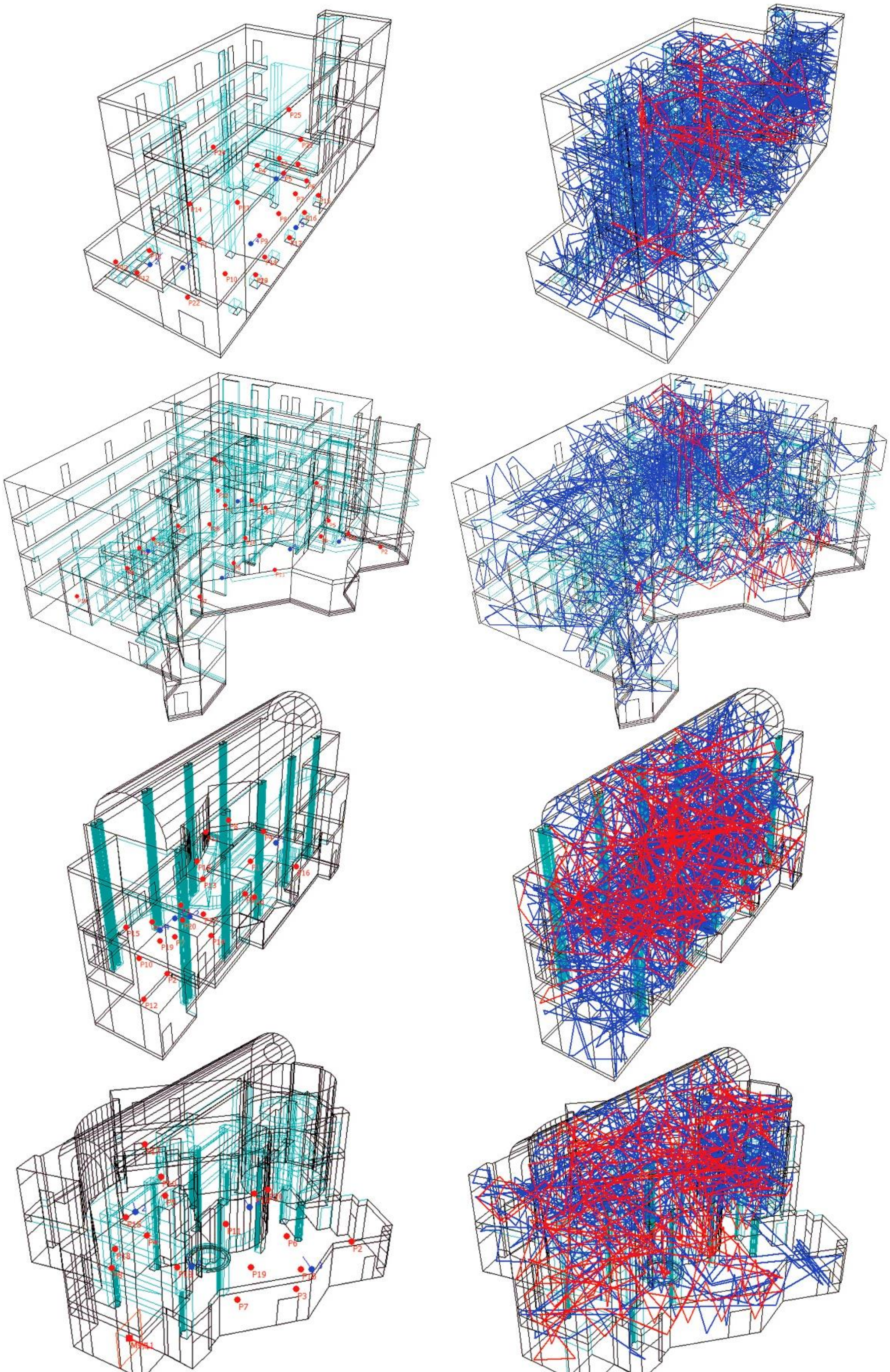


Fig.13. (left) 3D model with positions of additional sources (red) and receivers (blue) for replicating a crowd of people, (right) Ray tracing models; from top to bottom FC, A/H, FF and SA atrium

Next, realistic crowd auralisations from single speech audio are simulated using the multi-source signal auralization option in ODEON 16.10 to generate a realistic soundscape. Crowd auralizations use several speech signals with different pitches, tempos, and spectrums. In this study, using the Audio FX option, 20 variations of the same signal input are generated by ODEON to be used in the auralization differing in pitch, tempo, and spectrum from the original signal. Then impulse responses are calculated and binaural filters are created followed by convolutions. In the auralization setup, the overall recording level is set at 25 dB.

In the next step to obtain different sound energy decay rates, the absorptive material treatment to the ceiling surfaces of all four atriums is modified by applying a fine finish sound absorptive panel in different percentages of the ceiling areas 0% (base condition), 8%, 20%, 35%, 50%, and 100%. The absorptive panels are applied on the ceilings since they are the most proper surfaces for adjusting the reverberation (Sü Gül et. al., 2020). Auralization steps are then followed for the base/present condition of the atriums and for all five adjusted absorption conditions. The EDT(s) and T30(s) results of all four atriums impulse responses at 500 Hz are demonstrated in Table 6 which are to be used in the grouping of the later stages of listening tests.

Table 6. EDT(s) and T30(s) at 500 Hz for all four different source-receiver combinations for different percentages of absorptive material treatment to the ceiling surface for all four atriums

Absorptive Material %		**SA**				**FF**			
		R4S12	**R3S16**	**R2S15**	**R1S13**	**R1S04**	**R2S03**	**R3S06**	**R4S07**
0%	EDT	2.49	2.44	2.64	2.39	4.2	4.35	4.88	5.17
	T30	2.77	2.74	2.57	2.74	4.53	4.61	4.7	4.63
8%	EDT	2.07	1.9	2.23	1.94	3.15	3.34	3.84	3.75
	T30	2.23	2.26	2.14	2.19	3.48	3.62	3.53	3.63
20%	EDT	1.69	1.46	1.8	1.59	2.33	2.56	2.95	2.8
	T30	1.74	1.78	1.8	1.73	2.66	2.66	2.7	2.66
35%	EDT	1.38	1.22	1.42	1.32	1.95	2	2.39	2.23
	T30	1.38	1.42	1.45	1.38	2.13	2.1	2.05	2.15
50%	EDT	1.16	1.09	1.14	1.16	1.63	1.64	1.9	1.88
	T30	1.17	1.25	1.26	1.18	1.76	1.74	1.67	1.88
100%	EDT	1.01	0.98	0.66	0.85	1	1.05	1.33	1.68
	T30	0.84	1.1	1.26	0.88	1	1.69	1.11	0.86

Absorptive Material %		**FC**				**A**			
		R2S17	**R3S2**	**R4S18**	**R5S16**	**R1S18**	**R3S16**	**R2S06**	**R4S03**
0%	EDT	2.24	2.16	2.2	2.48	2.22	2.19	2.55	2.74
	T30	3.06	2.85	2.8	2.86	2.82	3.04	2.82	2.87
8%	EDT	1.73	1.67	1.68	1.89	1.79	1.6	1.99	2.28
	T30	2.21	2.15	2.05	2.09	2.49	2.1	2.16	2.11
20%	EDT	1.35	1.26	1.27	1.29	1.42	1.17	1.93	1.82
	T30	1.56	1.65	1.54	1.59	2.26	1.74	1.6	1.8
35%	EDT	1.1	0.96	0.99	0.91	1.13	0.88	1.82	1.38
	T30	1.21	1.29	1.19	1.28	2.34	1.6	1.21	1.39
50%	EDT	0.98	0.79	0.85	0.78	1.07	0.77	1.65	1.07
	T30	1.08	1.07	0.97	1.15	2.52	1.56	1.01	1.12
100%	EDT	0.96	0.52	0.62	0.31	0.5	0.61	1.1	0.51
	T30	0.76	0.99	0.64	0.75	0.98	1.58	0.61	0.47

3.5. Listening Tests

A systematic listening test is one of the most utilized methods to assess an individual's perception and preference of the acoustical characteristics of a sound field. The previously obtained sound recordings at the auralization phase have been selected from different groups of T30 and EDT pairings to be applied in listening tests.

In a pilot study of this research (Naeemaee and Sü Gül, 2021), the listening tests are held over a sample group of 17 experienced acousticians ranging from 22 to 69 years old. For the listening test, the audio clips are classified into five different groups regarding their average reverberation time value (T30), as shown in Table 7. The outliers from each group are eliminated, leaving a total of 43 audio clips to be used for the questionnaire.

Table 7. Group divisions, their percentage of absorptive material treatment, and the T30 (s) range for the pilot study

Groups	Absorptive material %	T30 (s)
G1	0%	$2.8 \leq T30 \leq 2.87$
G2	8%	$2.05 \leq T30 \leq 2.15$
G3	20%	$1.51 \leq T30 \leq 1.59$
G4	35%-50%	$0.96 \leq T30 \leq 1.29$
G5	100%	$0.61 \leq T30 \leq 0.76$

The survey method involved three sections (see Appendix B): In the first section, which is a personal survey, the participants are asked about their gender, age, profession, and whether they have any hearing loss. In section two, the paired comparisons, the survey uses 43 audio clips. This section consists of ten questions comparing pairs of auralization corresponding to the mentioned five different groups. The last section of the survey is also composed of ten questions, including two audio clips from each group in random order, and participants are asked to assess the appropriateness (authenticity and/or naturalness) of the surrounding sound environment to the present context (the educational atrium). The scale follows the five-point ordinal-category scale of ISO/TS 12913-2:2018 soundscape standards, providing the participants with options of “not at all”, “slightly”, “moderately”, “very”, and “perfectly”.

However, in the future steps of this research due to the obtained outcomes from the pilot study, that is weak correlations between gender (male) and preference and inconsistent results regarding the T30s appropriateness scores, EDT is used for grouping rather than T30. According to some research, EDT is better at judging the subjective perception of reverberation than T30 (Barron, 2009; Kang, 2002). Additionally, for a more comprehensive study, the sample group is composed of the real users of the space, and the number of participants is raised to 67 in the listening test and 40 in the field survey to increase the accuracy of the subjective assessment. According to Chen and Kang (2004), the subjective perception and preference may be affected by the activity pattern or duration of stay. As such in this study’s questionnaire, chapters are designated to them. Since the distribution scores of appropriateness and T30 groups were inconsistent especially within middle groups, in addition to appropriateness, other subjective parameters such as loudness, reverberance, annoyance, and hearing clearly are added to the questionnaire.

3.5.1. Participants

For this study, the survey is held over a total of 67 architecture undergraduate students of Bilkent University who are in the third year of their program. All participants have a basic background in the field of acoustics; the test was conducted after they completed the course ARCH 341 (Architectural Lighting and Acoustics) at Bilkent University. The age of participants varies within the range of 20 to 23 years old and all are students who use these atrium spaces on daily bases.

Due to the complication resulting from the pandemic, the subjective experiments are conducted using an online platform where the participants are given instructions on how to take the survey. The participants are all familiar with the concept of reverberation time and early decay time prior to taking the survey. They are enquired to set the level of their headsets/headphones to a comfortable level and are asked not to change it until the end of the survey which is approximately 20 minutes to complete. After data collection, the participants with inconsistent or inadequate results are screened out for a more reliable evaluation. A summary of participants' general information can be seen in Table 8.

Table 8. Summary of participants

Gender	Profession	Age	Amount of days spend at atriums	Amount of time spend at atriums
Male: 19	Undergradute: 67	20 years: 13	Very rarely: 0	Less than an hour: 45
Female: 48		21 years: 30	1-2 days a week: 3	1-2 hour: 11
		22 years: 18	3-4 days a week: 29	3-4 hour: 9
		23 years: 6	5 or more days a week: 35	More than 4 hour: 2

3.5.2. Questionnaire

As for the questionnaire, the audio clips have been classified into six different groups. The grouping is done based on their average early decay time value (EDT), as shown in Table 9. From the collected data the outliers from all four atriums are eliminated before the grouping, leaving a total of 93 audio clips to be used for the subjective testing ranging from 0.50 s to 5.17 s.

Table 9. Group divisions based on EDT (s) range

Groups	EDT
G1	$0.50<EDT\leq1.00$
G2	$1.00<EDT\leq1.40$
G3	$1.40<EDT\leq1.95$
G4	$1.95<EDT\leq2.70$
G5	$2.70<EDT\leq3.75$
G6	$3.75<EDT\leq5.17$

The subjective testing method involves three sections (Appendix B): In the first section, which is a personal survey, the participants are asked about their gender, age, profession, and whether they have any hearing loss. They are also asked about the amount of time they spend at these atrium spaces during a week and the activities conducted by them. The main purpose of the first section is to assess the correlation between participants' preferences and their personal characteristics, the amount of time they spend at these atrium spaces, or the activities conducted by them. For section two, the participants are asked to assess each atrium on its subjective acoustical characteristics such as loudness, reverberation, annoyance, and appropriateness regarding the surrounding sound environment in their present context (the educational atriums). The scale follows the five-point ordinal-category scale of ISO/TS 12913-2:2018 soundscape standards (ISO, 2018), providing the participants with options of “not at all”, “slightly”, “moderately”, and “very/perfectly”. This section aims to first assess participants’ perceptions of these subjective acoustical characteristics and later investigate the correlation between them with one another and with participants’ preferences.

In the last section of the subjective testing, paired comparison tests are used to assess participants’ preferences. This method of assessing subjective preference has proven to provide more consistent data (Ermann, 2007; Fidell and Green, 1998; Hase et al., 2000) and higher power of discrimination (Bradley and Wang, 2010). The paired comparison test ranks the preference of stimuli in accordance with their EDT in this study. For this study, the survey uses 30 audio clips selected from the overall 93 audio clips to be used in the test. This section consists of 15 questions comparing pairs of auralisations corresponding to the mentioned six different groups. Pairs are randomly selected from 93 options while ensuring that audio clips from every group (1-6) are compared to each other at least once, and each group is presented as an option five times in a random order to increase the accuracy of the results. Questions are once again randomly presented to participants as AB sets to enable the comparison of stimuli A and B (Postma and Katz, 2016). The main goal of this section is to indicate which range of EDT is mostly preferred by the participants. To prevent participants from choosing aimlessly and being forced to pick between A and B, they are also given a third option stating “stimuli A and B sound similar”. That is in case they are unable to identify any differences between the pairs. The results of the listening tests and all previously described phases are further discussed in the following chapter.

CHAPTER 4

RESULTS

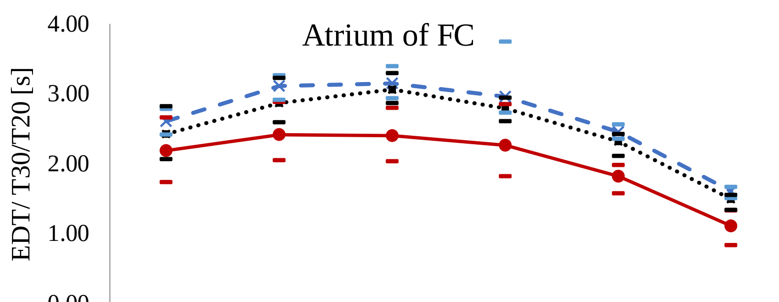
4.1. Field Measurement Results

The field measurements are held in reference to ISO 3382-1 standard (ISO, 2009). This chapter investigates the results of the field tests held at all four atriums. The chapter then continues by analyzing the data gathered from the field survey and listening tests.

4.1.1. Decay Rate Results

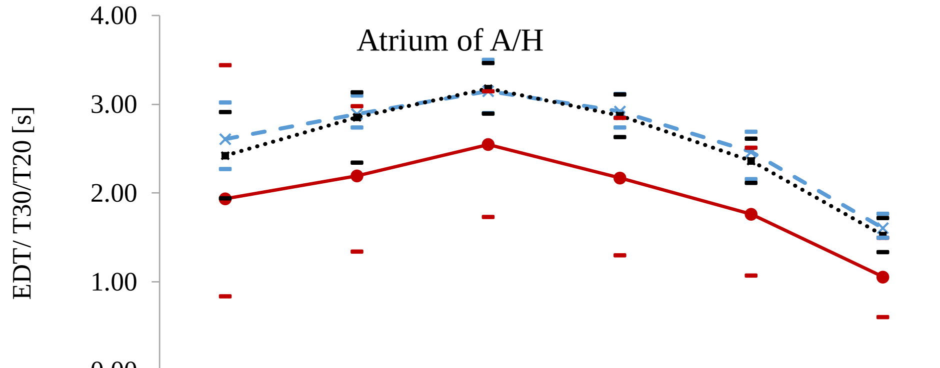
Reverberation time (T30, T20) is one of the primary parameters for the assessment of the acoustical characteristics of a space. EDT, on the other hand relates more to subjective perception and is dependent on the source positions (Barron, 2009; Kang, 2002). As such, for each atrium area, early decay time (EDT), and reverberation time over the first 20 dB decay (T20), and over the first 30 dB decay (T30) are examined. Later the mean decay rates of each atrium are compared to one another.

Figure 14 presents the decay rates of the FC atrium (3,585 m^3), including EDT, T30 and T20 (s) over a 1/1 octave band. The FC atrium decay rates follow similar trends where their values increase until mid-frequencies (250 Hz and 500 Hz) and then drop at higher frequencies reaching their minimum values at 4000 Hz. The drop is caused due to excessive volume and greater air absorption at higher octave bands. The average EDT value for this atrium varies between 0.83 to 2.88 s, with 2.4 s at mid-range frequencies. The values of T20 and T30 are more similar compared to the EDT values. The major difference, almost a 24 % difference, between EDT and T30 occurs between the 250 to 2000 Hz frequencies spectrums, with its peak at mid frequencies. Since EDT depends on the source and receivers' location, this can result from changes in positions. The EDT values for the FC atrium are lower than the T20s and T30s results. That is, the decay rate in the first 10 dB decreases much faster than in the first 20 and 30 dB. Moreover, when corresponding the measured T30 (see appendix A) with the location of the sources and receivers, it is indicated that the longest reverberation times at 500 Hz frequencies occur when the sound source is located at the right side of the atrium void with 4 m height ceiling. It is also the place where the people stands in line for the café chain.



	125	250	500	1K	2K	4K
EDT [s]	2.18	2.41	2.40	2.26	1.81	1.10
Max.	2.66	2.88	2.80	2.85	1.98	1.33
Min.	1.73	2.05	2.03	1.82	1.57	0.83
T30 [s]	2.60	3.11	3.15	2.96	2.45	1.60
Max.	2.78	3.26	3.39	3.75	2.56	1.66
Min.	2.41	2.91	2.94	2.73	2.35	1.50
T20 [s]	2.42	2.87	3.06	2.79	2.31	1.49
Max.	2.82	3.22	3.30	2.94	2.42	1.55
Min.	2.06	2.59	2.87	2.61	2.11	1.33

Fig. 14. Maximum, minimum and average values for EDT, T20, and T30, for FC atrium over 1/1 octave bands.

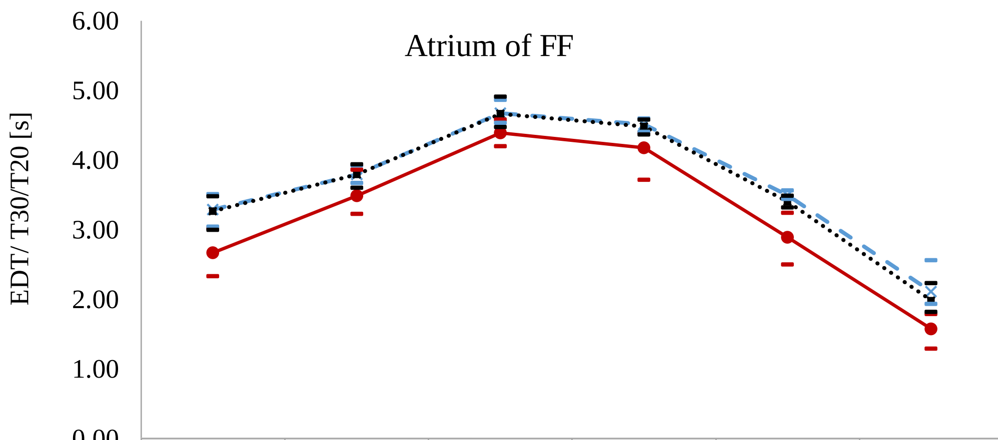


	125	250	500	1K	2K	4K
EDT [s]	1.94	2.20	2.55	2.17	1.76	1.06
Max.	3.44	2.98	3.15	2.85	2.51	1.50
Min.	0.84	1.34	1.73	1.30	1.07	0.60
T30 [s]	2.61	2.89	3.15	2.92	2.46	1.60
Max.	3.02	3.10	3.50	3.12	2.69	1.77
Min.	2.27	2.74	2.90	2.74	2.16	1.50
T20 [s]	2.42	2.86	3.18	2.87	2.36	1.52
Max.	2.91	3.13	3.47	3.11	2.61	1.72
Min.	1.94	2.34	2.89	2.63	2.12	1.34

Fig. 15. Maximum, minimum and average values for EDT, T20, and T30, for A/H atrium over 1/1 octave bands.

The decay rates for the A/H atrium with a volume of 8,482 m^3 are presented in Figure 15. Similar to the FC atrium, the decay rates of the A/H atrium also follow a similar trend where their numerical values increase until mid-frequencies (500Hz) and decrease until they reach their minimum amount at the highest frequencies. However, at this atrium, between the 125 Hz and 250 Hz, EDT and T30s have more similar growth when compared to T20. There is still an almost 20% difference between the EDT numerical values and T30 and T20 (s), which is more pronounced. EDT value for this atrium ranges from 0.60 to 3.44, reaching its average maximum value (3.15) at 500 Hz and its average minimum (1.06) at 4000 Hz.

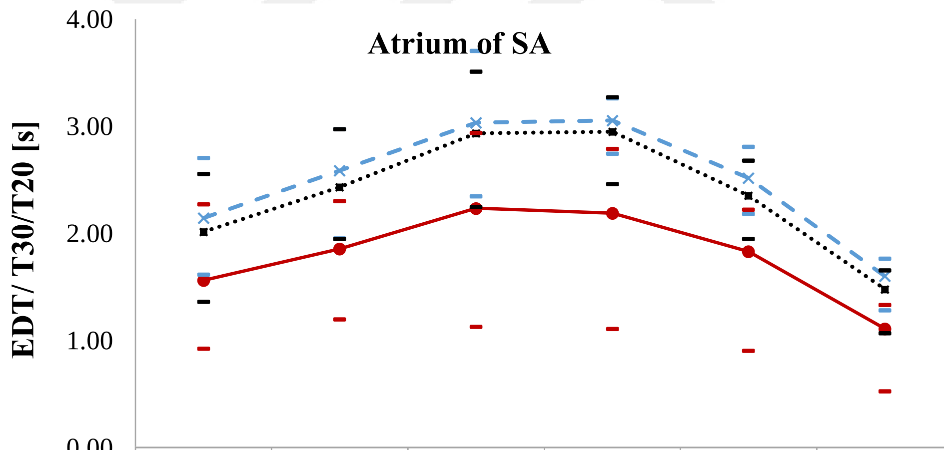
Additionally, EDT values show a notable deviation from the average values across all frequency spectrums, with their most significant at low frequencies. This may suggest that the EDT dependency at this atrium is much higher due to the nearby surfaces. The T30 and T20 average values of the A/H atrium are almost the same except at 125 Hz. Additionally, when the sound source is positioned at the center of the main atrium void (entrance), the longest reverberation times (T30) are recorded (see appendix A). At this location, the height of the atrium reaches approximately 14 m.



	125	250	500	1K	2K	4K
EDT [s]	2.67	3.49	4.39	4.18	2.89	1.57
Max.	3.02	3.86	4.58	4.39	3.24	1.79
Min.	2.33	3.23	4.20	3.72	2.50	1.29
T30 [s]	3.29	3.79	4.67	4.51	3.49	2.11
Max.	3.51	3.92	4.86	4.60	3.57	2.56
Min.	3.04	3.67	4.53	4.41	3.44	1.94
T20 [s]	3.27	3.79	4.66	4.48	3.40	1.98
Max.	3.48	3.94	4.91	4.58	3.49	2.23
Min.	3.00	3.60	4.47	4.37	3.32	1.82

Fig. 16. Maximum, minimum and average values for EDT, T20, and T30, for FF atrium over 1/1 octave bands.

The third atrium in which the field measurements are conducted is the FF atrium (3850 m^3). The decay rates of the FF atrium are presented in Figure 16. The FF atrium has the longest EDT of 4.58 s among all four atriums. Unlike FC and A/H atrium, there is less than a 5% difference between EDT values with T20 and T30 (s). Since the numerical values are very close, there are no significant differences between the decay rate of a specific source location and the overall atrium. The three parameters' trend has similar characteristics; inclination from low frequencies until mid-frequencies and then dropping again. The decay rates of the FF atrium reach their minimum values at 4000 Hz and their highest values at 500 Hz. The drop is caused due to excessive volume of FF and greater air absorption at higher octave bands. Moreover, the FF atrium has the least deviation of three parameters at all frequencies compared to the other three atriums. The reverberation times estimated from the sound source located at the center of the atrium void are recorded to have the longest reverberation times (see appendix A).

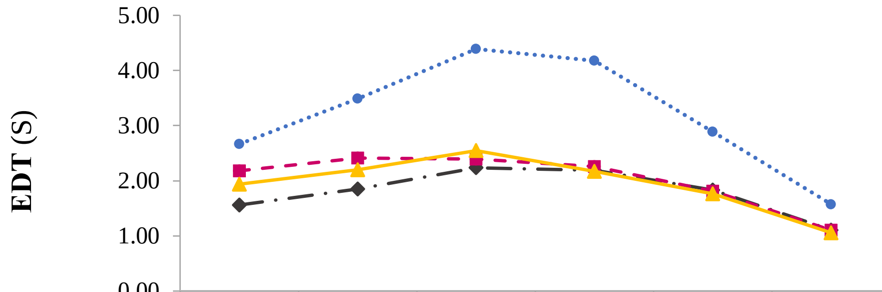


	125	250	500	1K	2K	4K
EDT [s]	1.56	1.85	2.23	2.19	1.83	1.11
Max.	2.27	2.30	2.94	2.79	2.22	1.33
Min.	0.92	1.20	1.13	1.11	0.91	0.52
T30 [s]	2.14	2.58	3.03	3.05	2.52	1.60
Max.	2.71	2.98	3.71	3.26	2.81	1.76
Min.	1.62	1.96	2.35	2.75	2.18	1.28
T20 [s]	2.01	2.43	2.93	2.95	2.35	1.48
Max.	2.56	2.97	3.51	3.27	2.68	1.65
Min.	1.36	1.95	2.25	2.46	1.95	1.07

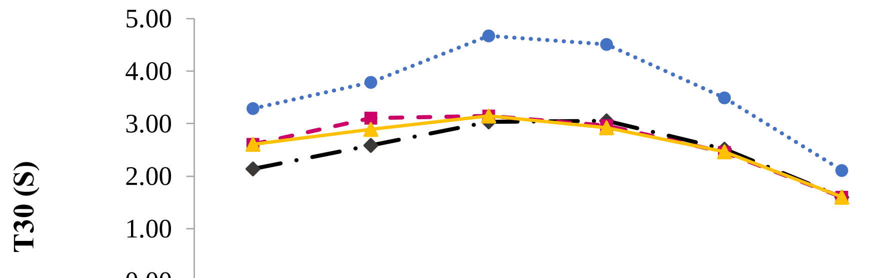
Fig. 17. Maximum, minimum and average values for EDT, T20, and T30, for SA atrium over 1/1 octave band.

Figure 17 demonstrates the decay rate results of the SA atrium building (4,540 m^3). Similar to the other four atriums, the decay rates of the SA atrium also follow a similar trend where their numerical values increase until mid-frequencies and decrease until they reach their minimum numerical values at the highest frequencies. The largest deviation between all three parameters and their average values occurs at this atrium, especially EDTs. The deviation between T20 and T30 stays approximately around 0.12 for all frequencies. There is still an almost 25% difference between the EDT numerical values and T30 (s). The early decay value for this atrium ranges from 0.52 s to 2.94 s, reaching its average maximum value (2.23 s) at 500Hz and its average minimum (1.11 s) at 4000 Hz.

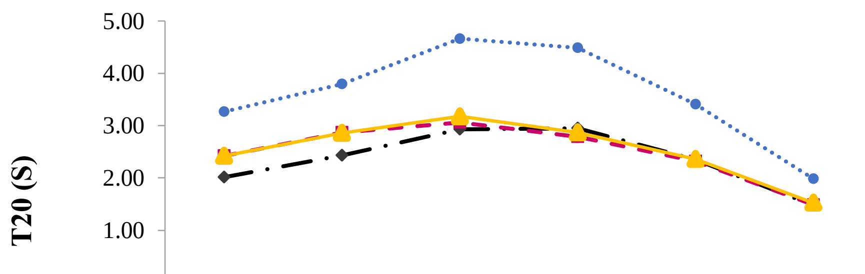
The decay rates of all four atriums are compared to each other in Figure 18. The trend for all three atriums of FC, A/H, and SA are similar for all three parameters. As for the FF atrium, the trend is similar with inclination till mid frequencies and then a drop. The steep increase and drop differ between FF and the other three atriums. The T30 values of these three atriums range between 3 s to 3.15 s at 500 Hz. The FF atrium has the longest decay rates for all three parameters. The EDT and T30 of the FF atrium reach 4.40 s and 4.67s, respectively. The FF and SA atrium are both categorized as linear atriums with barrel-vault roofs, and the FF atrium's volume (3,850 m^3) is almost half of the SA atrium (5,450 m^3) with similar interior finish materials. As such, it is expected for the SA atrium to have a longer reverberation time than FF (Çalışkan, 2010; Mahdavi et al., 2007; Nowicka, 2020; Zhao et al., 2015). However, the FF atrium has the longest decay rate values, while SA has the lowest among all four atrium spaces.



	125	250	500	1K	2K	4K
SA Building	1.56	1.85	2.23	2.19	1.83	1.11
FF Building	2.67	3.49	4.39	4.18	2.89	1.57
FC Building	2.18	2.41	2.40	2.26	1.81	1.10
A Building	1.94	2.20	2.55	2.17	1.76	1.06



	125	250	500	1K	2K	4K
SA Building	2.14	2.58	3.03	3.05	2.52	1.60
FF Building	3.29	3.79	4.67	4.51	3.49	2.11
FC Building	2.60	3.11	3.15	2.96	2.45	1.60
A Building	2.61	2.89	3.15	2.92	2.46	1.60

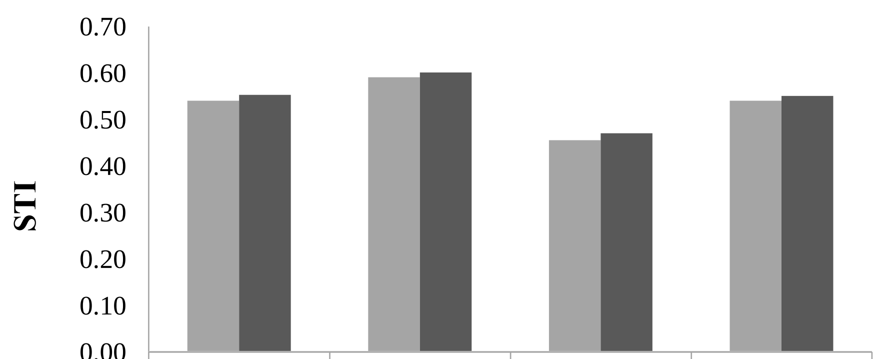


	0	0	0	0	0	0
#REF!	2.01	2.43	2.93	2.95	2.35	1.48
#REF!	3.27	3.79	4.66	4.48	3.40	1.98
#REF!	2.42	2.87	3.06	2.79	2.31	1.49
	2.42	2.86	3.18	2.87	2.36	1.52

Fig. 18. Average values for EDT, T20, and T30, for SA atrium over 1/1 octave bands.

4.1.2. Speech Intelligibility Results of All Four Atriums

With the help of the Speech Transmission Index (STI), speech intelligibility can be assessed. The speech transmission index demonstrates the speech quality while considering the impacts of reverberation and background noise (Steeneken & Houtgast, 1980). The results of STI analysis of unoccupied atriums with the background noise of 45 dB are demonstrated in Figure 19. The differences between STIs of males and females are minimal/insignificant at all four atriums. The STI values for all atriums are considerably similar except for the FF atrium, which has the lowest male and female STIs and highest reverberation time. The lowest recorded STI value is 0.46 for females at the FF atrium, whereas the highest value is 0.60 (STI male, A/H). It has been found that EDT values can impact STI values (Chen and Kang, 2004); as such, all three atriums of FC, A/H, and SA have similar STI values, and FF with the highest EDT is recorded to have the lowest STI values. According to Beranek (1988), STI values between 0.45 and 0.60 indicate Fair speech intelligibility. Therefore, all four atriums can be considered spaces with fair speech intelligibility. However, in case the background noise is higher than 45 dB, the intelligibility values will be even lower.



	SA	AB	FF	FC
Avg. F. STI	0.54	0.59	0.46	0.54
Avg. M. STI	0.55	0.60	0.47	0.55

Fig. 19. The STIs of males and females for all four atriums with 45 dB background noise.

4.2. Field Survey Results

The survey consists of two main sections, namely; A. user characteristics (age, gender, and profession), B. their auditory perception of these atrium spaces taking into consideration the annoyance, reverberation, appropriateness, and loudness. Participants are asked to rate the mentioned subjective criteria in section B for each atrium space. The surveys are collected by interviewing students on the site, who are already using one of the four following atriums to fill the questionnaires specific to that atrium. Based on the collected data, forty students between the ages of 18 and 26 years old, 19 female (48%) and 21 male (52%), participated in the survey. 95% of the participants are undergraduate students and 5% are graduate students at Bilkent University, both using these atriums frequently. Indeed, 30 % of the students noted that they visit the specific atrium 3 to 4 days and 40% claimed to visit them 5 or more days a week.

In order to assess the results from section B of the survey, grounded on ISO/TS 12913-3:2018 soundscape standards for the five-point ordinal-category scale of the questionnaire, scale values of 1, 2, 3, 4, and 5 are assigned respectively for “not at all”, “slightly”, “moderately”, “very”, and “perfectly/extremely”. The findings for each specific atrium are presented in graphs and discussed separately.

The data collected from the FC atrium demonstrated that this atrium is used by 50% of the participants for chatting and hanging out with friends. 40% of the participants mentioned that they visit FC for eating & drinking due to the chain café located at this atrium. The data show that 70% of students visit the FC, 2 to 4 days a week but 60% spend less than an hour at this atrium. Based on the subjective parameters rating assessment

(Fig. 20), the participants rated loudness (mean score: 2.8), and annoyance (mean score: 2.7) of the FC atrium below 3, namely moderate in subjective testing. The mean overall score is 2.3 for the perceived reverberation, which means slightly. That is the FC atrium is not perceived as loud, reverberant, or annoying by the users. However, at the same time, the ratings for the appropriateness or how clearly they can hear are moderate, with scores of 3.3 and 3.5, respectively. The participants mainly use one adjective to describe the FC atrium, and that is: spacious.

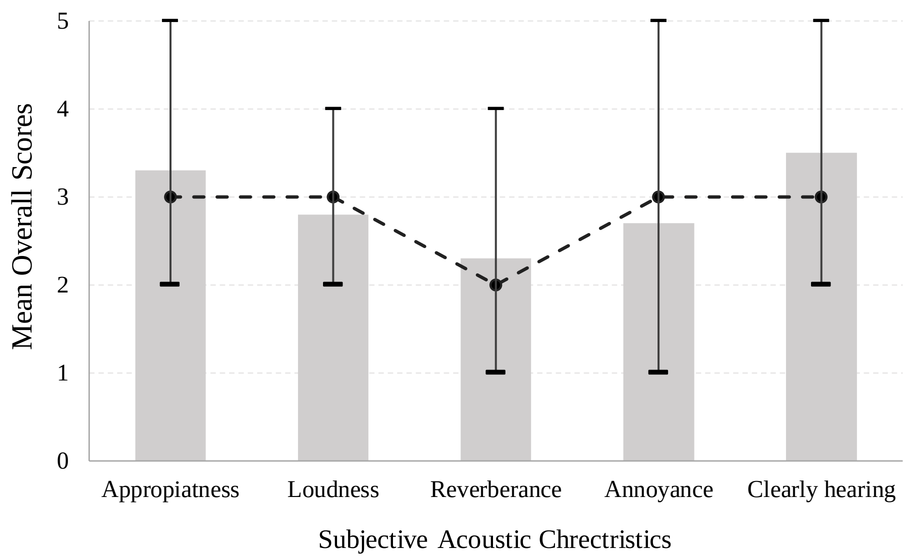


Figure. 20. Mean overall rating scores for each subjective acoustic characteristic of the FC atrium with the maximum and minimum values. The mode is presented with dashed lines.

According to the survey, students' activities at the A/H atrium are more evenly distributed; chatting and hanging out with friends (30%), eating and drinking (30%), and studying (40%). The data show that 60% of students visit the FC 1 to 2 days a week, and 30% visit more than 5 days a week. Additionally, 80% of students mentioned that they spend an average of 2-3 hours at this atrium but rarely 5 or more hours. Based on the subjective parameters rating assessment (Fig. 21), the majority of participants (80%) gave scores of

4 and 5 for being able to hear in the A/H atrium clearly. That is, they were perfectly able to hear one another. Participants rated loudness as 2.9 and used adjectives such as loud, noisy or crowded to describe this atrium. However, when asked to rate annoyance level at A/H, the mean score was calculated as 2 which is slightly annoyed. They gave an overall score of 2.4 for the reverberation level with the mode score being 2. Hence, students perceive the A/H atrium as slightly loud, reverberant, or annoying. Respectively, the ratings for appropriateness are shown to be moderate, with a score of 3.4.

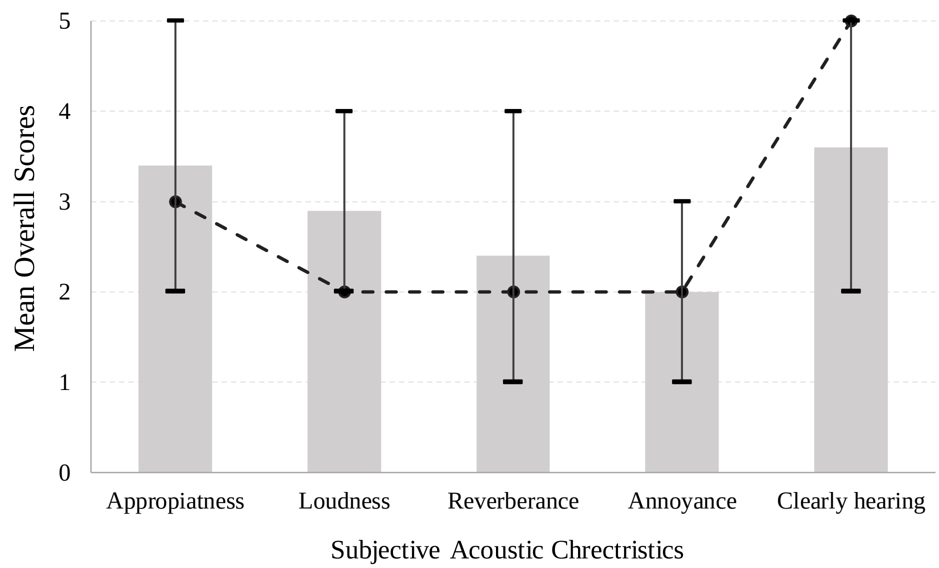


Fig. 21. Mean overall rating scores for each subjective acoustic characteristic of the A/H atrium with the maximum and minimum values. The mode is presented as dashed lines.

Unlike the FC and A/H atrium, the FF atrium is mainly used by students for working/studying (50%) and chatting (40%). Additionally, 10 % of participants mentioned they visit this atrium for final juries. More than half of these students (60%) claimed they visit the FF atrium more than 5 days a week and between them 40%, spend less than an hour at the atrium and 50% spend 3-5 hours working on PC or studying. The majority of students assigned the FF atrium a grade of 5 for being able to hear clearly and a score of 1 for the amount of annoyance based on the subjective parameters rating assessment (Fig. 22). That is considering some exceptions participants were able to hear perfectly and were not annoyed at all at FF. With a few exceptions, participants were able to hear clearly and did not find FF to be at all annoying. Nevertheless, they gave the FF atrium mild to moderate ratings for appropriateness, loudness, and reverberation with mean values of 2.7, 2.5, and 2.7, respectively. One adjective that is mainly used by the participants to describe the FF atrium is loud.

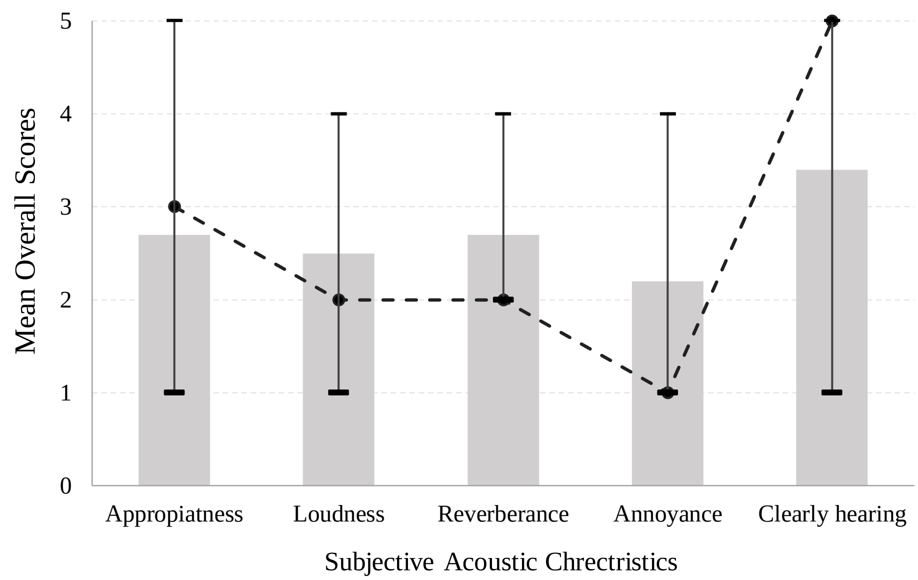


Fig. 22. Mean overall rating scores for each subjective acoustic characteristic of the FF atrium with the maximum and minimum values. The mode is presented with dashed lines.

Similar to the FF atrium, the SA atrium is also primarily used as a study area by the students (80%). 90% of students claimed that they visit the SA atrium 3 to 5 days a week. Additionally, 70% of students mentioned that they spend an average of 3-5 hours at this atrium, studying or working on their PCs. The majority of participants rate the SA atrium a mode score of 4 during the subjective parameters rating assessment (Fig. 21), refereeing it as a very reverberant space (mean score: 3.3). Additionally, they noted that the SA atrium is moderately loud, by rating 2.6 and 2.3, respectively. The atrium nevertheless is assessed as moderately to very appropriate and suitable for clarity of speech, or proper conversation. Additionally, students using the space comment that they prefer the atrium space not to be so silent, and they enjoy some noise (soundscape of the space).

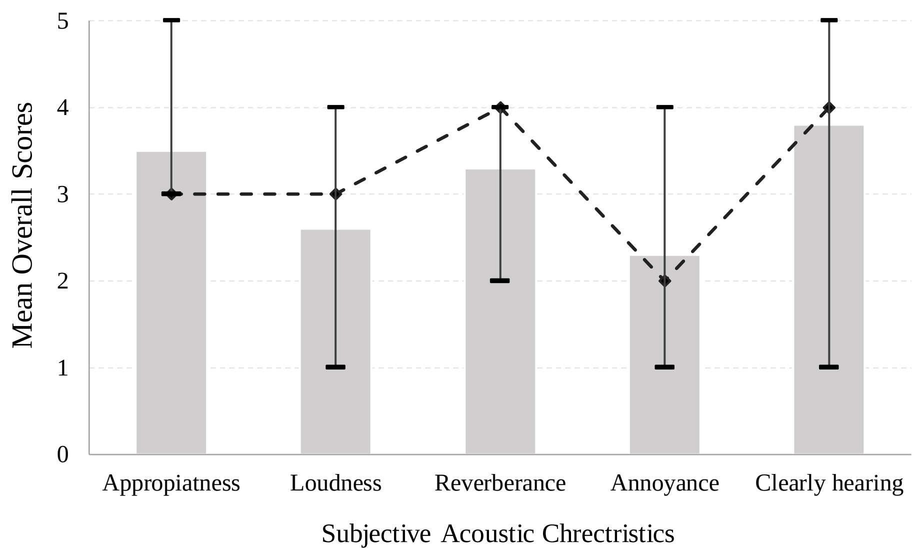
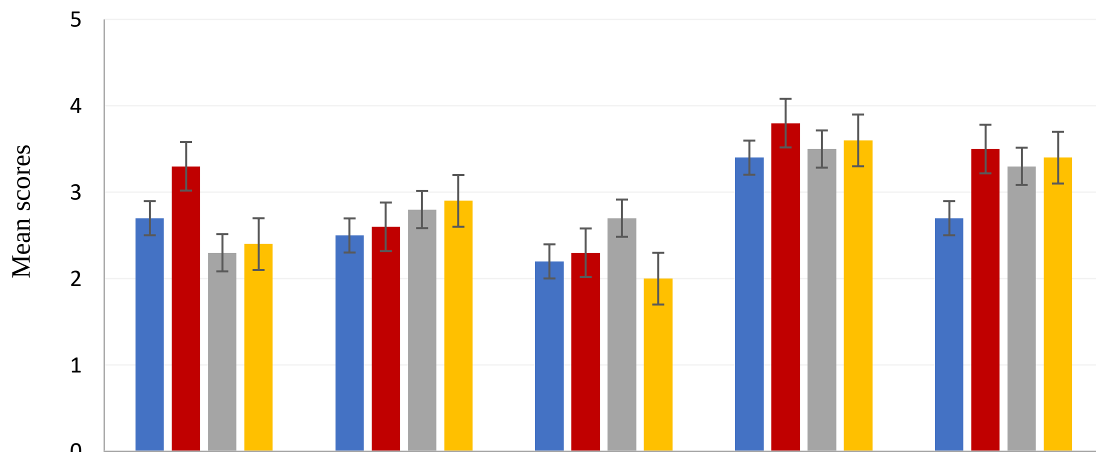


Fig. 23. Mean overall rating scores for each subjective acoustic characteristic of the SA atrium with the maximum and minimum values. The mode is presented with dashed lines.

The assessment of subjective characteristics of all four atriums by the participants is presented in Figure 24. Accordingly, the SA atrium is rated by the participants to be preceived as the most reverberant (still moderate) and appropriate atrium with 3.3 and 3.5 scores, namely above moderate in subjective testing. However, SA has the shortest reverberation time based on the results of the field measurements. This may be because of the individuals who spend 3 to 5 hours a day in the SA atrium, 80% of them use it as a study space 3-5 days each week. When asked if the participants are bothered or annoyed by the acoustics of these atriums, the FC atrium is rated as most disturbing with a mean score of 2.7 and A/H as the least disturbing, with a mean score of 2 (slightly). Participants declared that in approximately all four atriums, they are able to have proper conversation. The deviation of scores for the loudness of these atriums is also small, and participants rated all four atriums as moderately loud, with A/H being the loudest and FF being the least loud.



	Reverberance	Loudness	Annoyance	Speech clarity	Appropiatness
FF	2.7	2.5	2.2	3.4	2.7
SA	3.3	2.6	2.3	3.8	3.5
FC	2.3	2.8	2.7	3.5	3.3
A/H	2.4	2.9	2	3.6	3.4

Fig. 24. Mean overall rating scores for each subjective acoustic characteristic of all four atriums. The standard error for the scores is presented in error bar format.

4.2.1. Listening Test Results

Through the systematic listening test of this study at four of Bilkent University's educational atriums, the subjective perception and preference of a sample group of 67 people are assessed. Their preferences regarding the subjective parameters are analyzed. Further, the correlation between their preferences with age, gender, amount of time spent, and the activities conducted are investigated.

4.2.2. Personal Survey

According to data collected from the first section of the questionnaire, the personal survey, the sample group consisted of 48 (72%) female and 19 (28%) male participants. Participants are all undergraduate students with a background in the basic knowledge of acoustics. The majority of the participants (67%) noted that they mostly spend less than an hour at these atriums and about 95% of them visit atriums 4-5 days a week (Fig. 25). Furthermore, as shown in Table 10, the two main activities conducted by the students are first chatting/hanging out with friends (36.6%) and second; drinking and eating (18.6%).

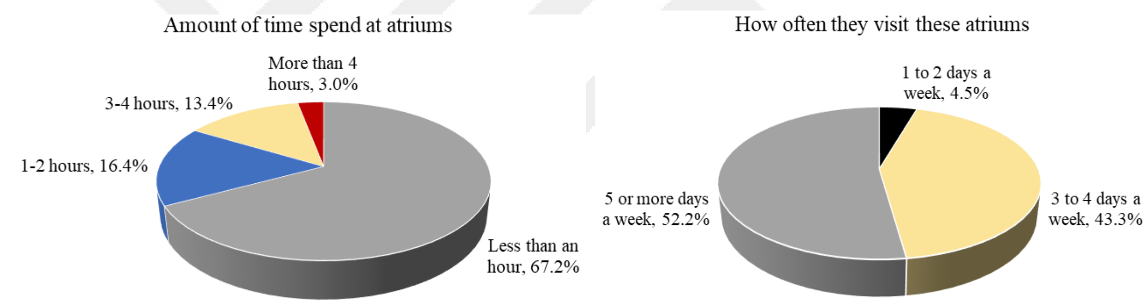


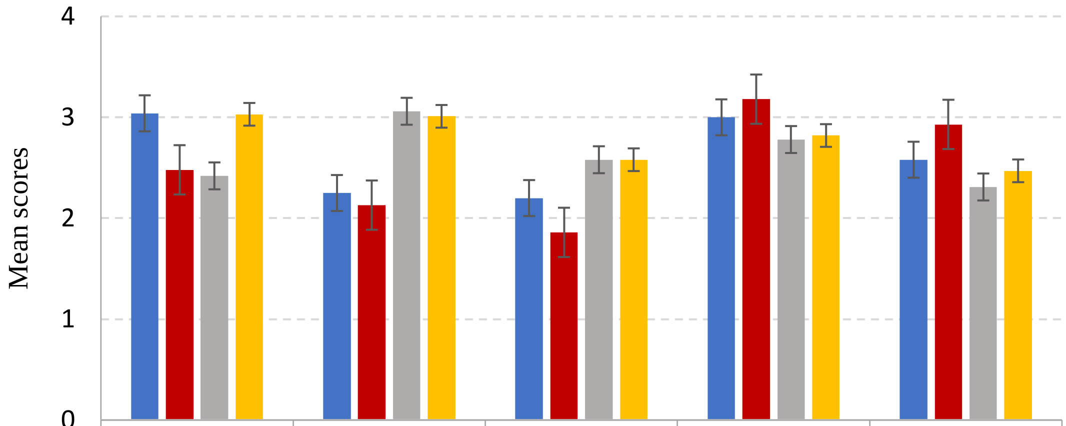
Fig. 25. The frequency of use by participants.

Table 10. The frequency and percentages of the conducted activities selected by participants.

Conducted Activity	Frequency (n)	Percentage (%)
Studying/reading	22	15.2%
Chatting/hanging out with friends	53	36.6%
Working with computers	15	10.3%
Drinking and eating	27	18.6%
Temporary exhibitions and final juries	18	12.4%
Other	10	6.9%

4.2.3. Questionnaire

In the second section of the questionnaire, participants are asked to rate the acoustical qualities of atrium spaces. Grounded on ISO/TS 12913-3:2018 soundscape standards for the five-point ordinal-category scale of the questionnaire, scale values of 1,2,3, and 4 are assigned respectively for “not at all”, “slightly”, “moderately”, and “very”. Using the numeric scale, the total score of each group’s appropriateness (authenticity and/or naturalness) per participant is calculated. The frequency graph of each atrium for the mean score of each specific characteristic (loudness, appropriateness, reverberance, annoyance, and speech clarity) is presented (Figure 26). Accordingly, it can be stated that FF and A/H Atriums are perceived as the most reverberant spaces with a score of 3. On the other hand, based on the field measurements the FF atrium is the most reverberant with T30 of 4.67 s and the other three atriums have approximately the same range of T30, 3.03 s to 3.15 s at 500 Hz. When comparing the loudness, atrium FC and A/H are rated as the loudest with a numerical value of 3. Participants noted that they are also mostly bothered by the acoustics of the FC and A/H atrium, scoring them as 2.58. When asked if participants are able to hear themselves and others clearly while speaking, FF and SA atriums are commented as the best and most appropriate in terms of acoustical qualities.



	Reverberance	Loudness	Annoyance	Speech clarity	Appropiatness
FF	3.04	2.25	2.2	3	2.58
SA	2.48	2.13	1.86	3.18	2.93
FC	2.42	3.06	2.58	2.78	2.31
A/H	3.03	3.01	2.58	2.82	2.47

Fig. 26. Mean overall rating scores for each subjective metric of all four atriums at listening test. The standard error for the scores is presented in error bar format.

Additionally, in this section, the dependent and independent variables from the personal survey section with the perceived parameters are analyzed using IBM SPSS Statistics 25. To determine whether there is a significant dependency between different variables, the non-parametric Kruskal-Wallis and Mann-Whitney test is used. The hypothesis must be rejected for these tests if the associated significance is less than 0.05. Initially, the dependency of ratings on gender, age, and the amount they spend at the atriums are investigated. The results suggest that the perceived characteristics are independent of the age and gender of the participants or the amount they spend at each atrium. Next, the analysis shows that how bothered are the participants at the A/H atrium is dependent on the frequency of times participants visit each atrium with a sig value of 0.043 (Appendix D). For the conditions that the students visit the A/H atrium 3-4 days and 5 or more days a week, there is a significant difference in their ratings of the annoyance of the A/H atrium with sig values of 0.22 and 0.11, respectively. The more the students visit and use these atriums the more sensitive they are to the acoustical environment.

4.2.4. Paired Comparisons

In this section of subjective testing, paired comparison tests are used to assess participants' preferences which have proven to provide more consistent data (Ermann, 2007; Fidell and Green, 1998; Hase et al., 2000) and higher power of discrimination (Bradley and Wang, 2010). Participants are asked to compare two pairs of audio clips (grouped based on EDT) and select the one they prefer. As such, the statistical analysis is grounded on the participants' selection of audio clips according to EDTs. The obtained results of the selection frequency of the participants are presented together with the primary statistical analysis (Fig. 27). According to the distribution of the frequencies, when audio clips from groups G1 ($0.50<EDT\leq1.00$) are paired with G6 ($3.75<EDT\leq5.17$), the participants have the highest rate of recognizing the different pairs. In comparison, minor recognition takes place when the group; G2 ($1.00<EDT\leq1.40$) is paired with G3 ($1.40<EDT\leq1.95$), where nearly 50% of the participants are unable to differentiate the stimuli from one another (Fig. 27).

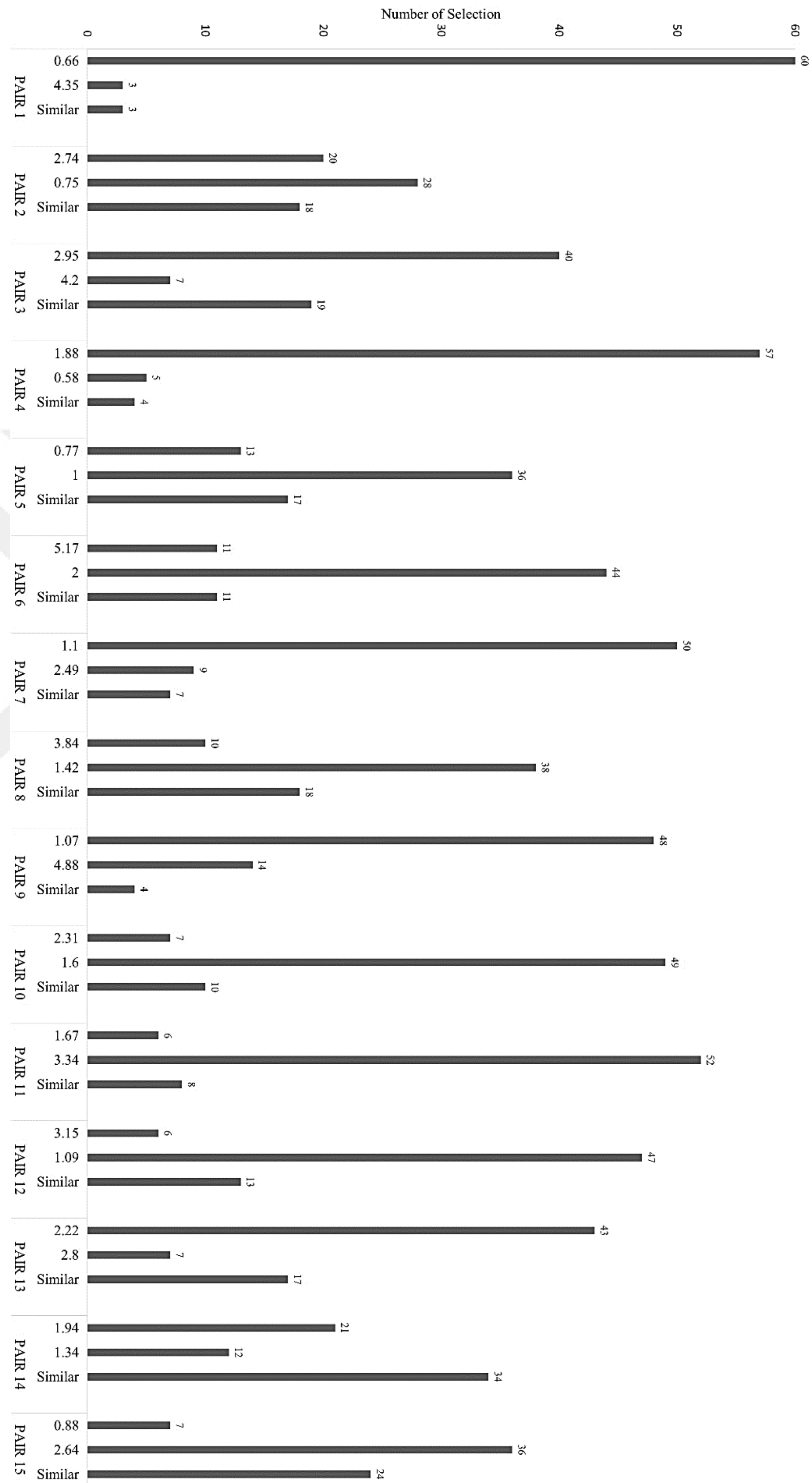


Fig. 27. Frequency distribution: number of times each stimuli is selected by the participants.

The primary aim of paired comparison section of the questionnaire is to assess the participants' preference in relation to EDT values. To this end, the frequency of selected audio clips is grouped in their relative EDT groups and scores for the number of times each group is selected or not selected are graphed (Fig. 28). Based on the results, the EDT groups G2 (1.00<EDT≤1.40) and G3 (1.40<EDT≤1.95) are mostly preferred by the participants with the highest scores. When audio clips from G2 and G3 are presented to participants as options, they are selected 193 and 171 times, respectively. Overall between all six groups, the audio clips from group G2 receive the highest range of preferred EDT. That is when audios from G2 are presented to the participants as one of the pairs, it is selected as the preferred option except when paired with audios from G3, where a number of exceptions occur. On the contrary, the audio clips from G6 (3.75<EDT≤5.17) are the least preferred by participants (Fig. 28) receiving a rating of 230 for not being selected. Moreover, the scores for the audio clips of groups G4 and G5 are almost evenly distributed between being selected and not being selected. That means, these audios preferred by 50 % of the participants and excluded by the other half of the sample group.

Later in order to assess participants' subjective ranking of the six early decay time (EDT) groups, the preferred/selected stimuli receive a +1 score, whereas the stimuli that are not selected are given a score of -1. In cases where participants could not differentiate between the pairs, both stimuli are given a score of 0 (Martellotta, 2008). For obtaining an overall score and rank of each group, the scores are summed, and the results of each listening test are presented in a graph of preference indicating how many times each group (with different EDT ranges) is selected/preferred by participants (Fig. 29). Accordingly, the two groups of G1 and G2 with the ranking scores of 130 and 85 are mostly preferred.

On the contrary, both groups G6 and G1, are least preferred by the participants with scores of -185 nad -39 correspondingly.

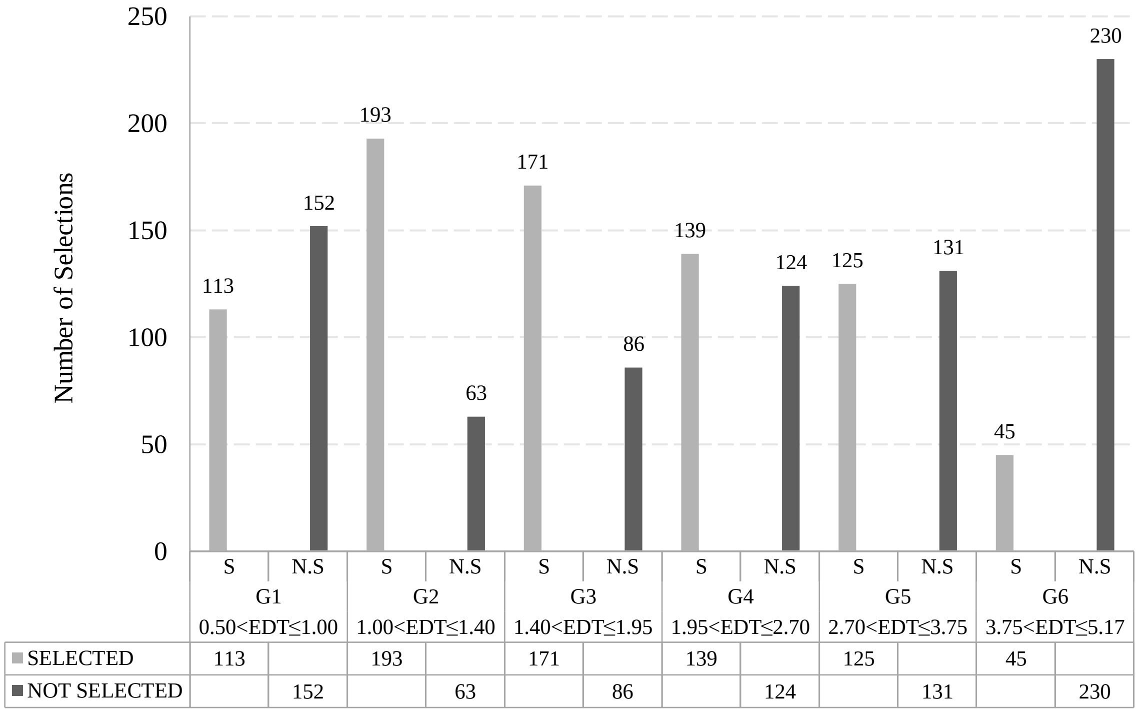


Fig.28. Selection scores for each early decay time (EDT) group by participants.

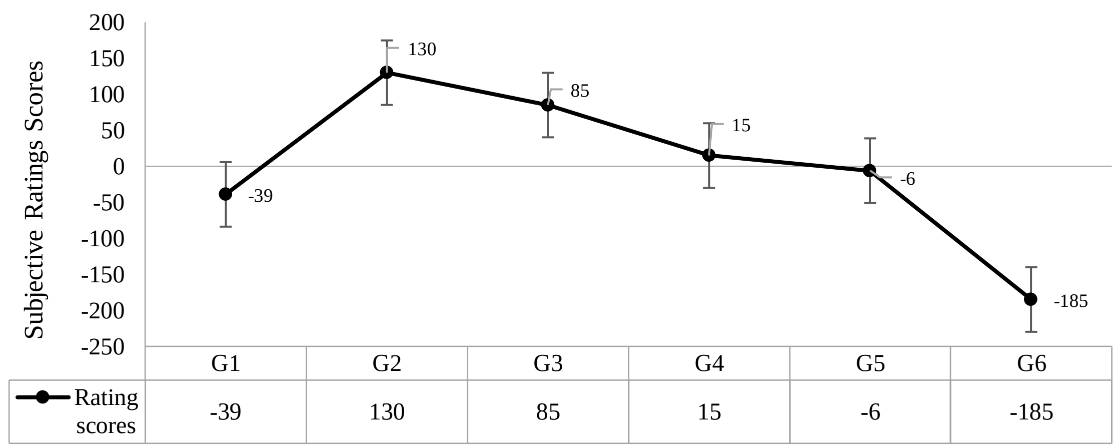


Fig.29. Participants' subjective ranking of the six early decay time (EDT) groups' evaluation scores. The negative numbers show that the particular group is not selected/preferred.

4.3. Correlations

One of the other fundamental aims of this study is to analyze the correlation that exists between the participants' preferences and their demographic characteristics such as the amount of time they spend in atrium spaces and the activity patterns. As such, the non-parametric Spearman correlation test is conducted in the statistical analysis of the gathered data at 95% and 99% significance levels (2-tailed) (Appendix D). For the Spearman correlation test, the hypothesis must be rejected if the associated significance is less than 0.05. The correlation coefficient, which ranges from –1 to +1, is analyzed in case of significance. The values higher than 0.3 indicates a significant correlation between the variables (Argyrous, 2014). When the value of the correlation coefficient gets closer to 1, it demonstrates a stronger correlation. The negative and positive signs determine the direction of the correlation.

By means of Spearman's rho and Kendall's tau-b non-parametric correlation test, the preference of participants in relation to their personal information, provided in the first part of the listening test, is analyzed. It is found that the preference for EDT and perceived subjective characteristics are independent of the participants' age or gender. Moreover, no significant correlation is found between the number of hours participants spend at these atriums and their preferences of the audio clip, or how they perceived the subjective characteristics of each atrium with the exception of A/H. At the A/H atrium, it is found that the participants' rating of annoyance with the acoustical environment is dependent on how frequently students visited this atrium. Additionally, no significant correlation is found between the activity patterns and both preferred EDTs and perceived subjective characteristics.

Moreover, the correlation of perceived subjective characteristics at each atrium is analyzed. First, the correlation of reverberation with other perceived parameters is investigated (Appendix D). At FF, SA, and A/H atrium, a moderate positive correlation is found between reverberation and both loudness and annoyance with an average correlation coefficient of approximately 0.519. Thus, the more reverberant an atrium, the louder and more annoying for its users. At the FC atrium, however, a weak positive correlation is suggested between reverberation and both loudness and annoyance with a correlation coefficient of 0.29 and 0.37, respectively. When the correlation between reverberation and speech clarity is assessed, a weak negative correlation is found at the FC and SA atrium and a moderate negative correlation is found at the A/H atrium with a correlation coefficient of -0.472. A weak negative correlation is also found at all atrium excluding FC.

Next, the relation between loudness and other perceived parameters is analyzed. A moderate positive correlation is suggested between the level of loudness and the annoyance ratings at all four atriums. Additionally, a moderate negative correlation between loudness and hearing clearly is found at the FF and A/H atrium with a correlation coefficient of -0.42 and at the SA atrium with a coefficient of -0.52. The correlation is significant at level 0.01. At the FF and FC atrium, a negative weak correlation exists between loudness and appropriateness of each space. The correlation is moderate at SA and A/H atrium at level 0.01 with a correlation coefficient of 0.50.

CHAPTER 5

DISCUSSION

5.1. Pilot Study

In a pilot study of the same research, the field measurements are held at four atriums, however, in the scope of the study, only the FC atrium is investigated. An online questionnaire is held over a sample group of 17 experienced acousticians. The grouping for the pilot study is based on the T30s, five groups of T30s ranging from 0.61s to 2.87 s are employed for the subjective testing. The statistical analysis revealed that the participants' preference is independent of their age and profession. Additionally, the longer T30s are ranked the higher in terms of their appropriateness in this context. According to both paired comparison and the five-point ordinal scale part of the survey, T30s ranging from 2.05 s to 2.15 s (G2) with an 8% acoustical treatment application on ceilings for the specific case of the FC atrium are mainly preferred and rated the highest as the most appropriate by the participants (Naeemaee and Sü Gül, 2021).

Nevertheless, to analyze the impacts of EDT on subjective preference which has proven to be more accurate in the judgment of perceived reverberation (Barron, 2009; Chen and Kang, 2004; Kang, 2002) the grouping of the audio clips is done based on their EDT, instead of T30 in further steps. Additionally, questionnaires are held over students of

Bilkent University who are current users of the atriums and are familiar with all four atriums.

5.2. Acoustical Characteristics of All Four Atriums

According to previous studies, in atrium spaces, due to their large volumes and complex shapes, the reverberation time tends to be at its highest at mid-frequencies (500 Hz and 1000 Hz). This is more commonly observed at atriums with minimum sound-absorbing material applications (Bradley and Oh, 1997). Likewise, based on the field measurements held at Bilkent University atriums, the same trend is observed at all atriums where the highest decay rates values (EDT, T30, and T20) are recorded at mid-frequencies (500 Hz and 1000 Hz).

Additionally, reverberation time is affected by the volume and absorption coefficient of the materials (Barron, 2009). The larger volumes led to longer reverberation times (Çalışkan, 2010; Mahdavi et al., 2007; Nowicka, 2020; Zhao et al., 2015). As such, the SA atrium which is the second largest atrium is expected to have one of the longest reverberation times based on its volume. However, it is recorded to have to shortest decay rates among all four atriums. And since the materials used at all atriums are similar, it can be due to the fact that the SA atrium is the only atrium with skylights which results in the absorption of low frequencies (Bradleborky and Oh, 1997; Chen & Kang, 2004). Moreover, Chen and Kang (2004) suggest that STI values are influenced by EDT values. As such, the FF with the highest EDT of 4.39 s at 500 Hz is recorded to have the lowest STI value of 0.46 among all four atriums. Moreover, at the A/H, SA, and FC, there is a nearly 20 % difference between the EDT and T30 values ranging from 0.6 s to 0.8 s.

Unlike the other three atriums, there is less than a 5% difference between EDT values with T30 (s) at the FF atrium with 0.3 s at 500 Hz.

5.3. Early Decay Time Preference and the Impact of External Elements

According to the frequency results of the paired comparison section, when consecutive groups are paired with each other, minor recognition is observed. That is, participants had difficulties differentiating the pairs when the EDT value difference is less than or equal to three times the Just Noticeable Difference. Moreover, according to Kuttruff (2016) in enclosed spaces too short reverberation times can result in an unnatural and uncomfortable feeling. Similarly, it was concluded from the frequency of selected audio clips that EDT groups G2 (1.00<EDT≤1.40) and G3 (1.40<EDT≤1.95) are mostly preferred by the participants with the highest scores. Whereas, both groups G6 (3.75<EDT≤5.17) and G1 (0.50<EDT≤1.00), are least preferred by the participants. Hence, as expected, participants do not prefer a room that is too dry (extreme ratio of applied absorption) or too live (no applied abruption) within the context of educational atriums. As a result, without considering the context of the space excessive use of sound absorptive materials to decrease reverberation times in atriums to the levels indicated by regulations (ex. Protection of Buildings from Noise, T.C. Official Gazette, 30082, May 31, 2017, Table 6.1) is not a necessity and it’s against the sustainability of materials in construction industry and architecture.

Chen and Kang (2004) suggested that the participants’ perception and preferences of an acoustical environment might be affected by the duration of stay or demographic characteristics which required further studies. As such, a negative correlation between duration of stay and preferred EDT is expected in this study. However, no significant correlation is found between participants' preferences and the frequency of visits or the amount of time participants spend at these atriums. Nevertheless, this might be due to the fact that the majority (67%) of the participants mentioned that they only spend less than an hour at each atrium, although 95% of the students argued that they visit 4-5 these atriums days a week.

Furthermore, it is anticipated that the activities conducted by individuals at atriums impact the preferred EDT values. The more active functions, the longer the preferred early decay and reverberation times. However, no significant correlation is found between the preferred EDTs and activity patterns. Finally, considering the skewness of female participants to male participants in the listening test, it is found that the EDT preference is independent of the gender of the participants.

5.4. Assessment of Subjective Acoustical Parameters

Although no significant correlation is found between the preferred EDTs and activity patterns while conducting the non-parametric Spearman correlation test, it is found that activity patterns may affect how spaces are perceived by participants. During the field survey, the SA atrium is rated as the most reverberant among all four atriums by participants who claimed to be using this atrium mostly as a work and study area. On the contrary, in the listening tests, the SA atrium is rated as one of the least reverberant among all four atrium by participants. In this case, only 25% of the participants claimed to be using this atrium as a work/study area. The SA atrium is measured to have the shortest reverberation time based on the field measurements. Additionally, the FC atrium is used by the majority of the students (90%) as a place for eating, chatting, or hanging out with friends. The FC atrium is also rated as the least reverberant atrium when in fact it is measured to have the second longest reverberation times over frequency spectrum. As such, it is suggested that activity patterns can impact the perception of subjective parameters by participants. The participants are more sensitive to the acoustical environment regarding the activity conducted (Chen and Kang, 2004). However, a more comprehensive study is needed. Similarly, it is important to consider the activity pattern of the space before applying excessive sound absorptive treatment to decrease reverberation times in atriums.

Moreover, no significant correlation is found between the duration of stay and how participants perceive the subjective characteristics of each atrium with the exception of A/H. At the A/H atrium, it is found that the participants' rating of annoyance with the acoustical environment is dependent on how frequently students visited this atrium. As for the relationship between gender and perceived acoustical environment in the field survey, no significant correlation is found in relation to the perception of subjective parameters and gender. This finding is also in correspondence with the previous literature (Chen and Kang, 2004; Dökmeci, 2009). In accordance with the overall rating of subjective parameters in all four atriums, the FF atrium is rated as the least appropriate with a mean score of 2.7 and the SA atrium as the most appropriate with a mean score of 3.5. Although the mean difference between SA, FC, and A/H is minimal.

CHAPTER 6

CONCLUSION

This research employs objective and subjective acoustical analysis of four frequently used educational atrium at Bilkent University. The study aims to assess the perception and preference of decay rate metrics (T30 and EDT) within the context of educational atriums over current users of spaces. The optimum criteria of reverberation times for atriums have not yet been well established. This causes in unnecessary applications of absorptive acoustical material within contemporary atriums, which indeed is not proper for the sustainability of materials or for sustainable architecture. This study aims to provide a ground for such discussion on the optimum criteria, which can in the future lead changes in standards and codes.

In the scope of the thesis, acoustical field measurements are performed at all four atriums in accordance with ISO 3382-1 standard. Later 3D models of atriums are generated and tuned in reference to measured T30s and EDTs for auralizations. Lastly, using the produced recordings by auralization, an online listening test is held over a sample group of 67 students. The listening test is divided into three sections; personal survey, questionnaire, and paired comparison.

From the field measurements, decay rates (EDT, T30, and T20) and STI are obtained and investigated. In overall, due to their large volume and complex shapes, decay rates at all four atriums have the highest numerical values (longer EDT, T30, and T20) at mid frequencies (500 Hz and 1k Hz). Additionally, according to the obtained STI values, all four atriums have a fair speech intelligibility ranging from 0.46 to 0.60. However, speech intelligibility is influenced by EDT, and as such the FF atrium with longer EDT has the lowest STI value of 0.46. The FF atrium's STI value can be even lower and be categorized as poor if background noise is higher than 45 dB.

The statistical analysis of paired comparison section reveals that minor recognition is observed when consecutive groups are paired with each other (consecutive EDT groups). The results highlight that the students who are the current users of assessed educational atriums do not prefer very dead or very live acoustical environment. For EDT an interval of 1.00 s – 1.95 s and for T30 an interval of 2.05 s – 2.15 s is found to be optimum for a volumetric space ranging from 3500 m^3 to 8500 m^3. This outcome can guide the acoustical design process of either to be renovated or newly designed atriums to prevent excessive use of sound absorptive materials leading to sustainability of materials. Additionally, considering the demographic characteristics of participants, it is revealed that the participants' preference for EDT values is independent of the frequency of visits and the activity pattern.

In the statistical analysis of subjective parameters, it is found there is no correlation between activity patterns and the perception of the acoustical environment. However, the frequency distributions suggest that activity patterns may indeed impact how spaces are perceived by the participants. That is the participants who mainly use the spaces for work/study are more sensitive to the acoustical quality of the atrium spaces. However, a more comprehensive study with a larger sample group and more diverse activity patterns is required. Additionally, the perception of subjective parameters is independent of the gender and frequency of visits excluding the A/H atrium where participants' rating of annoyance is dependent on how frequently students visited this atrium. Overall, among all four atriums, the FF atrium is rated as the least appropriate by the participants, and the SA atrium with a minimal mean difference from FC and A/H is rated as the most appropriate.

While the study is conducted on a sample group of 67 (online listening test) and 40 (field survey) Bilkent University students, there are still limitations regarding the participants. The sample size is skewed toward the female population in the listening test and the variety of activity patterns conducted by the participants is unbalanced in the field survey. As such, the sample size can be enlarged for future studies, and participants from graduate programs and academicians can also be included in order to increase the accuracy of the statistical analysis. Furthermore, to increase the diversity of participants' preferences, students from different departments can also be included in the online listening test. This work attempts to serve as a step toward a better understanding of user's preferential listening conditions in educational atriums regarding their context to prevent excessive use of absorptive material if unnecessary.

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APPENDICES

APPENDIX A_FIELD MEASUREMENTS

Table A 1. T30 at the FC atrium over 1/1 octave bands in seconds

FC (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	2.67	3.26	2.94	2.90	2.51	1.61
S1R2	2.65	3.08	3.23	2.90	2.50	1.62
S1R3	2.55	2.91	3.15	2.87	2.35	1.61
S1R4	2.54	3.12	3.04	2.96	2.49	1.62
S2R1	2.70	3.10	3.08	2.91	2.45	1.60
S2R2	2.78	3.04	3.05	2.80	2.35	1.50
S2R3	2.57	3.15	3.08	2.73	2.56	1.57
S2R4	2.62	3.26	3.39	2.94	2.44	1.66
S2R5	2.49	3.06	3.33	3.75	2.53	1.57
S2R6	2.41	3.07	3.16	2.83	2.38	1.59
S2R7	2.61	3.25	3.19	2.94	2.45	1.64
S3R1	2.65	2.99	3.12	2.97	2.44	1.61

Table A 2. T30 at the A/H atrium over 1/1 octave bands in seconds

A/H (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	2.50	2.90	3.12	2.90	2.38	1.55
S1R2	2.57	2.75	3.04	2.89	2.48	1.54
S1R3	3.02	2.88	2.90	2.83	2.53	1.69
S1R4	2.76	3.10	3.21	3.11	2.62	1.77
S1R5	2.65	2.99	3.50	3.12	2.48	1.60
S1R6	2.87	3.00	3.34	3.05	2.69	1.72
S2R6	2.52	2.74	3.15	2.86	2.16	1.50
S2R7	2.27	2.84	3.05	2.77	2.46	1.52
S2R8	2.31	2.75	3.27	2.94	2.41	1.55
S2R9	2.63	2.93	2.90	2.74	2.41	1.60

Table A 3. T30 at the FF atrium over 1/1 octave bands in seconds

FF (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	3.28	3.80	4.53	4.41	3.44	1.94
S1R2	3.04	3.81	4.56	4.57	3.49	2.03
S1R3	3.09	3.75	4.79	4.55	3.57	2.56
S2R1	3.34	3.92	4.59	4.52	3.49	2.06
S2R3	3.40	3.67	4.65	4.48	3.47	2.09
S2R4	3.51	3.84	4.86	4.51	3.50	2.08
S2R5	3.06	3.76	4.69	4.51	3.51	2.15
S2R6	3.47	3.88	4.54	4.47	3.48	1.99
S2R7	3.38	3.70	4.84	4.60	3.49	2.10

Table A 4. T30 at the SA atrium over 1/1 octave bands in seconds

SA (T30)						
S/R	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
S1R1	2.07	2.40	2.72	3.12	2.57	1.62
S1R2	2.04	2.68	3.08	3.13	2.52	1.62
S1R3	2.17	2.55	3.71	3.26	2.81	1.60
S1R4	2.13	2.79	3.01	3.10	2.51	1.65
S1R5	2.19	2.82	2.85	2.91	2.63	1.68
S2R6	2.71	2.97	3.49	3.26	2.68	1.76
S2R7	2.11	2.38	3.15	3.01	2.54	1.63
S3R5	2.49	2.98	3.29	3.26	2.62	1.75
S3R7	2.12	2.70	2.88	2.99	2.37	1.61
S3R8	1.93	1.96	2.84	2.81	2.25	1.40
S3R9	1.62	2.22	2.35	2.75	2.18	1.28

APPENDIX B_ QUESTIONNAIRES

B 1. The questionnaires used for the listening test of the pilot study.

Atrium's Acoustics

This survey is prepared for an Architecture Master of Science thesis at Bilkent University with the topic of Perceived Acoustics in Atriums.

Section A:

1. Gender

A. Male B. Female

2. Age

3. Profession

A. Undergraduate B. Master/PhD C. Instructor/ Prof. D. Other

4. Do you suffer from any hearing loss?

A. Yes B. No

Section B:

Please make sure that you do the listening test in a silent environment. Please set the level of your headsets/headphones to a comfortable level and do not change it until the end of the survey. You can stop at any time or replay the videos as you like.

For questions 5 to 14, please pick one of the two audios (sound environment) you prefer to be in for the given atrium.

The question under each pair:

Which sound environment would you prefer to be in for this atrium?

a) Option A
b) Option B
c) A and B are similar/ A and B sound similar

Section C:

For questions 15 to 24, please rate the audios regarding their appropriateness or authenticity to their present environment.

The question under each pair:

To what extent is the present surrounding sound environment appropriate to the present place?

a) Not at all
b) Slightly
c) Moderately
d) Very
e) perfectly

Would you please use this space for additional comments and critiques on the acoustics of this Atrium?

Thank you for your participation.

Have a great day!

B 2. The questionnaires used for the developed listening test.

Atrium's Acoustics

This survey is prepared for an Architecture Master of Science thesis at Bilkent University with the topic of Perceived Acoustics in Atriums.

Section A:

1. Gender

A. Male B. Female

2. Age

3. Profession

A. Undergraduate B. Master/PhD C. Instructor/ Prof. D. Other

4. Do you suffer from any hearing loss?

A. Yes B. No

Section B:

The survey analysis four atriums of Bilkent University: FC, SA, A/H and, FF building accordingly as shown in figures below. Please answer the following questions regarding these atriums.

1. How often do you visit these Atriums?
    a. 5 or more days a week
    b. 3 to 4 days a week
    c. 1 to 2 days a week
    d. Very rarely

2. How long do you spend in these Atriums?
    a. Less than an hour
    b. 1-2 hour
    c. 3-4 hour
    d. More than 4 hours

3. What are the main activities conducted by you at these atriums?
    a. Studying/Reading
    b. Chatting/hanging out with friends
    c. Working with computers
    d. Drinking and eating
    e. Visiting exhibitions and Final Jury
    f. Other

4. How loud this Atrium sounds to you? (The questions 4-8 are repeated for all four atriums)

   a. Not at all
   b. Slightly
   c. Moderately
   d. Very

5. How reverberant this Atrium sounds to you?
   a. Not at all
   b. Slightly
   c. Moderately
   d. Very

6. Are you bothered/annoyed by the sound environment in these Atriums?
   a. Not at all
   b. Slightly
   c. Moderately
   d. Very

7. Can you clearly hear and distinguish yourself and others?
   a. Not at all
   b. Slightly
   c. Moderately
   d. Perfectly

8. How appropriate this Atrium sounds to you?
   a. Not at all
   b. Slightly
   c. Moderately
   d. Perfectly

<u>Section C:</u>

For the questions below, please pick one of the two audios (sound environment) that you prefer to be in.

The question under each pair:

Which sound environment would you prefer to be in for this atrium?

d) Option A
e) Option B
f) A and B are similar/ A and B sound similar

APPENDIX C_3D Open GL views of atriums

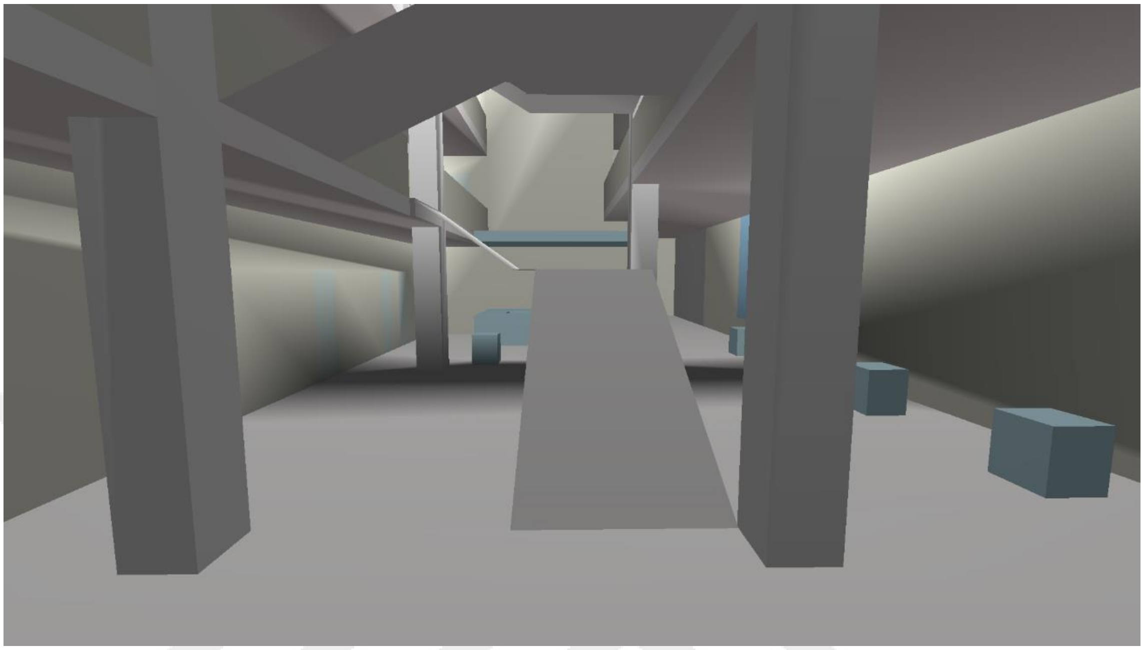

Figure C1. 3D Open GL views of the FC atrium simulated in ODEON software, atriums view from the main entrance

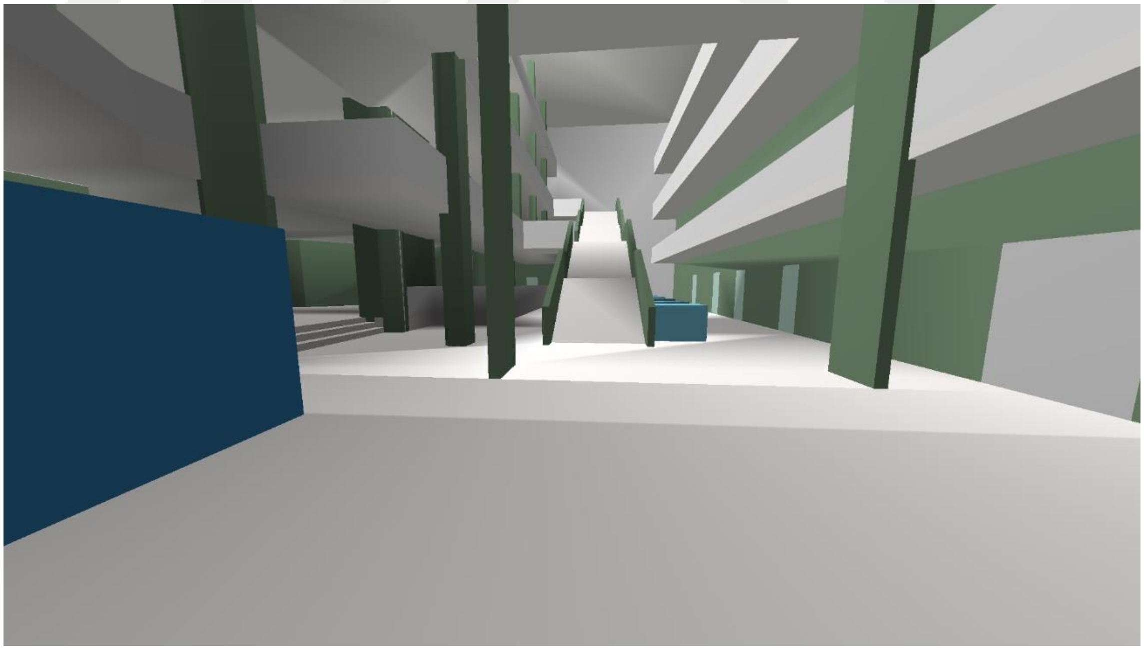

Figure C2. 3D Open GL views of the A/H atrium simulated in ODEON software, atriums view from the main entrance

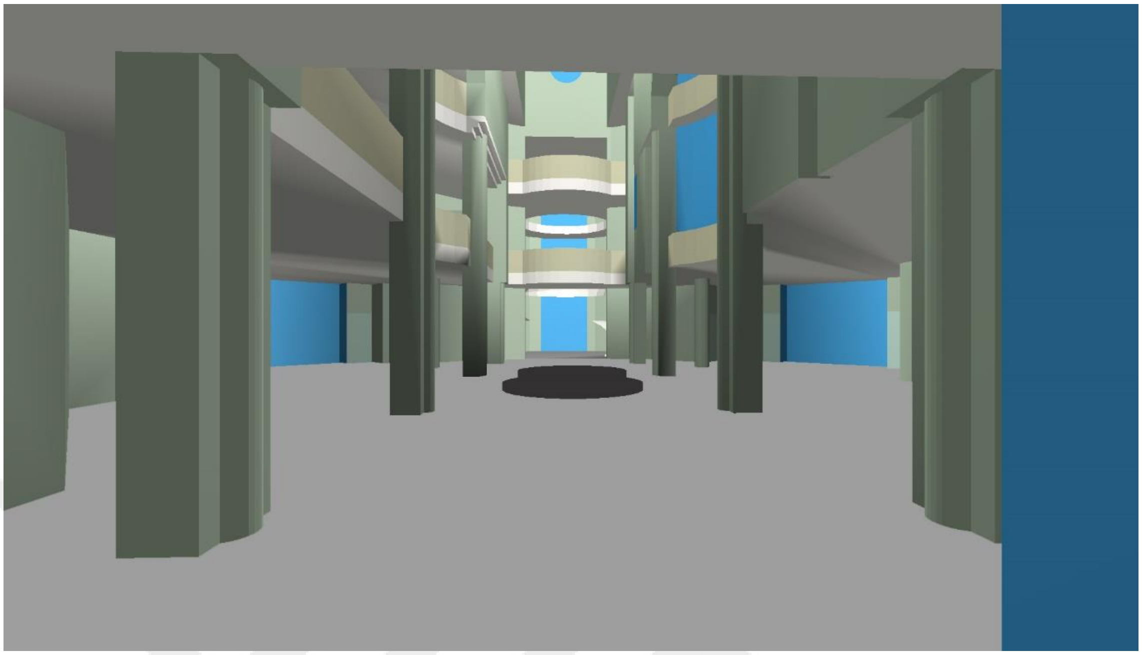

Figure C3. 3D Open GL views of the SA atrium simulated in ODEON software, atriums view from the main entrance

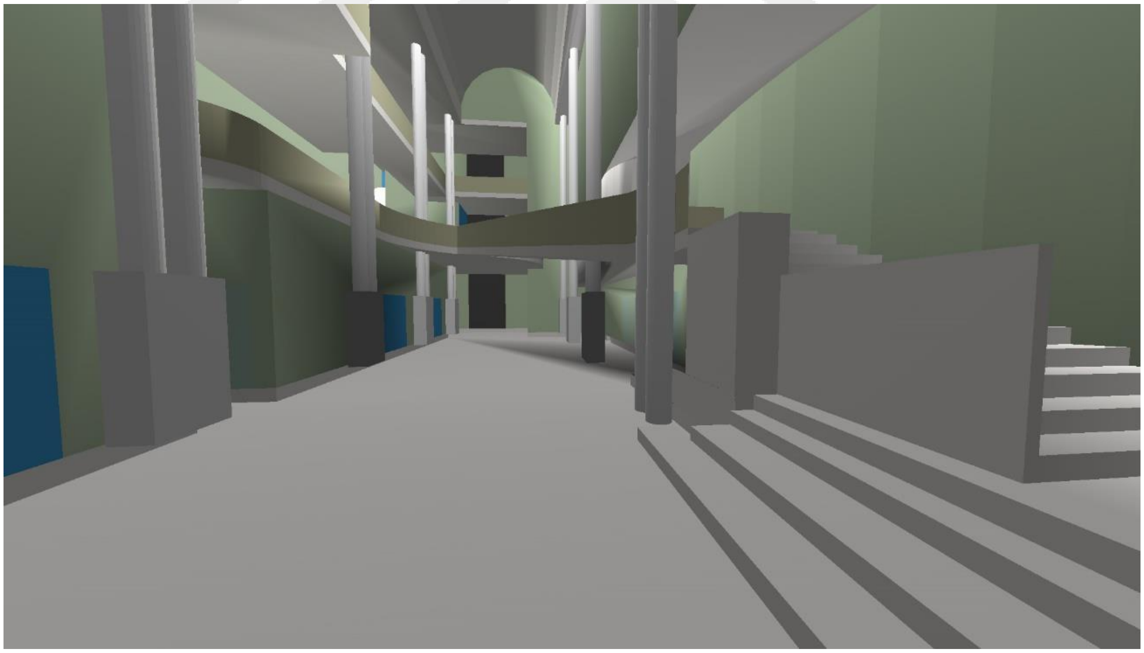

Figure C4. 3D Open GL views of the FF atrium simulated in ODEON software, atriums view from the main entrance

APPENDIX D_ Statistical analysis tests

D 1. The non-parametric Kruskal-Wallis test; Dependency between the perceived subjective characteristics and the frequency of visit at the A/H atrium.

	How loud A/H Atriums sounds to you?	Are you bothered/annoyed by the sound environment A/H Atriums?	Can you clearly hear and distinguish yourself and others at A/H?	How appropriate A/H Atrium sounds to you?
Kruskal-Wallis H	0.929	6.292	2.674	2.799
df	2	2	2	2
Asymp. Sig.	0.628	0.043	0.263	0.247

a. Kruskal Wallis Test

b. Grouping Variable: How often do you visit these Atriums?

D 2. Spearman's non-parametric correlation test; Correlation between the perceived subjective characteristics and the duration of stay.

			Loudness	Reverbrance	Annoyance	Speech clarity	Appropiateness
Spearman's rho	How often do you visit these Atriums?	Correlation Coefficient	-0.065	0.083	0.199	0.009	-0.144
		Sig. (2-tailed)	0.603	0.505	0.109	0.944	0.246
		N	67	67	66	67	67
	How long do you spend in these Atriums?	Correlation Coefficient	-0.122	-0.069	0.012	-0.025	-0.047
		Sig. (2-tailed)	0.324	0.578	0.927	0.840	0.706
		N	67	67	66	67	67
	How loud FF Atriums sounds to you?	Correlation Coefficient	1.000	.529**	.524**	-.419**	-.296*
		Sig. (2-tailed)		0.000	0.000	0.000	0.015
		N	67	67	66	67	67
	How reverberant FF Atrium sounds to you?	Correlation Coefficient	.529**	1.000	.547**	-0.209	-.350**
		Sig. (2-tailed)	0.000		0.000	0.090	0.004
		N	67	67	66	67	67
	Are you bothered/annoyed by the sound environment FF Atriums?	Correlation Coefficient	.524**	.547**	1.000	-.422**	-.525**
		Sig. (2-tailed)	0.000	0.000		0.000	0.000
		N	66	66	66	66	66
	Can you clearly hear and distinguish yourself and others at FF?	Correlation Coefficient	-.419**	-0.209	-.422**	1.000	.545**
		Sig. (2-tailed)	0.000	0.090	0.000		0.000
		N	67	67	66	67	67
	How appropriate FF Atrium sounds to you?	Correlation Coefficient	-.296*	-.350**	-.525**	.545**	1.000
		Sig. (2-tailed)	0.015	0.004	0.000	0.000	
		N	67	67	66	67	67

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

			Loudness	Reverbrance	Annoyance	Speech clarity	Appropiateness
Spearman's rho	How often do you visit these Atriums?	Correlation Coefficient	-0.055	-0.012	-0.089	0.003	0.058
		Sig. (2-tailed)	0.657	0.925	0.477	0.980	0.663
		N	67	66	66	67	59
	How long do you spend in these Atriums?	Correlation Coefficient	0.115	0.053	0.077	-0.110	0.101
		Sig. (2-tailed)	0.354	0.671	0.540	0.376	0.444
		N	67	66	66	67	59
	How loud FC Atriums sounds to you?	Correlation Coefficient	1.000	.287*	.453**	-0.204	-.313*
		Sig. (2-tailed)		0.019	0.000	0.098	0.016
		N	67	66	66	67	59
	How reverberant FC Atrium sounds to you?	Correlation Coefficient	.287*	1.000	.365**	-.248*	-0.240
		Sig. (2-tailed)	0.019		0.003	0.045	0.067
		N	66	66	65	66	59
	Are you bothered/annoyed by the sound environment FC Atriums?	Correlation Coefficient	.453**	.365**	1.000	-0.225	-.403**
		Sig. (2-tailed)	0.000	0.003		0.069	0.002
		N	66	65	66	66	58
	Can you clearly hear and distinguish yourself and others at FC?	Correlation Coefficient	-0.204	-.248*	-0.225	1.000	.466**
		Sig. (2-tailed)	0.098	0.045	0.069		0.000
		N	67	66	66	67	59
	How appropriate FC Atrium sounds to you?	Correlation Coefficient	-.313*	-0.240	-.403**	.466**	1.000
		Sig. (2-tailed)	0.016	0.067	0.002	0.000	
		N	59	59	58	59	59

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

			Loudness	Reverbrance	Annoyance	Speech clarity	Appropiateness
Spearman's rho	How often do you visit these Atriums?	Correlation Coefficient	-0.220	-0.075	-0.156	0.190	-0.011
		Sig. (2-tailed)	0.074	0.545	0.210	0.127	0.932
		N	67	67	66	66	59
	How long do you spend in these Atriums?	Correlation Coefficient	0.104	0.121	0.193	0.044	0.037
		Sig. (2-tailed)	0.402	0.329	0.120	0.727	0.783
		N	67	67	66	66	59
	How loud SA Atriums sounds to you?	Correlation Coefficient	1.000	.521**	.555**	-.525**	-.565**
		Sig. (2-tailed)		0.000	0.000	0.000	0.000
		N	67	67	66	66	59
	How reverberant SA Atrium sounds to you?	Correlation Coefficient	.521**	1.000	.517**	-.292*	-.428**
		Sig. (2-tailed)	0.000		0.000	0.017	0.001
		N	67	67	66	66	59
	Are you bothered/annoyed by the sound environment SA Atriums?	Correlation Coefficient	.555**	.517**	1.000	-.483**	-.658**
		Sig. (2-tailed)	0.000	0.000		0.000	0.000
		N	66	66	66	65	58
	Can you clearly hear and distinguish yourself and others at SA?	Correlation Coefficient	-.525**	-.292*	-.483**	1.000	.605**
		Sig. (2-tailed)	0.000	0.017	0.000		0.000
		N	66	66	65	66	58
	How appropriate SA Atrium sounds to you?	Correlation Coefficient	-.565**	-.428**	-.658**	.605**	1.000
		Sig. (2-tailed)	0.000	0.001	0.000	0.000	
		N	59	59	58	58	59

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

			Loudness	Reverbrance	Annoyance	Speech clarity	Appropiateness
Spearman's rho	How often do you visit these Atriums?	Correlation Coefficient	0.028	-0.087	-0.150	0.050	-0.103
		Sig. (2-tailed)	0.823	0.482	0.229	0.686	0.439
		N	67	67	66	67	59
	How long do you spend in these Atriums?	Correlation Coefficient	-0.049	0.047	-0.035	-0.080	-0.077
		Sig. (2-tailed)	0.696	0.705	0.781	0.522	0.565
		N	67	67	66	67	59
	How loud A/H Atriums sounds to you?	Correlation Coefficient	1.000	.422**	.470**	-.426**	-.470**
		Sig. (2-tailed)		0.000	0.000	0.000	0.000
		N	67	67	66	67	59
	How reverberant A/H Atrium sounds to you?	Correlation Coefficient	.422**	1.000	.515**	-.472**	-.345**
		Sig. (2-tailed)	0.000		0.000	0.000	0.007
		N	67	67	66	67	59
	Are you bothered/annoyed by the sound environment A/H Atriums?	Correlation Coefficient	.470**	.515**	1.000	-.478**	-.412**
		Sig. (2-tailed)	0.000	0.000		0.000	0.001
		N	66	66	66	66	58
	Can you clearly hear and distinguish yourself and others at A/H?	Correlation Coefficient	-.426**	-.472**	-.478**	1.000	.614**
		Sig. (2-tailed)	0.000	0.000	0.000		0.000
		N	67	67	66	67	59
	How appropriate A/H Atrium sounds to you?	Correlation Coefficient	-.470**	-.345**	-.412**	.614**	1.000
		Sig. (2-tailed)	0.000	0.007	0.001	0.000	
		N	59	59	58	59	59

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

D 3. Correlation between the perceived subjective characteristics and the participants' gender.

			GENDER	How loud FF Atriums sounds to you?	How loud FC Atriums sounds to you?	How loud SA Atriums sounds to you?	How loud A/H Atriums sounds to you?	How reverberant FF Atrium sounds to you?	How reverberant FC Atrium sounds to you?	How reverberant SA Atrium sounds to you?	How reverberant A/H Atrium sounds to you?
Kendall's tau_b	GENDER	Correlation Coefficient	1.000	-0.151	-.255*	0.053	-0.023	-0.161	0.022	0.166	-0.003
		Sig. (2-tailed)		0.186	0.026	0.647	0.843	0.162	0.848	0.149	0.982
		N	67	67	67	67	67	67	66	67	67

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

			GENDER	Are you bothered/annoyed by the sound environment FF Atriums?	Are you bothered/annoyed by the sound environment FC Atriums?	Are you bothered/annoyed by the sound environment SA Atriums?	Are you bothered/annoyed by the sound environment A/H Atriums?	Can you clearly hear and distinguish yourself and others at FF?	Can you clearly hear and distinguish yourself and others at FC?	Can you clearly hear and distinguish yourself and others at SA?	Can you clearly hear and distinguish yourself and others at A/H?
Kendall's tau_b	GENDER	Correlation Coefficient	1.000	0.036	-0.051	0.064	0.158	0.049	0.048	-0.120	-0.172
		Sig. (2-tailed)		0.751	0.653	0.579	0.166	0.670	0.677	0.306	0.139
		N	67	66	66	66	66	67	67	66	67

			GENDER	How appropriate FF Atrium sounds to you?	How appropriate FC Atrium sounds to you?	How appropriate SA Atrium sounds to you?	How appropriate A/H Atrium sounds to you?
Kendall's tau_b	GENDER	Correlation Coefficient	1.000	0.010	-0.004	-0.117	-0.202
		Sig. (2-tailed)		0.932	0.971	0.341	0.104
		N	67	67	59	59	59